Password-Based AKEM and HPKE

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Our Work

Password Authenticated Key Encapsulation Mechanism (PAKEM)

- Establish a session key in one round
- Authenticate the client using a password
- Achieve confidentiality, authentication, and password safety

Password Authenticated Hybrid Encryption (PAHE)

- Extend PAKEM to arbitrary-length messages
- Authenticate the client via password
- Preserve confidentiality, authentication, and password safety

Filling the Gap?

Key Establishment

	One Message	Authenticated	via Password?
KEM	✓	×	×
AKE	×	✓	×
AKEM	✓	✓	×
PAKE	×	✓	✓
PAKEM	✓	✓	✓

Hybrid Encryption

	One Message	Authenticated	via Password?	Arbitrary Length
KEM/DEM	✓	×	×	✓
PAKE + SKE	×	✓	✓	✓
HPKE	✓	✓	×	✓
PAPKE	✓	✓	✓	×
PAHE	✓	✓	✓	✓

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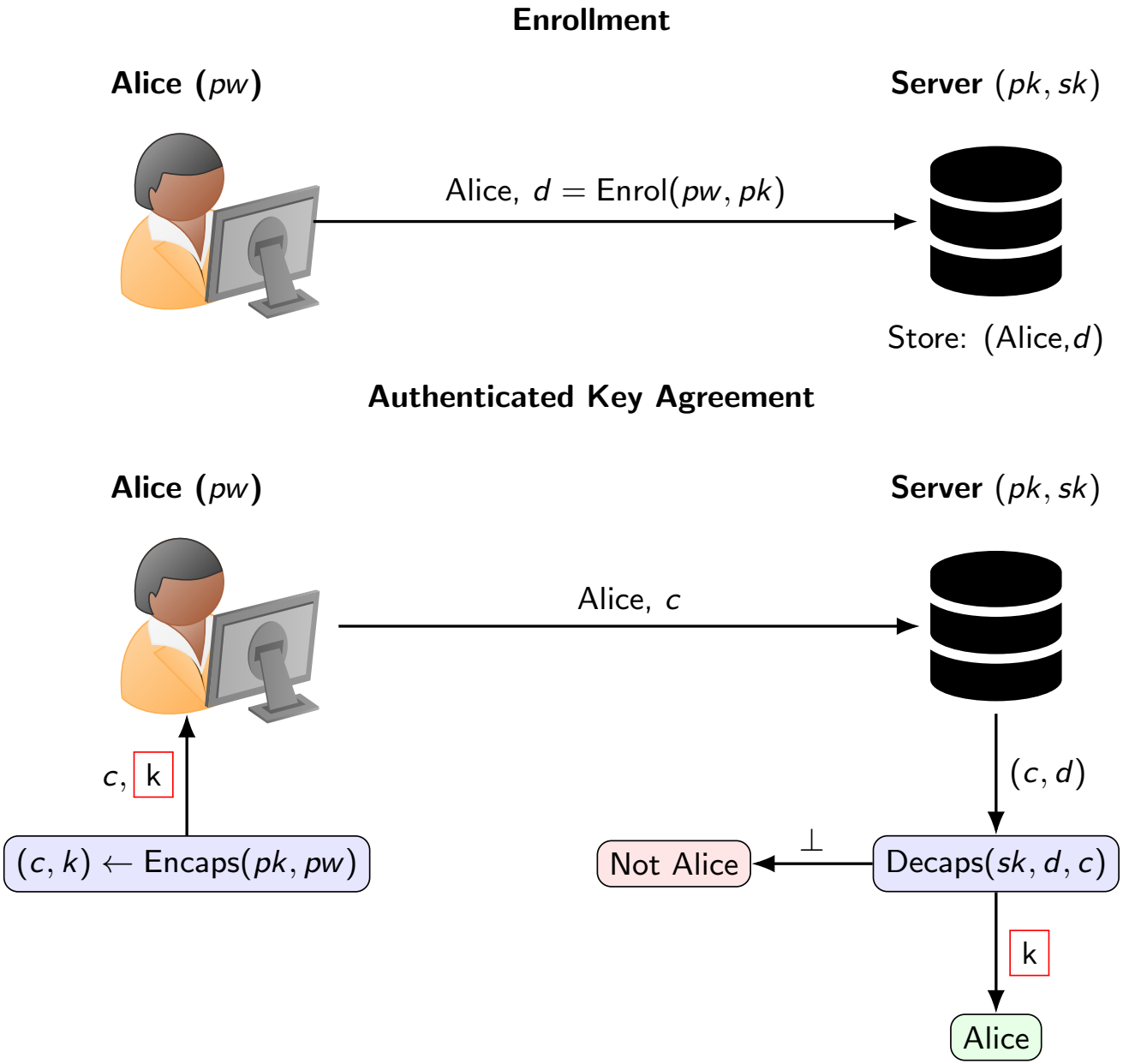
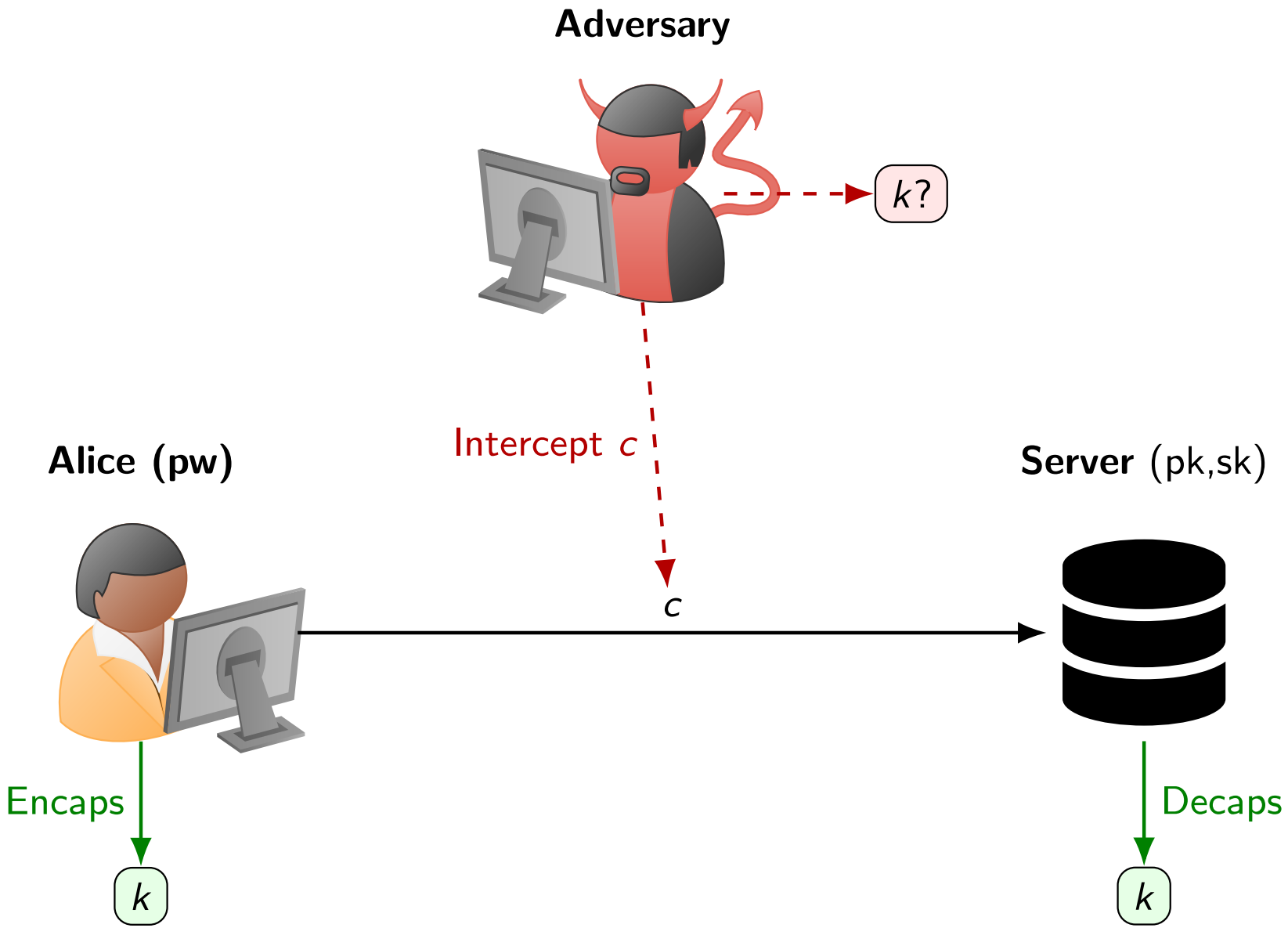
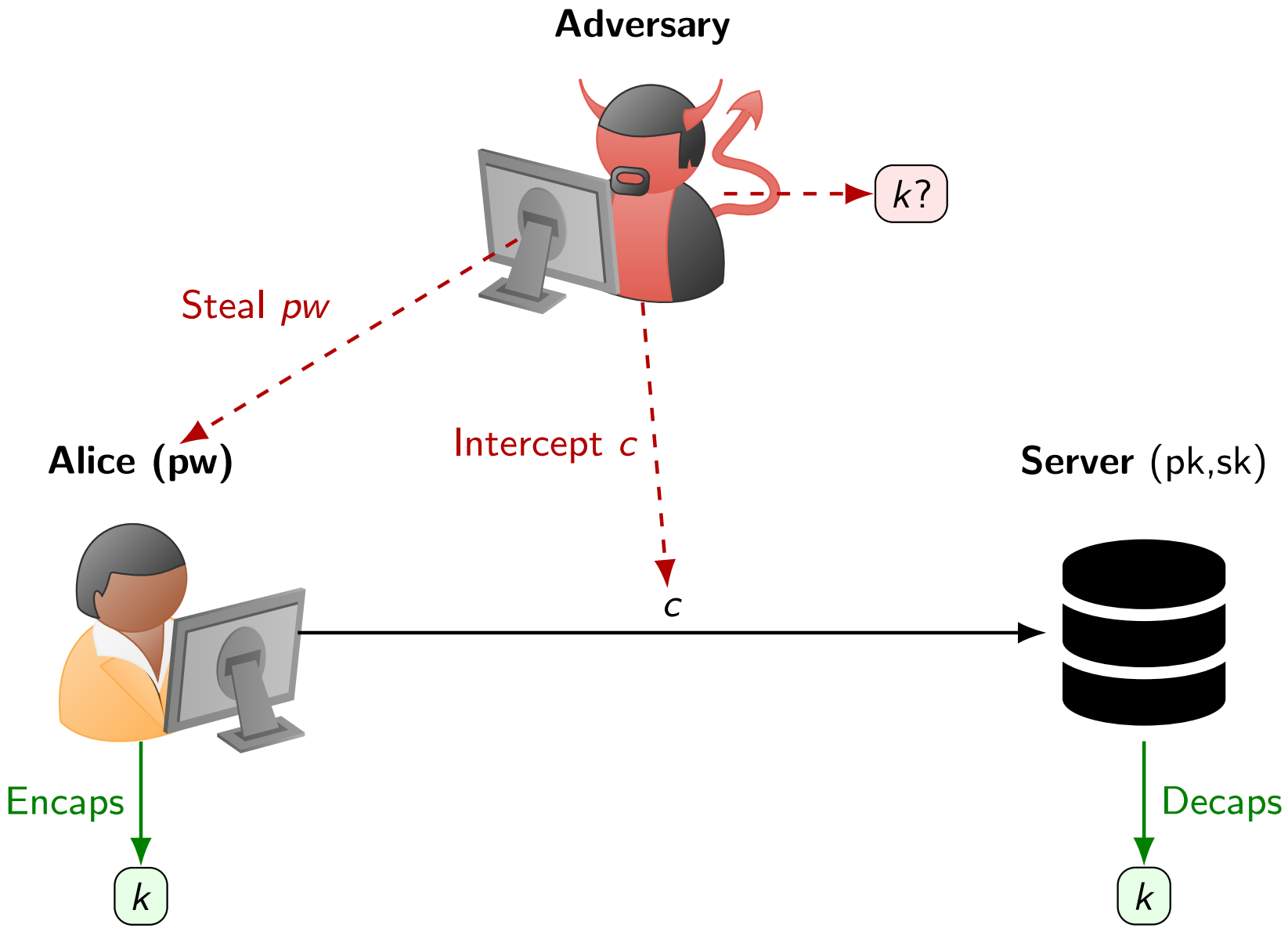
Overview


Enrollment
Alice (pw)
Server (pk, sk)
Alice, $d = \text{Enrol}(pw, pk)$
Store: (Alice, d)
Authenticated Key Agreement
Alice (pw)
Server (pk, sk)
Alice, c
c, k
(c, d)
$(c, k) \leftarrow \text{Encaps}(pk, pw)$
Not Alice
$\perp$
$\text{Decaps}(sk, d, c)$
k
Alice

