Anonymous, Robust Post-Quantum Public Key Encryption

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APPLIED CRYPTO GROUP

Joint work with Paul Grubbs and Kenneth G. Paterson

[Full version of paper: https://eprint.iacr.org/2021/708.pdf]

NIST PQC Round-3 KEMs

PQC Standardization Process: Third Round Candidate Announcement

NIST is announcing the third round finalists of the NIST Post-Quantum Cryptography Standardization Process. More details are included in NISTIR 8309.

July 22, 2020

It has been almost a year and a half since the second round of the NIST PQC Standardization Process began. After careful consideration, NIST would like to announce the candidates that will be moving on to the third round.

Third Round Finalists	Alternate Candidates
Public-Key Encryption/KEMs	Public-Key Encryption/KEMs
Classic McEliece	BIKE
CRYSTALS-KYBER	FrodoKEM
NTRU	HQC
SABER	NTRU Prime
	SIKE

ORGANIZATIONS

Information Technology Laboratory

Computer Security Division

Cryptographic Technology Group

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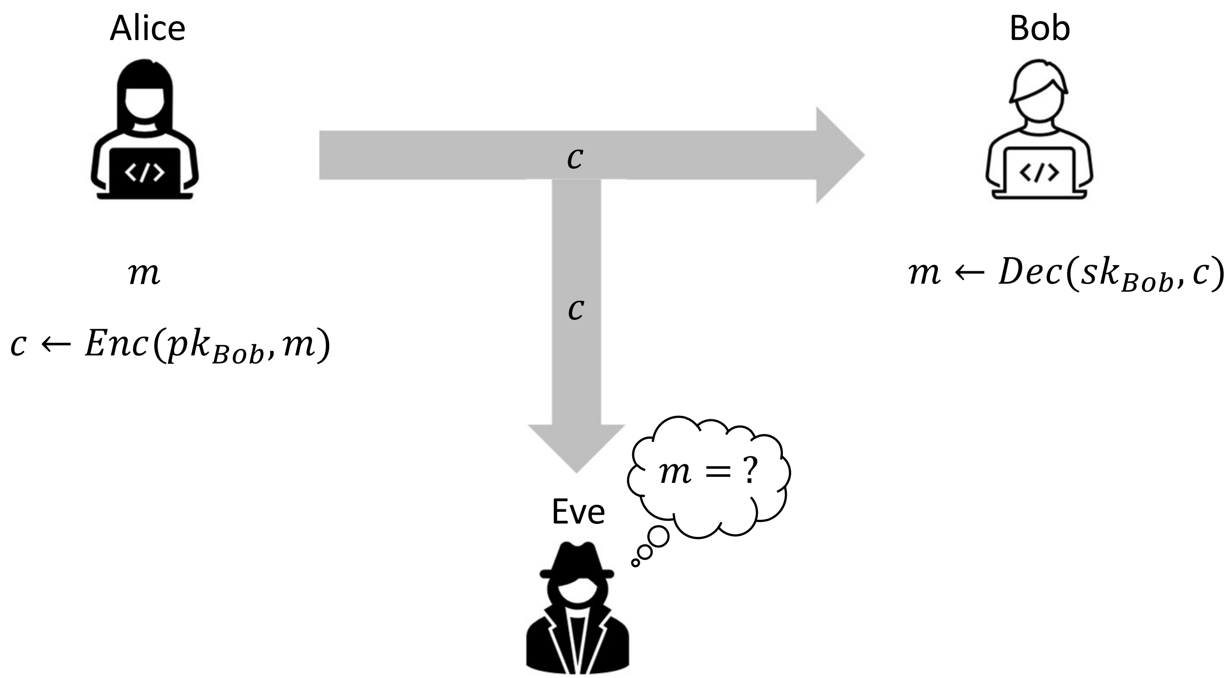
4.A.2 Security Definition for Encryption/Key-Establishment

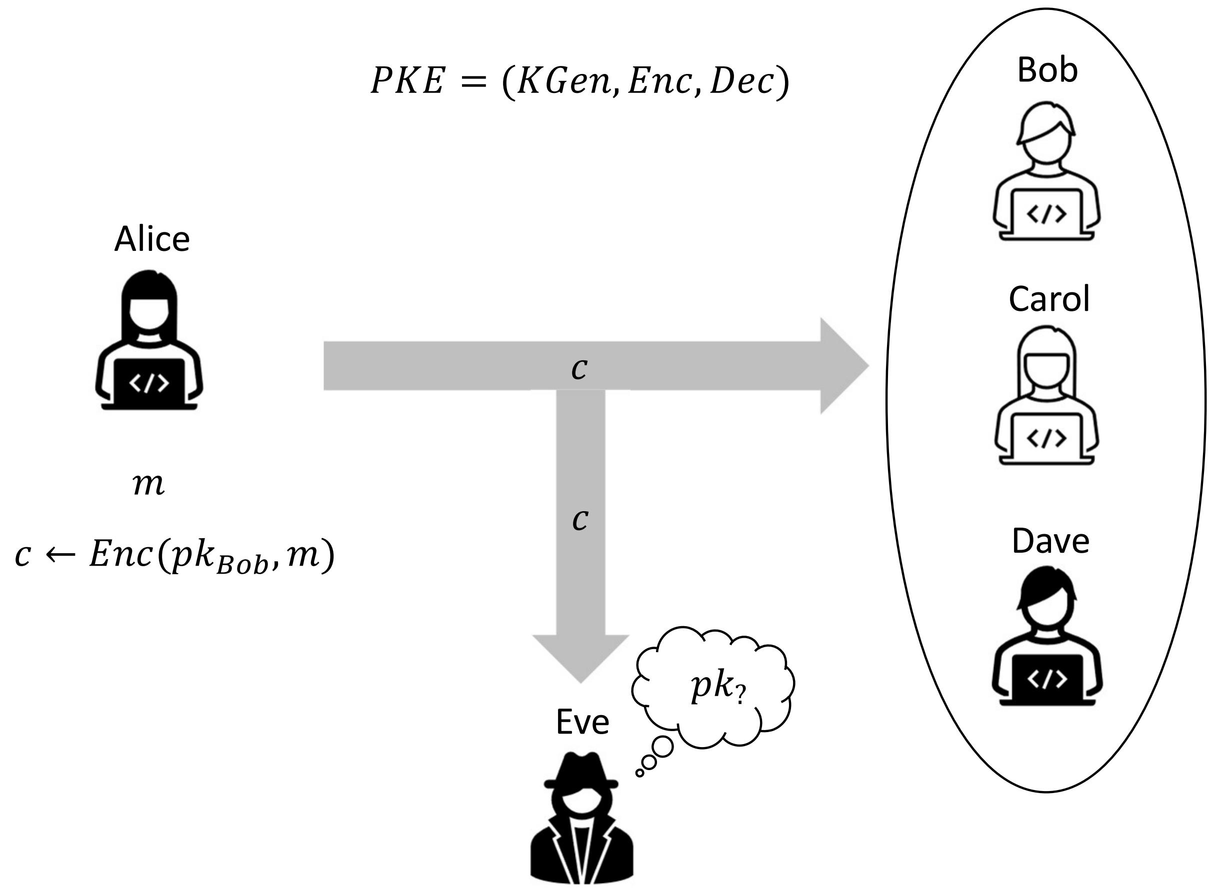
NIST intends to standardize one or more schemes that enable "semantically secure" encryption or key encapsulation with respect to adaptive chosen ciphertext attack, for general use. This property is generally denoted *IND-CCA2 security* in academic literature.

IND-CCA Security

$$PKE = (KGen, Enc, Dec)$$



Anonymity (ANO-CCA security)



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Formalized in a public-key setting by [Bellare-Boldyreva-Desai-Pointcheval'01].

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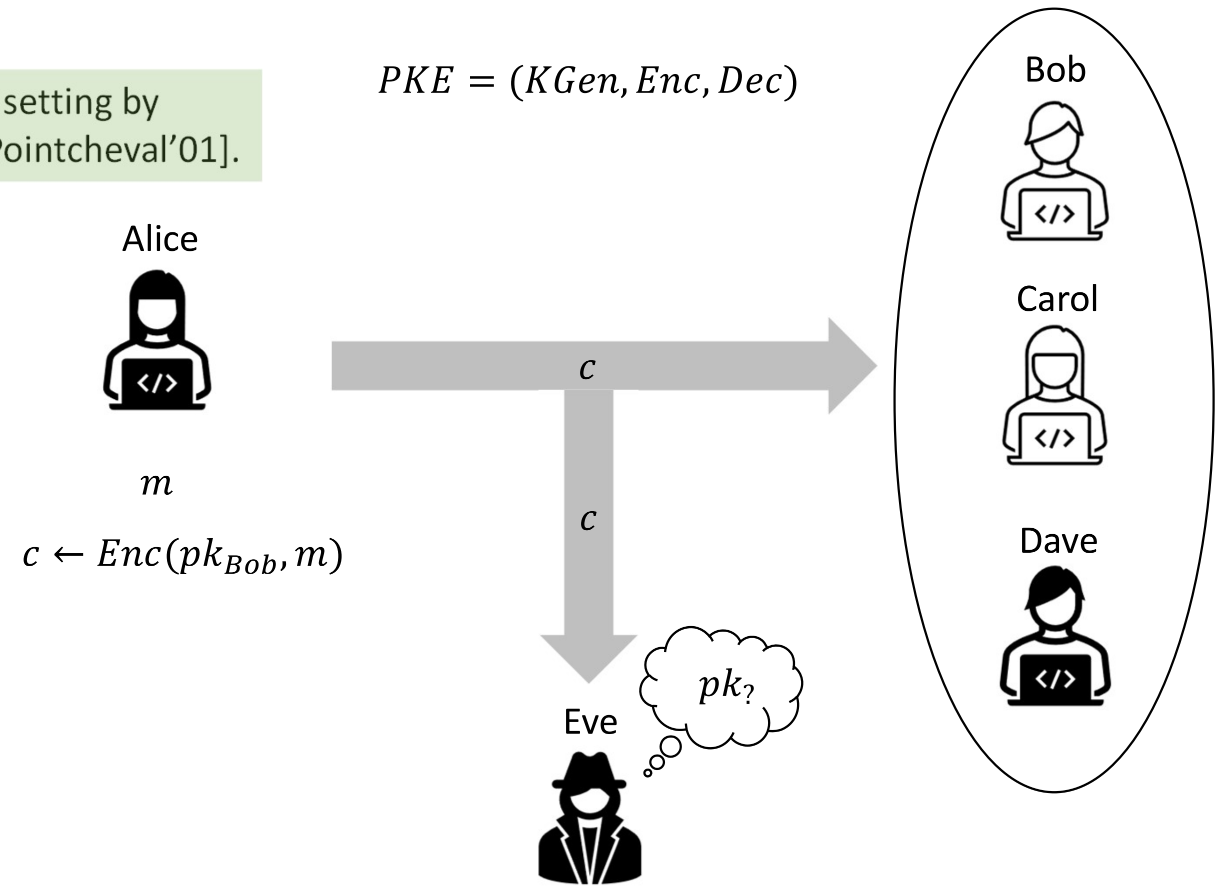

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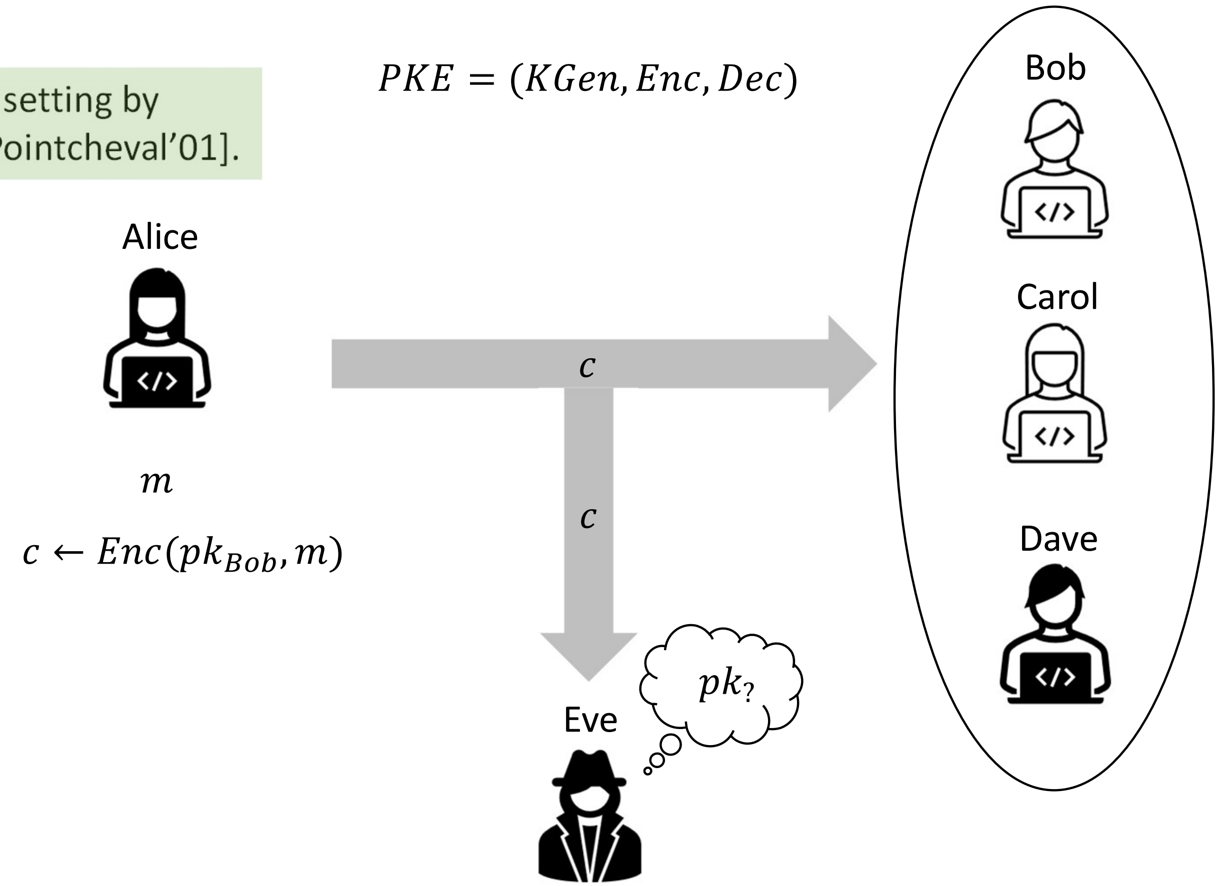


Anonymity (ANO-CCA security)

Formalized in a public-key setting by [Bellare-Boldyreva-Desai-Pointcheval’01].

