Shadowfax: Combiners for Deniability

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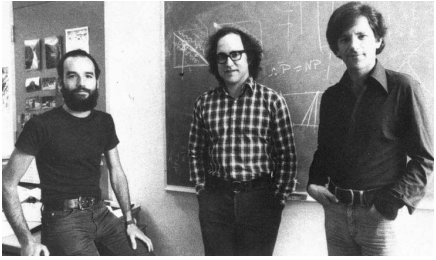
Cryptographic Applications Workshop at EUROCRYPT 2025, Madrid, Spain.

MOTIVATION: RSA, DH, SHOR AND QUANTUM



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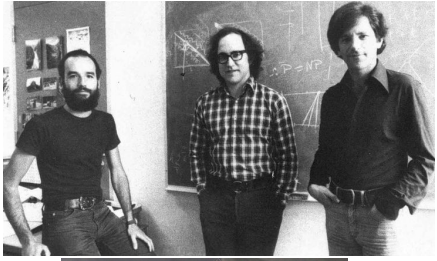

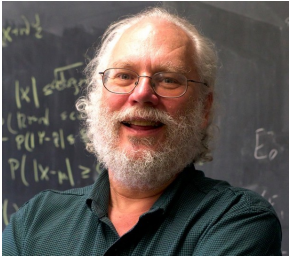

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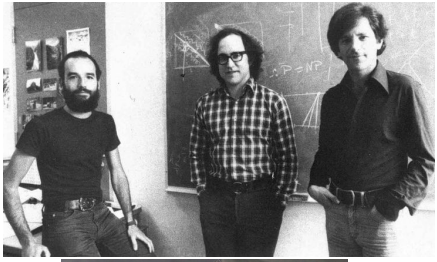

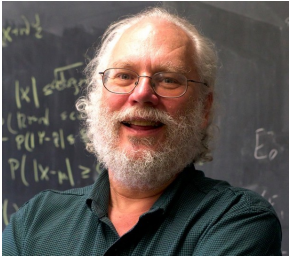

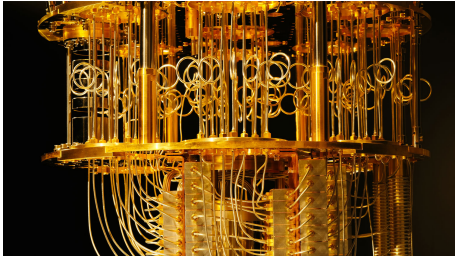

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- Protocols are being adapted to be post-quantum secure.
  - **X3DH → PQXDH** (deployed in **Signal**) [MP16, KS24].
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  - **TLS →** [BCNS15], [PST20], [BBCT22], [Lan16], [Lan18], [KV19], [WR19], ...
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SOME SECURITY NOTIONS ARE LOST DURING PQC MIGRATION

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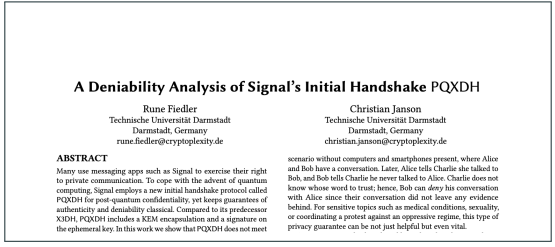

A Deniability Analysis of Signal's Initial Handshake PQXDH

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ABSTRACT

Many use messaging apps such as Signal to exercise their right to private communication. To cope with the advent of quantum computing, Signal employs a new initial handshake protocol called PQXDH for post-quantum confidentiality, yet keeps guarantees of authenticity and deniability classical. Compared to its predecessor X3DH, PQXDH includes a KEM encapsulation and a signature on the ephemeral key. In this work we show that PQXDH does not meet scenario without computers and smartphones present, where Alice and Bob have a conversation. Later, Alice tells Charlie she talked to Bob, and Bob tells Charlie he never talked to Alice. Charlie does not know whose word to trust; hence, Bob can *deny* his conversation with Alice since their conversation did not leave any evidence behind. For sensitive topics such as medical conditions, sexuality, or coordinating a protest against an oppressive regime, this type of privacy guarantee can be not just helpful but even vital.

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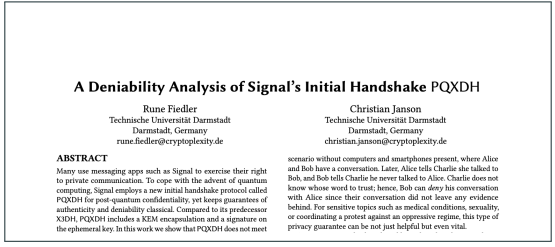

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Q: "Can combiners preserve deniability in a post-quantum setting at minimal additional cost?"

OUTLINE

- Combiners: Two Classes
- Case Study: Authenticated KEM
- Black-box Construction: Problems
- Shadowfax
  - Construction
  - Instantiation
  - Comparison

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COMBINERS

- Construct a secure scheme Π from two schemes Π_1 and Π_2.
- Security is *binary*: either secure or insecure.
- Goal: $\Pi_1 \vee \Pi_2 \implies \Pi$.
- Examples of Π:
  - $\mathsf{PRG} := \mathsf{PRG}_1(s_1) \oplus \mathsf{PRG}_2(s_2)$
  - KEM with $k = \mathsf{H}(k_1, k_2, c_1, c_2)$ (RO model)
  - KEM with $k = \mathsf{PRF}(k_1, c_1 \| c_2) \oplus \mathsf{PRF}(k_2, c_1 \| c_2)$ (standard model [GHP18])

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- Build Π from classical ($\Pi_{\text{pre-Q}}$) and post-quantum ($\Pi_{\text{post-Q}}$) components.

Q: *Why use combiners for PQC migration?*

A: Classical implementations are mature; PQC is harder to implement. (code audits)

A: PQC schemes may lack formal proofs. (formal verification)

A: Most importantly, risk mitigation against assumption failures:

- **Quantum computers become practical: Break classical assumptions (factoring, discrete log).**
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$$\textbf{Can relax to: } \textbf{Assumption}_{\textbf{pre-Q}} \vee \textbf{Assumption}_{\textbf{post-Q}} \implies \Pi$$

CASE STUDY: AUTHENTICATED KEM

AUTHENTICATED KEY ENCAPSULATION MECHANISM (AKEM) [ABH+21, GJK24]

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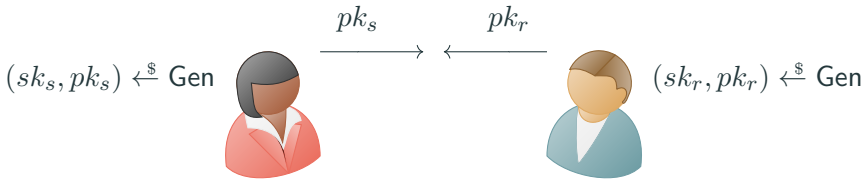
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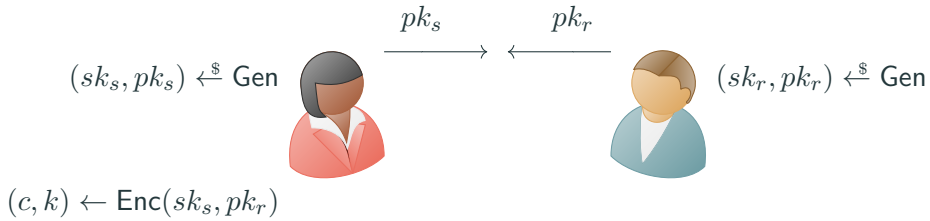
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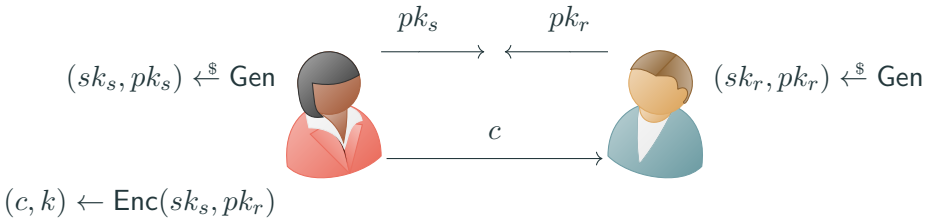