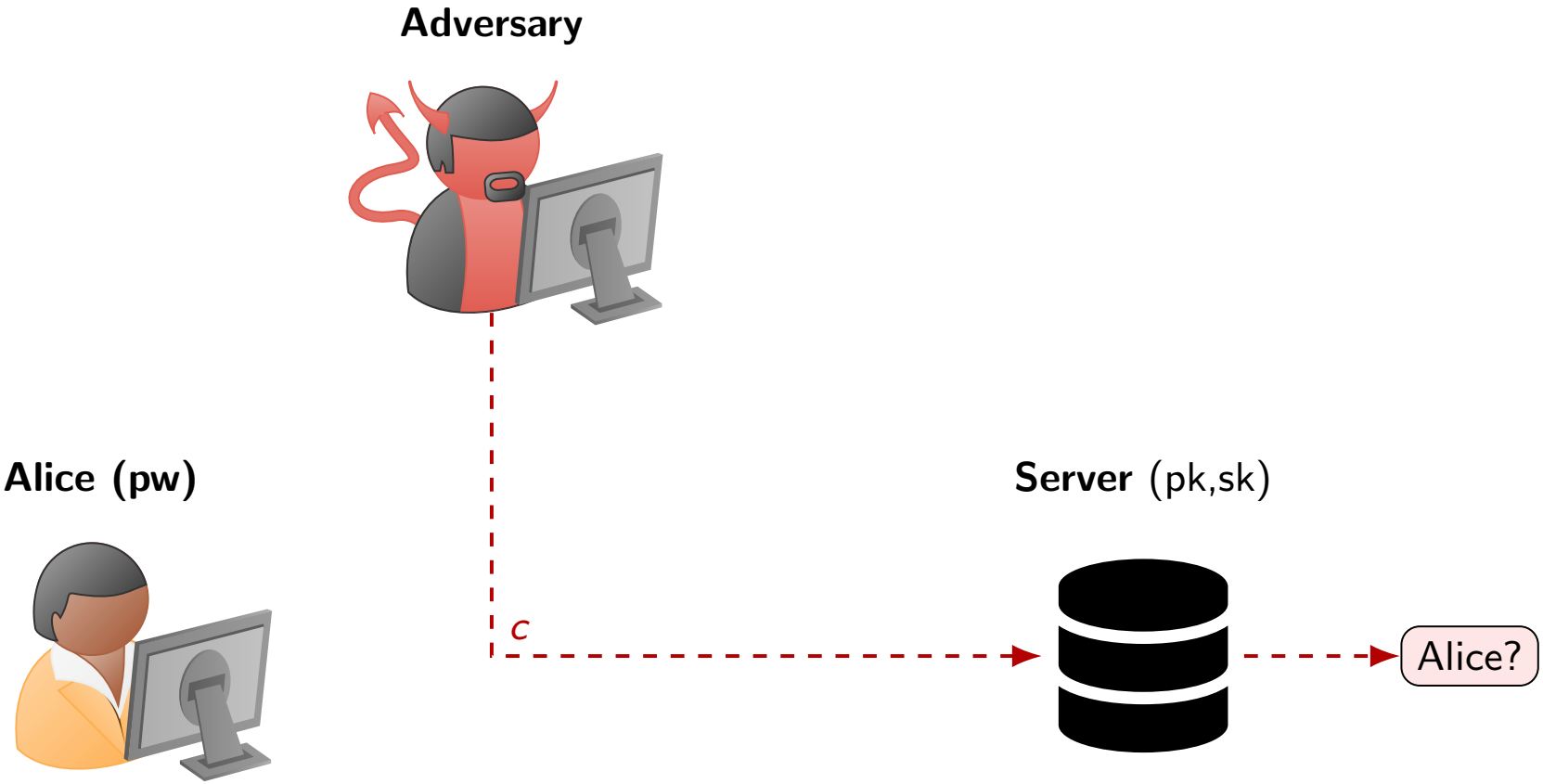
Outsider-CCA



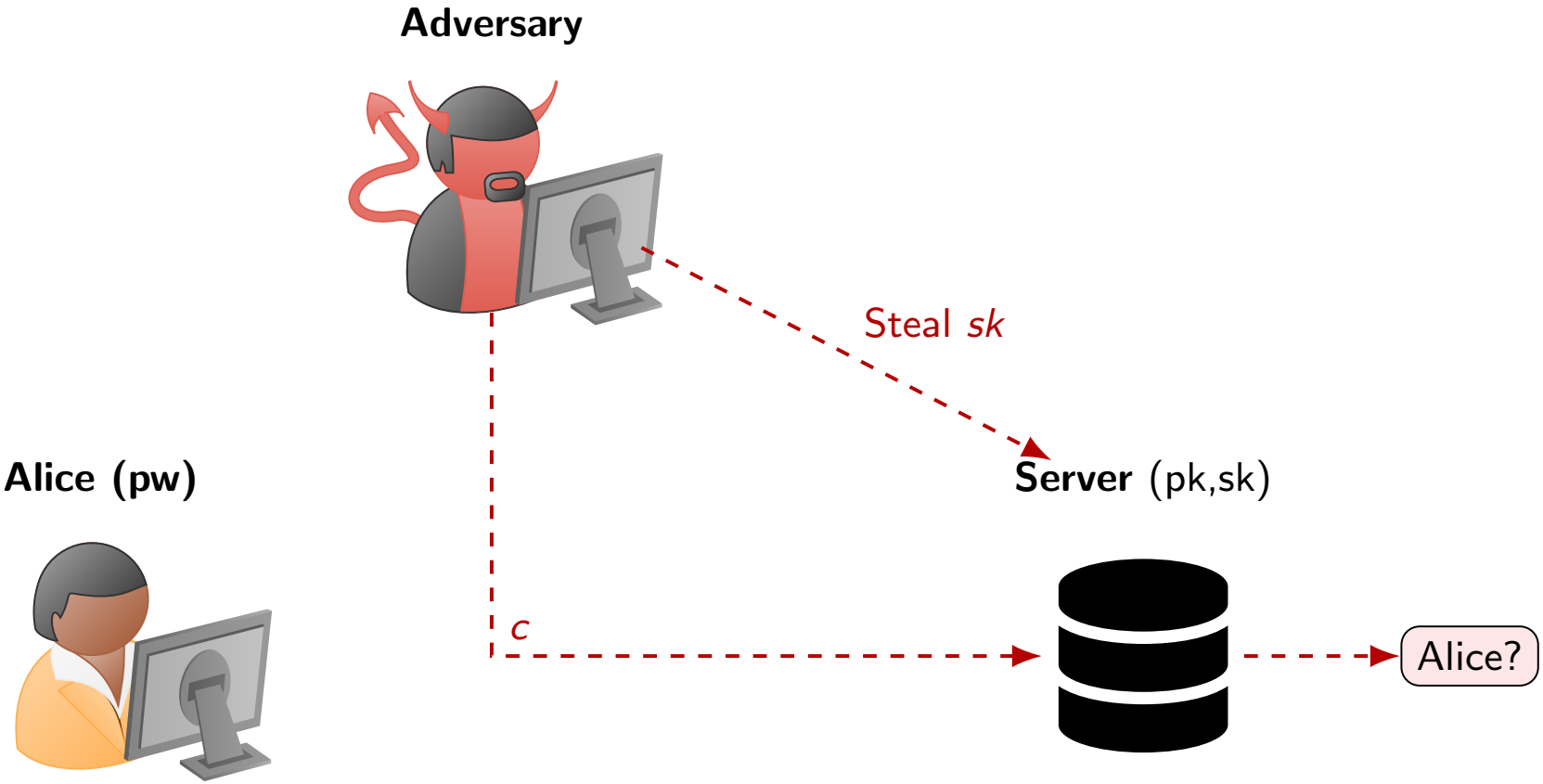
Insider-CCA


Adversary
k?
Steal pw
Intercept c
Alice (pw)
Server (pk,sk)
c
Encaps
Decaps
k
k

Outsider-Auth



Insider-Auth



Generic Construction

$\underline{\mathsf{Gen}(\lambda)}$:
$(pk_1, sk_1) \leftarrow K.KeyGen(1^\lambda)$
Return pk_1, sk_1

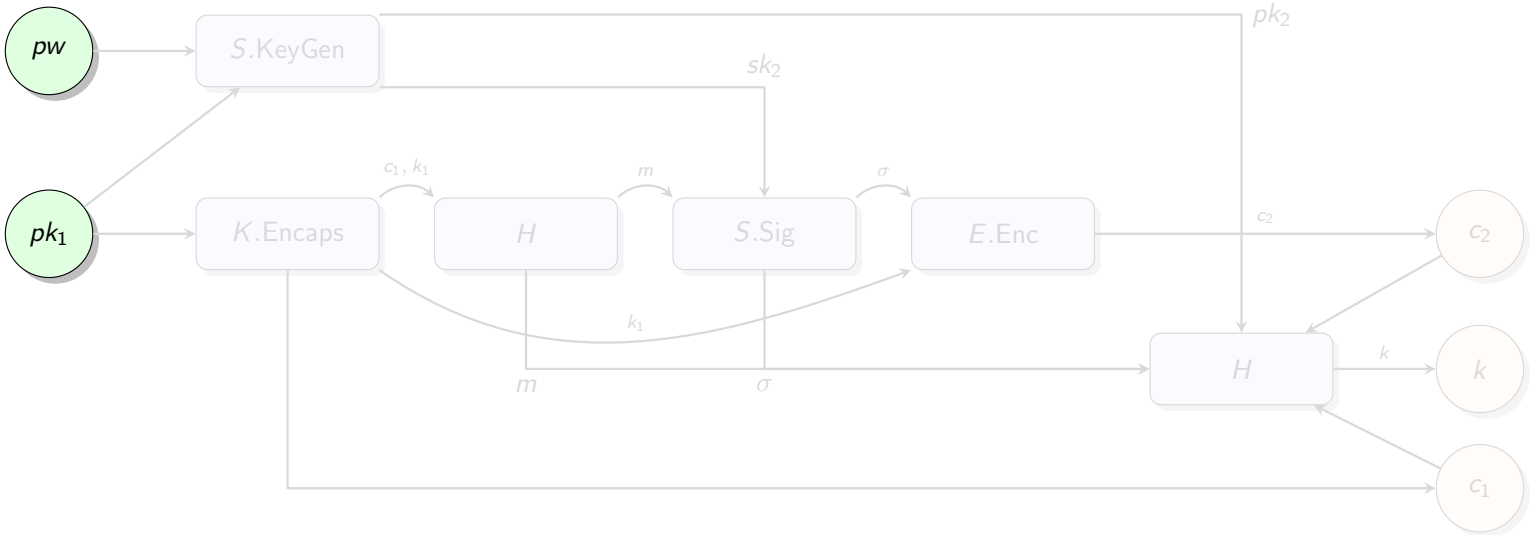
$\underline{\mathsf{Encaps}(pk_1, pw)}$:
$(c_1, k_1) \leftarrow K.Encaps(pk_1)$
$m \leftarrow H(c_1||k_1)$
$(pk_2, sk_2) \leftarrow S.KeyGen(1^\lambda; H(pw||pk_1))$
$\sigma \leftarrow S.Sig(sk_2, m)$
$c_2 \leftarrow E.Enc(k_1, \sigma)$
Return $c = (c_1, c_2), k = H(c_1||c_2||m||\sigma||pk_2)$

$\underline{\mathsf{Enrol}(pk_1, pw)}$:
$r \leftarrow H(pw||pk_1)$
$(pk_2, sk_2) \leftarrow S.KeyGen(1^\lambda; r)$
Return $d = pk_2$

$\underline{\mathsf{Decaps}(sk_1, pk_2, c = (c_1, c_2))}$:
$k_1 \leftarrow K.Decaps(sk_1, c_1)$
$m \leftarrow H(c_1||k_1)$
$\sigma \leftarrow E.Dec(k_1, c_2)$
If $S.Vrfy(pk_2, m, \sigma)$:
  Return $k = H(c_1||c_2||m||\sigma||pk_2)$
Else: **Return** $\perp$

Figure: PAKEM from KEM K, Signature S, DEM E and Hash function H.

Generic Construction



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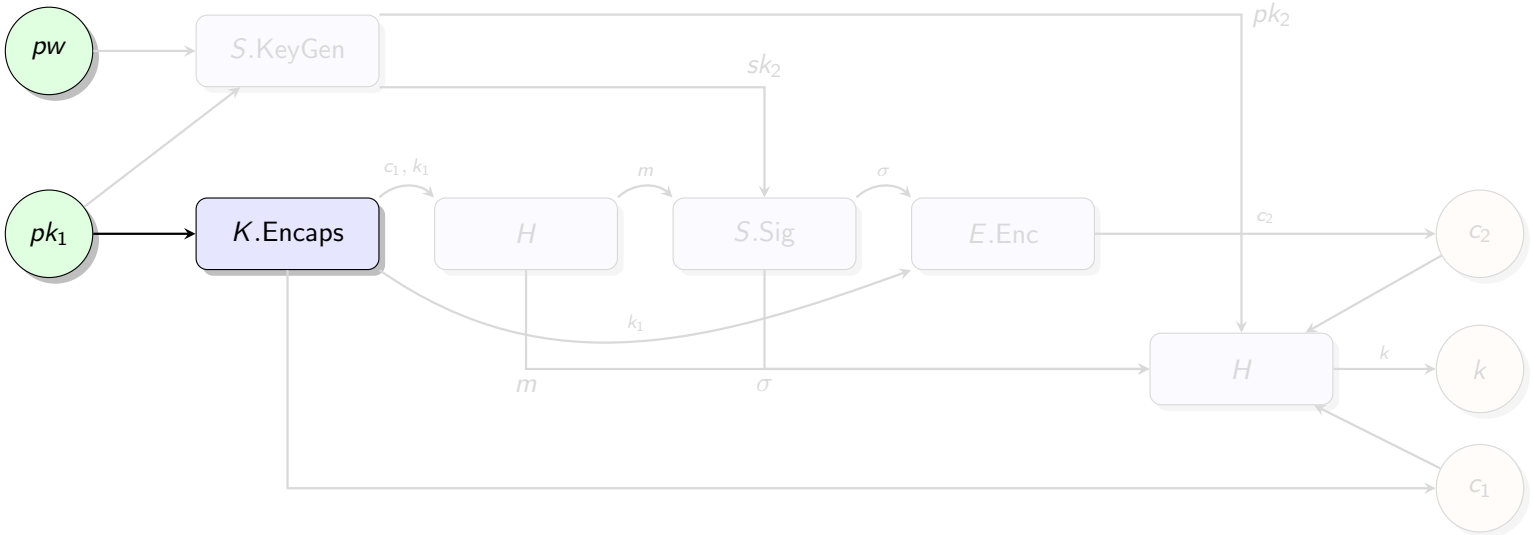

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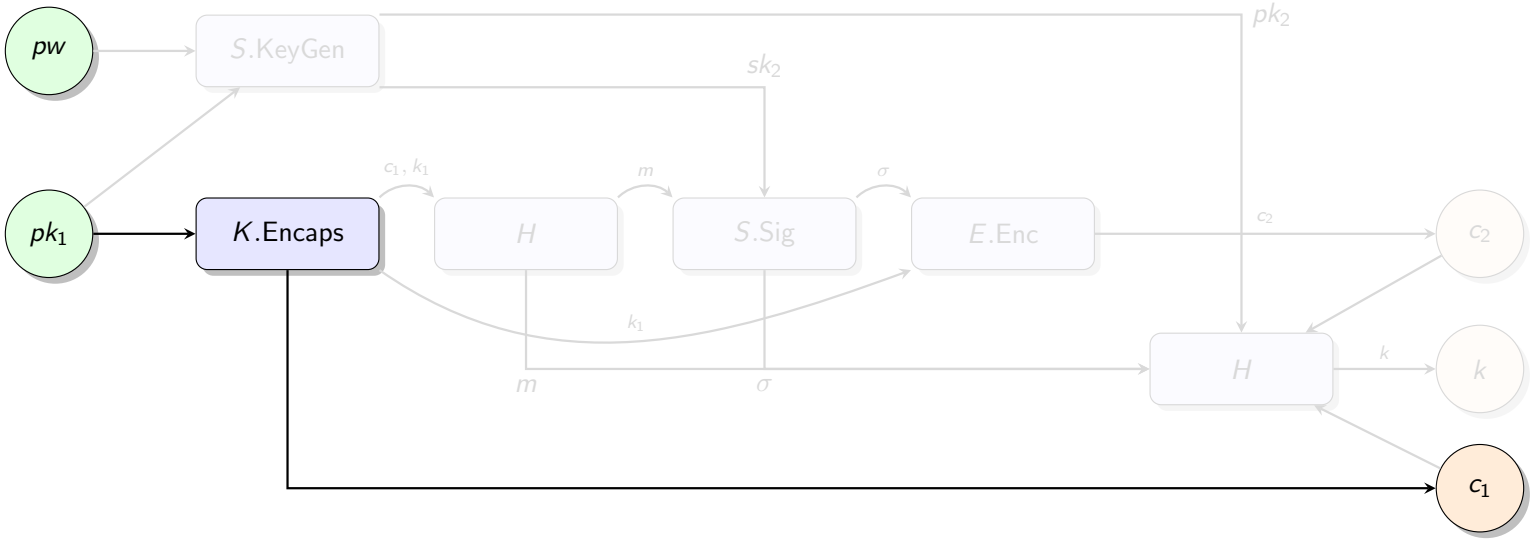