$PKE = (KGen, Enc, Dec)$

Alice

m

$c \leftarrow Enc(pk_{Bob}, m)$

c

c

Eve

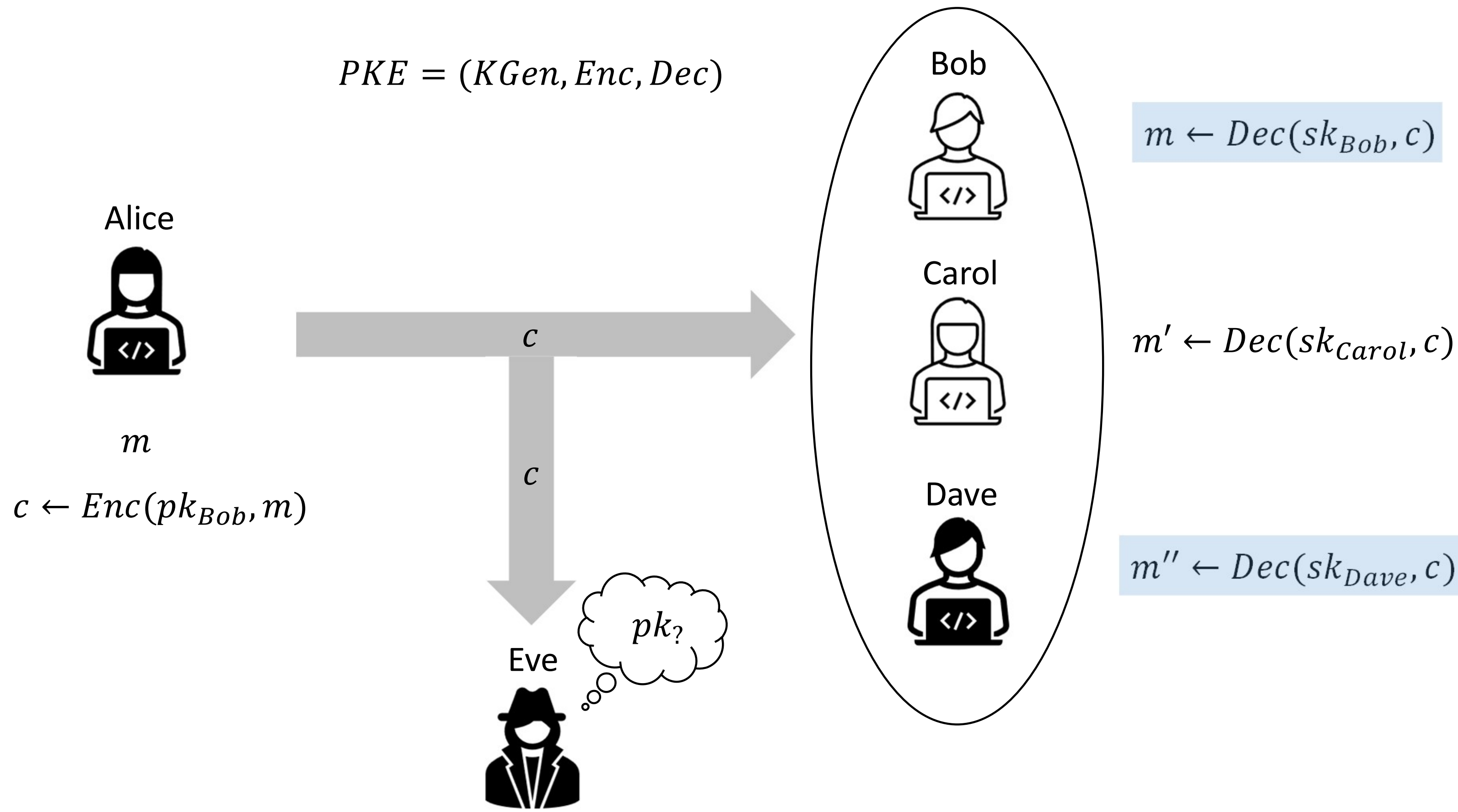
$pk_?$

Bob

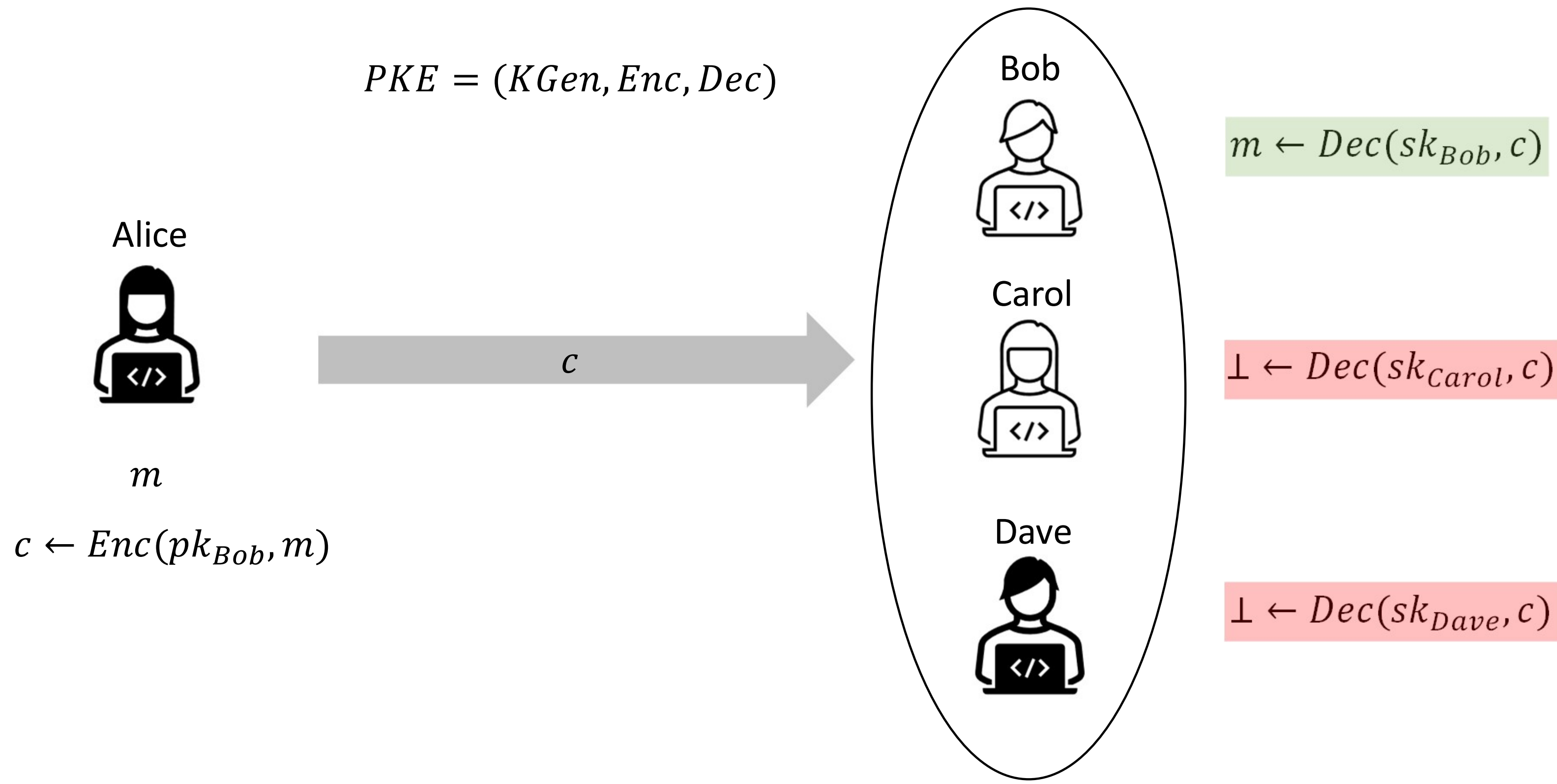
Carol

Dave

Anonymity (ANO-CCA security)



Robustness (SROB-CCA security)



Robustness (SROB-CCA security)

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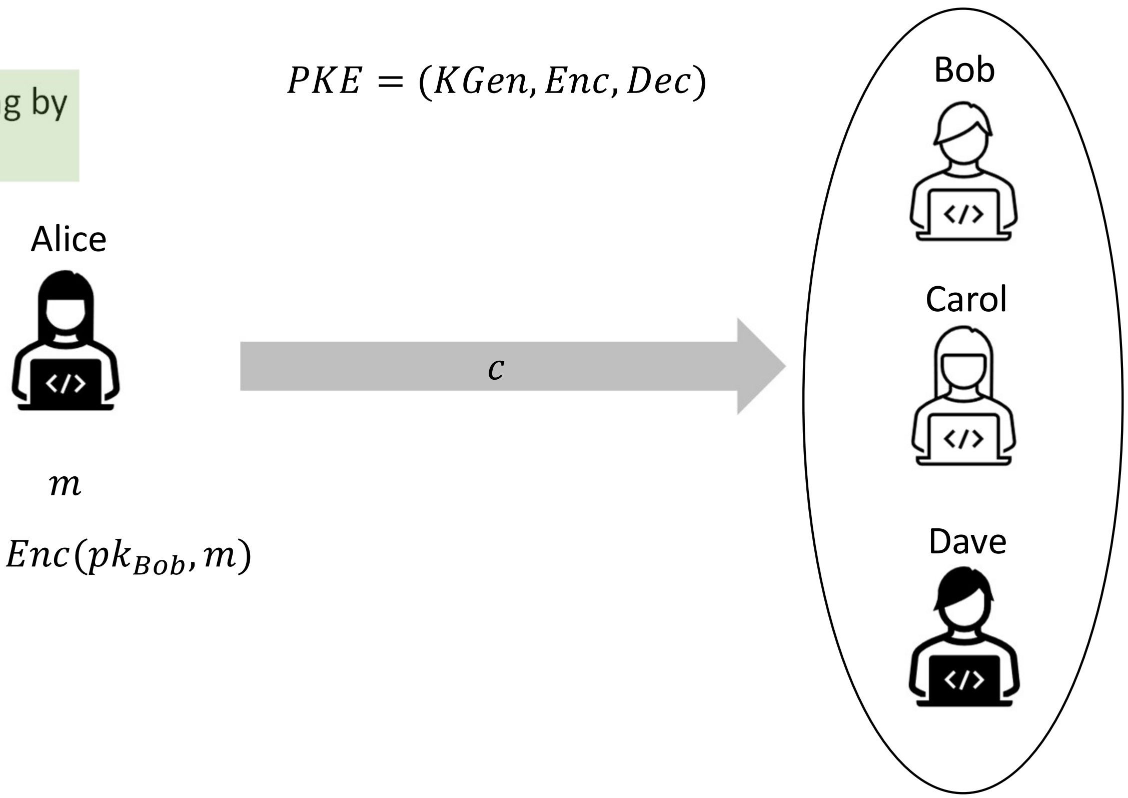

m

$c \leftarrow Enc(pk_{Bob}, m)$

$m \leftarrow Dec(sk_{Bob}, c)$

$\perp \leftarrow Dec(sk_{Carol}, c)$

$\perp \leftarrow Dec(sk_{Dave}, c)$

KEM-DEM Paradigm

Public-Key Encryption/KEMs

Classic McEliece

CRYSTALS-KYBER

NTRU

SABER

Public-Key Encryption/KEMs

BIKE

FrodoKEM

HQC

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SIKE

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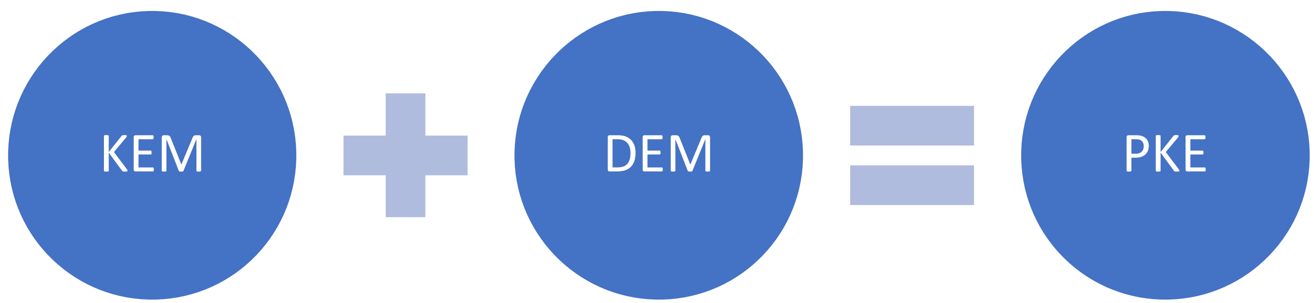

IND-CCA secure

(one-time) authenticated encryption

IND-CCA secure ✓

KEM-DEM Paradigm

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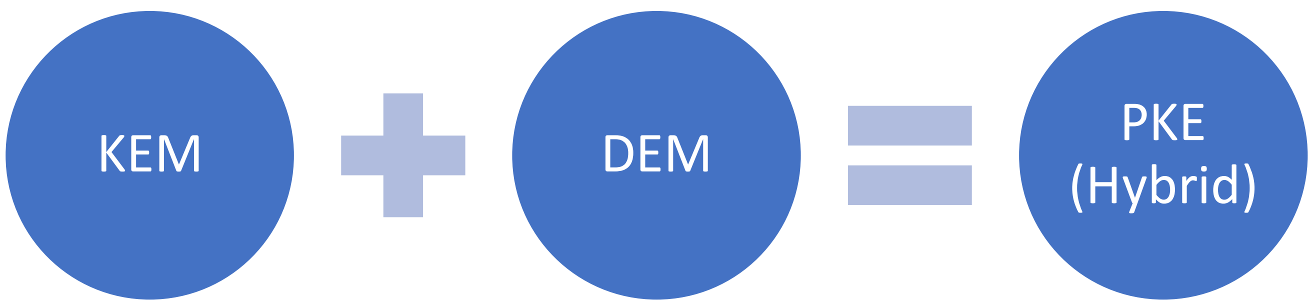

$(c_{KEM}, k) \leftarrow Encap(pk_{Bob})$

IND-CCA secure

$c_{DEM} \leftarrow Enc^{sym}(k, m)$

(one-time) authenticated encryption

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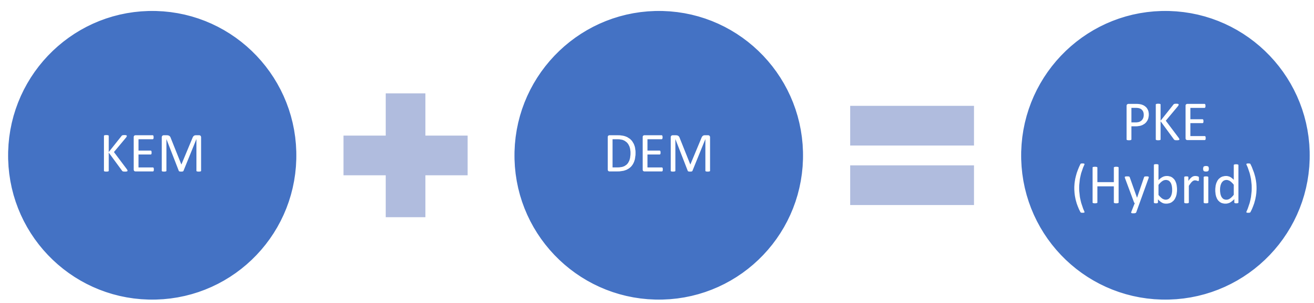

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IND-CCA secure +
ANO-CCA secure

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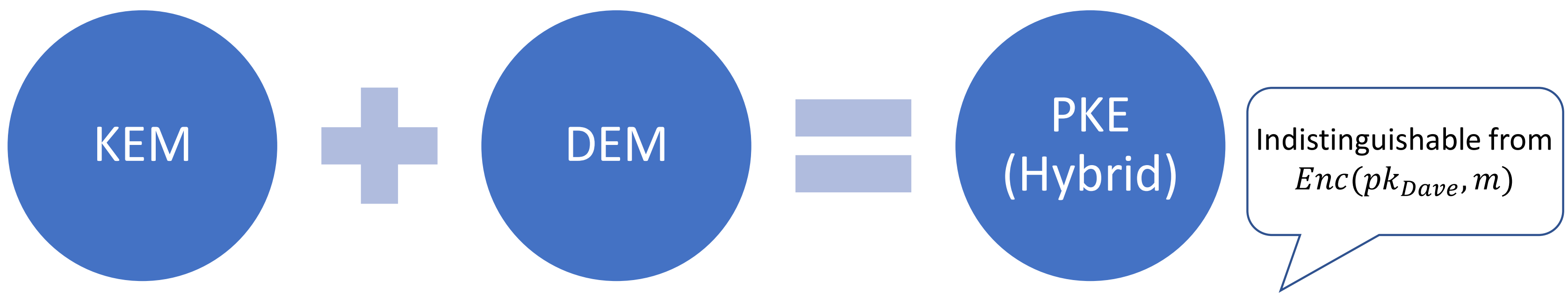

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Shown in [Grubbs-Maram-Paterson'22]; generalization of [Mohassel'10].

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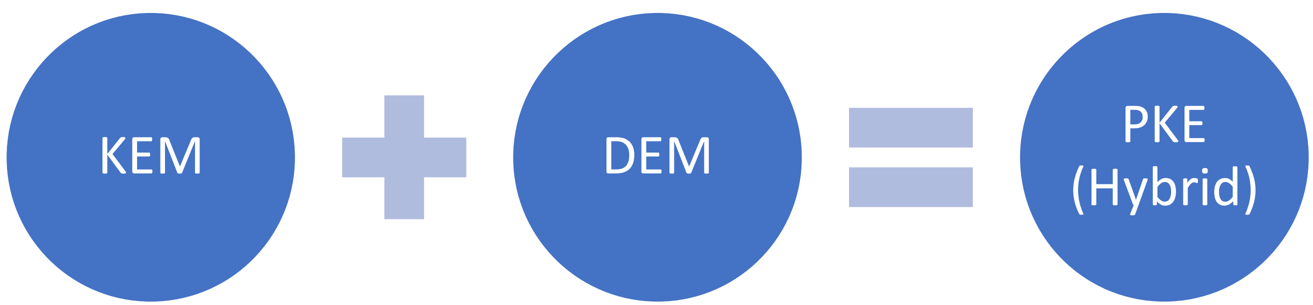

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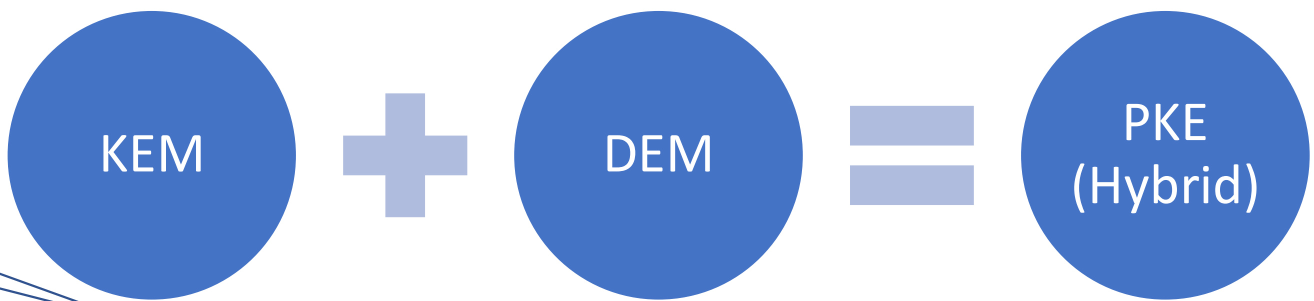
Indistinguishable from $Encap(pk_{Dave})$



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IND-CCA + ANO-CCA secure

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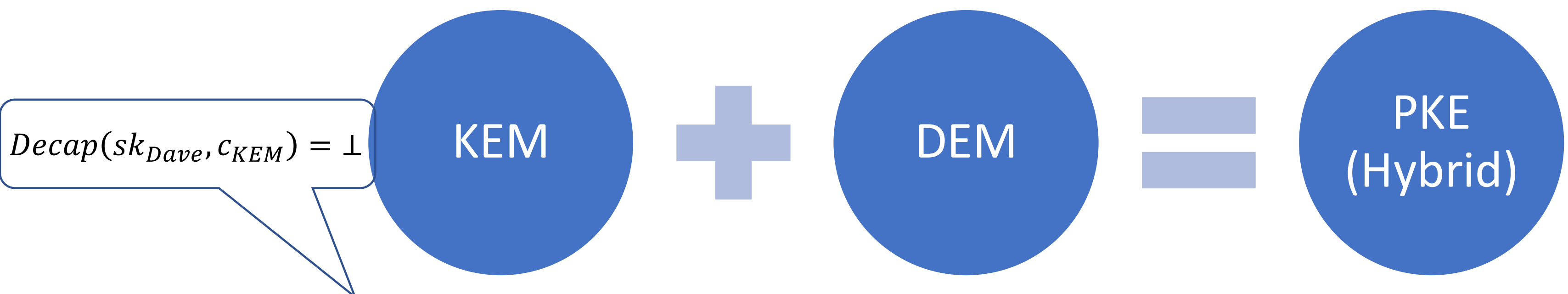

$(c_{KEM}, k) \leftarrow Encap(pk_{Bob})$

IND-CCA + ANO-CCA secure + weakly robust

$c_{DEM} \leftarrow Enc^{sym}(k, m)$

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[Mohassel'10] only considered KEMs constructed <u>directly</u> from PKE schemes.