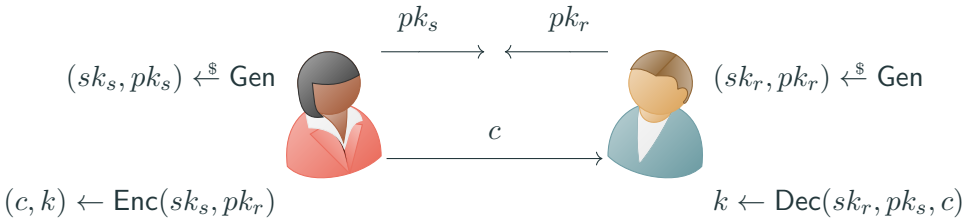
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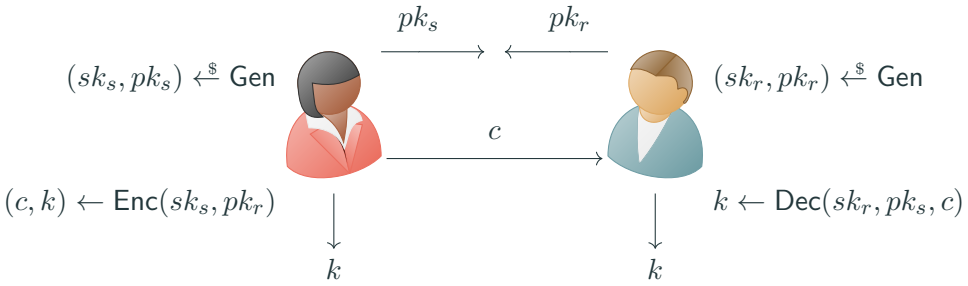

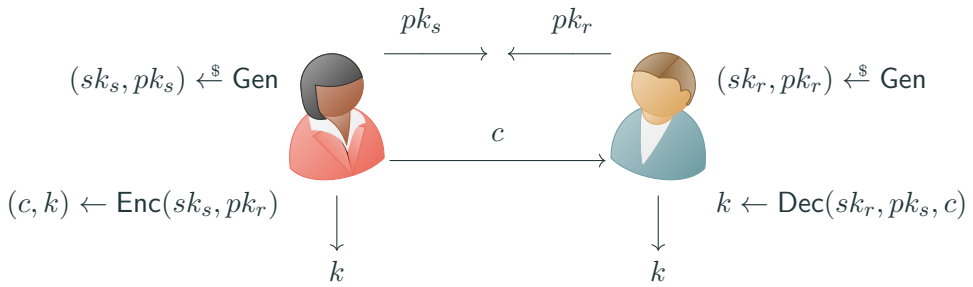

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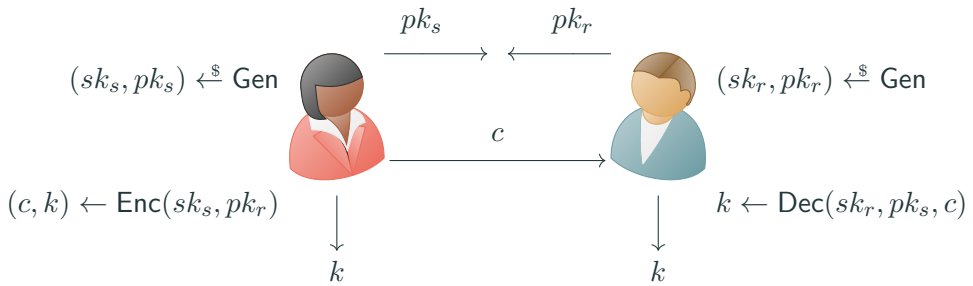

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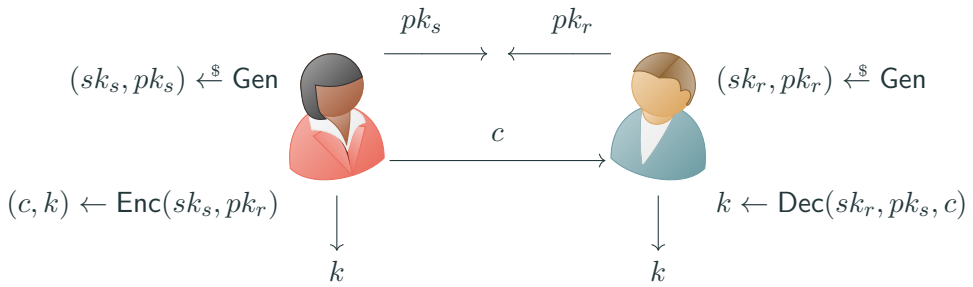

- **Confidentiality:** k should look random.
- **Authenticity:** r knows s sent the ciphertext c.
- **Deniability:** s can deny having sent c to r.
  - $\exists\, \mathsf{Sim} : \mathsf{Enc}(sk_s, pk_r) \approx \mathsf{Sim}(\dots)$ (honest/dishonest receivers)

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- Messaging
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- Designing a protocol that needs one-shot authentication? Let us know!

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$\underline{\mathsf{Gen}}$	$\underline{\mathsf{Enc}(sk_s =: (sk_1, sk_2), pk_r =: (pk_1, pk_2))}$	$\underline{\mathsf{Dec}(pk_s =: (pk_1, pk_2), sk_r =: (sk_1, sk_2), c)}$
$(sk_1, pk_1) \xleftarrow{\$} \mathsf{AKEM}_1.\mathsf{Gen}$	$(c_1, k_1) \xleftarrow{\$} \mathsf{AKEM}_1.\mathsf{Enc}(sk_1, pk_1)$	$\textbf{parse } c \to (c_1, c_2)$
$(sk_2, pk_2) \xleftarrow{\$} \mathsf{AKEM}_2.\mathsf{Gen}$	$(c_2, k_2) \xleftarrow{\$} \mathsf{AKEM}_2.\mathsf{Enc}(sk_2, pk_2)$	$k_1 \leftarrow \mathsf{AKEM}_1.\mathsf{Dec}(pk_1, sk_1, c_1)$
$\textbf{return } ((sk_1, sk_2), (pk_1, pk_2))$	$c \coloneqq (c_1, c_2)$	$k_2 \leftarrow \mathsf{AKEM}_2.\mathsf{Dec}(pk_2, sk_2, c_2)$
	$k \coloneqq \mathsf{H}(k_1, k_2, pk_s, pk_r, c)$	$k \coloneqq \mathsf{H}(k_1, k_2, pk_s, pk_r, c)$
	$\textbf{return } (c, k)$	$\textbf{return } k$

BLACK-BOX CONSTRUCTION OF A DENIABLE AKEM $:= [\mathsf{AKEM}_1, \mathsf{AKEM}_2, \mathsf{H}]$

$\underline{\mathsf{Gen}}$	$\underline{\mathsf{Enc}(sk_s =: (sk_1, sk_2), pk_r =: (pk_1, pk_2))}$	$\underline{\mathsf{Dec}(pk_s =: (pk_1, pk_2), sk_r =: (sk_1, sk_2), c)}$
$(sk_1, pk_1) \xleftarrow{\$} \mathsf{AKEM}_1.\mathsf{Gen}$	$(c_1, k_1) \xleftarrow{\$} \mathsf{AKEM}_1.\mathsf{Enc}(sk_1, pk_1)$	**parse** $c \to (c_1, c_2)$
$(sk_2, pk_2) \xleftarrow{\$} \mathsf{AKEM}_2.\mathsf{Gen}$	$(c_2, k_2) \xleftarrow{\$} \mathsf{AKEM}_2.\mathsf{Enc}(sk_2, pk_2)$	$k_1 \leftarrow \mathsf{AKEM}_1.\mathsf{Dec}(pk_1, sk_1, c_1)$
return $((sk_1, sk_2), (pk_1, pk_2))$	$c \coloneqq (c_1, c_2)$	$k_2 \leftarrow \mathsf{AKEM}_2.\mathsf{Dec}(pk_2, sk_2, c_2)$
	$k \coloneqq \mathsf{H}(k_1, k_2, pk_s, pk_r, c)$	$k \coloneqq \mathsf{H}(k_1, k_2, pk_s, pk_r, c)$
	return (c, k)	**return** k

BLACK-BOX CONSTRUCTION OF A DENIABLE AKEM := $[\mathsf{AKEM}_1, \mathsf{AKEM}_2, \mathsf{H}]$

$\underline{\mathsf{Gen}}$	$\underline{\mathsf{Enc}(sk_s =: (sk_1, sk_2), pk_r =: (pk_1, pk_2))}$	$\underline{\mathsf{Dec}(pk_s =: (pk_1, pk_2), sk_r =: (sk_1, sk_2), c)}$
$(sk_1, pk_1) \xleftarrow{\$} \mathsf{AKEM}_1.\mathsf{Gen}$	$(c_1, k_1) \xleftarrow{\$} \mathsf{AKEM}_1.\mathsf{Enc}(sk_1, pk_1)$	**parse** $c \to (c_1, c_2)$
$(sk_2, pk_2) \xleftarrow{\$} \mathsf{AKEM}_2.\mathsf{Gen}$	$(c_2, k_2) \xleftarrow{\$} \mathsf{AKEM}_2.\mathsf{Enc}(sk_2, pk_2)$	$k_1 \leftarrow \mathsf{AKEM}_1.\mathsf{Dec}(pk_1, sk_1, c_1)$
return $((sk_1, sk_2), (pk_1, pk_2))$	$c \coloneqq (c_1, c_2)$	$k_2 \leftarrow \mathsf{AKEM}_2.\mathsf{Dec}(pk_2, sk_2, c_2)$
	$k \coloneqq \mathsf{H}(k_1, k_2, pk_s, pk_r, c)$	$k \coloneqq \mathsf{H}(k_1, k_2, pk_s, pk_r, c)$
	return (c, k)	**return** k