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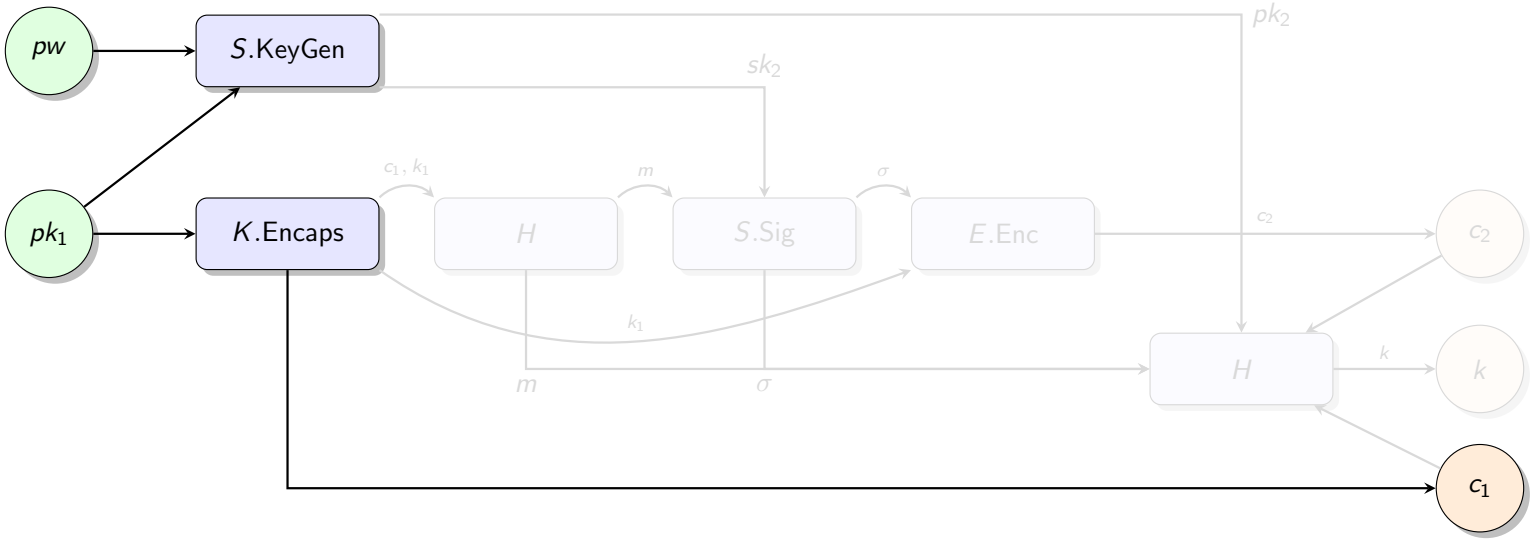

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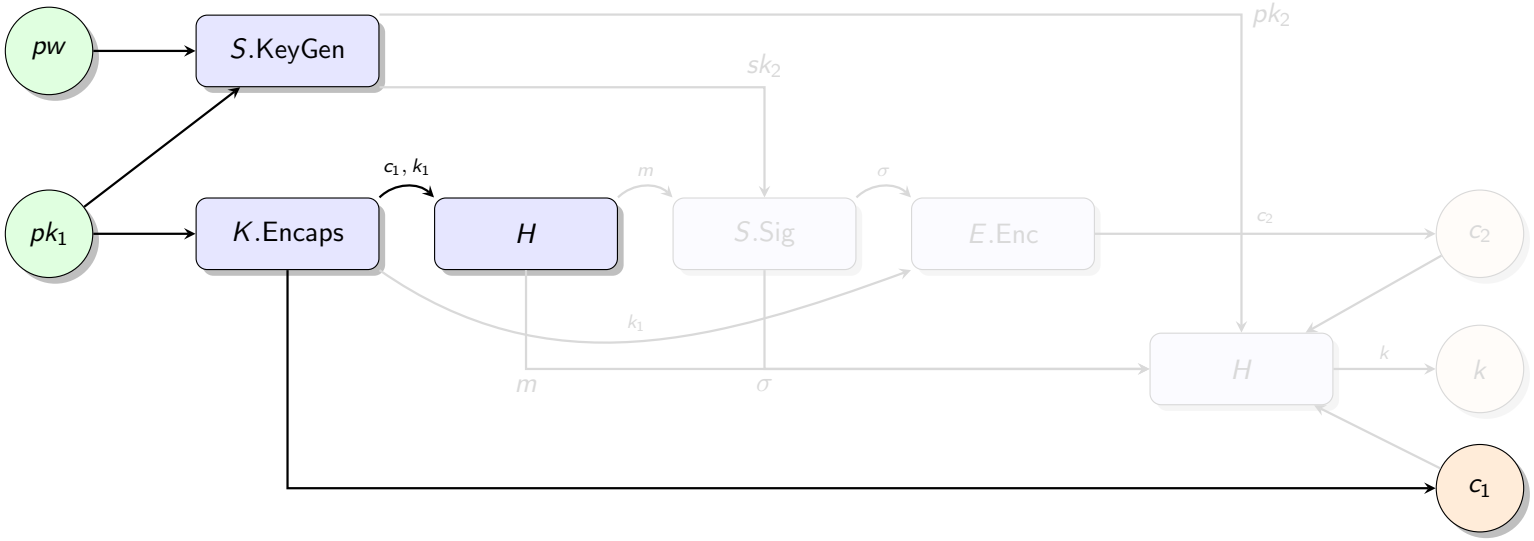

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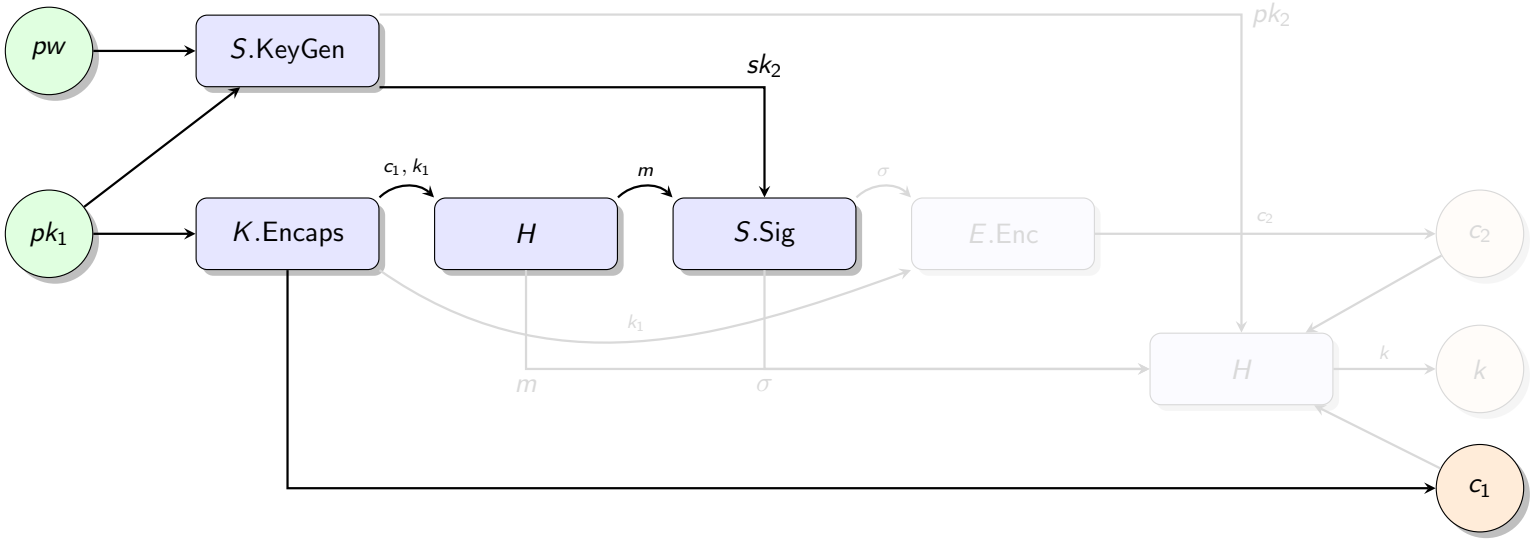

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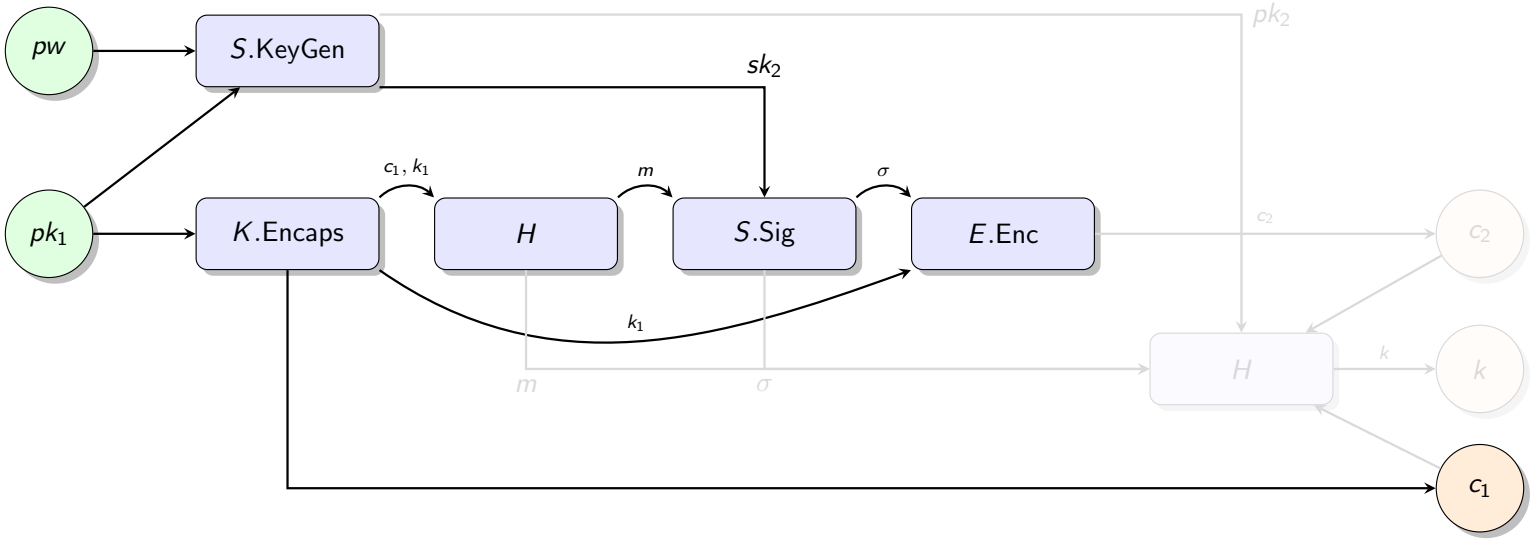

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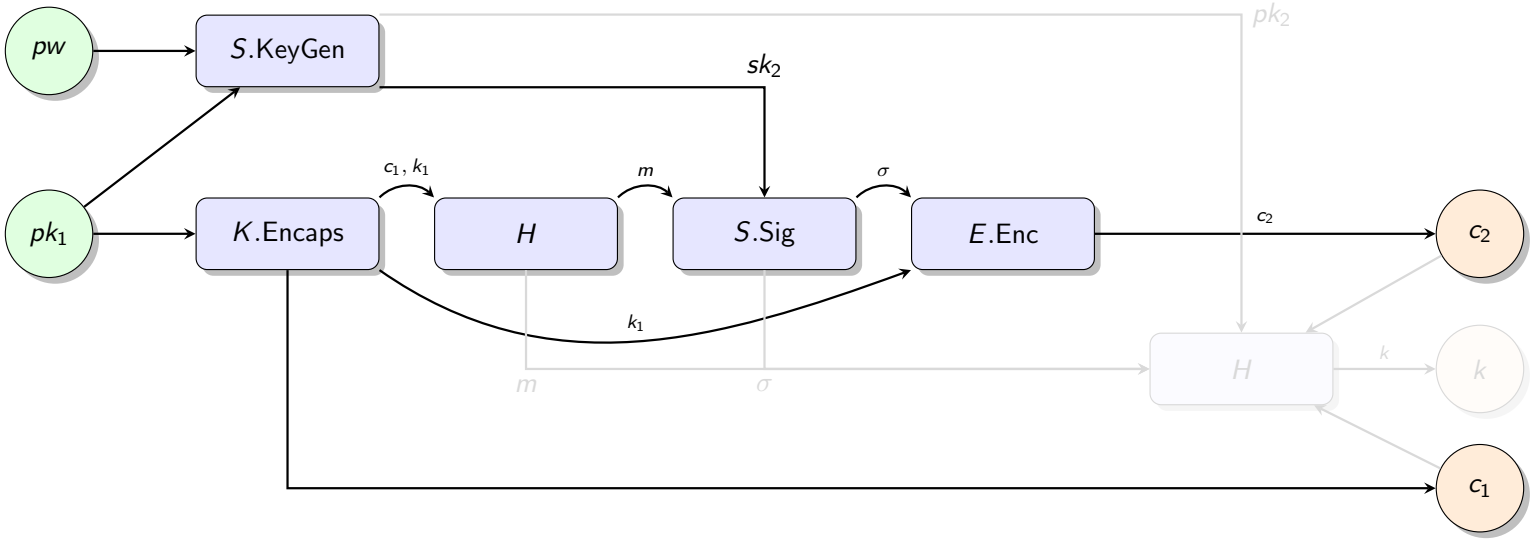