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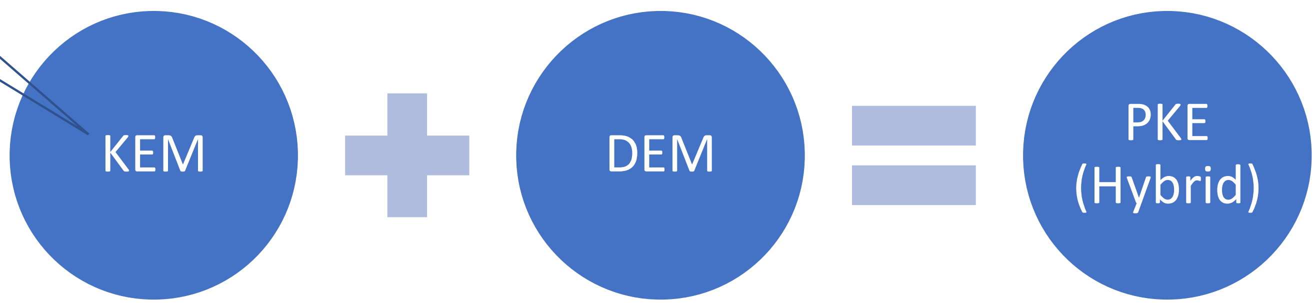

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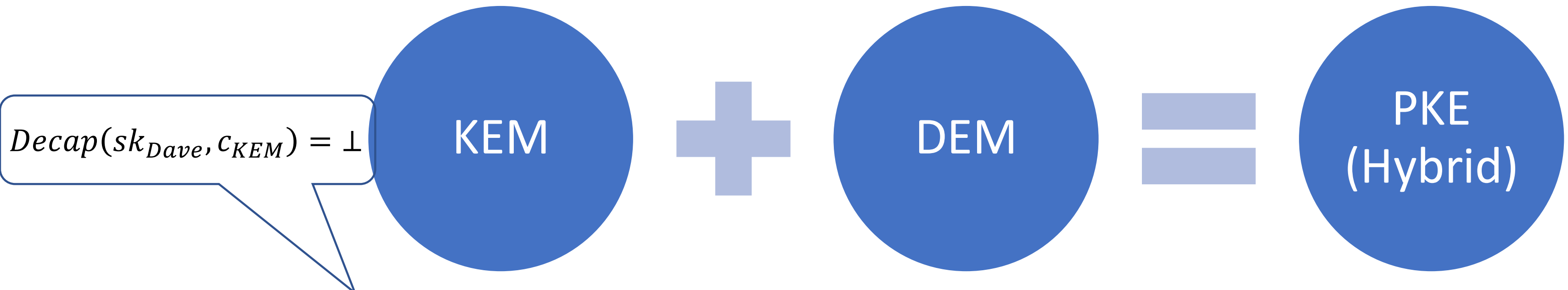

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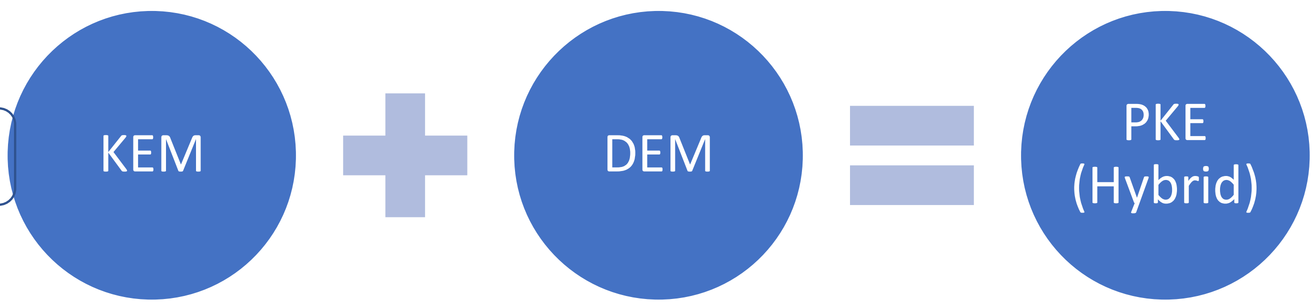
$Decap(sk_{Dave}, c_{KEM}) = \bot$



... is also necessary.

$(c_{KEM}, k) \leftarrow Encap(pk_{Bob})$

IND-CCA + ANO-CCA secure
+ weakly robust

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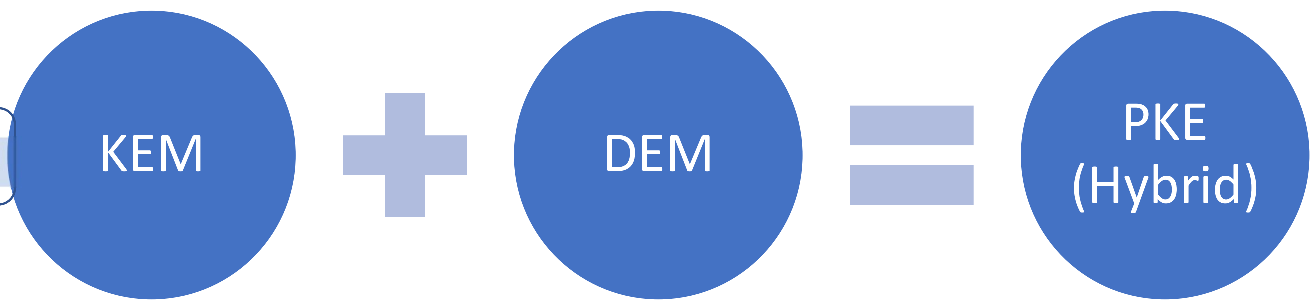

$Decap(sk_{Dave}, c_{KEM}) = \perp$

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"Implicit-rejection" KEMs!

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KEM + DEM = PKE (Hybrid)

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... is also necessary.

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“Implicit-rejection” KEMs!

Cannot be even weakly robust.

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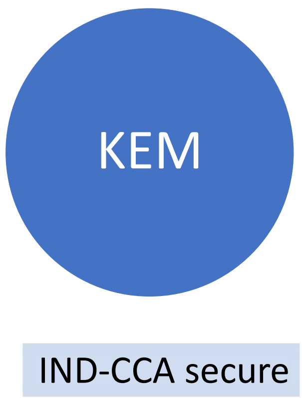
Fujisaki-Okamoto Transformation



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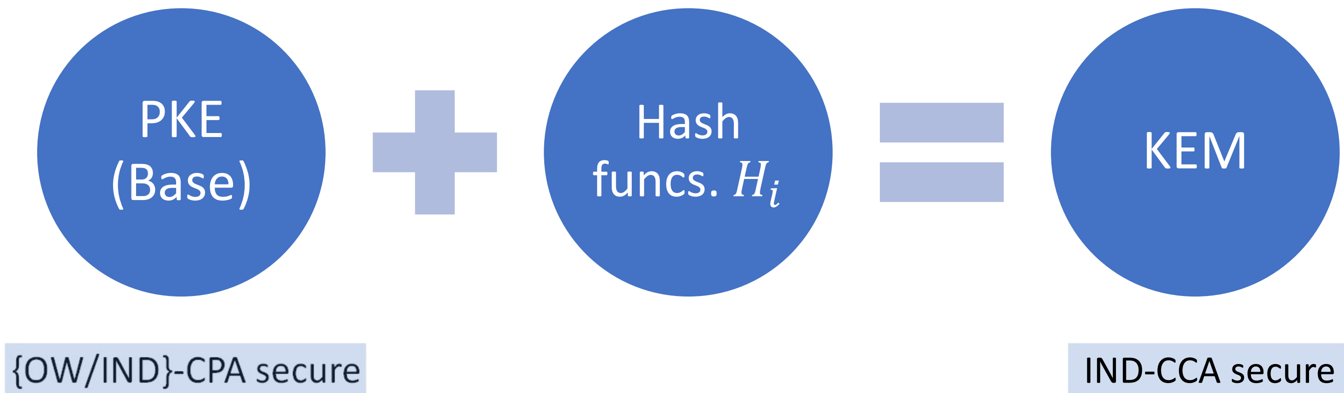

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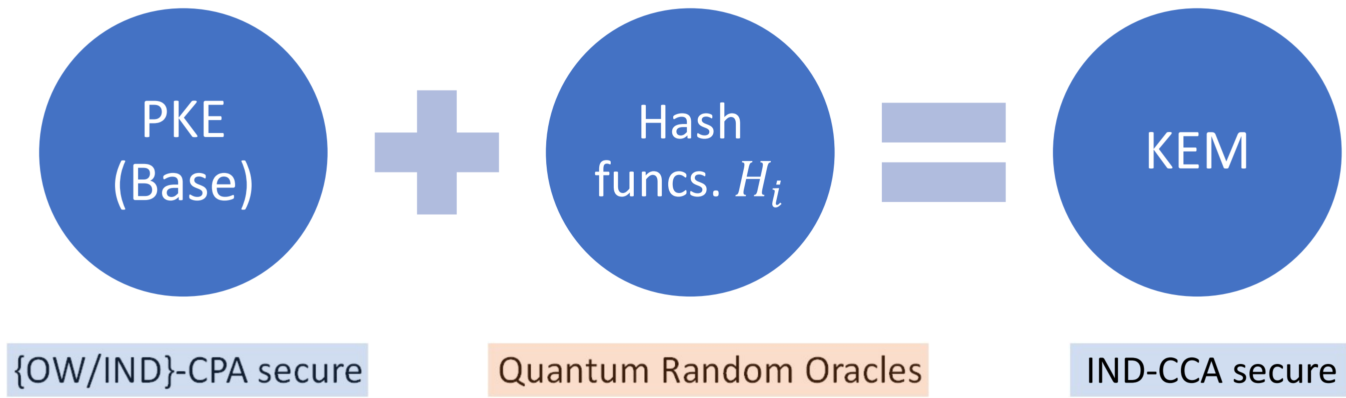

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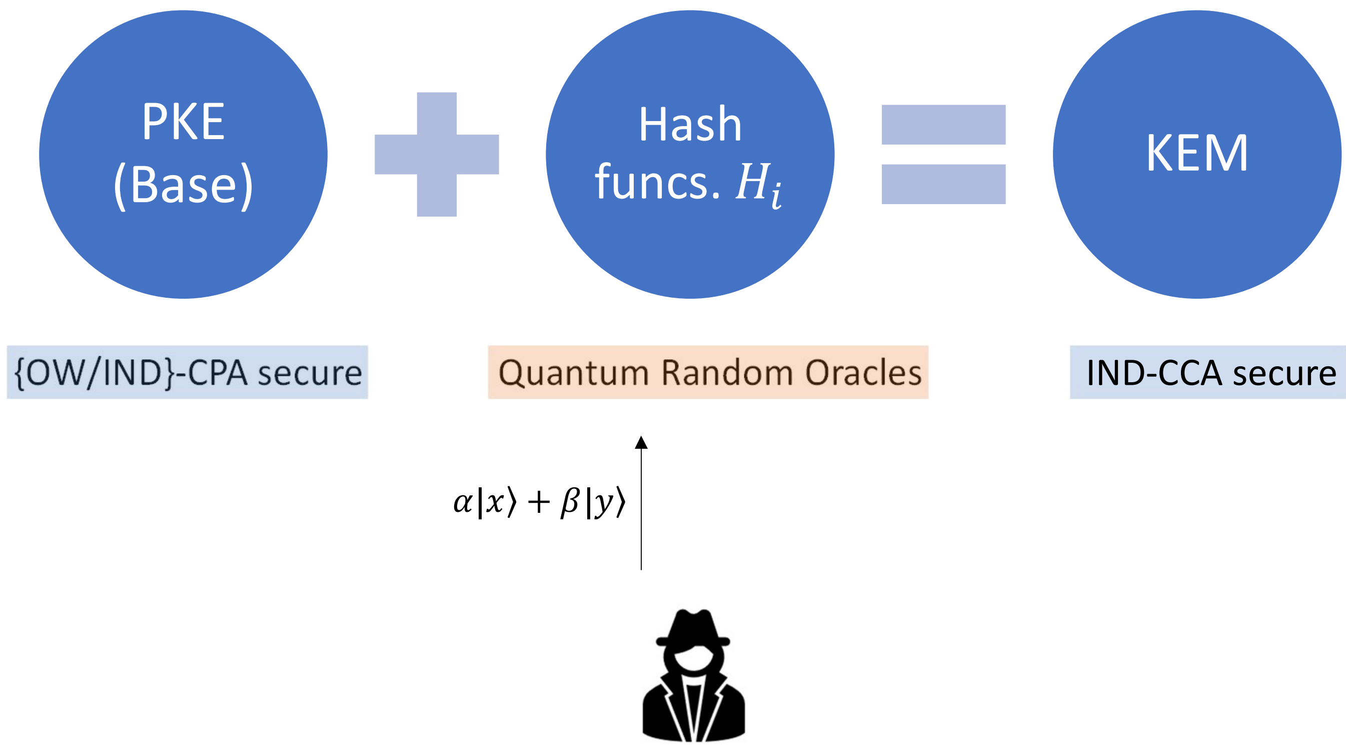

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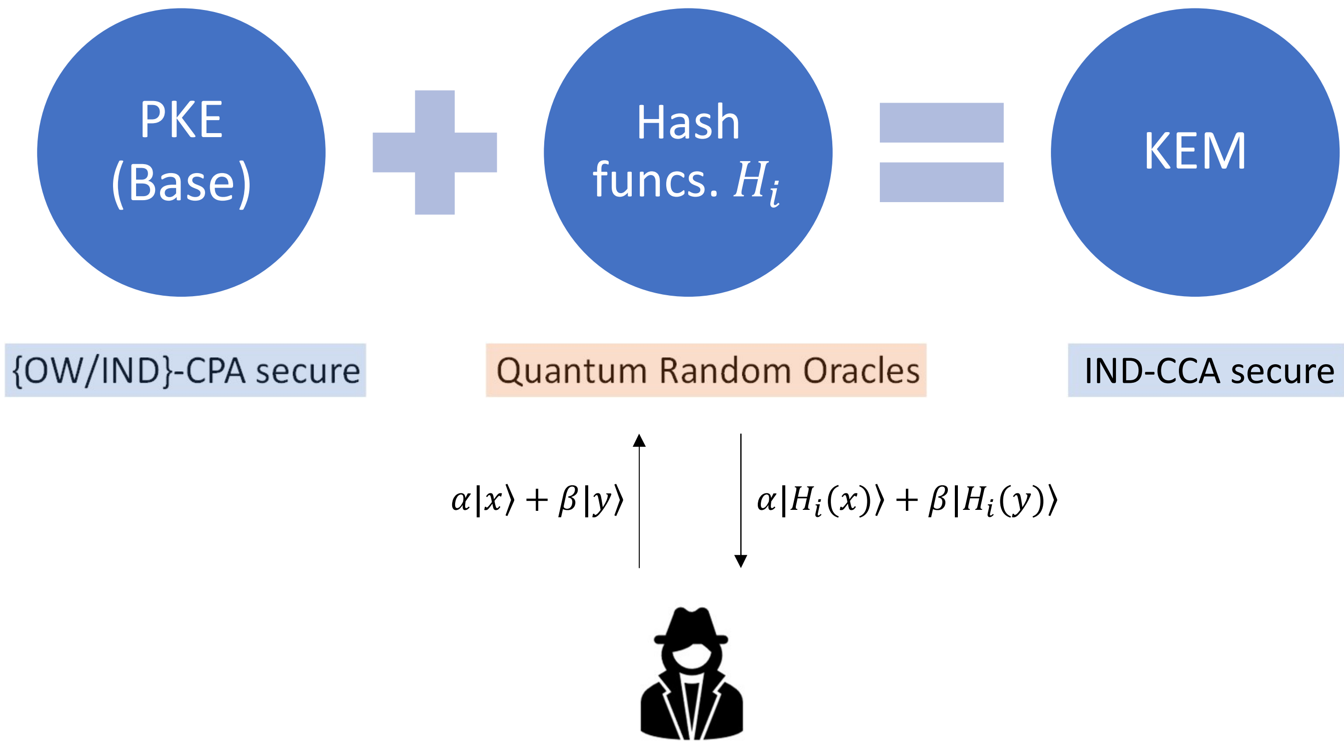