BLACK-BOX CONSTRUCTION OF A DENIABLE $\mathsf{AKEM} := [\mathsf{AKEM}_1, \mathsf{AKEM}_2, \mathsf{H}]$

$\underline{\mathsf{Gen}}$	$\underline{\mathsf{Enc}(sk_s =: (sk_1, sk_2), pk_r =: (pk_1, pk_2))}$	$\underline{\mathsf{Dec}(pk_s =: (pk_1, pk_2), sk_r =: (sk_1, sk_2), c)}$
$(sk_1, pk_1) \xleftarrow{\$} \mathsf{AKEM}_1.\mathsf{Gen}$	$(c_1, k_1) \xleftarrow{\$} \mathsf{AKEM}_1.\mathsf{Enc}(sk_1, pk_1)$	**parse** $c \to (c_1, c_2)$
$(sk_2, pk_2) \xleftarrow{\$} \mathsf{AKEM}_2.\mathsf{Gen}$	$(c_2, k_2) \xleftarrow{\$} \mathsf{AKEM}_2.\mathsf{Enc}(sk_2, pk_2)$	$k_1 \leftarrow \mathsf{AKEM}_1.\mathsf{Dec}(pk_1, sk_1, c_1)$
return $((sk_1, sk_2), (pk_1, pk_2))$	$c \coloneqq (c_1, c_2)$	$k_2 \leftarrow \mathsf{AKEM}_2.\mathsf{Dec}(pk_2, sk_2, c_2)$
	$k \coloneqq \mathsf{H}(k_1, k_2, pk_s, pk_r, c)$	$k \coloneqq \mathsf{H}(k_1, k_2, pk_s, pk_r, c)$
	return (c, k)	**return** k

BLACK-BOX CONSTRUCTION OF A DENIABLE $\mathsf{AKEM} := [\mathsf{AKEM}_1, \mathsf{AKEM}_2, \mathsf{H}]$

$\underline{\mathsf{Gen}}$	$\underline{\mathsf{Enc}(sk_s =: (sk_1, sk_2), pk_r =: (pk_1, pk_2))}$	$\underline{\mathsf{Dec}(pk_s =: (pk_1, pk_2), sk_r =: (sk_1, sk_2), c)}$
$(sk_1, pk_1) \xleftarrow{\$} \mathsf{AKEM}_1.\mathsf{Gen}$	$(c_1, k_1) \xleftarrow{\$} \mathsf{AKEM}_1.\mathsf{Enc}(sk_1, pk_1)$	**parse** $c \to (c_1, c_2)$
$(sk_2, pk_2) \xleftarrow{\$} \mathsf{AKEM}_2.\mathsf{Gen}$	$(c_2, k_2) \xleftarrow{\$} \mathsf{AKEM}_2.\mathsf{Enc}(sk_2, pk_2)$	$k_1 \leftarrow \mathsf{AKEM}_1.\mathsf{Dec}(pk_1, sk_1, c_1)$
return $((sk_1, sk_2), (pk_1, pk_2))$	$c \coloneqq (c_1, c_2)$	$k_2 \leftarrow \mathsf{AKEM}_2.\mathsf{Dec}(pk_2, sk_2, c_2)$
	$k \coloneqq \mathsf{H}(k_1, k_2, pk_s, pk_r, c)$	$k \coloneqq \mathsf{H}(k_1, k_2, pk_s, pk_r, c)$
	return (c, k)	**return** k

- **Confidentiality:** follows from either AKEM_1 **or** AKEM_2 ($\approx$ KEM combiner)
  - However, k also hashes sender and receiver public keys to satisfy **Ins-CCA**.
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BLACK-BOX CONSTRUCTION OF A DENIABLE $\mathsf{AKEM} := [\mathsf{AKEM}_1, \mathsf{AKEM}_2, \mathsf{H}]$

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$(sk_1, pk_1) \xleftarrow{\$} \mathsf{AKEM}_1.\mathsf{Gen}$	$(c_1, k_1) \xleftarrow{\$} \mathsf{AKEM}_1.\mathsf{Enc}(sk_1, pk_1)$	**parse** $c \to (c_1, c_2)$
$(sk_2, pk_2) \xleftarrow{\$} \mathsf{AKEM}_2.\mathsf{Gen}$	$(c_2, k_2) \xleftarrow{\$} \mathsf{AKEM}_2.\mathsf{Enc}(sk_2, pk_2)$	$k_1 \leftarrow \mathsf{AKEM}_1.\mathsf{Dec}(pk_1, sk_1, c_1)$
return $((sk_1, sk_2), (pk_1, pk_2))$	$c \coloneqq (c_1, c_2)$	$k_2 \leftarrow \mathsf{AKEM}_2.\mathsf{Dec}(pk_2, sk_2, c_2)$
	$k \coloneqq \mathsf{H}(k_1, k_2, pk_s, pk_r, c)$	$k \coloneqq \mathsf{H}(k_1, k_2, pk_s, pk_r, c)$
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Black-box construction of a deniable $\mathsf{AKEM} := [\mathsf{AKEM}_1, \mathsf{AKEM}_2, \mathsf{H}]$

$\underline{\mathsf{Gen}}$	$\underline{\mathsf{Enc}(sk_s =: (sk_1, sk_2), pk_r =: (pk_1, pk_2))}$	$\underline{\mathsf{Dec}(pk_s =: (pk_1, pk_2), sk_r =: (sk_1, sk_2), c)}$
$(sk_1, pk_1) \xleftarrow{\$} \mathsf{AKEM}_1.\mathsf{Gen}$	$(c_1, k_1) \xleftarrow{\$} \mathsf{AKEM}_1.\mathsf{Enc}(sk_1, pk_1)$	**parse** $c \to (c_1, c_2)$
$(sk_2, pk_2) \xleftarrow{\$} \mathsf{AKEM}_2.\mathsf{Gen}$	$(c_2, k_2) \xleftarrow{\$} \mathsf{AKEM}_2.\mathsf{Enc}(sk_2, pk_2)$	$k_1 \leftarrow \mathsf{AKEM}_1.\mathsf{Dec}(pk_1, sk_1, c_1)$
return $((sk_1, sk_2), (pk_1, pk_2))$	$c \coloneqq (c_1, c_2)$	$k_2 \leftarrow \mathsf{AKEM}_2.\mathsf{Dec}(pk_2, sk_2, c_2)$
	$k \coloneqq \mathsf{H}(k_1, k_2, pk_s, pk_r, c)$	$k \coloneqq \mathsf{H}(k_1, k_2, pk_s, pk_r, c)$
	return (c, k)	**return** k

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BLACK-BOX CONSTRUCTION OF A DENIABLE $\mathsf{AKEM} := [\mathsf{AKEM}_1, \mathsf{AKEM}_2, \mathsf{H}]$

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$(sk_2, pk_2) \xleftarrow{\$} \mathsf{AKEM}_2.\mathsf{Gen}$	$(c_2, k_2) \xleftarrow{\$} \mathsf{AKEM}_2.\mathsf{Enc}(sk_2, pk_2)$	$k_1 \leftarrow \mathsf{AKEM}_1.\mathsf{Dec}(pk_1, sk_1, c_1)$
return $((sk_1, sk_2), (pk_1, pk_2))$	$c \coloneqq (c_1, c_2)$	$k_2 \leftarrow \mathsf{AKEM}_2.\mathsf{Dec}(pk_2, sk_2, c_2)$
	$k \coloneqq \mathsf{H}(k_1, k_2, pk_s, pk_r, c)$	$k \coloneqq \mathsf{H}(k_1, k_2, pk_s, pk_r, c)$
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Q: *What does it mean to lose deniability?*

Cannot construct $\mathsf{Sim} : \mathsf{Enc}(sk_s, pk_r) \approx \mathsf{Sim}(\dots)$

Q: *Computationally or Statistically Indistinguishable?*

Comp. deniability: $\neg\text{Assumption}_{\text{pre-Q}} \vee \neg\text{Assumption}_{\text{post-Q}} \implies \neg\text{Deniability}$

Stat. deniability: $\neg\text{Assumption}_{\text{pre-Q}} \vee \neg\text{Assumption}_{\text{post-Q}} \not\Longrightarrow \neg\text{Deniability}$

A: Use statistical deniability. **Not possible** for confidentiality/authenticity!