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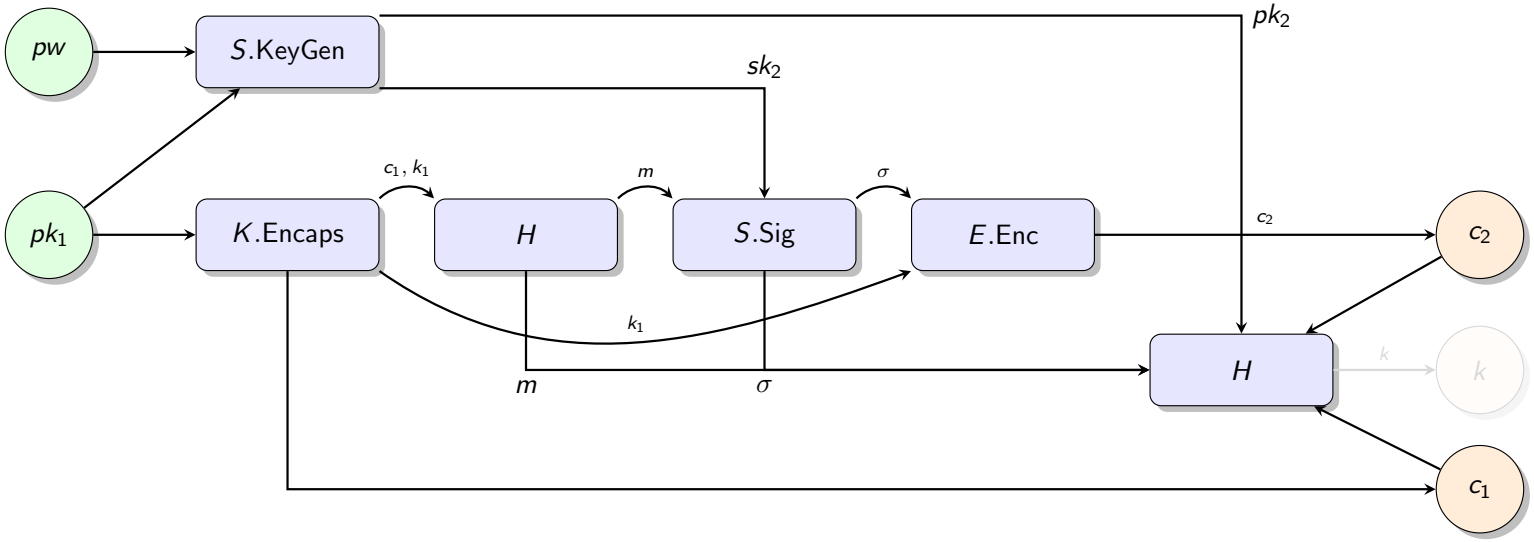

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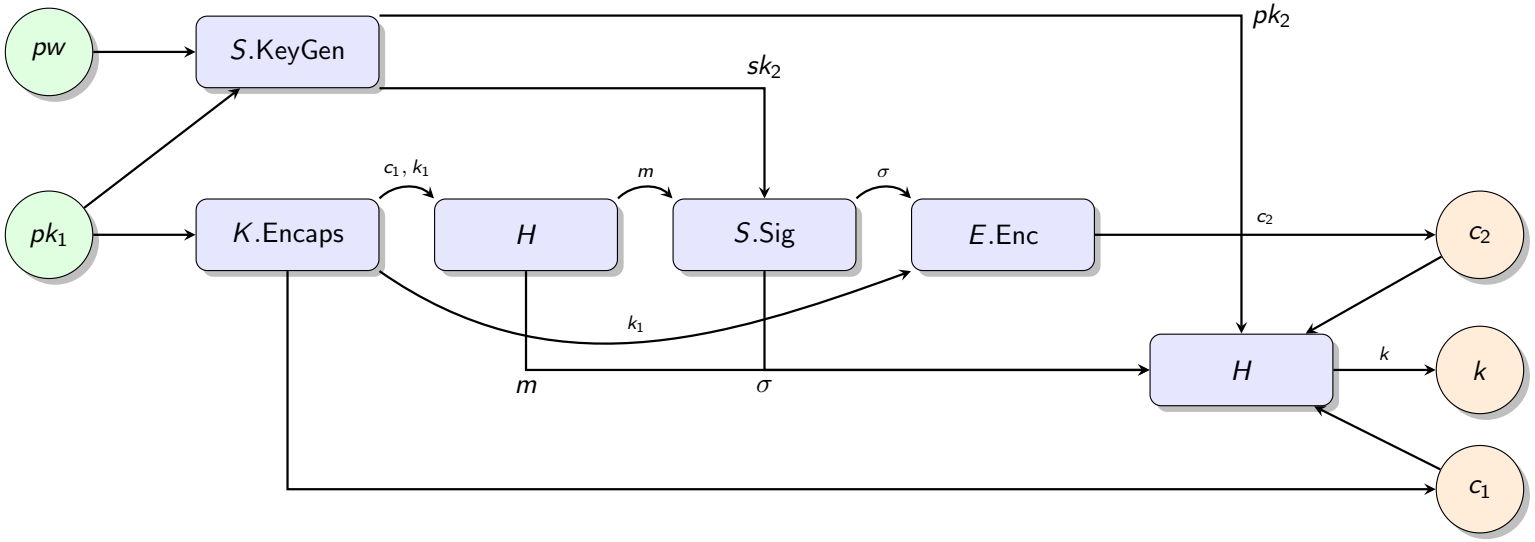

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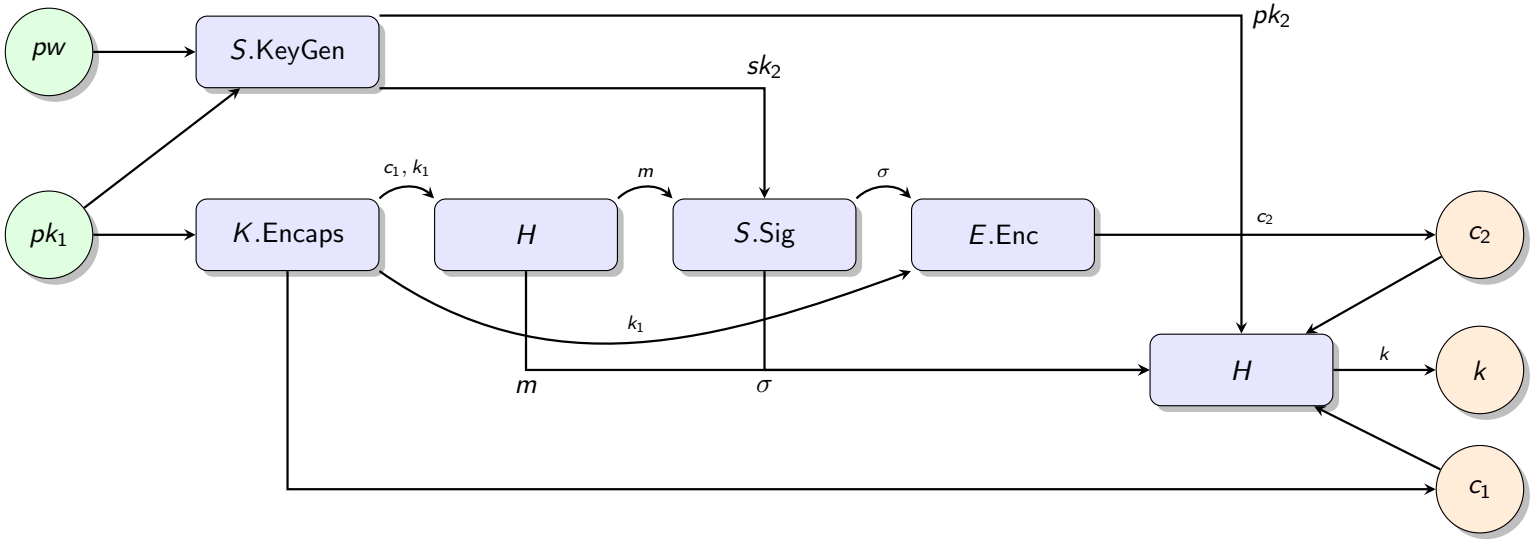

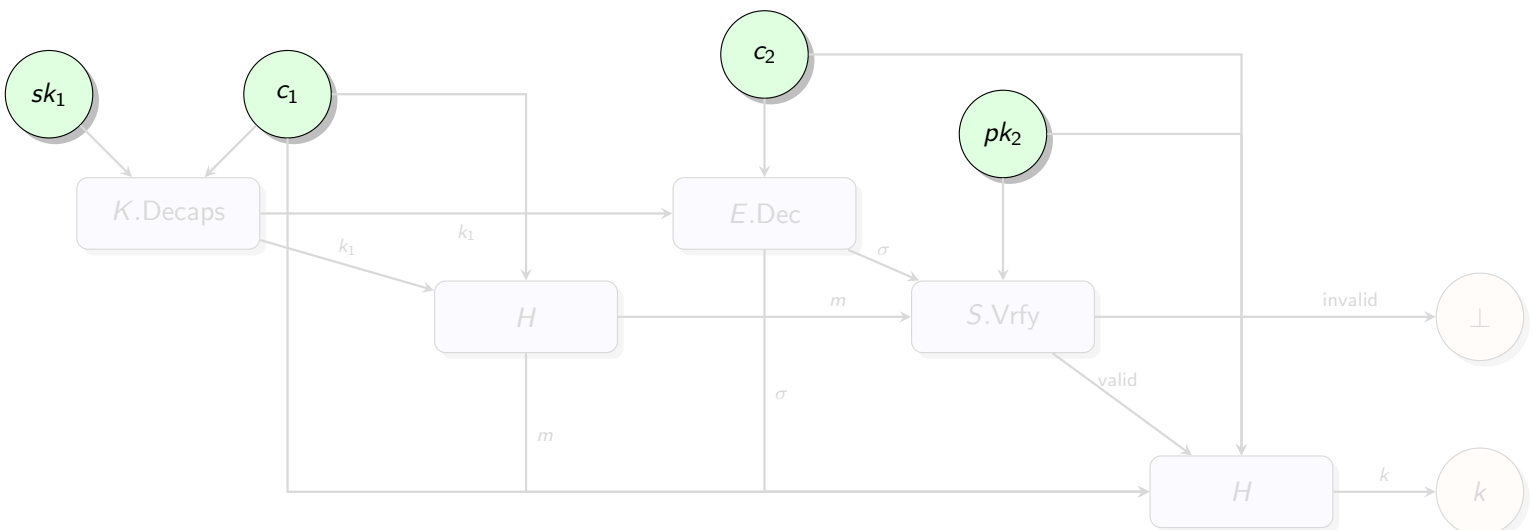

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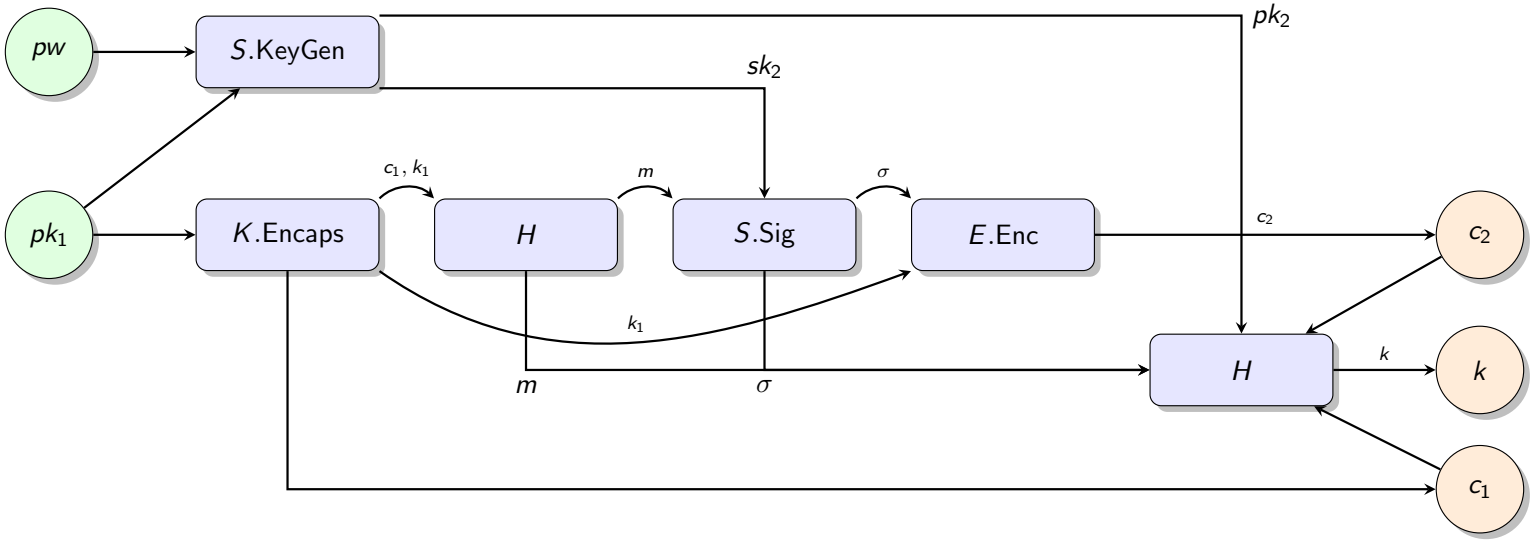