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KGen'	$\mathsf{Encap}(\mathsf{pk})$	$\mathsf{Decap}(\mathsf{sk}', c)$
$(\mathsf{pk}, \mathsf{sk}) \leftarrow \mathsf{KGen}$	$m \leftarrow_{\$} \mathcal{M}$	Parse $\mathsf{sk}' = (\mathsf{sk}, s)$
$s \leftarrow_{\$} \mathcal{M}$	$c \leftarrow \mathsf{Enc}(\mathsf{pk}, m; G(m))$	$m' \leftarrow \mathsf{Dec}(\mathsf{sk}, c)$
$\mathsf{sk}' = (\mathsf{sk}, s)$	$k \leftarrow H(m, c)$	$c' \leftarrow \mathsf{Enc}(\mathsf{pk}, m'; G(m'))$
return $(\mathsf{pk}, \mathsf{sk}')$	**return** (c, k)	**if** $c' = c$ **then**
		return $H(m', c)$
		else return $H(s, c)$

$\mathsf{FO}^{\not\perp}$

Fujisaki-Okamoto Transformation

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$\mathsf{sk}' = (\mathsf{sk}, s)$	$k \leftarrow H(m, c)$	$c' \leftarrow \mathsf{Enc}(\mathsf{pk}, m'; G(m'))$
return $(\mathsf{pk}, \mathsf{sk}')$	**return** (c, k)	**if** $c' = c$ **then**
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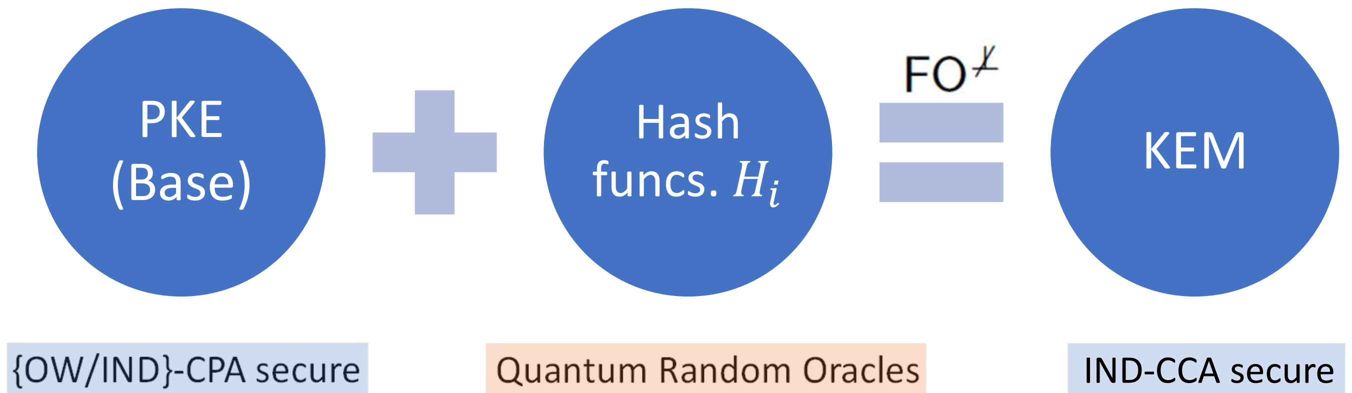
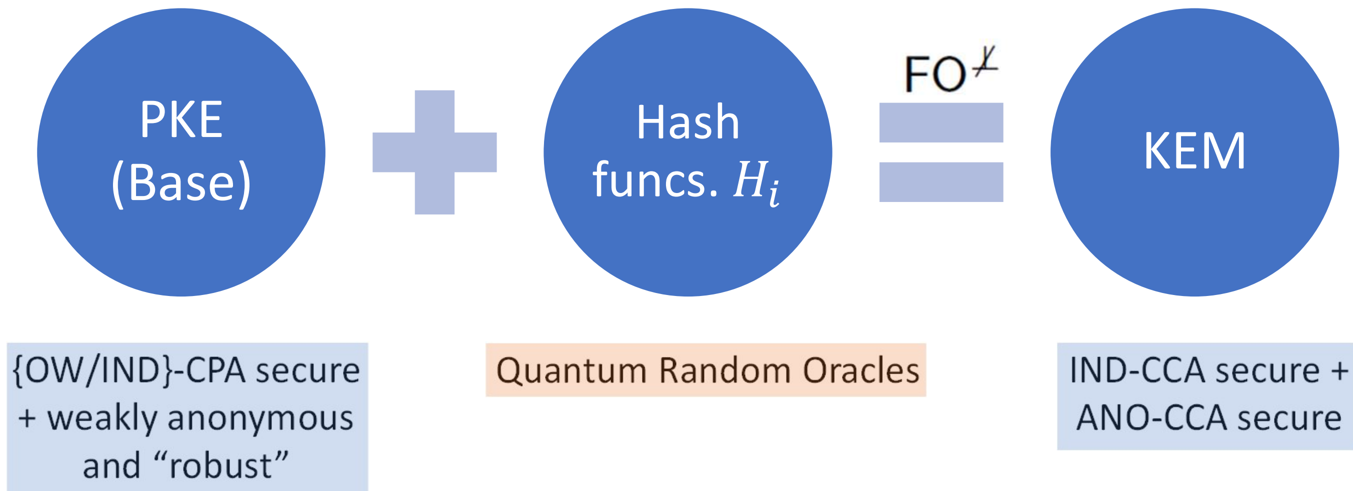
$\mathsf{FO}^{\not\perp}$

Anonymity from FO transforms



Shown in [Jiang-Zhang-Chen-Wang-Ma’18]

Anonymity from FO transforms



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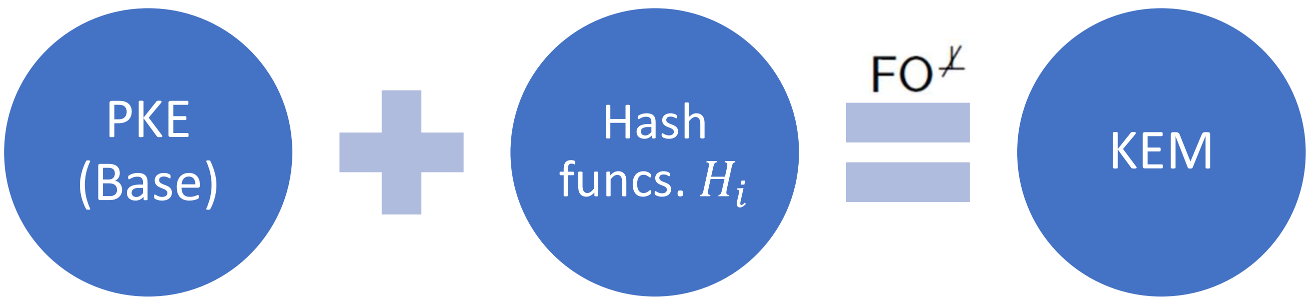


{OW/IND}-CPA secure + weakly anonymous and "robust"

Quantum Random Oracles

IND-CCA secure + ANO-CCA secure

Shown in [Grubbs-Maram-Paterson'22]

Extended [Jiang et. al.'18]'s proof techniques from a *single-key* setting (IND-CCA) to a *two-key* setting (ANO-CCA).

KEM-DEM Paradigm

Public-Key Encryption/KEMs

- Classic McEliece
- CRYSTALS-KYBER
- NTRU
- SABER

"Implicit-rejection" KEMs!

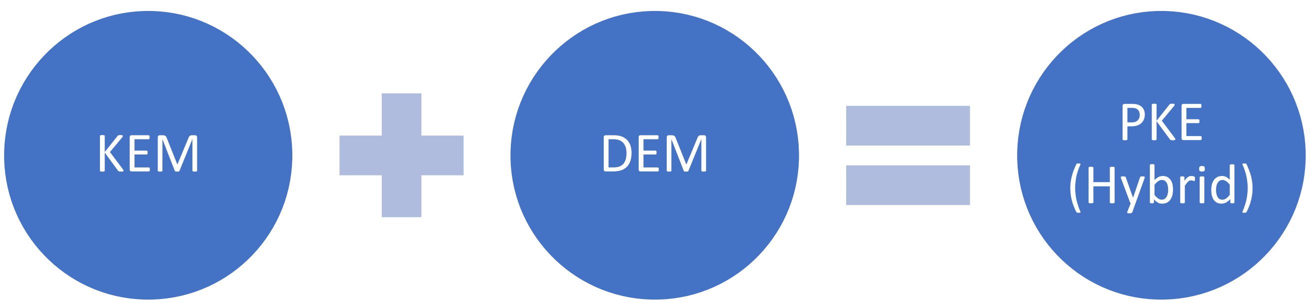
Cannot be even weakly robust.

Public-Key Encryption/KEMs

- BIKE
- FrodoKEM
- HQC
- NTRU Prime
- SIKE

Shown in [Grubbs-Maram-Paterson'22]; generalization of [Mohassel'10].

$KEM = (KGen, Encap, Decap)$ $DEM = (Enc^{sym}, Dec^{sym})$ $PKE = (KGen, Enc, Dec)$



$(c_{KEM}, k) \leftarrow Encap(pk_{Bob})$

IND-CCA + ANO-CCA secure + weakly robust

... is also necessary.

$c_{DEM} \leftarrow Enc^{sym}(k, m)$

(one-time) authenticated encryption

$(c_{KEM}, c_{DEM}) \leftarrow Enc(pk_{Bob}, m)$

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Classic McEliece (CM)

Public-Key Encryption/KEMs	Public-Key Encryption/KEMs
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CRYSTALS-KYBER	FrodoKEM
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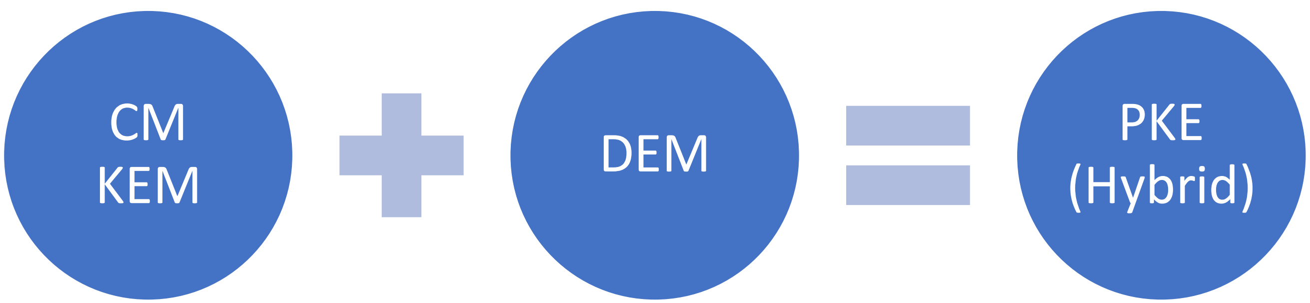
CM uses a *deterministic* base PKE scheme.



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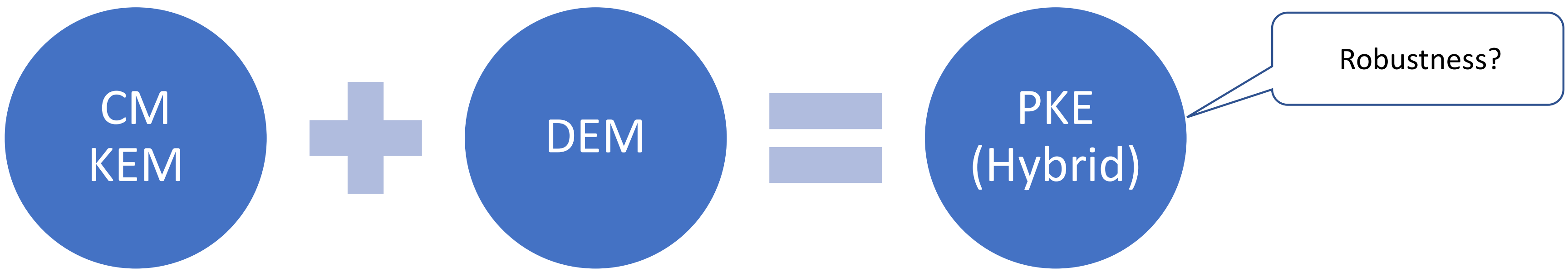

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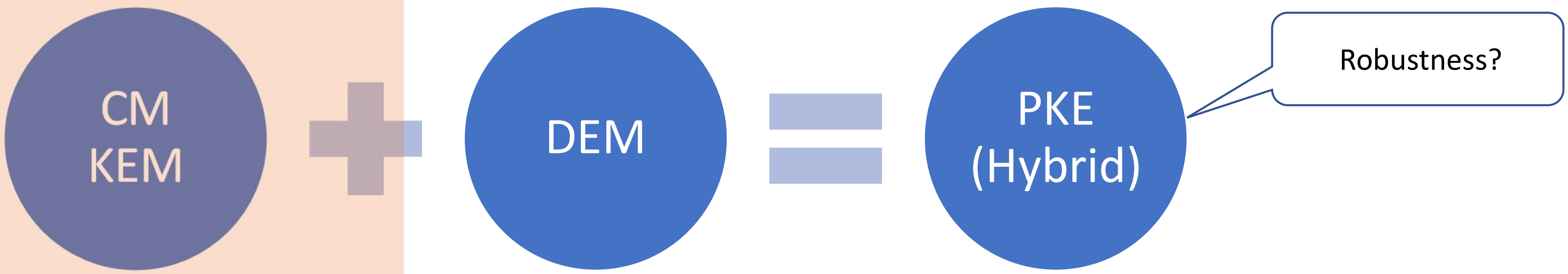

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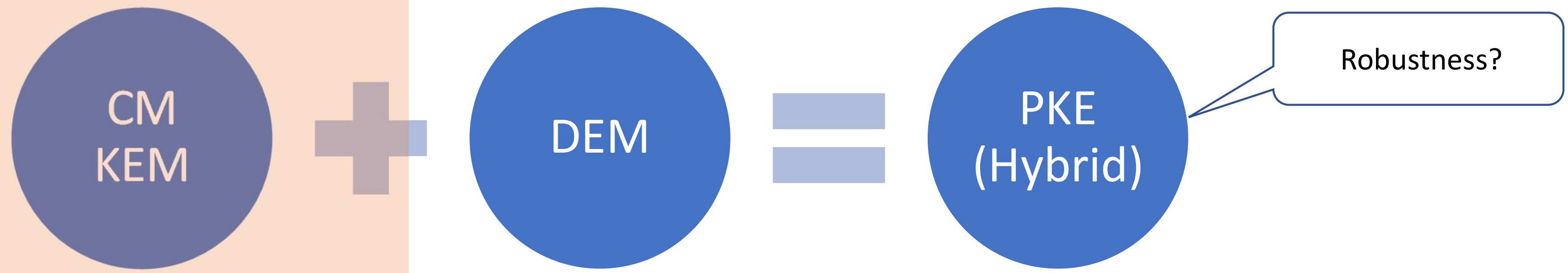

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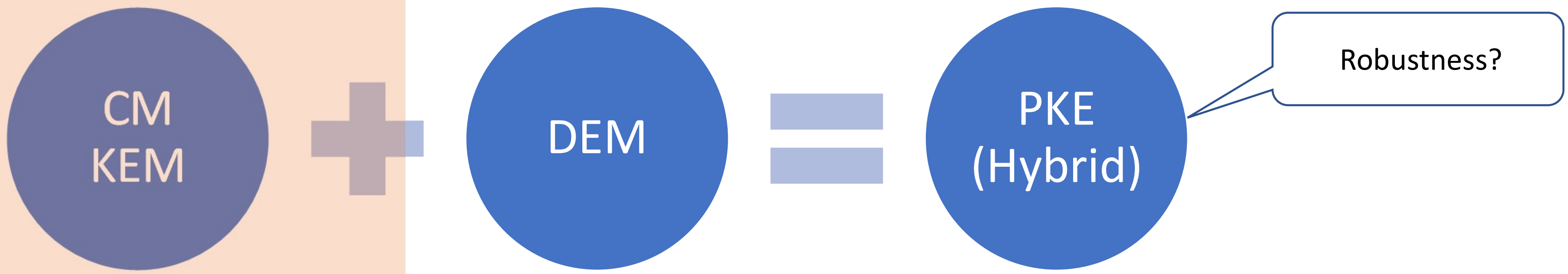