- PAKE combiners rely on statical password hiding [HR25].
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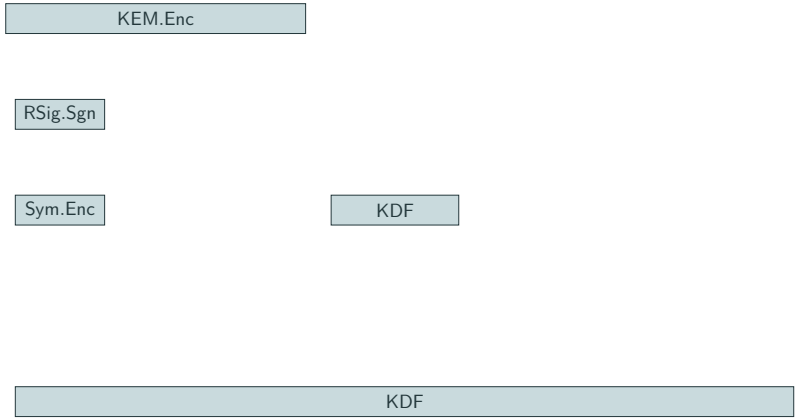
SHADOWFAX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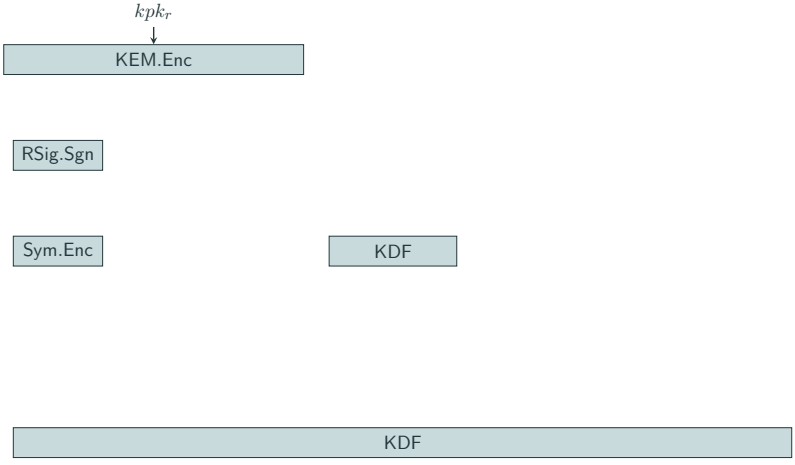
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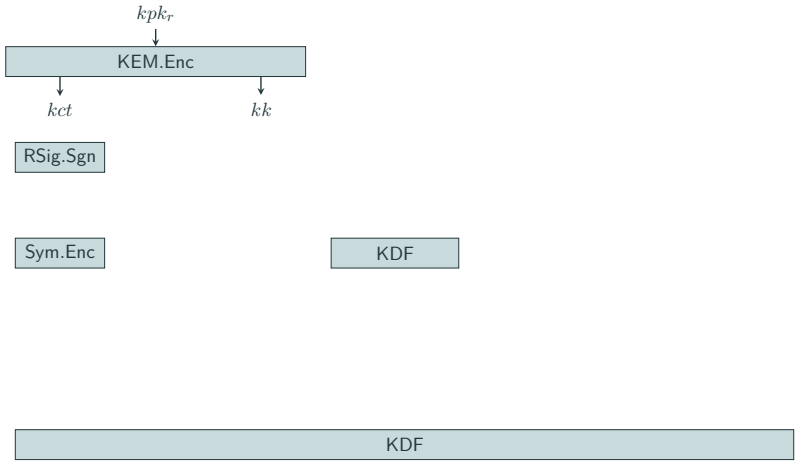
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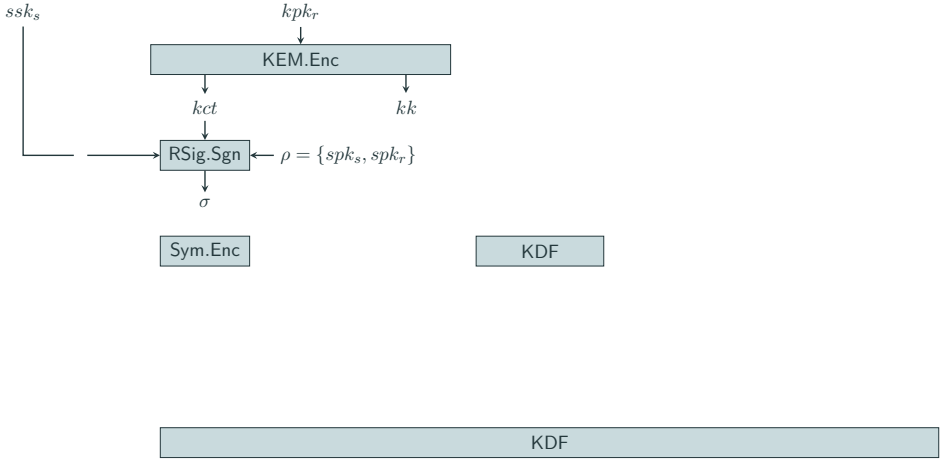
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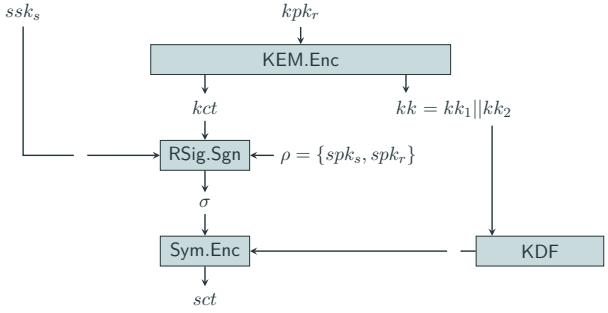
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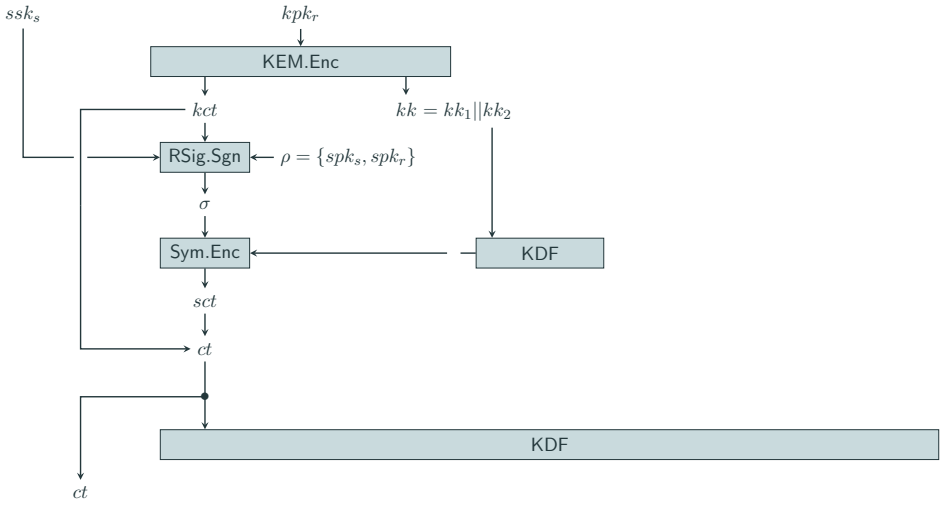
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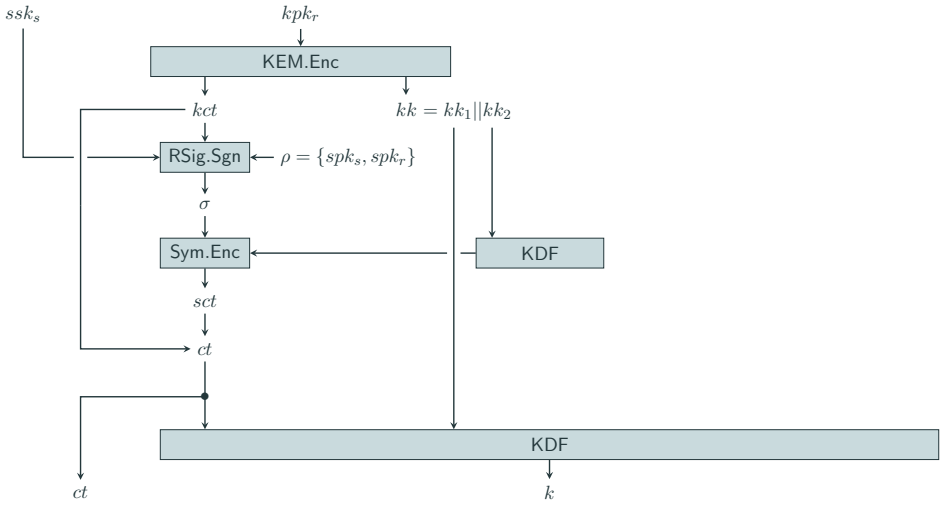
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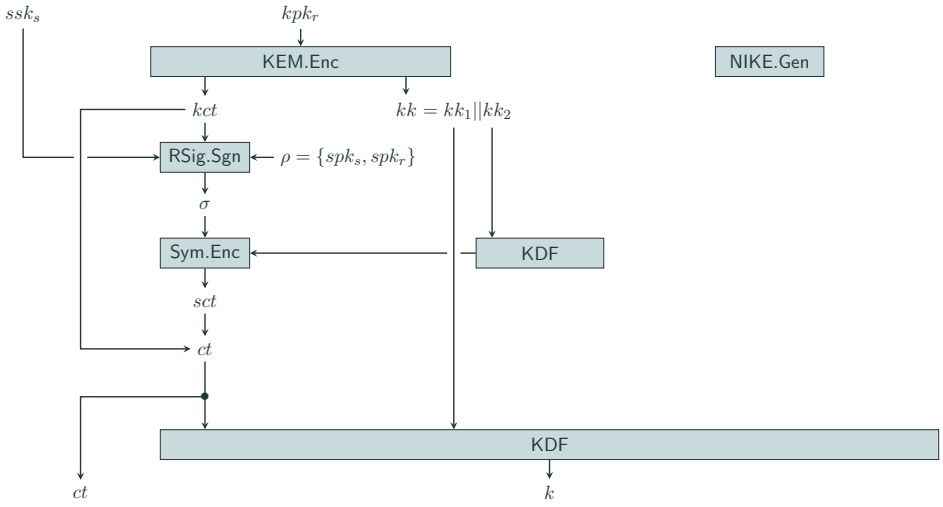
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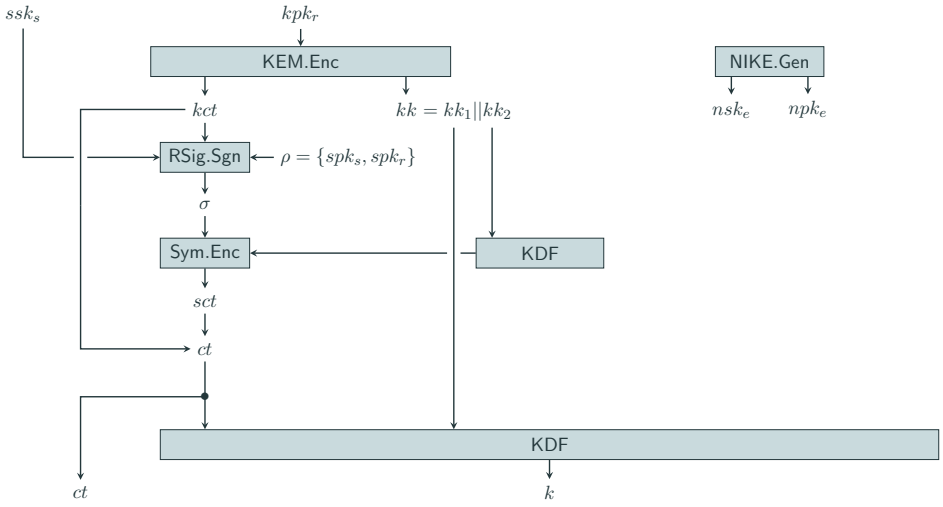
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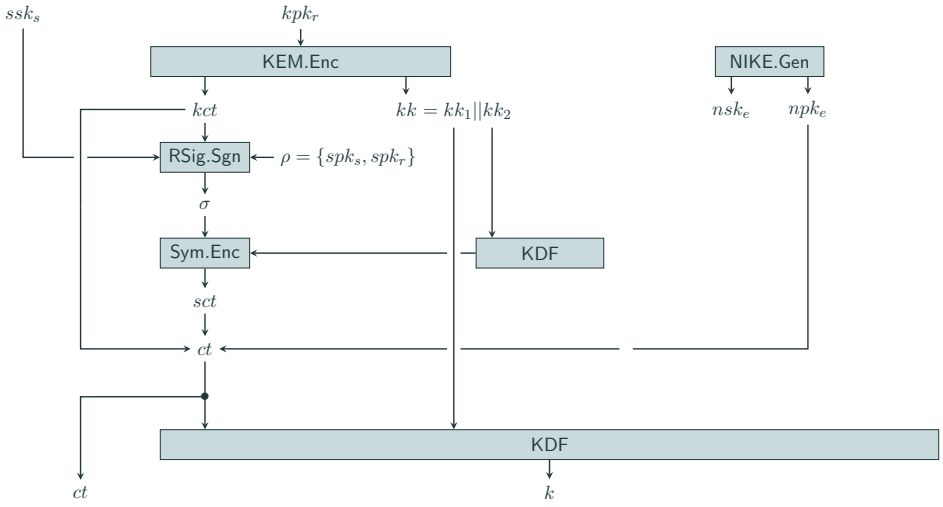