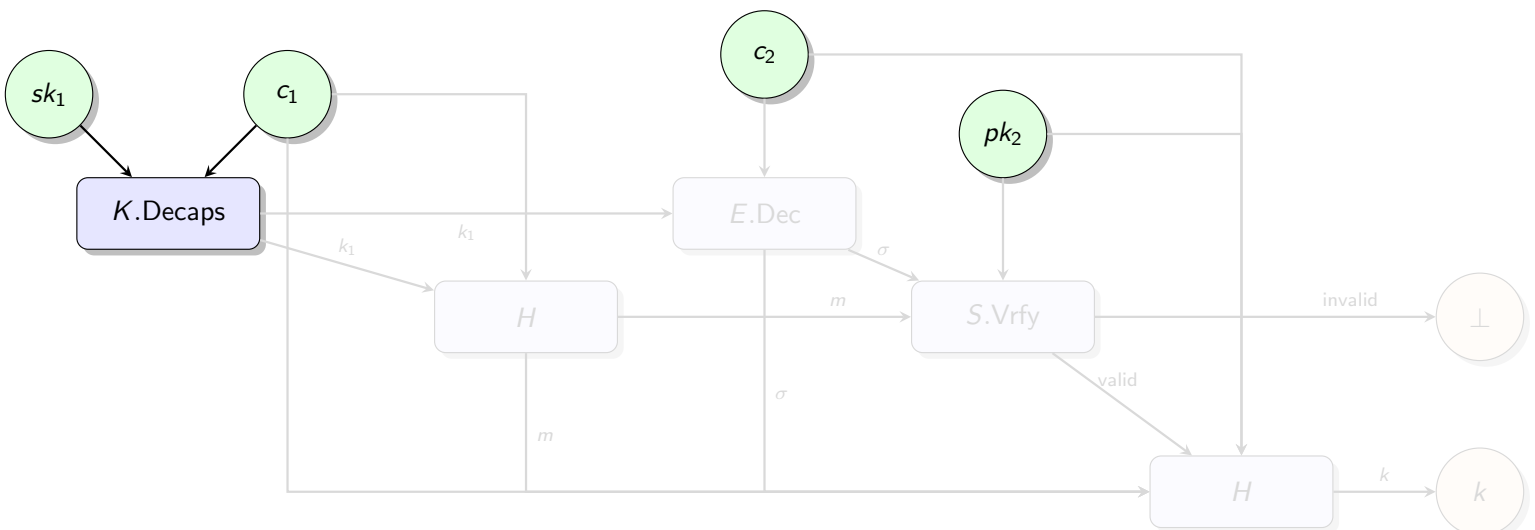

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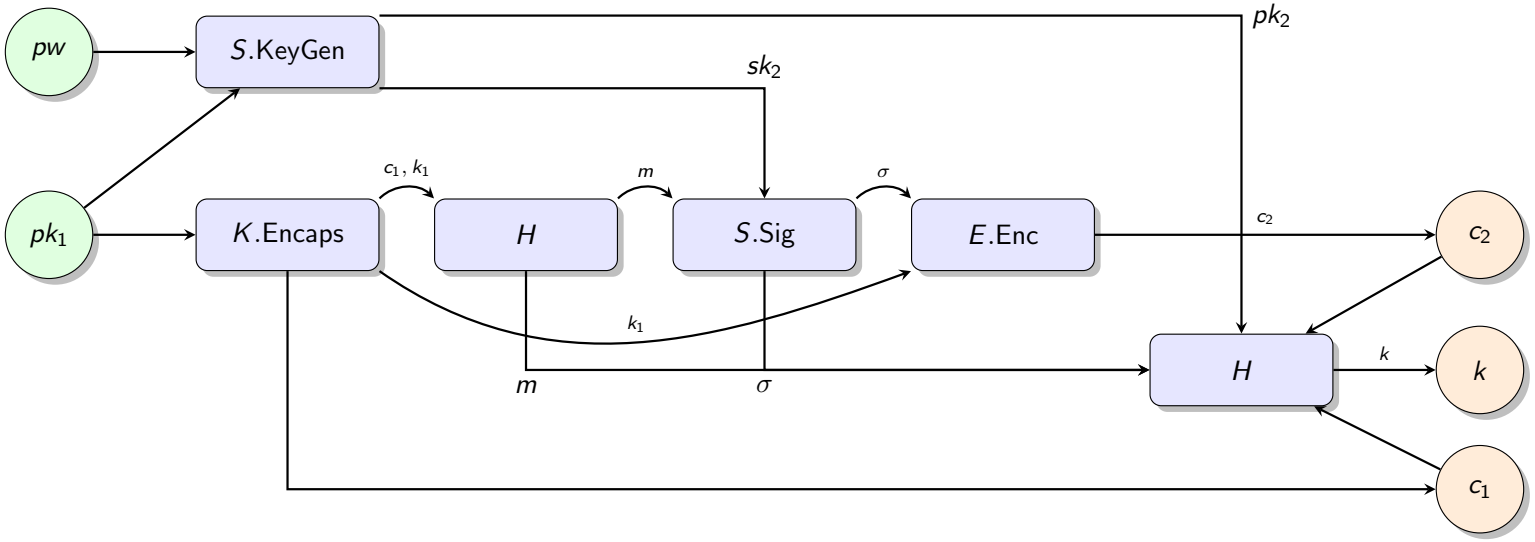

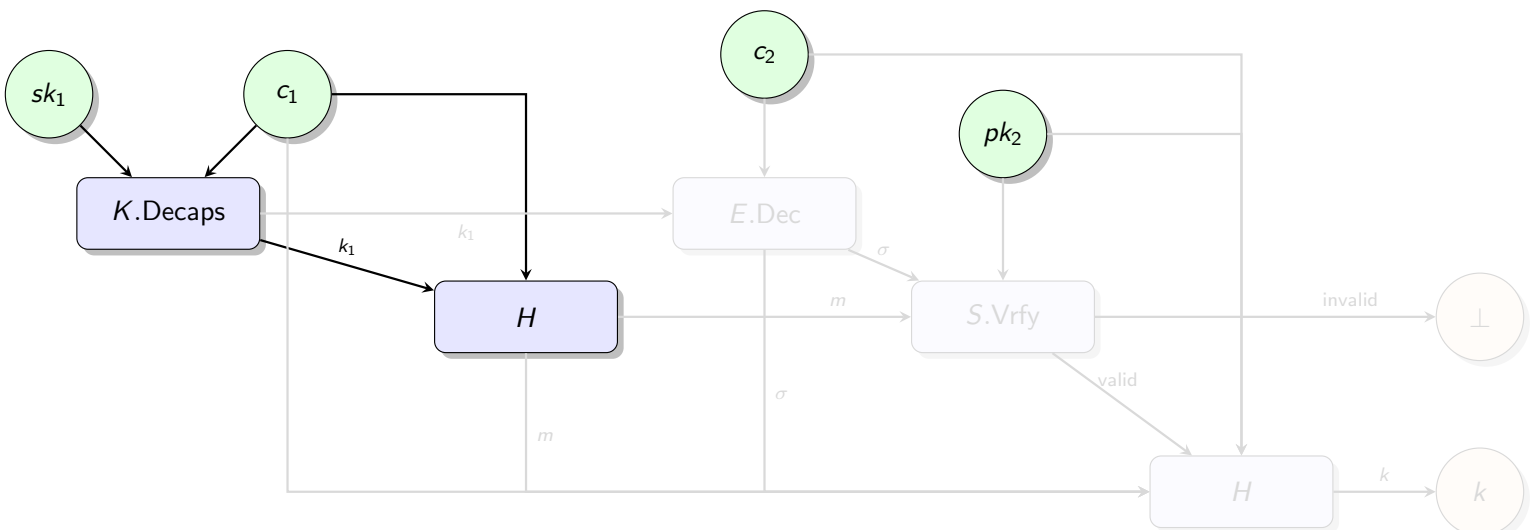

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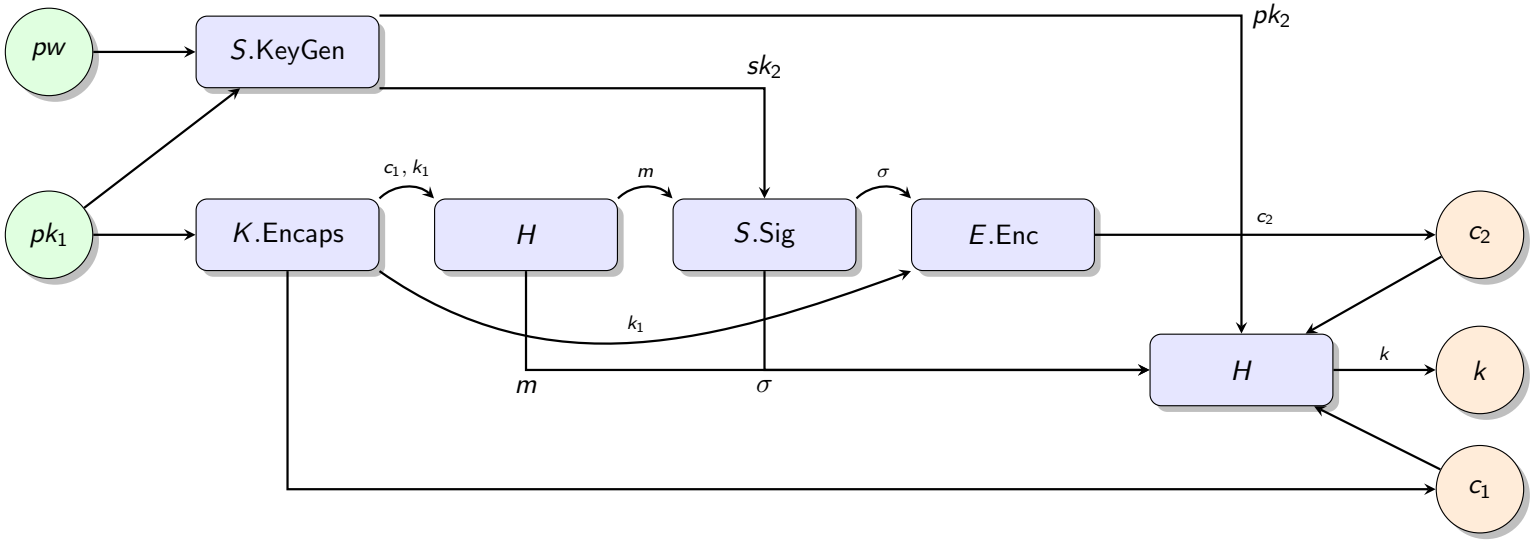

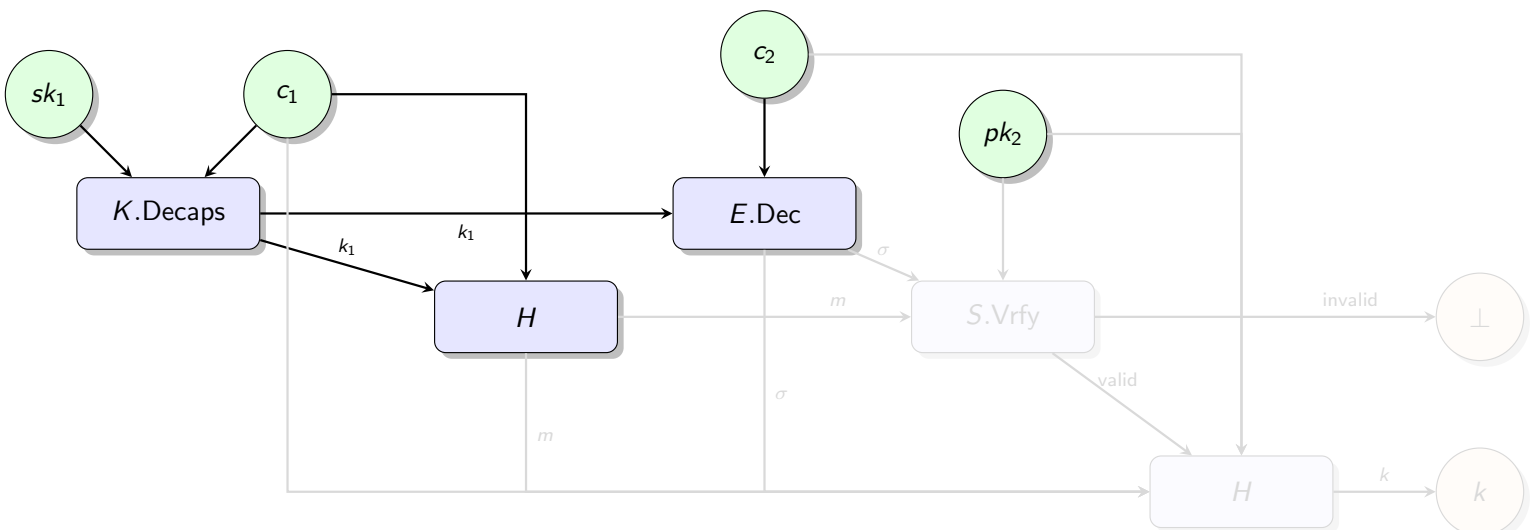

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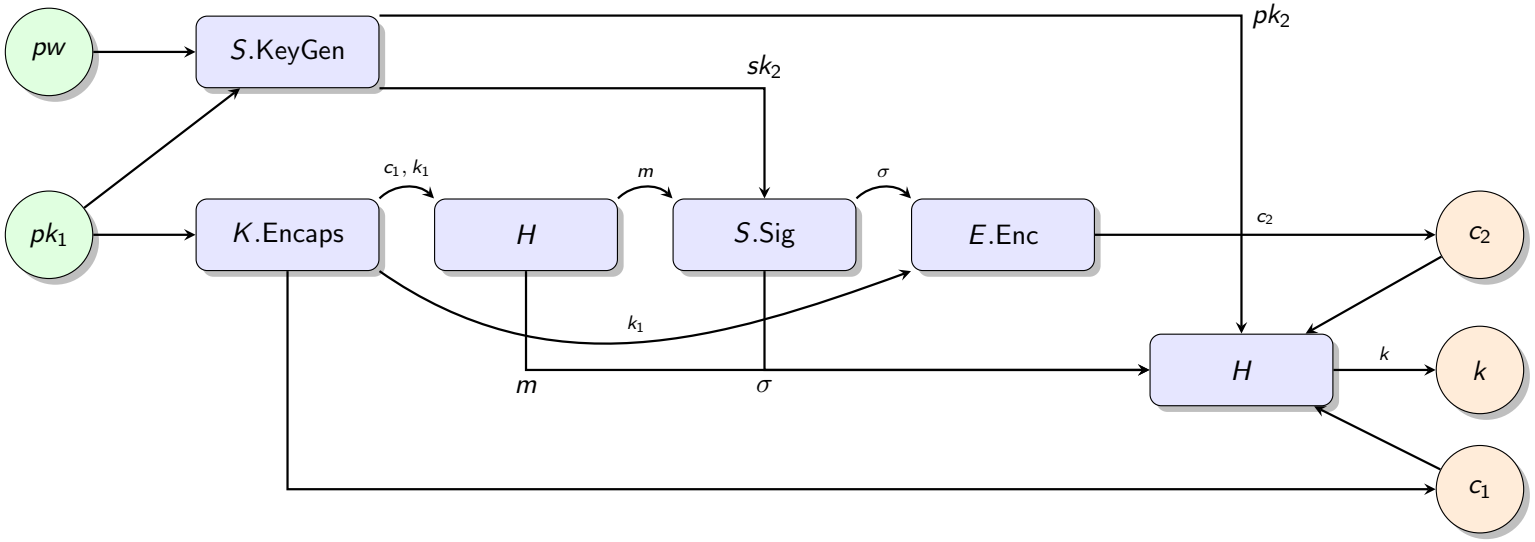