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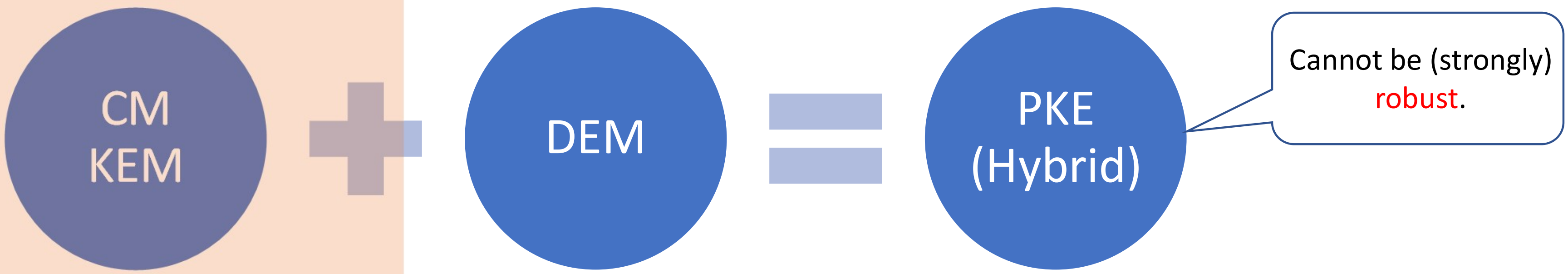

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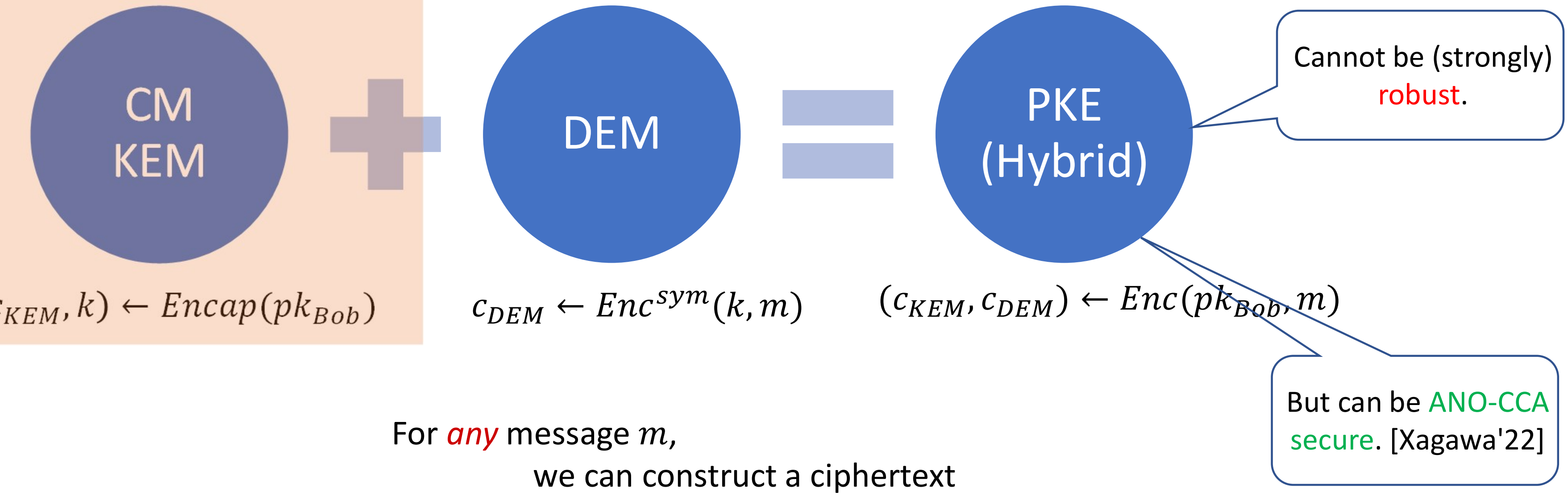

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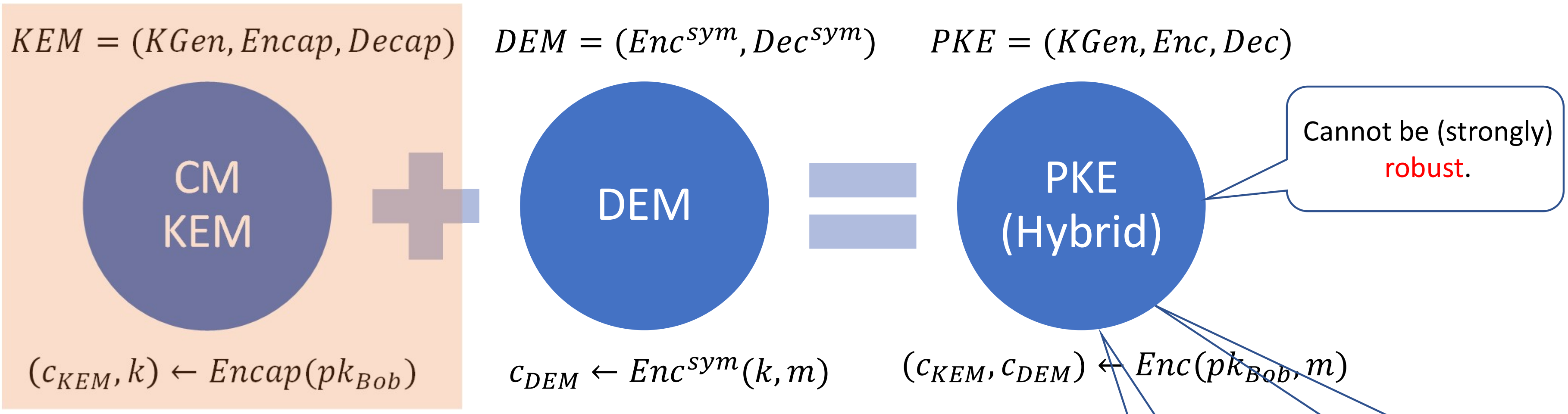

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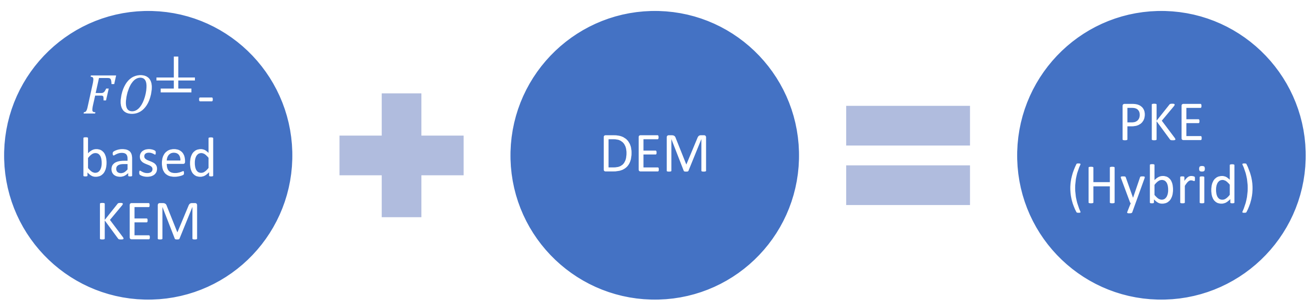

$(c_{KEM}, k) \leftarrow Encap(pk_{Bob})$

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(one-time) authenticated encryption

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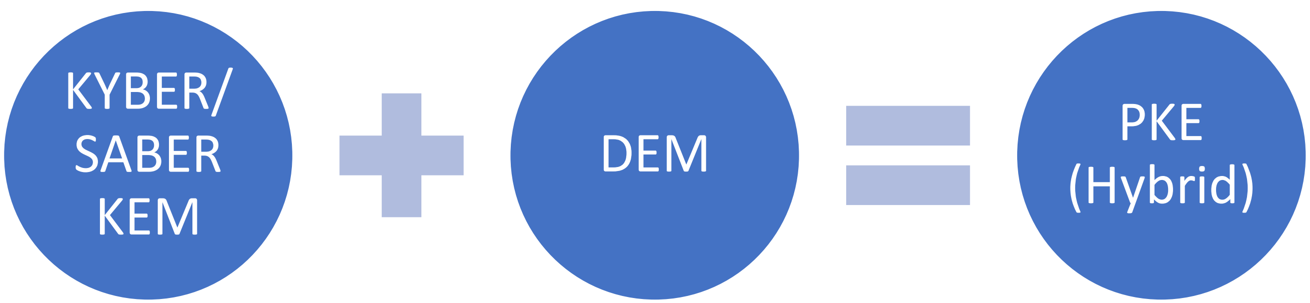

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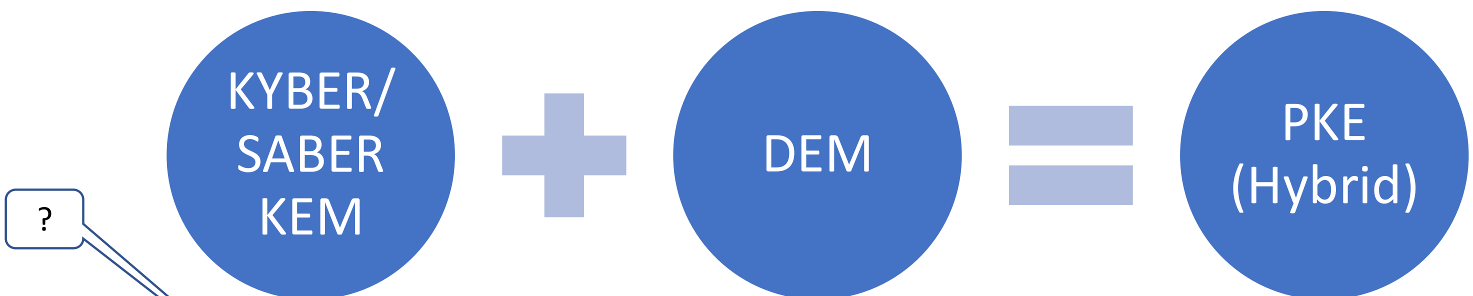

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KGen'	$\mathsf{Encap}(\mathsf{pk})$	$\mathsf{Decap}(\mathsf{sk}', c)$
$(\mathsf{pk}, \mathsf{sk}) \leftarrow \mathsf{KGen}$	$m \leftarrow_{\$} \mathcal{M}$	Parse $\mathsf{sk}' = (\mathsf{sk}, s)$
$s \leftarrow_{\$} \mathcal{M}$	$r \leftarrow G(m)$	$m' \leftarrow \mathsf{Dec}(\mathsf{sk}, c)$
$\mathsf{sk}' = (\mathsf{sk}, s)$	$c \leftarrow \mathsf{Enc}(\mathsf{pk}, m; r)$	$r' \leftarrow G(m')$
return $(\mathsf{pk}, \mathsf{sk}')$	$k \leftarrow H(m, c)$	$c' \leftarrow \mathsf{Enc}(\mathsf{pk}, m'; r')$
	return (c, k)	**if** $c' = c$ **then**
		return $H(m', c)$
		else return $H(s, c)$

$\mathsf{FO}^{\not\perp}$

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$(\mathsf{pk}, \mathsf{sk}) \leftarrow \mathsf{KGen}$	$m \leftarrow_{\$} \mathcal{M}$	Parse $\mathsf{sk}' = (\mathsf{sk}, \mathsf{pk}, F(\mathsf{pk}), s)$
$s \leftarrow_{\$} \mathcal{M}$	$m \leftarrow F(m)$	$m' \leftarrow \mathsf{Dec}(\mathsf{sk}, c)$
$\mathsf{sk}' \leftarrow (\mathsf{sk}, \mathsf{pk}, F(\mathsf{pk}), s)$	$(\hat{k}, r) \leftarrow G(F(pk), m)$	$(\hat{k}', r') \leftarrow G(F(\mathsf{pk}), m')$
return $(\mathsf{pk}, \mathsf{sk}')$	$c \leftarrow \mathsf{Enc}(\mathsf{pk}, m; r)$	$c' \leftarrow \mathsf{Enc}(\mathsf{pk}, m'; r')$
	$k \leftarrow \mathsf{KDF}(\hat{k}, F(c))$	**if** $c' = c$ **then**
	return (c, k)	**return** $\mathsf{KDF}(\hat{k}', F(c))$
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CRYSTALS-KYBER, Saber

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CRYSTALS-KYBER

NTRU

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BIKE

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“$k \leftarrow H(m, c)$”

KGen'	$\mathsf{Encap}(\mathsf{pk})$	$\mathsf{Decap}(\mathsf{sk}', c)$
$(\mathsf{pk}, \mathsf{sk}) \leftarrow \mathsf{KGen}$	$m \leftarrow_{\$} \mathcal{M}$	Parse $\mathsf{sk}' = (\mathsf{sk}, s)$
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$\mathsf{sk}' = (\mathsf{sk}, s)$	$c \leftarrow \mathsf{Enc}(\mathsf{pk}, m; r)$	$r' \leftarrow G(m')$
return $(\mathsf{pk}, \mathsf{sk}')$	$k \leftarrow H(m, c)$	$c' \leftarrow \mathsf{Enc}(\mathsf{pk}, m'; r')$
	return (c, k)	**if** $c' = c$ **then**
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“$k \leftarrow H(G(m), F(c))$”

KGen'	$\mathsf{Encap}(\mathsf{pk})$	$\mathsf{Decap}(\mathsf{sk}', c)$
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$s \leftarrow_{\$} \mathcal{M}$	$m \leftarrow F(m)$	$m' \leftarrow \mathsf{Dec}(\mathsf{sk}, c)$
$\mathsf{sk}' \leftarrow (\mathsf{sk}, \mathsf{pk}, F(\mathsf{pk}), s)$	$(\hat{k}, r) \leftarrow G(F(pk), m)$	$(\hat{k}', r') \leftarrow G(F(\mathsf{pk}), m')$
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CRYSTALS-KYBER, Saber

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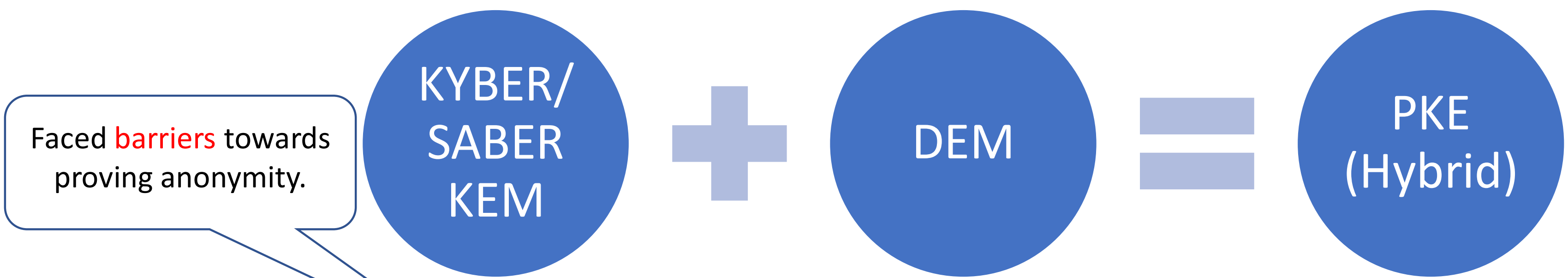

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(one-time) authenticated encryption

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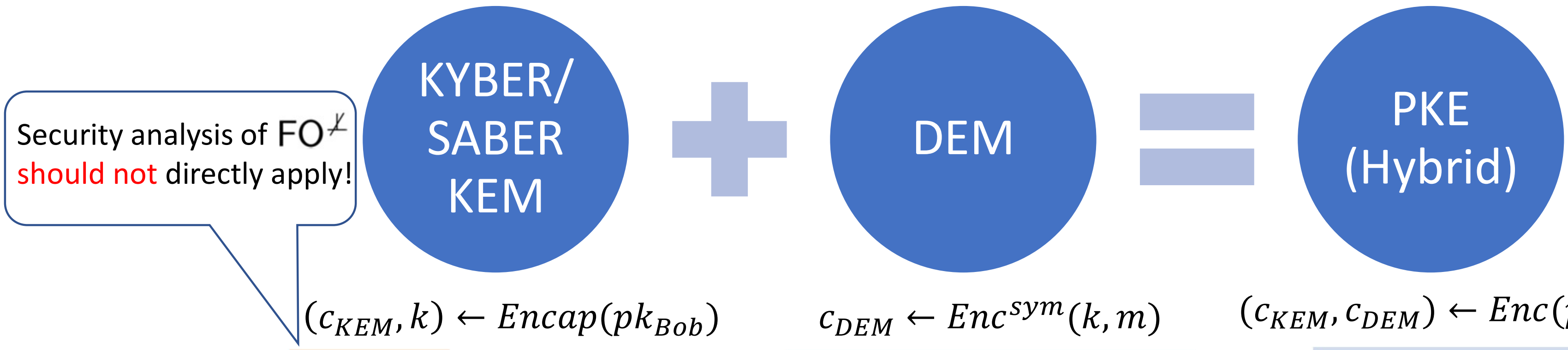