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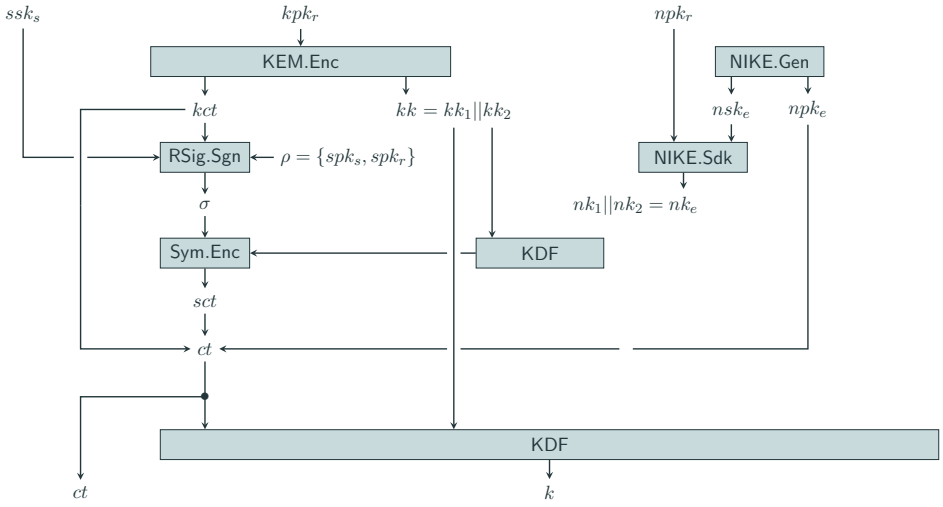
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npk_r
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NIKE.Gen
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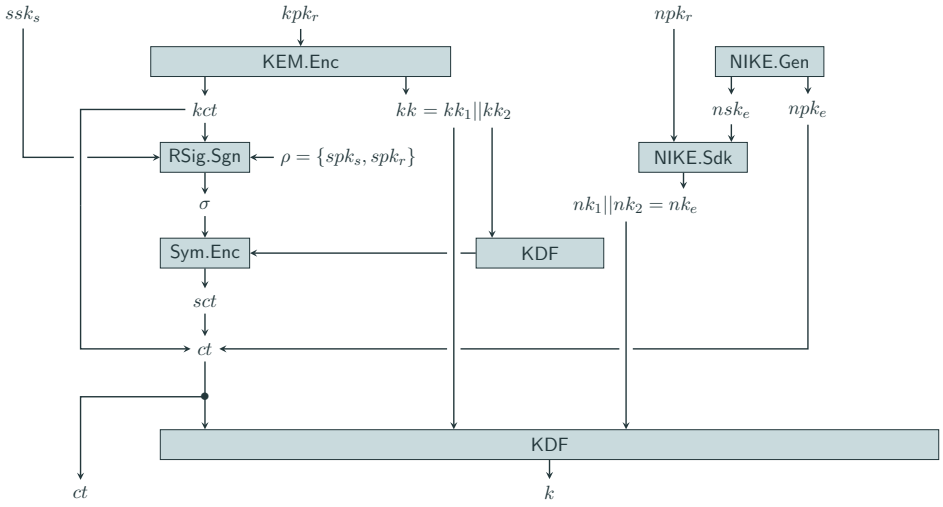
$kk = kk_1||kk_2$
nsk_e
npk_e
RSig.Sgn
$\rho = \{spk_s, spk_r\}$
NIKE.Sdk
σ
$nk_1||nk_2 = nk_e$
Sym.Enc
KDF
sct
ct
KDF
ct
k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Sym.Enc
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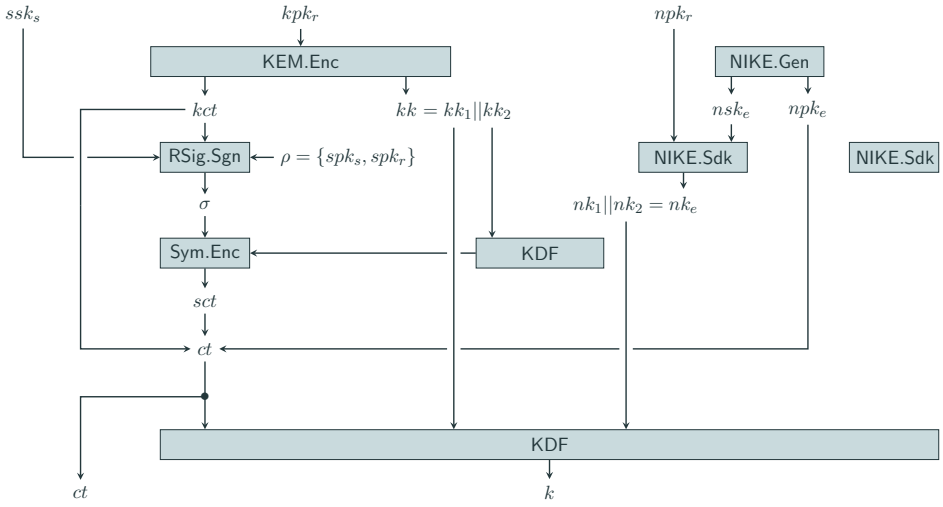
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NIKE.Sdk
NIKE.Sdk
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$nk_1||nk_2 = nk_e$
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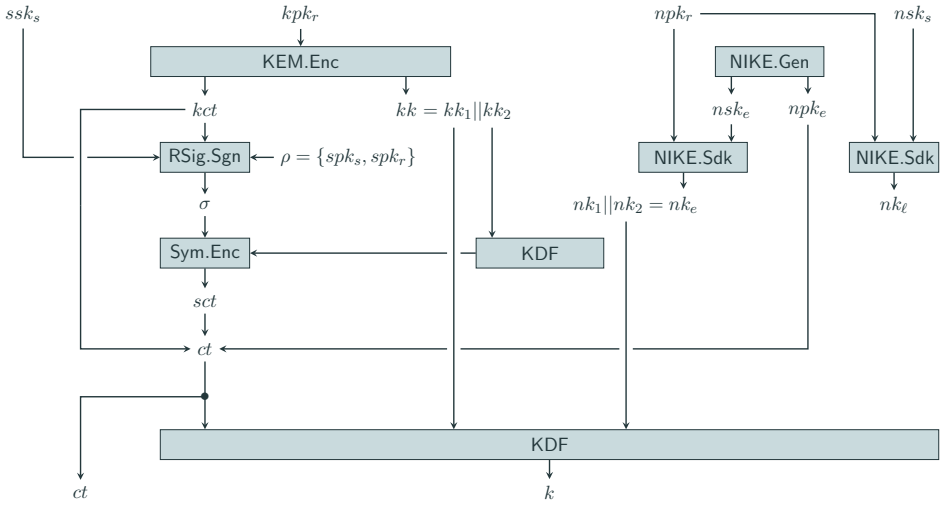
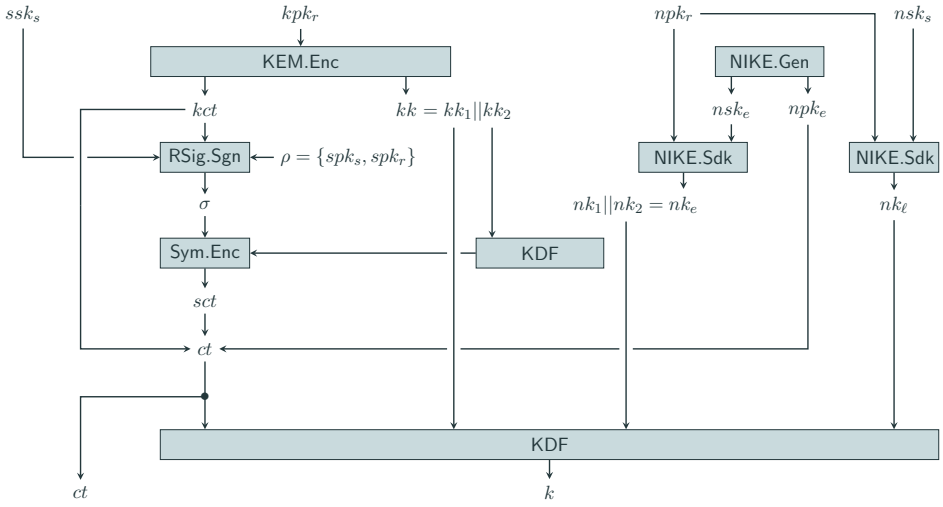
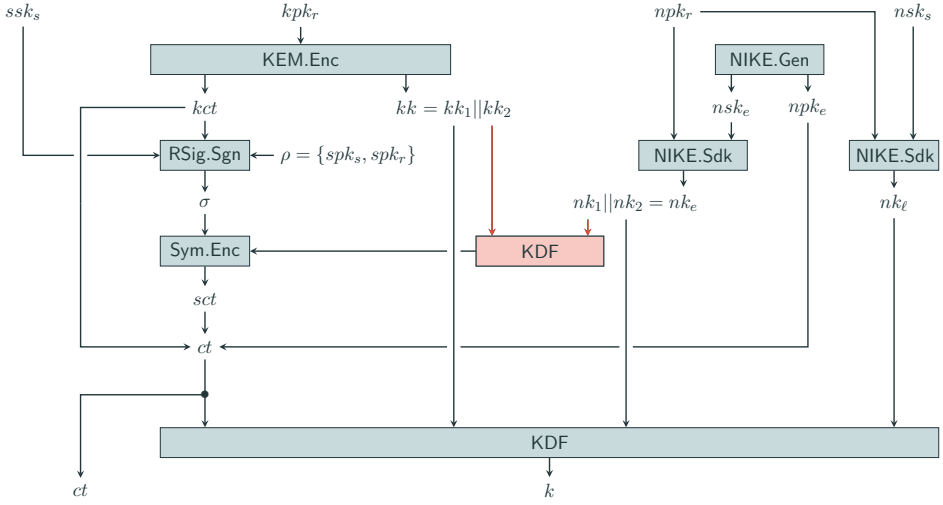
sct
ct
KDF
ct
k