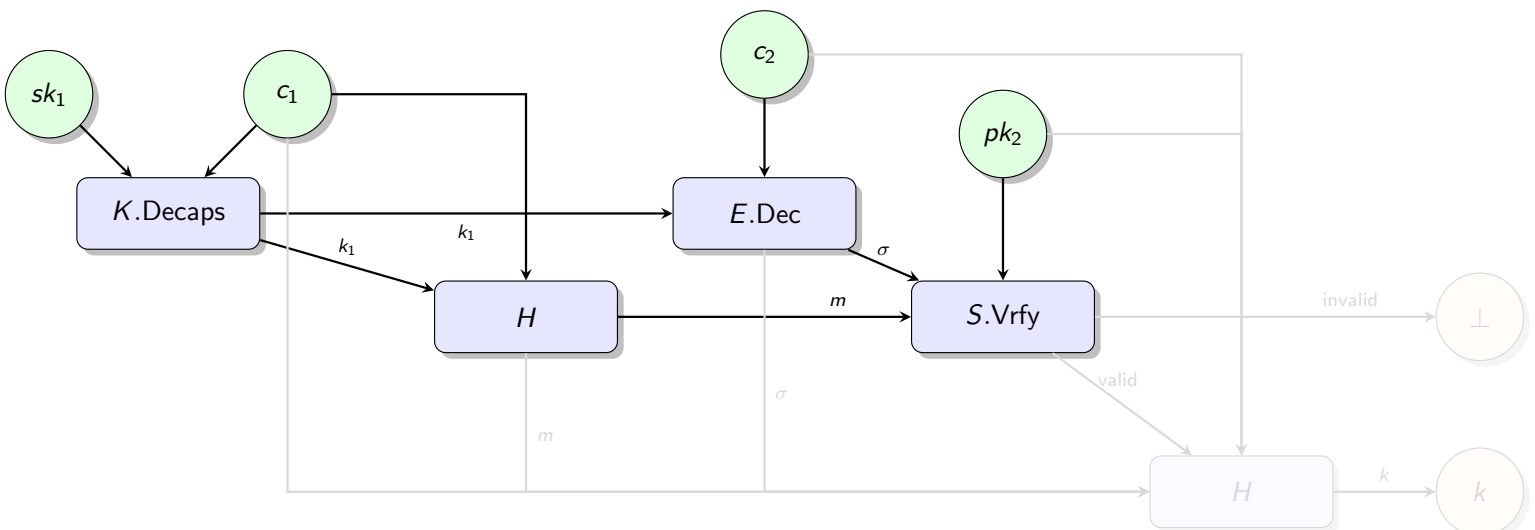

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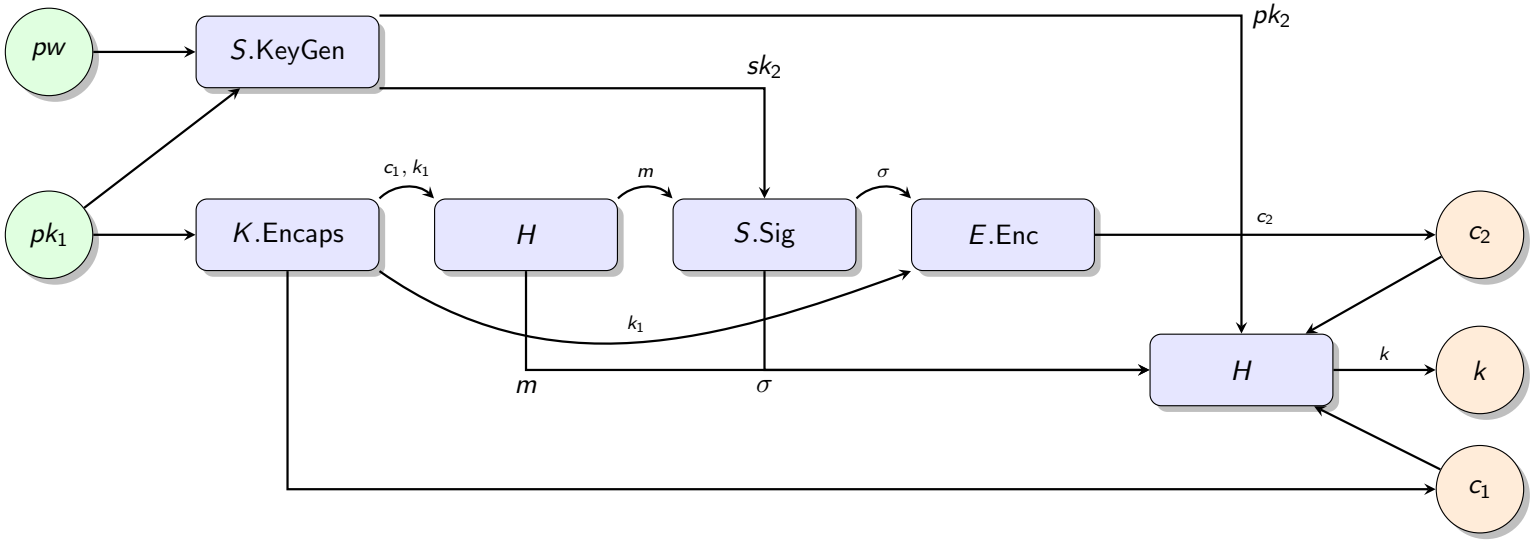

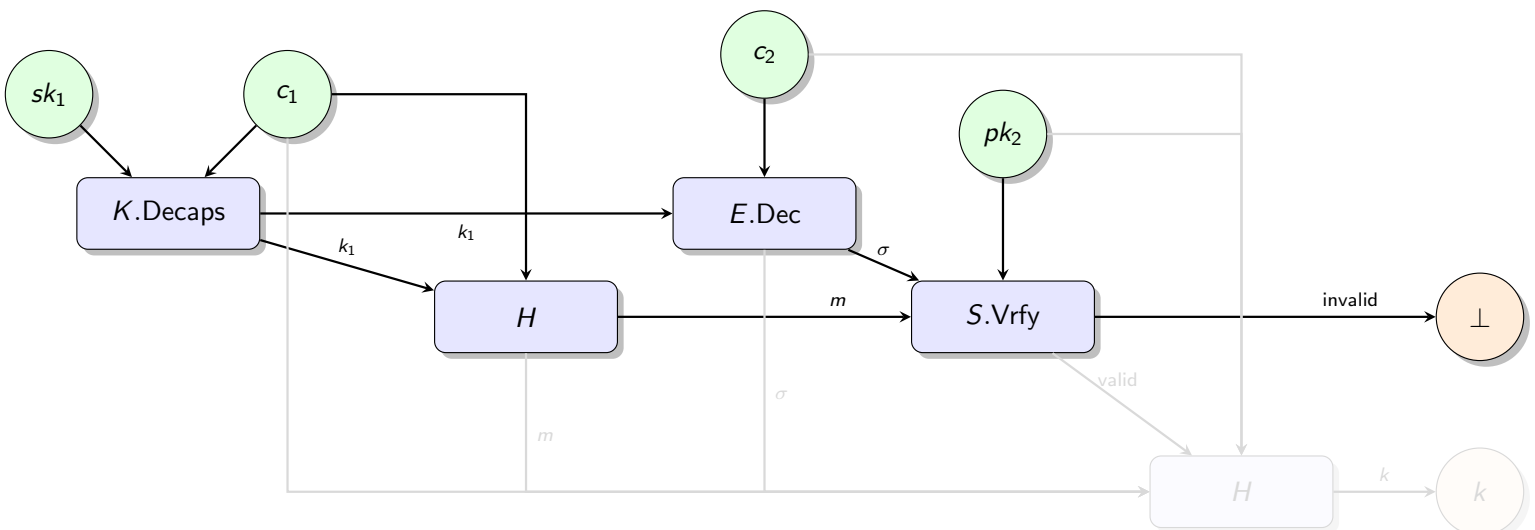

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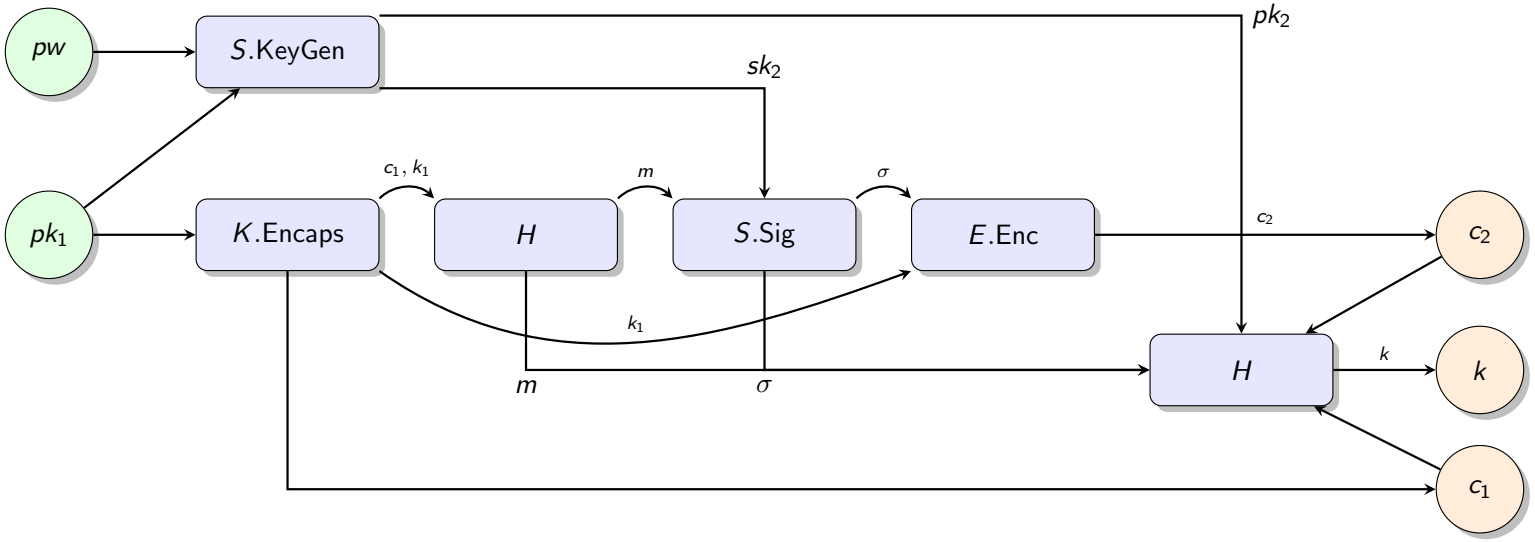

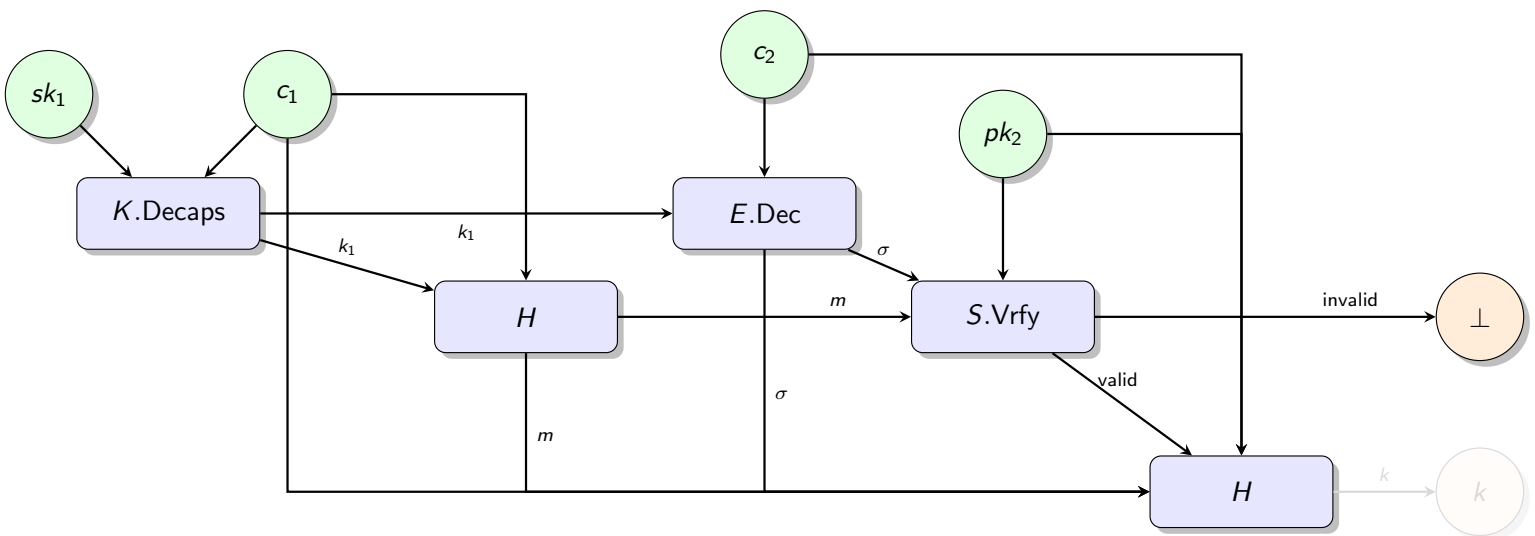

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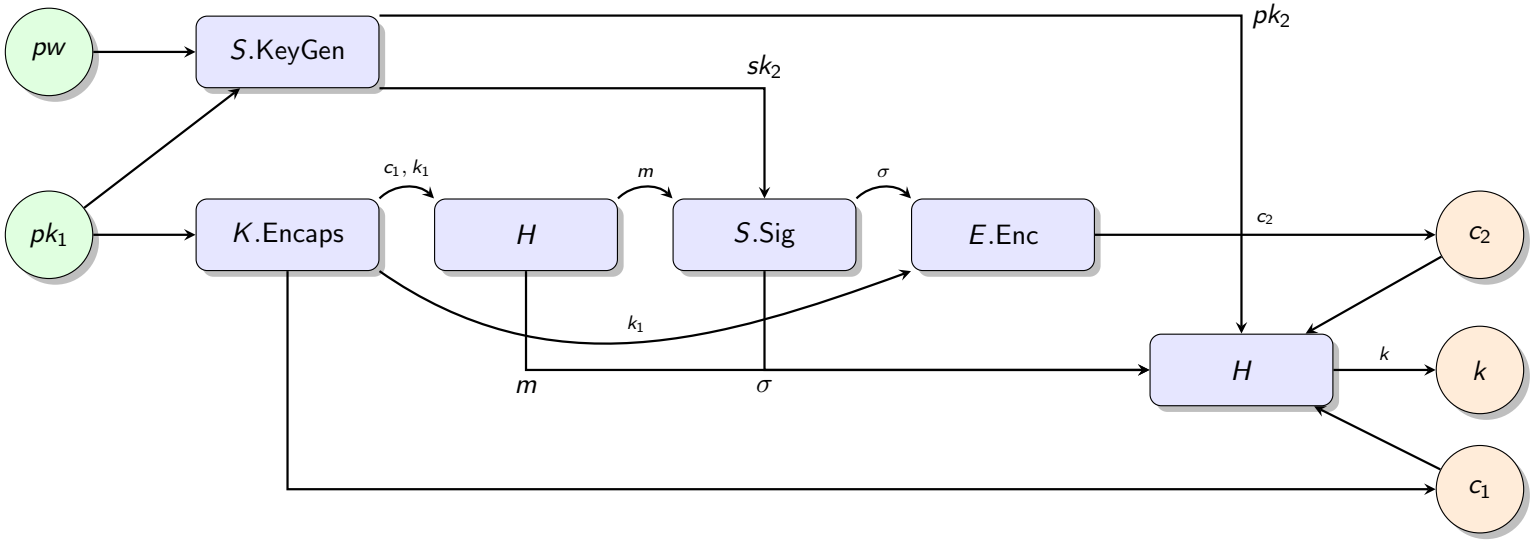