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Is "robust". [Grubbs-Maram-Paterson'22]

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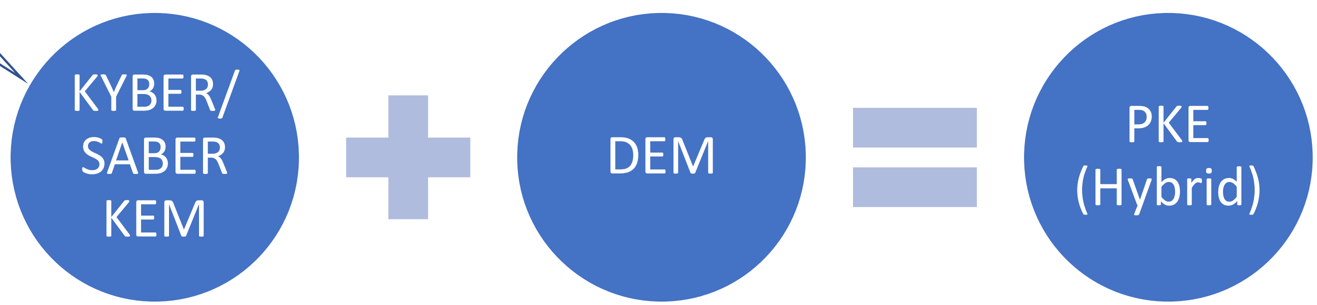

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$Decap(sk_{Bob}, c) \neq Decap(sk_{Dave}, c)$

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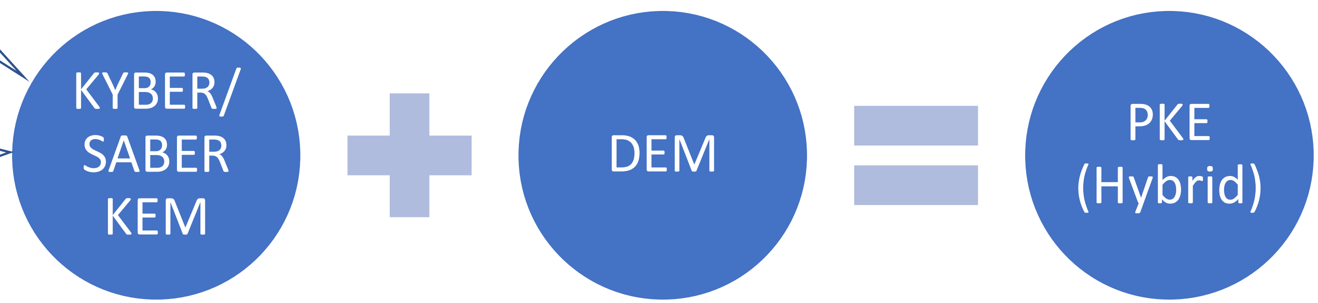

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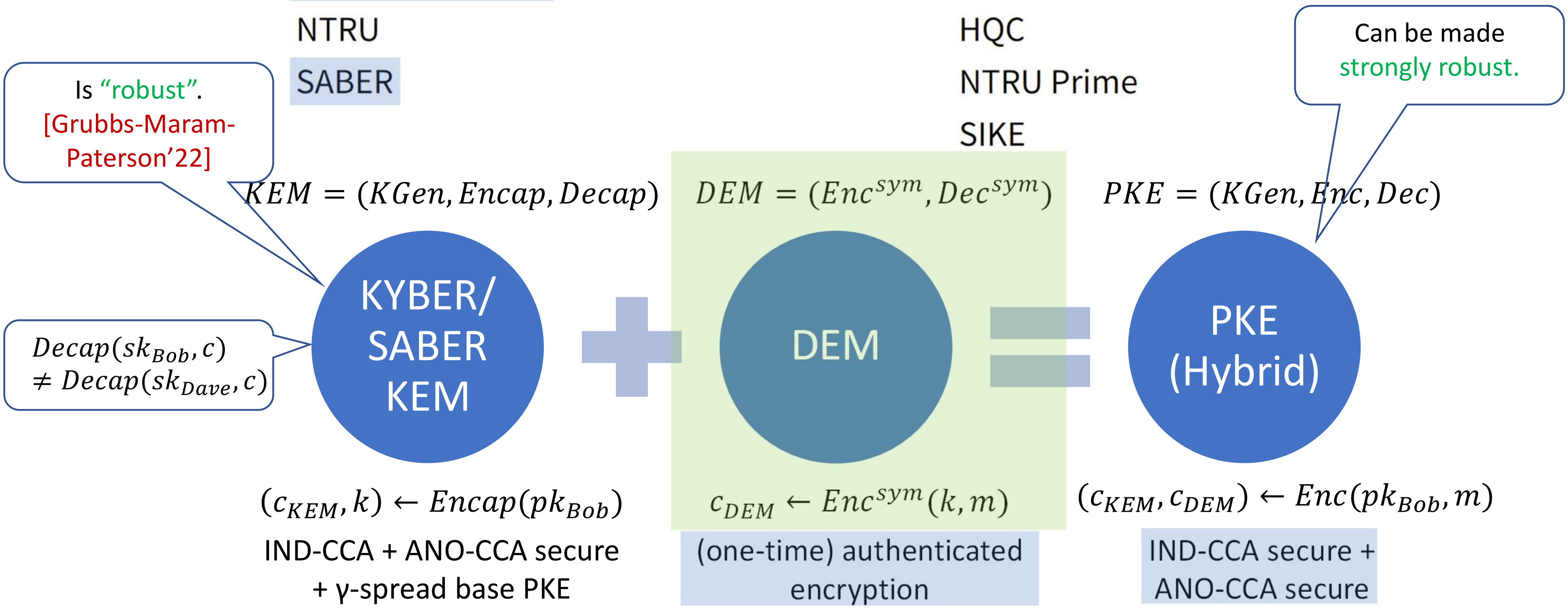

FrodoKEM

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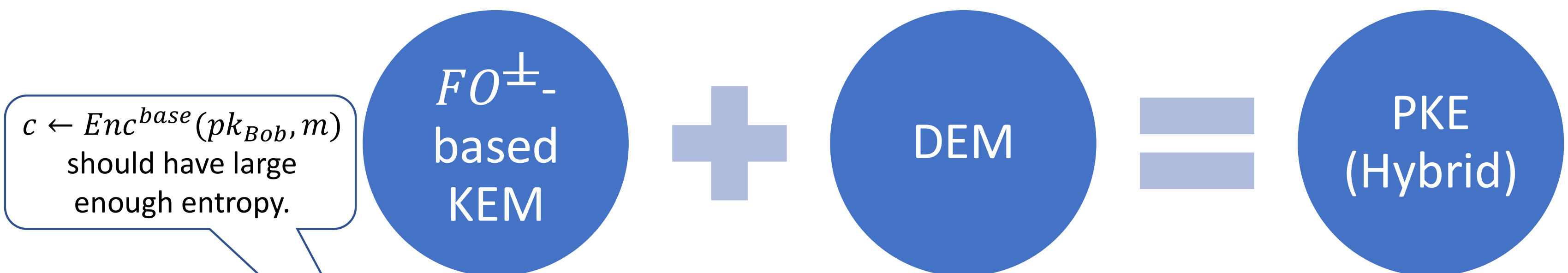
Public-Key Encryption/KEMs

- BIKE
- FrodoKEM
- HQC
- NTRU Prime
- SIKE

$KEM = (KGen, Encap, Decap)$ $DEM = (Enc^{sym}, Dec^{sym})$ $PKE = (KGen, Enc, Dec)$



$(c_{KEM}, k) \leftarrow Encap(pk_{Bob})$

IND-CCA + ANO-CCA secure + γ-spread base PKE

$c_{DEM} \leftarrow Enc^{sym}(k, m)$

(one-time) authenticated encryption

$(c_{KEM}, c_{DEM}) \leftarrow Enc(pk_{Bob}, m)$

IND-CCA secure + ANO-CCA secure

FrodoKEM

<u>Public-Key Encryption/KEMs</u>

Classic McEliece

CRYSTALS-KYBER

NTRU

SABER

<u>Public-Key Encryption/KEMs</u>

BIKE

FrodoKEM

HQC

NTRU Prime

SIKE

$KEM = (KGen, Encap, Decap)$ $DEM = (Enc^{sym}, Dec^{sym})$ $PKE = (KGen, Enc, Dec)$

Frodo KEM + DEM = PKE (Hybrid)

$c \leftarrow Enc^{base}(pk_{Bob}, m)$ should have large enough entropy.

$(c_{KEM}, k) \leftarrow Encap(pk_{Bob})$

IND-CCA + ANO-CCA secure + γ-spread base PKE

$c_{DEM} \leftarrow Enc^{sym}(k, m)$

(one-time) authenticated encryption

$(c_{KEM}, c_{DEM}) \leftarrow Enc(pk_{Bob}, m)$

IND-CCA secure + ANO-CCA secure

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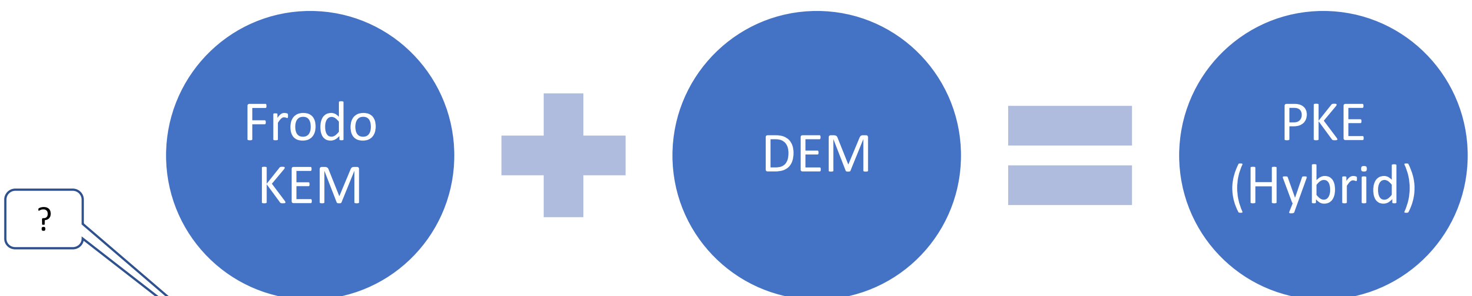

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Classic McEliece	BIKE
CRYSTALS-KYBER	FrodoKEM
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SABER	NTRU Prime
	SIKE

KGen'	$\mathsf{Encap}(\mathsf{pk})$	$\mathsf{Decap}(\mathsf{sk}', c)$
$(\mathsf{pk}, \mathsf{sk}) \leftarrow \mathsf{KGen}$	$m \leftarrow_\$ \mathcal{M}$	Parse $\mathsf{sk}' = (\mathsf{sk}, s)$
$s \leftarrow_\$ \mathcal{M}$	$r \leftarrow G(m)$	$m' \leftarrow \mathsf{Dec}(\mathsf{sk}, c)$
$\mathsf{sk}' = (\mathsf{sk}, s)$	$c \leftarrow \mathsf{Enc}(\mathsf{pk}, m; r)$	$r' \leftarrow G(m')$
return $(\mathsf{pk}, \mathsf{sk}')$	$k \leftarrow H(m, c)$	$c' \leftarrow \mathsf{Enc}(\mathsf{pk}, m'; r')$
	return (c, k)	**if** $c' = c$ **then**
		return $H(m', c)$
		else return $H(s, c)$

$\mathrm{FO}^{\not\perp}$

KGen'	$\mathsf{Encap}(\mathsf{pk})$	$\mathsf{Decap}(\mathsf{sk}', c)$
$(\mathsf{pk}, \mathsf{sk}) \leftarrow \mathsf{KGen}$	$m \leftarrow_\$ \mathcal{M}$	Parse $\mathsf{sk}' = (\mathsf{sk}, \mathsf{pk}, F(\mathsf{pk}), s)$
$s \leftarrow_\$ \mathcal{M}$	$(\hat{k}, r) \leftarrow G(F(pk), m)$	$m' \leftarrow \mathsf{Dec}(\mathsf{sk}, c)$
$\mathsf{sk}' \leftarrow (\mathsf{sk}, \mathsf{pk}, F(\mathsf{pk}), s)$	$c \leftarrow \mathsf{Enc}(\mathsf{pk}, m; r)$	$(\hat{k}', r') \leftarrow G(F(\mathsf{pk}), m')$
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FrodoKEM

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SIKE

"$k \leftarrow H(m, c)$"

KGen′	Encap(pk)	Decap(sk′, c)
1 : (pk, sk) ← KGen	1 : $m \leftarrow_\$ \mathcal{M}$	1 : Parse sk′ = (sk, s)
2 : $s \leftarrow_\$ \mathcal{M}$	2 : $r \leftarrow G(m)$	2 : $m' \leftarrow$ Dec(sk, c)
3 : sk′ = (sk, s)	3 : $c \leftarrow$ Enc(pk, m; r)	3 : $r' \leftarrow G(m')$
4 : **return** (pk, sk′)	4 : $k \leftarrow H(m, c)$	4 : $c' \leftarrow$ Enc(pk, m'; r')
	5 : **return** (c, k)	5 : **if** $c' = c$ **then**
		6 : **return** $H(m', c)$
		7 : **else return** $H(s, c)$

$\mathrm{FO}^{\not\perp}$

"$k \leftarrow H(G(m), c)$"

KGen′	Encap(pk)	Decap(sk′, c)
1 : (pk, sk) ← KGen	1 : $m \leftarrow_\$ \mathcal{M}$	1 : Parse sk′ = (sk, pk, F(pk), s)
2 : $s \leftarrow_\$ \mathcal{M}$	2 : $(\hat{k}, r) \leftarrow G(F(pk), m)$	2 : $m' \leftarrow$ Dec(sk, c)
3 : sk′ ← (sk, pk, F(pk), s)	3 : $c \leftarrow$ Enc(pk, m; r)	3 : $(\hat{k}', r') \leftarrow G(F(\mathrm{pk}), m')$
4 : **return** (pk, sk′)	4 : $k \leftarrow H(\hat{k}, c)$	4 : $c' \leftarrow$ Enc(pk, m'; r')
	5 : **return** (c, k)	5 : **if** $c' = c$ **then**
		6 : **return** $H(\hat{k}', c)$
		7 : **else return** $H(s, c)$

FrodoKEM

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	return (c, k)	**if** $c' = c$ **then**
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$\mathsf{FO}^{\not\perp}$

"$k \leftarrow H(G(m), c)$"

Only nested hashing of m and not c.

KGen′	Encap(pk)	Decap(sk′, c)
$(\mathsf{pk}, \mathsf{sk}) \leftarrow \mathsf{KGen}$	$m \leftarrow_{\$} \mathcal{M}$	Parse $\mathsf{sk}' = (\mathsf{sk}, \mathsf{pk}, F(\mathsf{pk}), s)$
$s \leftarrow_{\$} \mathcal{M}$	$(\hat{k}, r) \leftarrow G(F(\mathsf{pk}), m)$	$m' \leftarrow \mathsf{Dec}(\mathsf{sk}, c)$
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return $(\mathsf{pk}, \mathsf{sk}')$	$k \leftarrow H(\hat{k}, c)$	$c' \leftarrow \mathsf{Enc}(\mathsf{pk}, m'; r')$
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		return $H(\hat{k}', c)$
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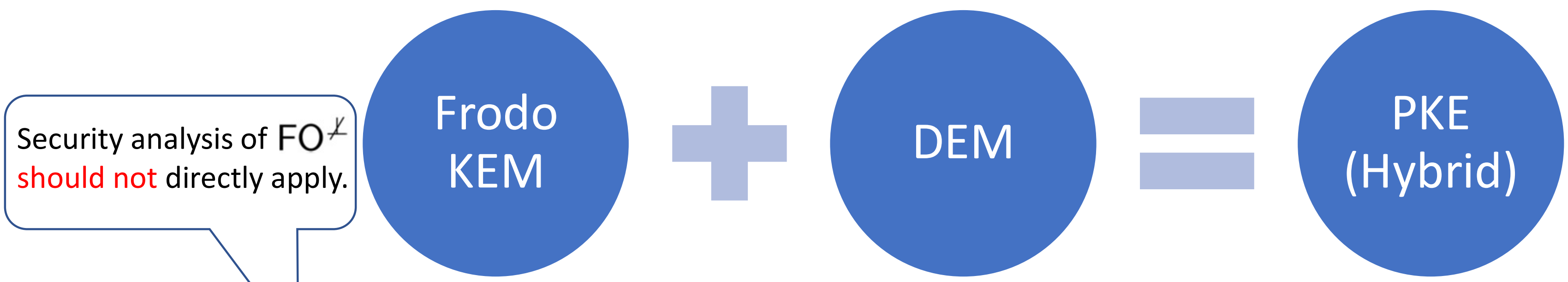

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(one-time) authenticated encryption