ssk_s
kpk_r
KEM.Enc
kct
$kk = kk_1||kk_2$
RSig.Sgn
$\rho = \{spk_s, spk_r\}$
σ
Sym.Enc
KDF
sct
ct
ct
KDF
k
npk_r
NIKE.Gen
nsk_e
npk_e
NIKE.Sdk
$nk_1||nk_2 = nk_e$
nsk_s
NIKE.Sdk
nk_ℓ

DENIABLE AKEM := (Gen, Enc, Dec) — SHADOWFAX CONSTRUCTION




ssk_s
kpk_r
KEM.Enc
kct
$kk = kk_1||kk_2$
RSig.Sgn
$\rho = \{spk_s, spk_r\}$
σ
Sym.Enc
KDF
sct
ct
ct
npk_r
NIKE.Gen
nsk_e
npk_e
NIKE.Sdk
$nk_1||nk_2 = nk_e$
nsk_s
NIKE.Sdk
nk_ℓ
KDF
k

INSTANTIATIONS OF PRIMITIVES USED IN SHADOWFAX

Primitive	Scheme (variant)	Assumption	Size (in bytes)		
			σ	c	pk
NIKE	X25519 [Ber06]	CDH	—	32	32

INSTANTIATIONS OF PRIMITIVES USED IN SHADOWFAX

Primitive	**Scheme (variant)**	**Assumption**	**Size (in bytes)**		
			σ	c	pk
NIKE	`X25519` [Ber06]	CDH	—	32	32
KEM	`bat_257_512` [FKPY22]	NTRU, Ring-LWR	—	473	521

INSTANTIATIONS OF PRIMITIVES USED IN SHADOWFAX

Primitive	Scheme (variant)	Assumption	Size (in bytes)		
			σ	c	pk
NIKE	`X25519` [Ber06]	CDH	—	32	32
KEM	`bat_257_512` [FKPY22]	NTRU, Ring-LWR	—	473	521
	`ML-KEM-512` [ML-24]	M-LWE	—	768	800

INSTANTIATIONS OF PRIMITIVES USED IN SHADOWFAX

Primitive	Scheme (variant)		Assumption	Size (in bytes)		
				σ	c	pk
NIKE	`X25519` [Ber06]		CDH	—	32	32
KEM	`bat_257_512` [FKPY22]		NTRU, Ring-LWR	—	473	521
	`ML-KEM-512` [ML-24]		M-LWE	—	768	800
RSig	Gandalf[TpdGen, PreSmp] [GJK24]	Antrag [ENS+23], Mitaka [EFG+22]	NTRU, Ring-ISIS	1 236	—	896

INSTANTIATIONS OF PRIMITIVES USED IN SHADOWFAX

Primitive	Scheme (variant)		Assumption	Size (in bytes)		
				σ	c	pk
NIKE	`X25519` [Ber06]		CDH	—	32	32
KEM	`bat_257_512` [FKPY22]		NTRU, Ring-LWR	—	473	521
	`ML-KEM-512` [ML-24]		M-LWE	—	768	800
RSig	Gandalf[TpdGen, PreSmp] [GJK24]	Antrag [ENS+23], Mitaka [EFG+22]	NTRU, Ring-ISIS	1 236	—	896
		`Falcon-512` [PFH+22]		1 276	—	897

INSTANTIATIONS OF PRIMITIVES USED IN SHADOWFAX

Primitive	Scheme (variant)		Assumption	Size (in bytes)		
				σ	c	pk
NIKE	`X25519` [Ber06]		CDH	—	32	32
KEM	`bat_257_512` [FKPY22]		NTRU, Ring-LWR	—	473	521
	`ML-KEM-512` [ML-24]		M-LWE	—	768	800
RSig	Gandalf[TpdGen, PreSmp] [GJK24]	Antrag [ENS+23], Mitaka [EFG+22]	NTRU, Ring-ISIS	1 236	—	896
		`Falcon-512` [PFH+22]		1 276	—	897

- We opt for the most compact instantiations.
- However, also possible to use NIST PQC standards.