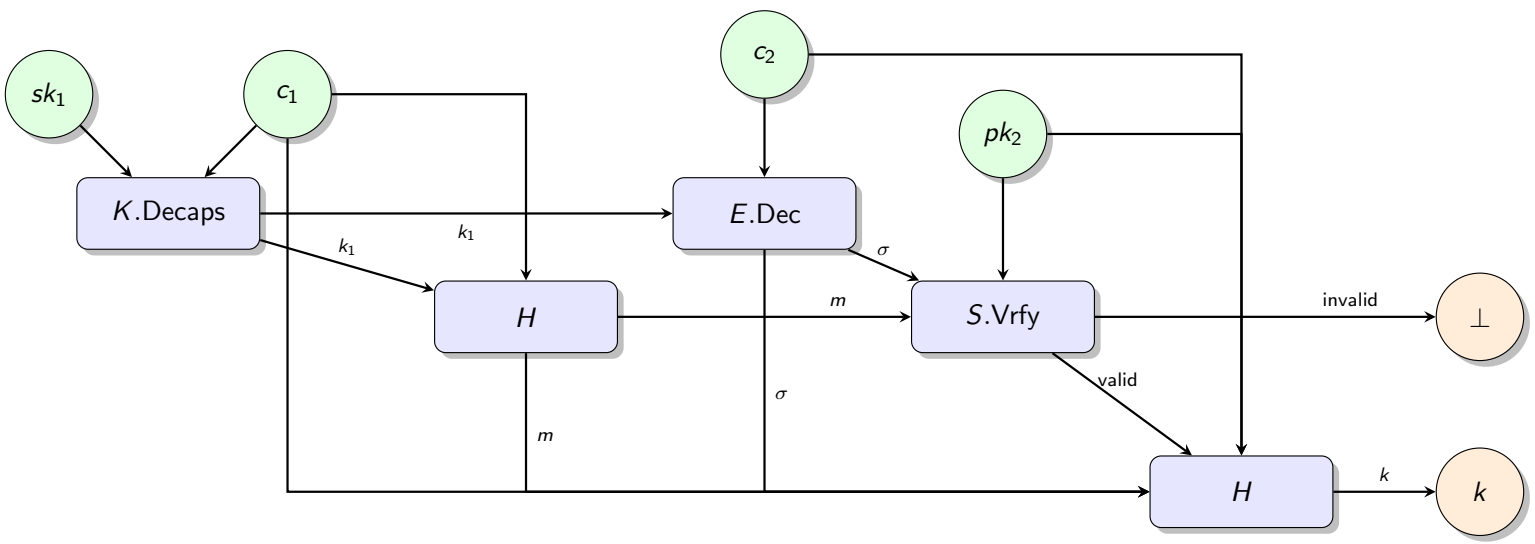

Proved Security

KEM	Signature	DEM	Hash	PAKEM
IND-CCA	-	IND-CCA	RO	Insider-CCA
-	EUF-CMA	-	RO	Insider-Auth

Table: Security assumptions of the construction and corresponding security.

PAKEM Property	Reduction
Insider-CCA	$\mathrm{Adv}^{(q_d,q_c)\text{-Insider-CCA}}_{\mathcal{A},\mathrm{PAKEM}} \leq \mathrm{Adv}^{\text{IND-CCA}}_{\mathcal{B},K} + \mathrm{Adv}^{\text{IND-CCA}}_{\mathcal{C},E} + \mathsf{negl}(\lambda)$
Insider-Auth	$\mathrm{Adv}^{(q_d,q_c)\text{-Insider-Auth}}_{\mathcal{A},\mathrm{PAKEM}} \leq \mathrm{Adv}^{\text{EUF}-\text{CMA}}_{\mathcal{A},S} + \mathsf{negl}(\lambda)$

Table: Reduction bound for PAKEM corresponding security property.

Building Blocks

Our instantiation uses the following four algorithms:

- **CRYSTALS-Kyber**: IND-CCA-secure KEM
- **CRYSTALS-Dilithium**: EUF-CMA-secure signature scheme
- **AES-256 GCM**: IND-CCA-secure DEM
- **SHA3-512**: Hash function modeled as a random oracle

Performance

NIST Level	Scheme	Bandwidth (bytes)	Storage (bytes)	Runtime (μs)		
				Setup	Encaps/Sign	Decaps/Verify
Level 1	PAKEM	3,228	3,744	50.84	126.44	70.65
	Kyber-512	780	2,432	12.81	16.21	11.39
	Dilithium2	2,432	1,312	28.92	79.34	29.04
Level 3	PAKEM	4,422	5,536	80.31	193.02	105.20
	Kyber-768	1,100	3,584	17.48	21.85	16.01
	Dilithium3	3,305	1,952	48.81	128.93	47.73
Level 5	PAKEM	6,204	7,328	119.51	244.42	155.30
	Kyber-1024	1,580	4,736	23.99	30.06	22.52
	Dilithium5	4,607	2,592	76.31	156.66	75.29

Table: Bandwidth, storage, and runtime (mean over 10,000 iterations) comparison between PAKEM, Kyber and Dilithium.

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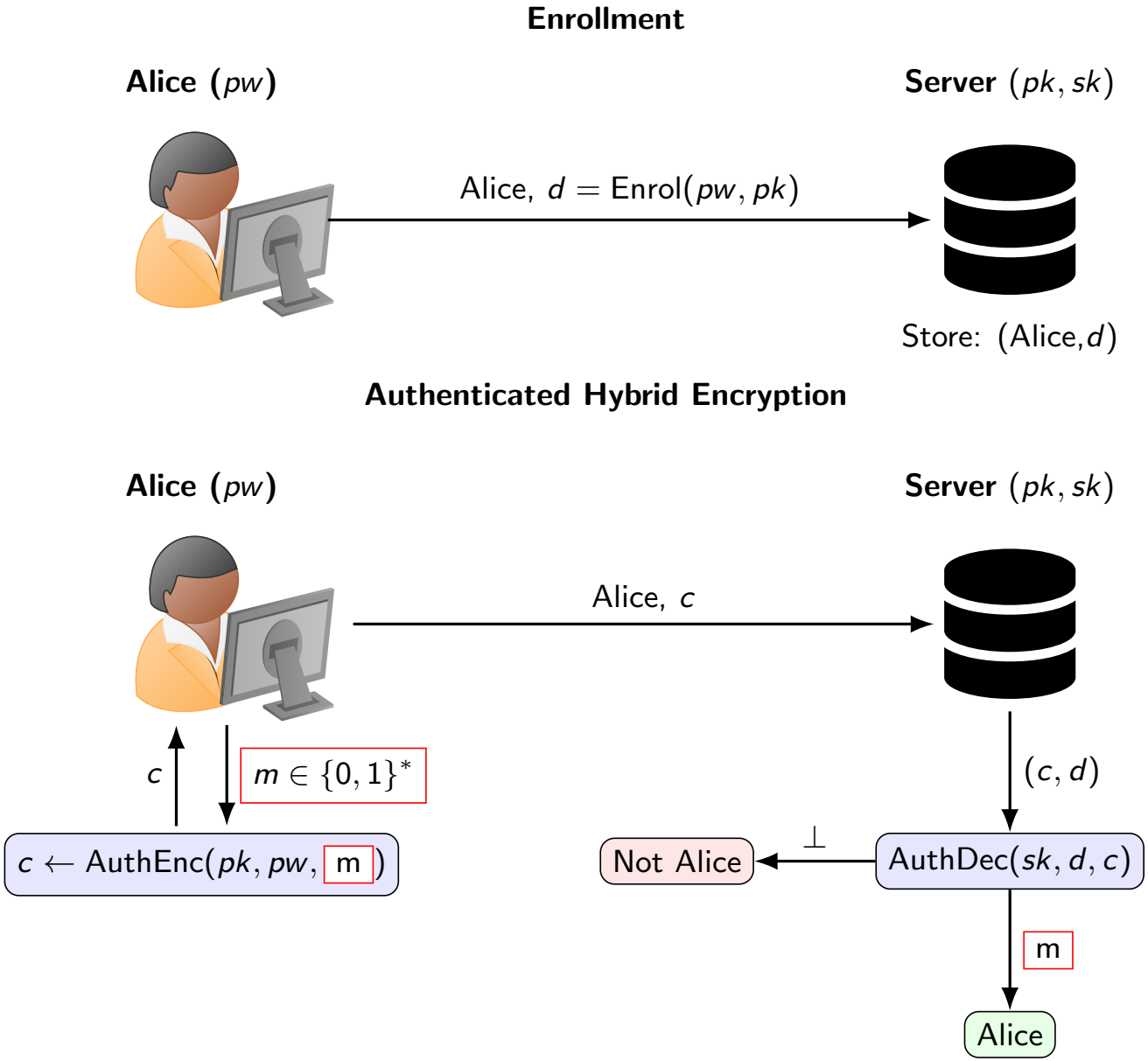
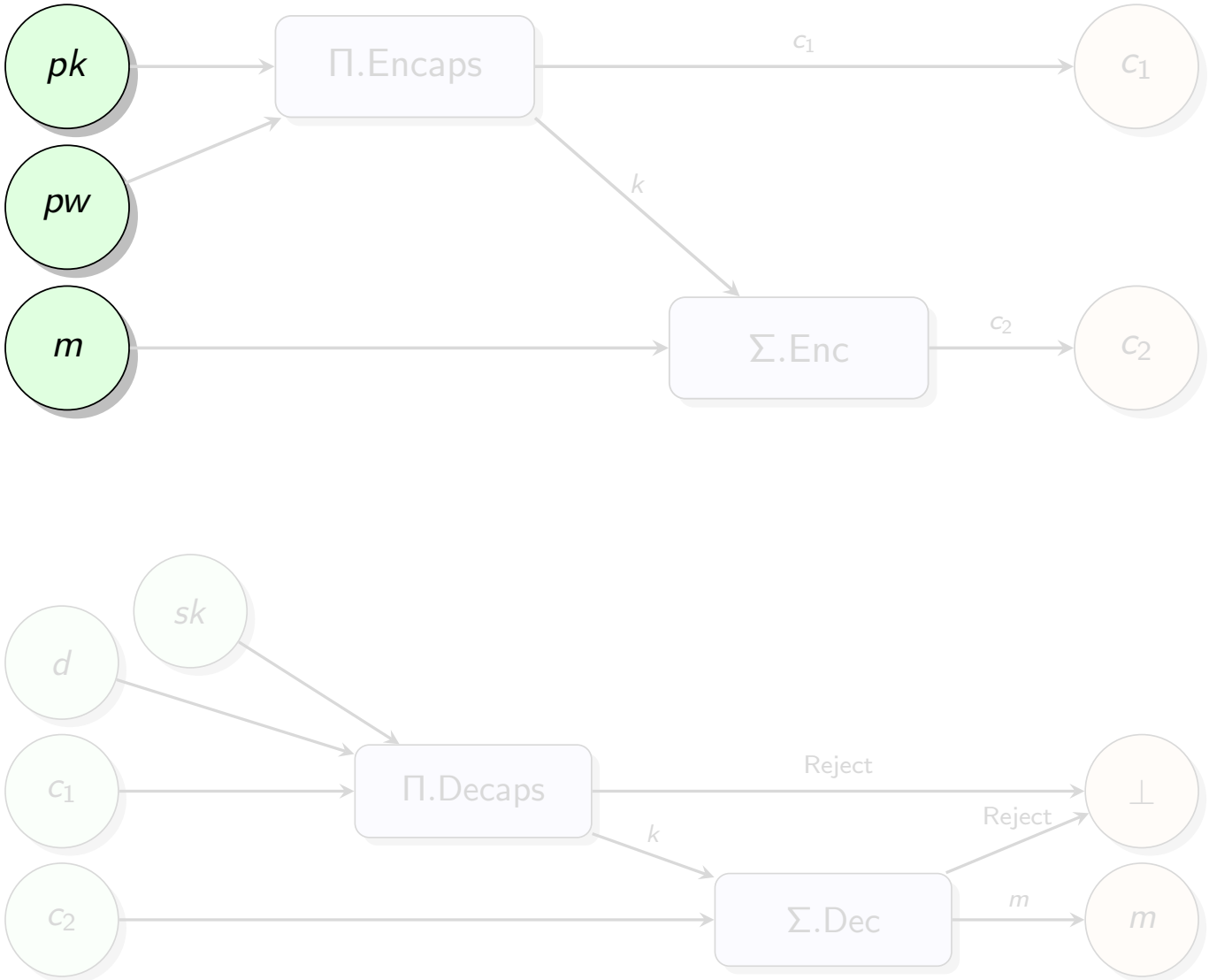
PAHE Overview