$(c_{KEM}, c_{DEM}) \leftarrow Enc(pk_{Bob}, m)$

IND-CCA secure + ANO-CCA secure

FrodoKEM

Public-Key Encryption/KEMs	Public-Key Encryption/KEMs
Classic McEliece	BIKE
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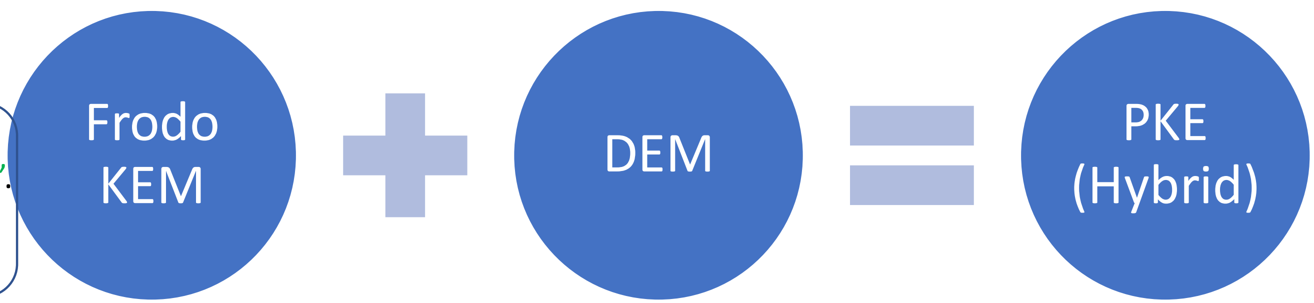

But (provable) IND-CCA security can be "recovered". [Grubbs-Maram-Paterson'21]

$(c_{KEM}, k) \leftarrow Encap(pk_{Bob})$

IND-CCA + ANO-CCA secure + γ-spread base PKE

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IND-CCA secure + ANO-CCA secure

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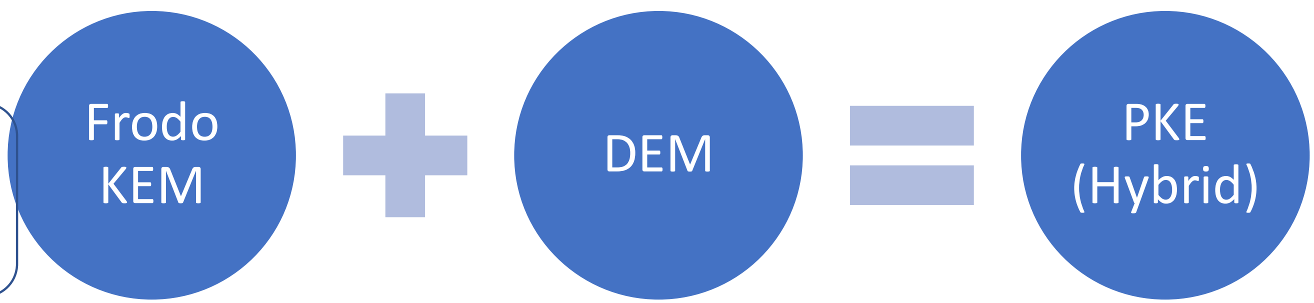

FrodoKEM is ANO-CCA secure in the QROM. [Grubbs-Maram -Paterson'21]

$(c_{KEM}, k) \leftarrow Encap(pk_{Bob})$

IND-CCA + ANO-CCA secure + γ-spread base PKE

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(one-time) authenticated encryption

$(c_{KEM}, c_{DEM}) \leftarrow Enc(pk_{Bob}, m)$

IND-CCA secure + ANO-CCA secure

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Classic McEliece

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SABER

<u>Public-Key Encryption/KEMs</u>

BIKE

FrodoKEM

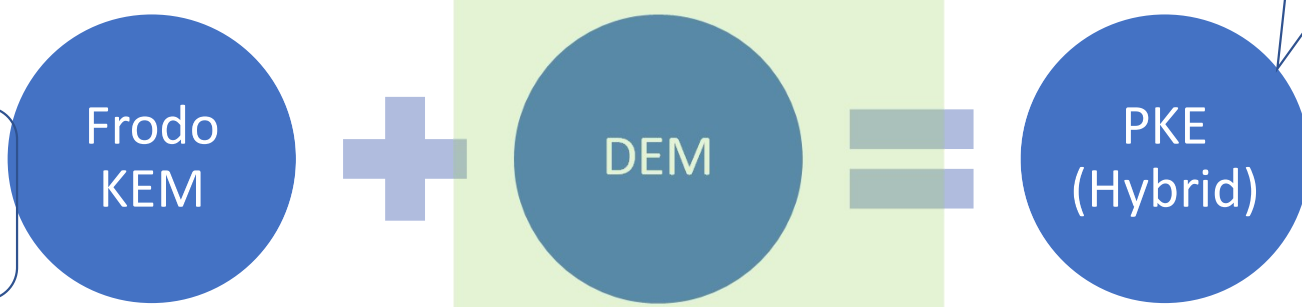
HQC

NTRU Prime

SIKE

FrodoKEM does result in anonymous and robust PKE in a PQ setting.

$KEM = (KGen, Encap, Decap)$ $DEM = (Enc^{sym}, Dec^{sym})$ $PKE = (KGen, Enc, Dec)$



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$(c_{KEM}, k) \leftarrow Encap(pk_{Bob})$

IND-CCA + ANO-CCA secure + γ-spread base PKE

$c_{DEM} \leftarrow Enc^{sym}(k, m)$

(one-time) authenticated encryption

$(c_{KEM}, c_{DEM}) \leftarrow Enc(pk_{Bob}, m)$

IND-CCA secure + ANO-CCA secure

Other Contributions

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Encap(pk)	Decap(sk, c)
$m \leftarrow_{\$} \mathcal{M}$	Parse $c = (c_1, c_2)$
$c_1 \leftarrow \mathsf{Enc}(\mathsf{pk}, m; G(m))$	$m' \leftarrow \mathsf{Dec}(\mathsf{sk}, c_1)$
$c_2 \leftarrow H'(m)$	$c_1' \leftarrow \mathsf{Enc}(\mathsf{pk}, m'; G(m'))$
	if $c_1' = c_1 \land H'(m') = c_2$ **then**
$c \leftarrow (c_1, c_2)$	
$k = H(m, c)$	**return** $H(m', c)$
return (c, k)	**else return** $\perp$

$\mathsf{HFO}^{\perp}$

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Results in IND-CCA secure KEMs in the QROM. [Jiang-Zhang-Ma'19]

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$c_2 \leftarrow H'(m)$	$c_1' \leftarrow \mathsf{Enc}(\mathsf{pk}, m'; G(m'))$
$\boxed{c_2 \leftarrow H'(m, c_1)}$	**if** $c_1' = c_1 \wedge H'(m') = c_2$ **then**
$c \leftarrow (c_1, c_2)$	$\boxed{\textbf{if } c_1' = c_1 \wedge H'(m', c_1) = c_2 \textbf{ then}}$
$k = H(m, c)$	**return** $H(m', c)$
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$\mathsf{HFO}^{\perp}$ $\boxed{\mathsf{HFO}^{\perp'}}$

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$c_2 \leftarrow H'(m)$	$c'_1 \leftarrow \mathsf{Enc}(\mathsf{pk}, m'; G(m'))$
$\boxed{c_2 \leftarrow H'(m, c_1)}$	**if** $c'_1 = c_1 \wedge H'(m') = c_2$ **then**
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$\mathsf{HFO}^{\perp}$ $\boxed{\mathsf{HFO}^{\perp'}}$

Results in IND-CCA secure KEMs in the QROM. [Jiang-Zhang-Ma'19]

Results in IND-CCA, ANO-CCA and SROB secure KEMs in the QROM. [Grubbs-Maram-Paterson'22]

Conclusions

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- Hybrid PKE schemes derived from Classic McEliece cannot be (strongly) robust.
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- We identified barriers towards proving IND-CCA and ANO-CCA security of CRYSTALS-KYBER and SABER in the QROM.

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- Hybrid PKE schemes derived from Classic McEliece cannot be (strongly) robust.
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- We identified barriers towards proving IND-CCA and ANO-CCA security of CRYSTALS-KYBER and SABER in the QROM.
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Conclusions

- We provide insights into obtaining anonymous and robust hybrid PKE schemes – via the KEM-DEM composition – when the KEM is implicitly rejecting (i.e., non-robust).
- We showed that the $\mathsf{FO}^{\not\perp}$ transform does result in ANO-CCA secure and "robust" KEMs in a post-quantum setting (i.e., the QROM).
- Hybrid PKE schemes derived from Classic McEliece cannot be (strongly) robust.
  - Though they can be made ANO-CCA secure as shown in [Xagawa'22].
- We identified barriers towards proving IND-CCA and ANO-CCA security of CRYSTALS-KYBER and SABER in the QROM.
  - At the same time, we showed they do result in strongly robust hybrid PKE schemes.
- Finally, we showed that FrodoKEM does result in ANO-CCA secure and strongly robust hybrid PKE schemes in the QROM.

Extra Slides

Classic McEliece (CM)

2.2.3 Encoding subroutine

The following algorithm ENCODE takes two inputs: a weight-t column vector $e \in \mathbb{F}_2^n$; and a public key T, i.e., an $(n-k) \times k$ matrix over $\mathbb{F}_2$. The algorithm output $\text{ENCODE}(e, T)$ is a vector $C_0 \in \mathbb{F}_2^{n-k}$. Here is the algorithm:

1. Define $H = (I_{n-k} \mid T)$.
2. Compute and return $C_0 = He \in \mathbb{F}_2^{n-k}$.

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1. Define $H = (I_{n-k} \mid T)$.
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Fix any "message" $e = \binom{e_{n-k}}{0^k}$:

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- ($n - k \geq t$ in all CM parameters)
- $C_0 = (I_{n-k}|T)\binom{e_{n-k}}{0^k} = e_{n-k}$ – i.e., independent of public-key T.
- Because of perfect correctness, C_0 must decrypt to fixed e under *any private key* of CM's base PKE scheme.

Classic McEliece (CM)

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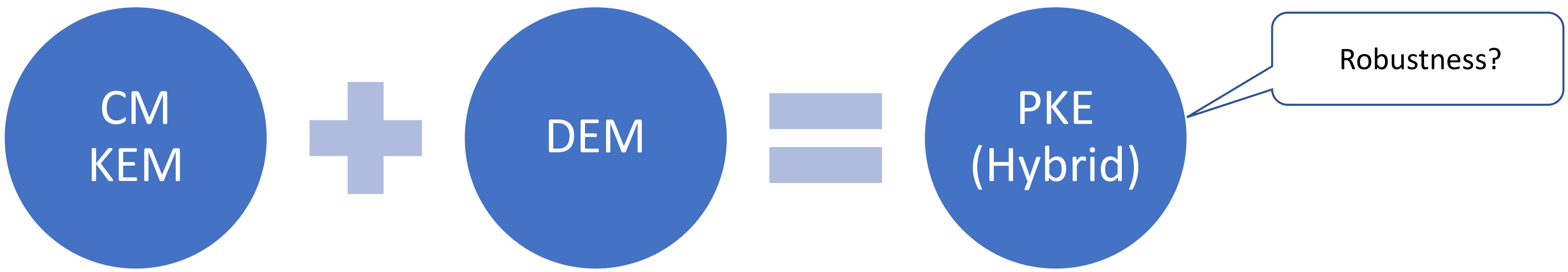

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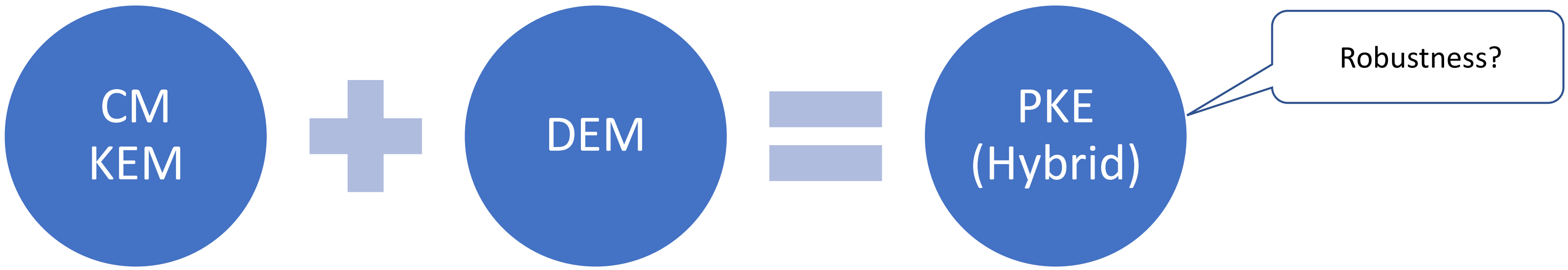

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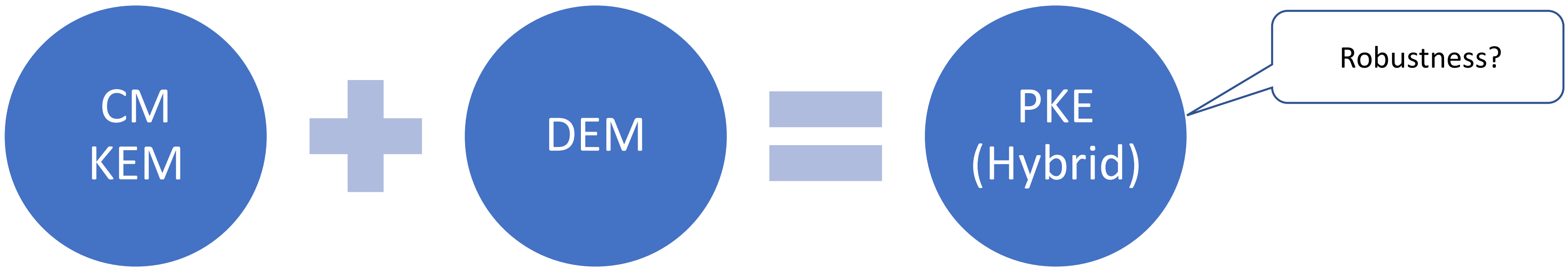

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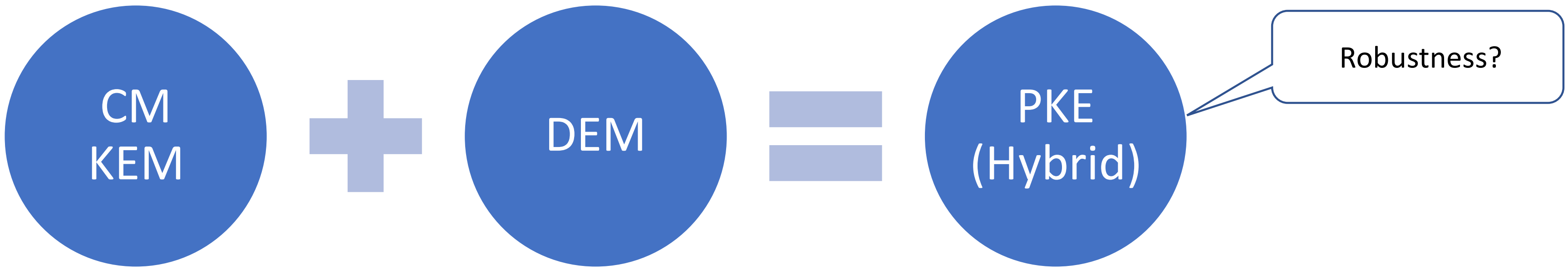

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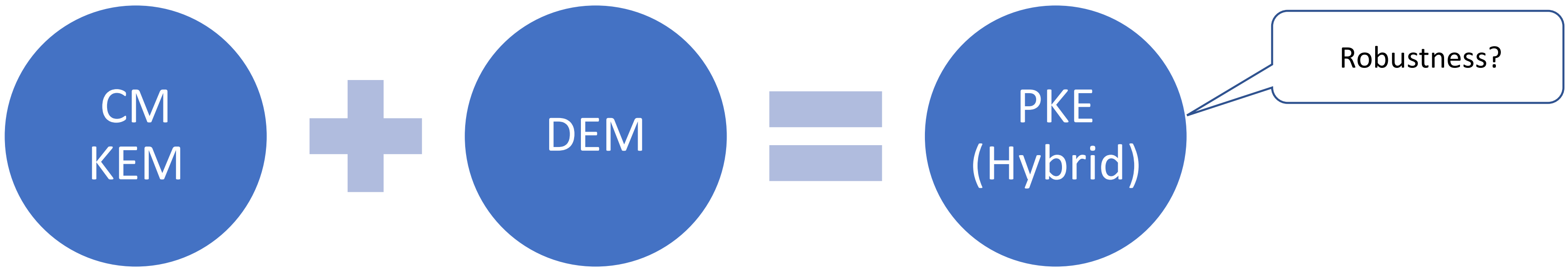