AKEM INSTANTIATIONS

Scheme	Instantiation	Deniability	Assumption		Size (in bytes)	
			pre-Q	post-Q	c	pk
DH-AKEM [ABH+21]	`X25519`	**DR-Den***	✓	✗	32	32

Deniability properties marked with an "$*$" have not been formally proven in the respective work.

AKEM instantiations

Scheme	Instantiation	Deniability	Assumption		Size (in bytes)	
			pre-Q	post-Q	c	pk
DH-AKEM [ABH+21]	`X25519`	**DR-Den***	✓	✗	32	32
EtStH-AKEM [AJKL23]	`bat_257_542` + Antrag	✗	✗	✓	1 119	1 417
	`ML-KEM-512` + `Falcon-512`				1 434	1 697

Deniability properties marked with an "$*$" have not been formally proven in the respective work.

AKEM instantiations

Scheme	Instantiation	Deniability	Assumption		Size (in bytes)	
			pre-Q	post-Q	c	pk
DH-AKEM [ABH+21]	`X25519`	**DR-Den***	✓	✗	32	32
EtStH-AKEM [AJKL23]	`bat_257_542` + Antrag	✗	✗	✓	1 119	1 417
	`ML-KEM-512` + `Falcon-512`				1 434	1 697
NIKE-AKEM [AJKL23]	Swoosh [GdKQ+24]	**DR-Den***	✗	✓	$> 221\,184$	$> 221\,184$

Deniability properties marked with an "$*$" have not been formally proven in the respective work.

AKEM instantiations

Scheme	Instantiation	Deniability	Assumption		Size (in bytes)	
			pre-Q	post-Q	c	pk
DH-AKEM [ABH+21]	`X25519`	**DR-Den***	✓	✗	32	32
EtSt-AKEM [AJKL23]	`bat_257_542` + Antrag	✗	✗	✓	1 119	1 417
	`ML-KEM-512` + `Falcon-512`				1 434	1 697
NIKE-AKEM [AJKL23]	Swoosh [GdKQ+24]	**DR-Den***	✗	✓	$> 221\,184$	$> 221\,184$
FrodoKEX+ [CHN+24]	n/a	**DR-Den**	✗	✓	72	21 300

Deniability properties marked with an "$*$" have not been formally proven in the respective work.

AKEM instantiations

Scheme	Instantiation	Deniability	Assumption		Size (in bytes)	
			pre-Q	post-Q	c	pk
DH-AKEM [ABH+21]	`X25519`	**DR-Den***	✓	✗	32	32
EtSt H-AKEM [AJKL23]	`bat_257_542` + Antrag	✗	✗	✓	1 119	1 417
	`ML-KEM-512` + `Falcon-512`				1 434	1 697
NIKE-AKEM [AJKL23]	Swoosh [GdKQ+24]	**DR-Den***	✗	✓	$> 221\,184$	$> 221\,184$
FrodoKEX+ [CHN+24]	n/a	**DR-Den**	✗	✓	72	21 300
PQ-AKEM [GJK24]	NTRU-A + Gandalf [Antrag, Mitaka]	**HR-Den** & **DR-Den**	✗	✓	2 044	1 664
	`bat_257_542` + Gandalf [Antrag, Mitaka]				1 749	1 417

Deniability properties marked with an "$*$" have not been formally proven in the respective work.

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Scheme	Instantiation	Deniability	Assumption		Size (in bytes)	
			pre-Q	post-Q	c	pk
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EtSt H-AKEM [AJKL23]	bat_257_542 + Antrag	✗	✗	✓	1 119	1 417
	ML-KEM-512 + Falcon-512				1 434	1 697
NIKE-AKEM [AJKL23]	Swoosh [GdKQ+24]	**DR-Den***	✗	✓	> 221 184	> 221 184
FrodoKEX+ [CHN+24]	n/a	**DR-Den**	✗	✓	72	21 300
PQ-AKEM [GJK24]	NTRU-A + Gandalf [Antrag, Mitaka]	**HR-Den** & **DR-Den**	✗	✓	2 044	1 664
	bat_257_542 + Gandalf [Antrag, Mitaka]				1 749	1 417
Shadowfax [GHJ25]	X25519 + bat_257_542 + Gandalf [Antrag, Mitaka]	**HR-Den** & **DR-Den**	✓	✓	1 781	1 449
	X25519 + ML-KEM-512 + Gandalf [Falcon-512]				2 076	1 729

Deniability properties marked with an "∗" have not been formally proven in the respective work.

AKEM INSTANTIATIONS

Scheme	Instantiation	Deniability	Assumption		Size (in bytes)	
			pre-Q	post-Q	c	pk
DH-AKEM [ABH+21]	X25519	**DR-Den***	✓	✗	32	32
EtSt H-AKEM [AJKL23]	bat_257_542 + Antrag	✗	✗	✓	1 119	1 417
	ML-KEM-512 + Falcon-512				1 434	1 697
NIKE-AKEM [AJKL23]	Swoosh [GdKQ+24]	**DR-Den***	✗	✓	$> 221\,184$	$> 221\,184$
FrodoKEX+ [CHN+24]	n/a	**DR-Den**	✗	✓	72	21 300
PQ-AKEM [GJK24]	NTRU-A + Gandalf [Antrag, Mitaka]	**HR-Den** & **DR-Den**	✗	✓	2 044	1 664
	bat_257_542 + Gandalf [Antrag, Mitaka]				1 749	1 417
Shadowfax [GHJ25]	X25519 + bat_257_542 + Gandalf [Antrag, Mitaka]	**HR-Den** & **DR-Den**	✓	✓	1 781	1 449
	X25519 + ML-KEM-512 + Gandalf [Falcon-512]				2 076	1 729

Deniability properties marked with an "$*$" have not been formally proven in the respective work.

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Scheme	Instantiation	Deniability	Assumption		Size (in bytes)	
			pre-Q	post-Q	c	pk
DH-AKEM [ABH+21]	X25519	**DR-Den***	✓	✗	32	32
EtSt H-AKEM [AJKL23]	bat_257_542 + Antrag	✗	✗	✓	1 119	1 417
	ML-KEM-512 + Falcon-512				1 434	1 697
NIKE-AKEM [AJKL23]	Swoosh [GdKQ+24]	**DR-Den***	✗	✓	$> 221\,184$	$> 221\,184$
FrodoKEX+ [CHN+24]	n/a	**DR-Den**	✗	✓	72	21 300
PQ-AKEM [GJK24]	NTRU-A + Gandalf [Antrag, Mitaka]	**HR-Den** & **DR-Den**	✗	✓	2 044	1 664
	bat_257_542 + Gandalf [Antrag, Mitaka]				1 749	1 417
Shadowfax [GHJ25]	X25519 + bat_257_542 + Gandalf [Antrag, Mitaka]	**HR-Den** & **DR-Den**	✓	✓	1 781	1 449
	X25519 + ML-KEM-512 + Gandalf [Falcon-512]				2 076	1 729

Deniability properties marked with an "$*$" have not been formally proven in the respective work.

AKEM	Gen		Enc		Dec	
	kcc	**ms**	**kcc**	**ms**	**kcc**	**ms**

RSig	Gen		Sgn		Ver	
	kcc	**ms**	**kcc**	**ms**	**kcc**	**ms**

Cycle counts (in kilocycles) and time (in milliseconds) on a 3GHz Firestorm core of an Apple M1 Pro.

AKEM	Gen		Enc		Dec	
	kcc	**ms**	**kcc**	**ms**	**kcc**	**ms**
DH-AKEM [ABH+21]	208	0.07	628	0.21	419	0.14

RSig	Gen		Sgn		Ver	
	kcc	**ms**	**kcc**	**ms**	**kcc**	**ms**

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PQ-AKEM [GJK24]	24 748	8.25	1 215	0.41	332	0.11

RSig	Gen		Sgn		Ver	
	kcc	**ms**	**kcc**	**ms**	**kcc**	**ms**

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Shadowfax [GHJ25]	24 770	8.27	1 846	0.62	746	0.25

RSig	Gen		Sgn		Ver	
	kcc	**ms**	**kcc**	**ms**	**kcc**	**ms**

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Shadowfax [GHJ25]	24 770	8.27	1 846	0.62	746	0.25
RSig	**Gen**		**Sgn**		**Ver**	
	kcc	**ms**	**kcc**	**ms**	**kcc**	**ms**
Raptor [LAZ19]	71 420	23.81	7 980	2.66	505	0.17

Cycle counts (in kilocycles) and time (in milliseconds) on a 3GHz Firestorm core of an Apple M1 Pro.