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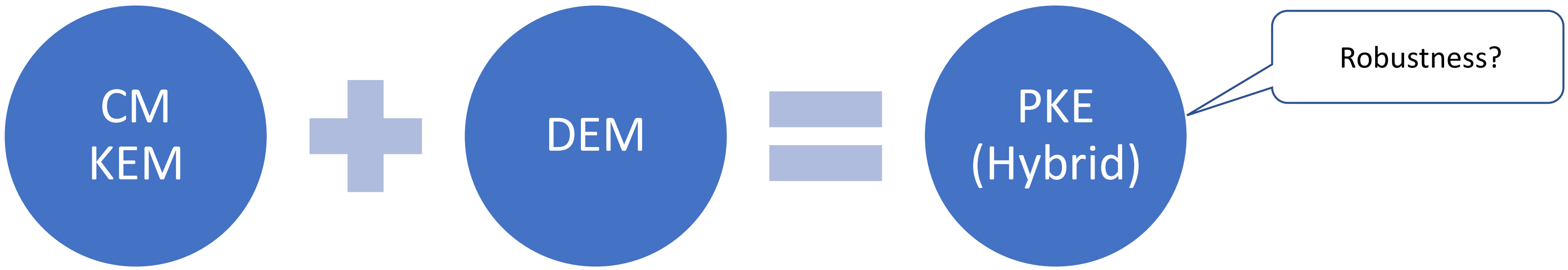

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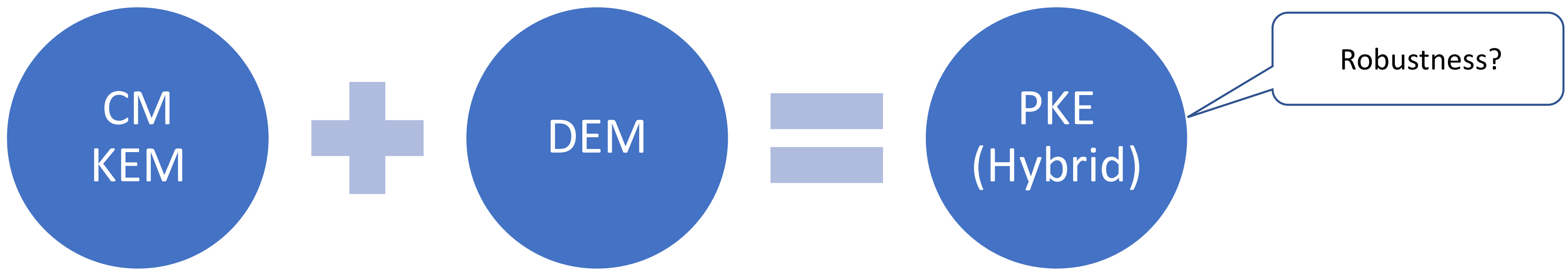

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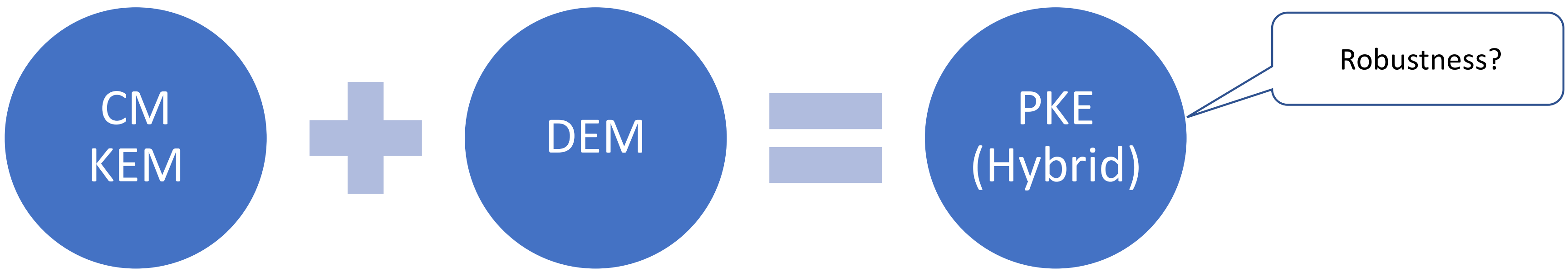

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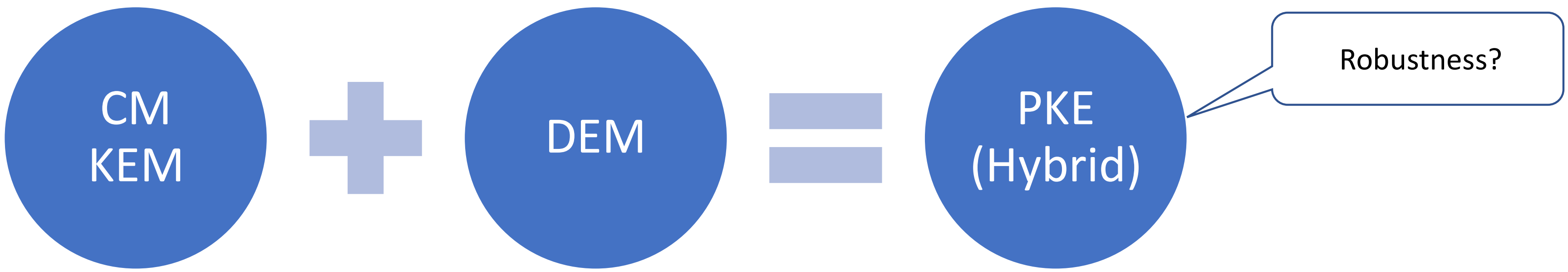

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For *any* CM private key sk_*,

$$Dec(sk_*, c) = m \ (\neq \perp).$$

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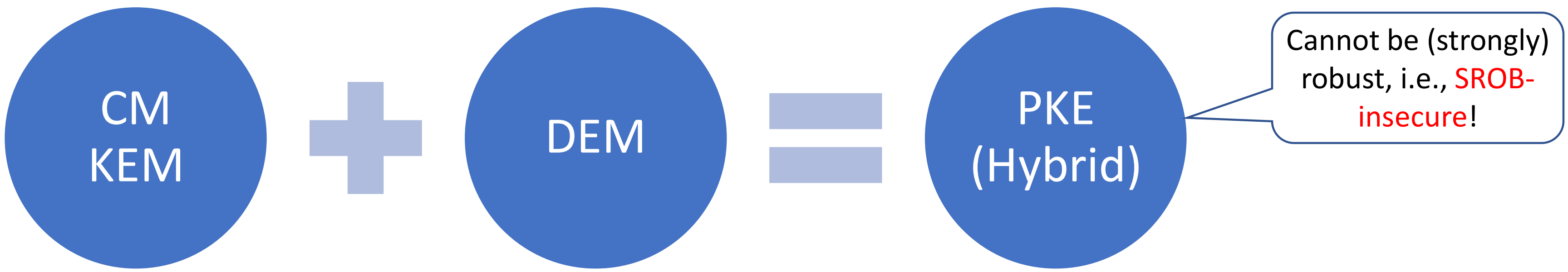

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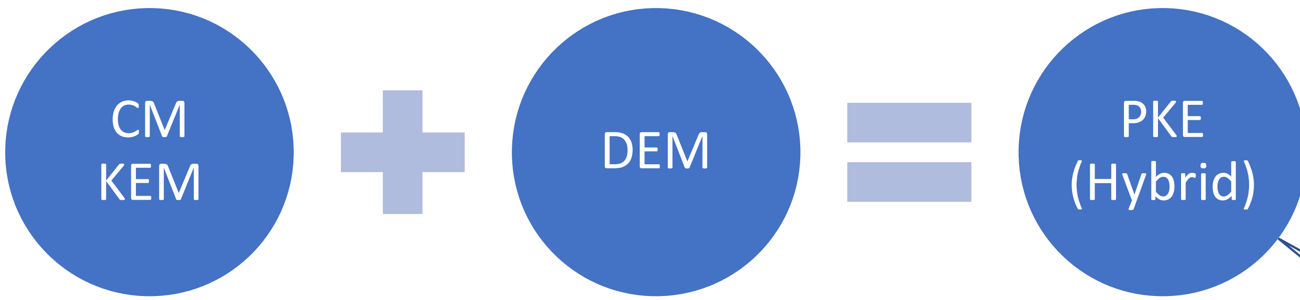

Cannot be (strongly) robust, i.e., SROB-insecure!

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But can be ANO-CCA secure. [Xagawa'22]

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KEM-DEM Paradigm

Public-Key Encryption/KEMs	Public-Key Encryption/KEMs
Classic McEliece	BIKE
CRYSTALS-KYBER	FrodoKEM
NTRU	HQC
SABER	NTRU Prime
	SIKE

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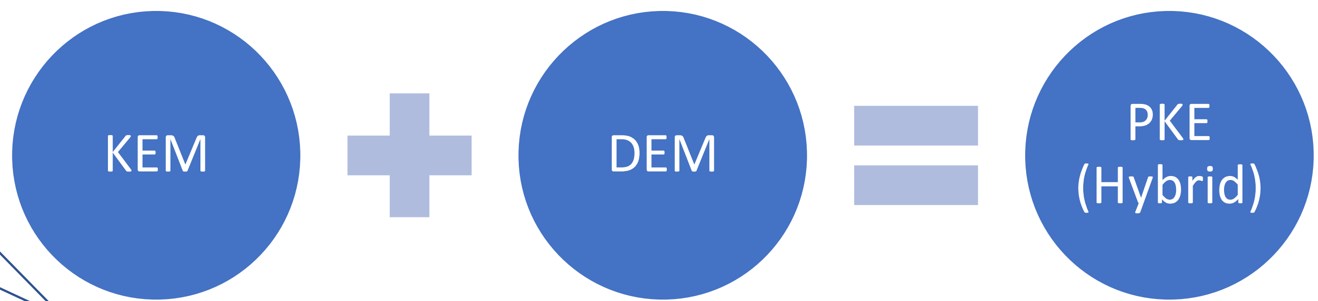


Indistinguishable from a uniformly random DEM key k'

$(c_{KEM}, k) \leftarrow Encap(pk_{Bob})$

IND-CCA secure

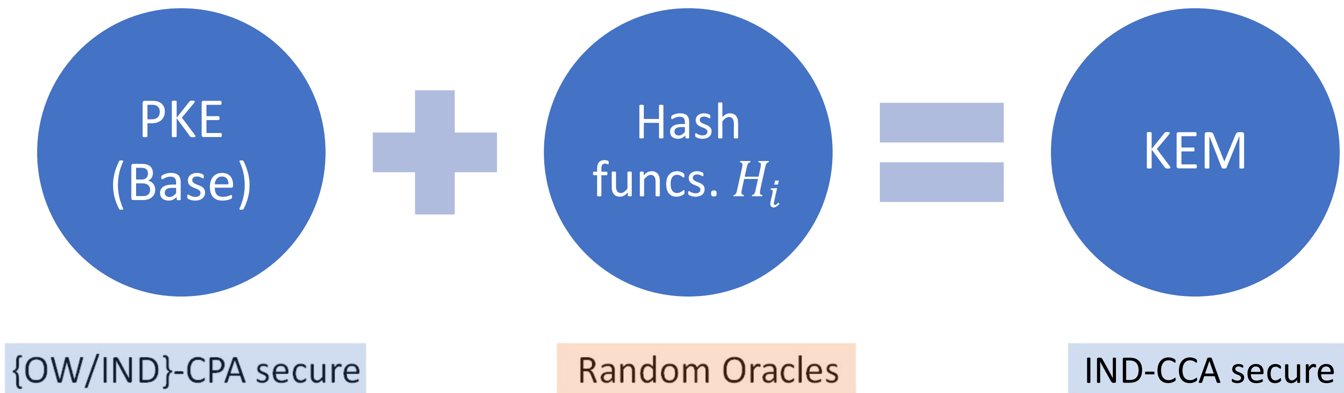
$c_{DEM} \leftarrow Enc^{sym}(k, m)$

(one-time) authenticated encryption

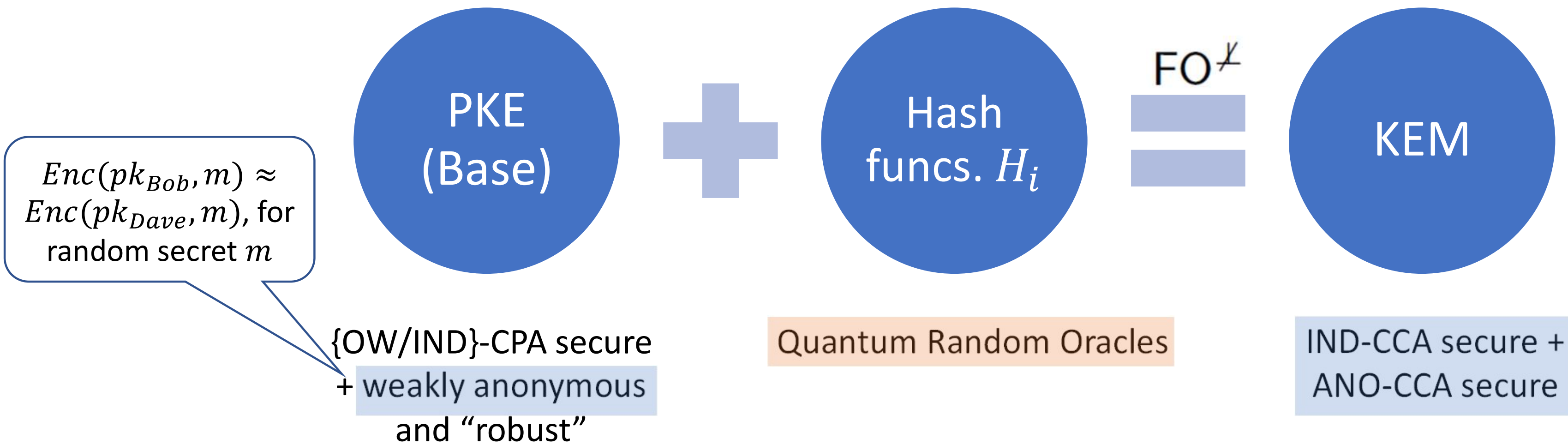
$(c_{KEM}, c_{DEM}) \leftarrow Enc(pk_{Bob}, m)$

IND-CCA secure

Fujisaki-Okamoto Transformation



Anonymity from FO transforms



Shown in [Grubbs-Maram-Paterson’22]

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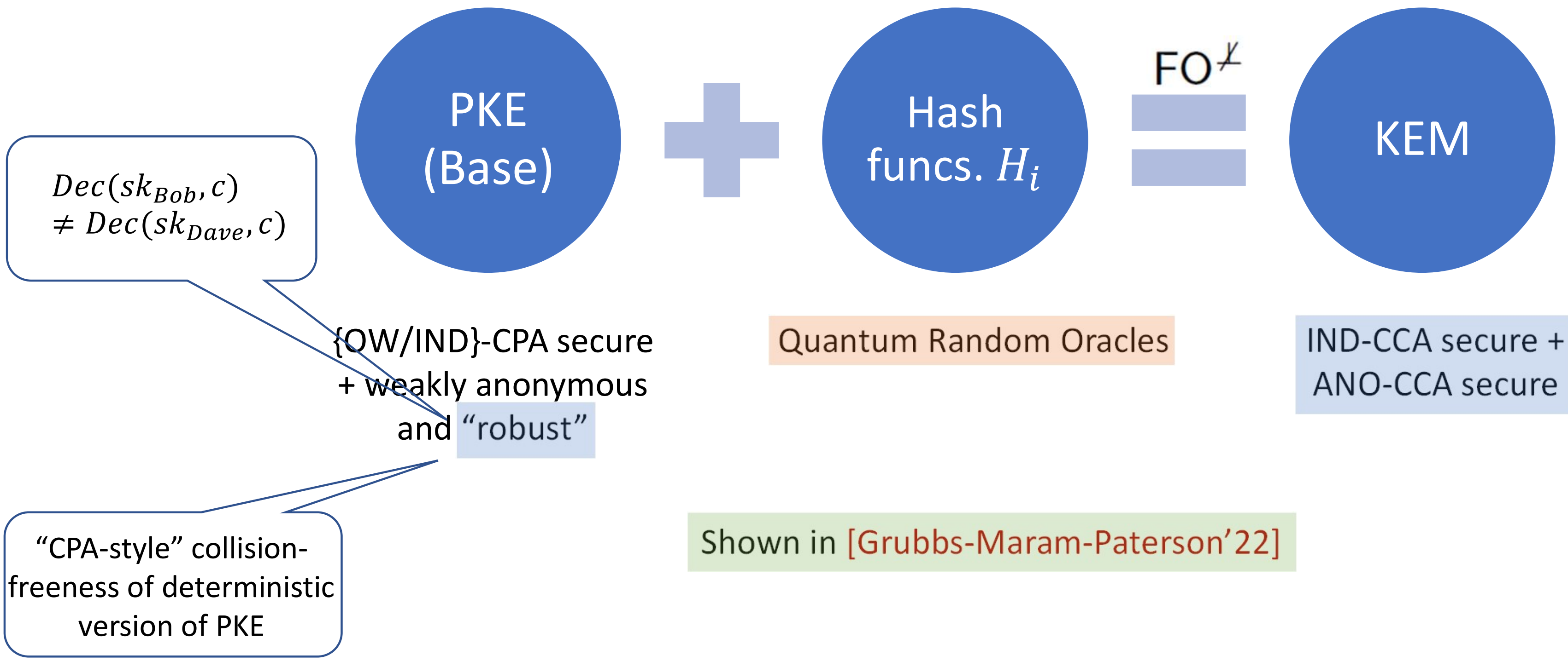

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