AKEM	Gen		Enc		Dec	
	kcc	**ms**	**kcc**	**ms**	**kcc**	**ms**
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RSig	**Gen**		**Sgn**		**Ver**	
	kcc	**ms**	**kcc**	**ms**	**kcc**	**ms**
Raptor [LAZ19]	71 420	23.81	7 980	2.66	505	0.17
Gandalf [GJK24]	13 145	4.38	1 110	0.37	95	0.03

Cycle counts (in kilocycles) and time (in milliseconds) on a 3GHz Firestorm core of an Apple M1 Pro.

SUMMARY

- Generic combiners may be too restrictive for PQC migration.
- SHADOWFAX: a deniable AKEM combiner from NIKE, KEM and RSig:
  - Compact instantiation with $|c| = 1.8$ KB and $|pk| = 1.5$ KB.
- Implementation of SHADOWFAX and GANDALF ring signature scheme [GJK24].

ia.cr/2025/154 — github.com/vincentvbh/shadowfax

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p4i11ip

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$b \xleftarrow{\$} \{0,1\}$

$pk_1, \ldots, pk_n$

$\ldots$

if $b = 0$

$(c, k) \xleftarrow{\$} \mathsf{Enc}(sk_s, pk_r)$

if $b = 1$

$(c, k) \xleftarrow{\$} \mathsf{Sim}(\ldots)$

$\texttt{Chall}(s \in [n], r \in [n])$

(c, k)

if $b = b'$

return win

b'

Honest receiver: $\mathsf{Sim}(\emptyset), \mathsf{A}(sk_s)$

Dishonest receiver: $\mathsf{Sim}(sk_r), \mathsf{A}(sk_s, sk_r)$

$b \xleftarrow{\$} \{0,1\}$

$\texttt{Encps}(s \in [n], pk)$

$(c,k) \xleftarrow{\$} \mathsf{Enc}(sk_s, pk)$

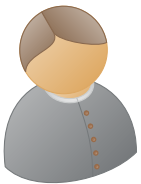
$(c,k) \xleftarrow{\$} \mathsf{Enc}(sk_s, pk_r)$

if $b = 0$

  continue

if $b = 1$

  $k \xleftarrow{\$} \mathcal{K}$



$\texttt{Decps}(pk, r \in [n], c)$

$k \leftarrow \mathsf{Dec}(pk, sk_r, c)$

if $b = b'$

  return win

$\texttt{Chall}(sk, r \in [n])/\texttt{Chall}(s \in [n], r \in [n])$

b'

(c,k)

ADDITIONAL SLIDES

Games $(\mathrm{n}, Q_{\mathtt{Enc}}, Q_{\mathtt{Chl}})$-**Out-Aut**$_{\mathsf{AKEM}}(\mathsf{A})$
$(\mathrm{n}, Q_{\mathtt{Enc}}, Q_{\mathtt{Dec}}, Q_{\mathtt{Chl}})$-**Ins-Aut**$_{\mathsf{AKEM}}(\mathsf{A})$

for $i \in [n]$
  $(sk_i, pk_i) \xleftarrow{\$} \mathsf{Gen}$
$\mathcal{D} \leftarrow \emptyset$
$b \xleftarrow{\$} \{0,1\}$
$b' \xleftarrow{\$} \mathsf{A}^{\mathtt{Encps},\mathtt{Chall}}(pk_1, \ldots, pk_n)$ // **Out-Aut**
$b' \xleftarrow{\$} \mathsf{A}^{\mathtt{Encps},\mathtt{Decps},\mathtt{Chall}}(pk_1, \ldots, pk_n)$ // **Ins-Aut**
return $[\![b = b']\!]$

Oracle $\mathtt{Chall}(pk, r \in [n], c)$ // **Out-Aut**
if $\exists\, k : (pk, pk_r, c, k) \in \mathcal{D}$
  return k
$k \leftarrow \mathsf{Dec}(pk, sk_r, c)$
if $b = 0$
  continue
if $b = 1 \wedge pk \in \{pk_1, \ldots, pk_n\} \wedge k \neq \bot$
  $k \xleftarrow{\$} \mathcal{K}$
  $\mathcal{D} \leftarrow \mathcal{D} \cup \{(pk, pk_r, c, k)\}$
return k

Oracle $\mathtt{Encps}(s \in [n], pk)$
$(c, k) \xleftarrow{\$} \mathsf{Enc}(sk_s, pk)$
$\mathcal{D} \leftarrow \mathcal{D} \cup \{(pk_s, pk, c, k)\}$
return (c, k)

Oracle $\mathtt{Decps}(pk, r \in [n], c)$ // **Ins-Aut**
$k \leftarrow \mathsf{Dec}(pk, sk_r, c)$
return k

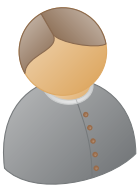
Oracle $\mathtt{Chall}(s \in [n], sk, c)$ // **Ins-Aut**
if $\exists\, k : (pk_s, \mu(sk), c, k) \in \mathcal{D}$
  return k
$k \leftarrow \mathsf{Dec}(pk_s, sk, c)$
if $b = 0$
  continue
if $b = 1 \wedge k \neq \bot$
  $k \xleftarrow{\$} \mathcal{K}$
  $\mathcal{D} \leftarrow \mathcal{D} \cup \{(pk_s, \mu(sk), c, k)\}$
return k

1.

AKEM security notion: outsider-aut [ABH+21]

$b \xleftarrow{\$} \{0,1\}$

if $\exists$ previous query
  return previous k
$k \leftarrow \mathsf{Dec}(pk, sk_r, c)$
if $b = 1 \wedge pk$ honest $\wedge\ k \neq \perp$
  $k \xleftarrow{\$} \mathcal{K}$
return k



$pk_1, \ldots, pk_n$

$\texttt{Encps}(s \in [n], pk)$

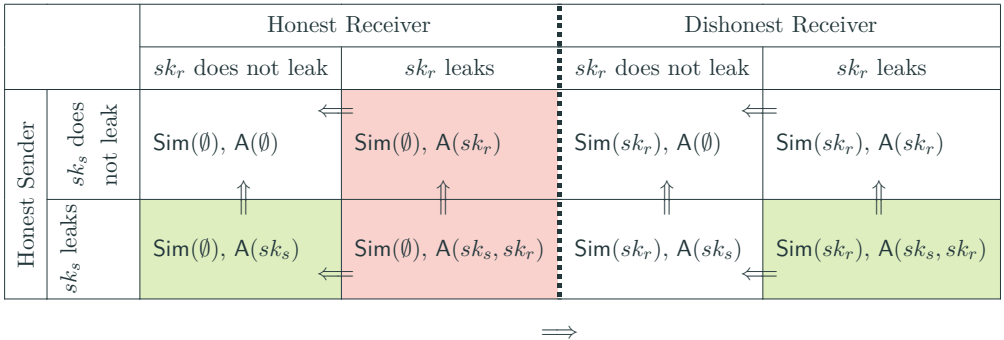
(c, k)

$\texttt{Chall}(pk, r \in [n], c)$

k

b'

if $b = b'$
  return win



- E.g. A non-interactive key exchange (NIKE) used for implicit authentication is dishonest receiver deniable, but not honest receiver deniable. [1]

[1] A single NIKE does not suffice as an AKEM.

Games $(\mathrm{n}, Q_{\mathtt{Chl}})$-$\mathbf{DR}$-$\mathbf{Den}_{\mathsf{AKEM},\mathsf{Sim}}(\mathsf{A})$

$(\mathrm{n}, Q_{\mathtt{Chl}})$-$\mathbf{HR}$-$\mathbf{Den}_{\mathsf{AKEM},\mathsf{Sim}}(\mathsf{A})$

$\mathcal{R}, \mathcal{C} \leftarrow \emptyset$
for $i \in [n]$
  $(sk_i, pk_i) \xleftarrow{\$} \mathsf{Gen}$
$b \xleftarrow{\$} \{0,1\}$
$b' \leftarrow \mathsf{A}^{\mathtt{Rev},\mathtt{Chall}}(pk_1, \ldots, pk_n)$
if $\mathcal{R} \cap \mathcal{C} \neq \emptyset$ // **HR-Den**
  return $b \xleftarrow{\$} \{0,1\}$ // **HR-Den**
return $[\![b = b']\!]$

$\mathtt{Rev}(i \in [n])$
$\mathcal{R} \leftarrow \mathcal{R} \cup \{i\}$
return sk_i

Oracle $\mathtt{Chall}(s \in [n], r \in [n])$
$\mathcal{C} \leftarrow \mathcal{C} \cup \{r\}$
$(c, k) \xleftarrow{\$} \mathsf{Enc}(sk_s, pk_r)$
if $b = 0$
  continue
if $b = 1$
  $(c, k) \xleftarrow{\$} \mathsf{Sim}(pk_s, pk_r, sk_r)$ // **DR-Den**
  $(c, k) \xleftarrow{\$} \mathsf{Sim}(pk_s, pk_r)$ // **HR-Den**
return (c, k)