Generic Construction From PAKEM and DEM



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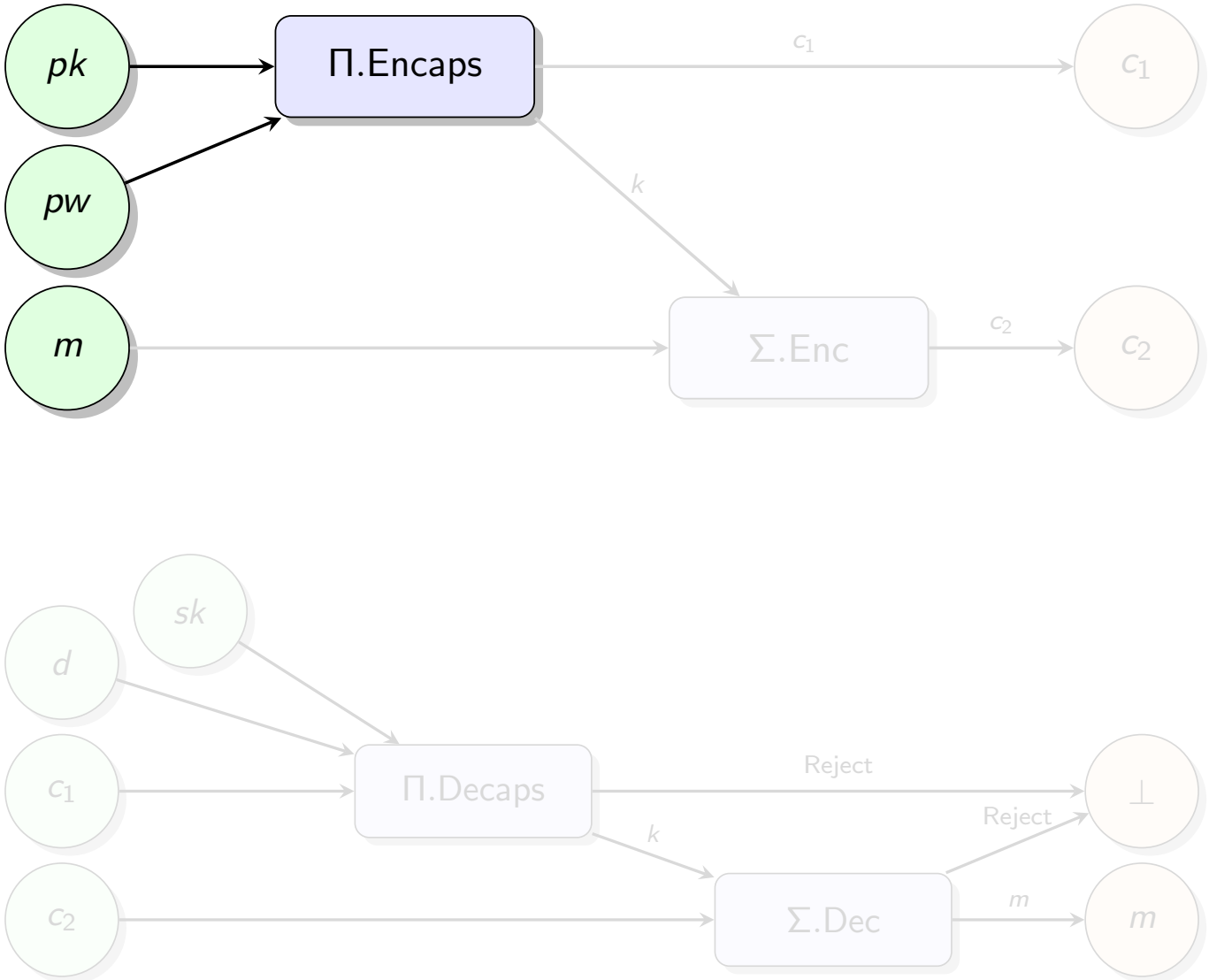

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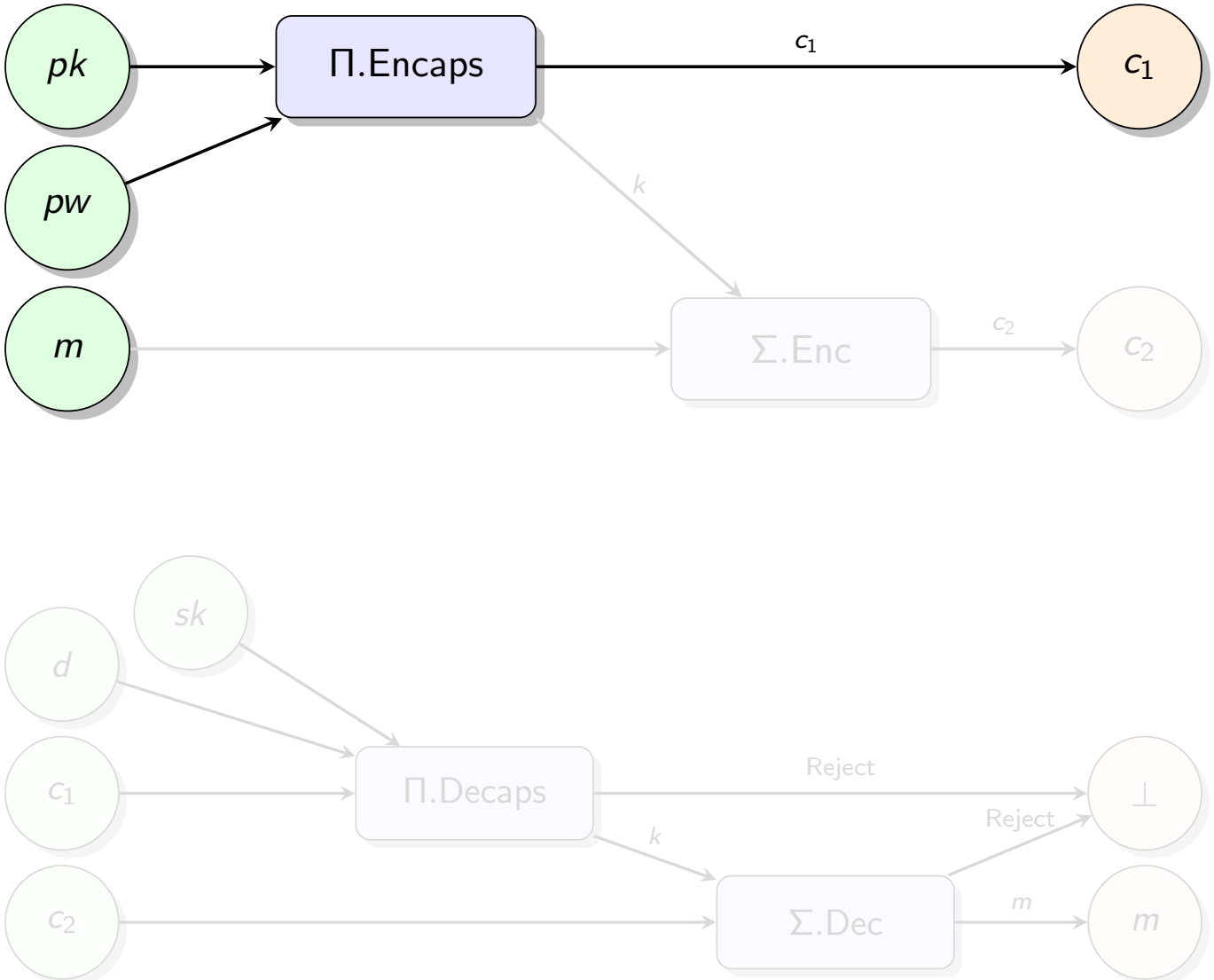

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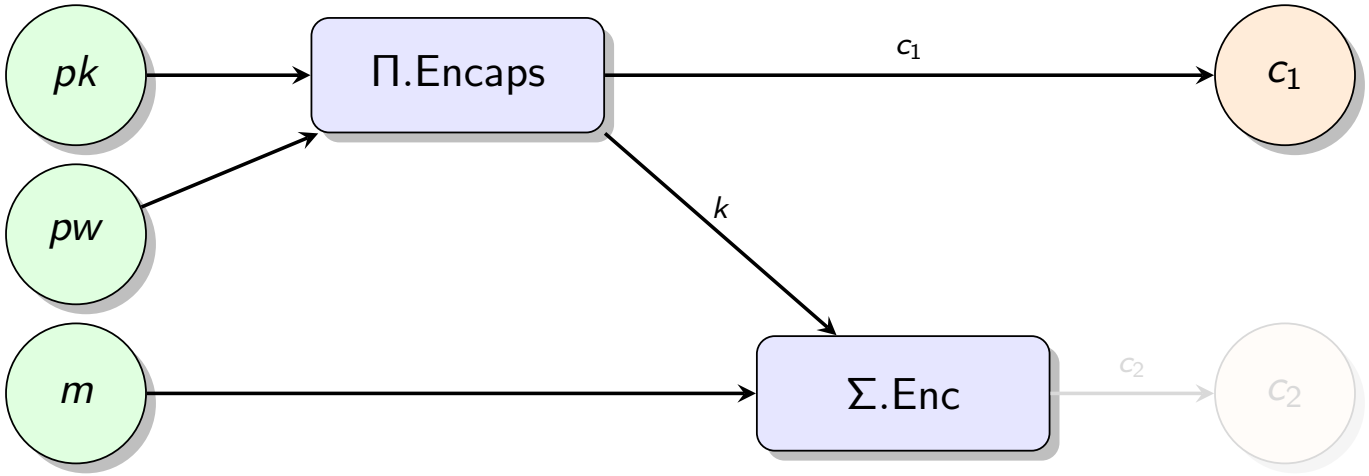

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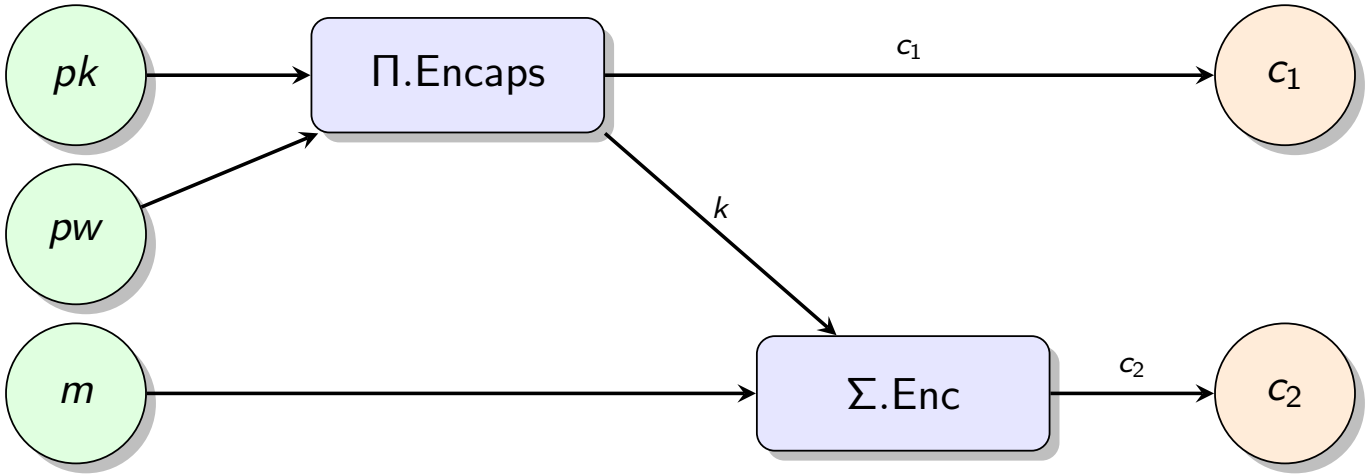

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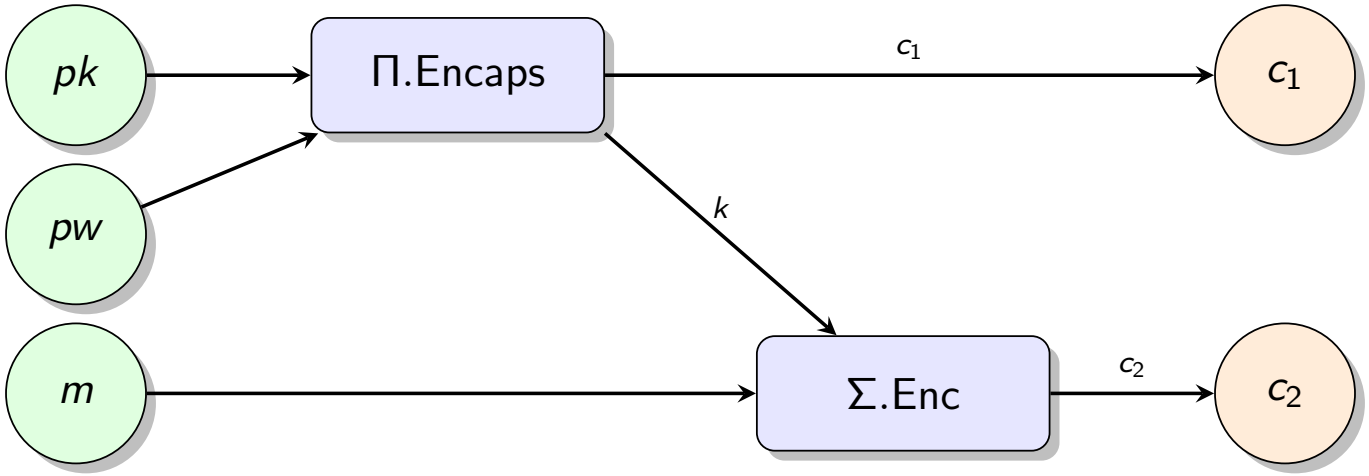

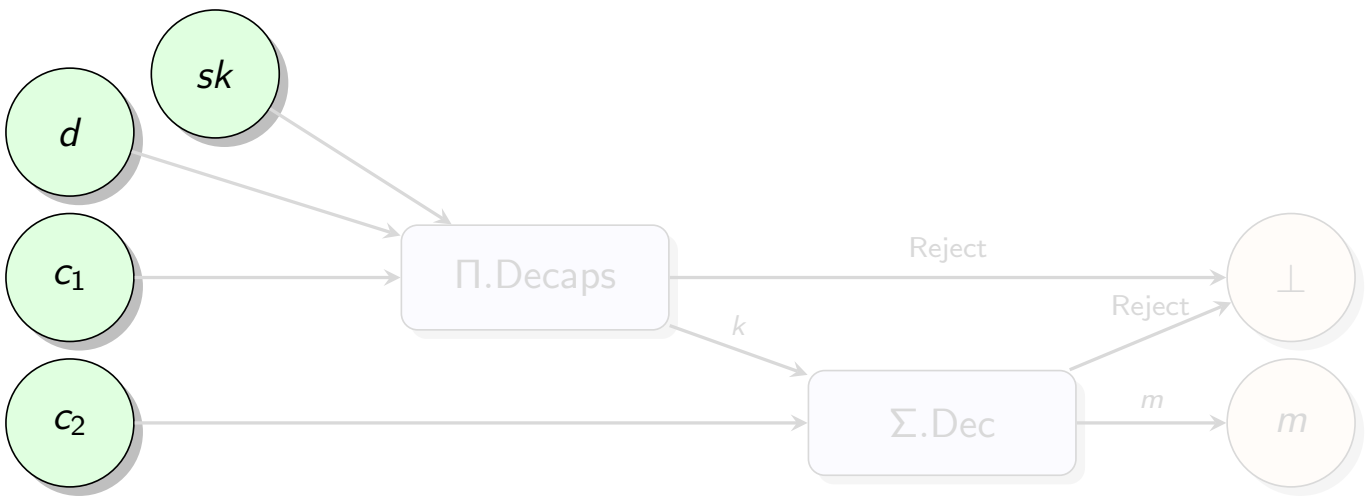

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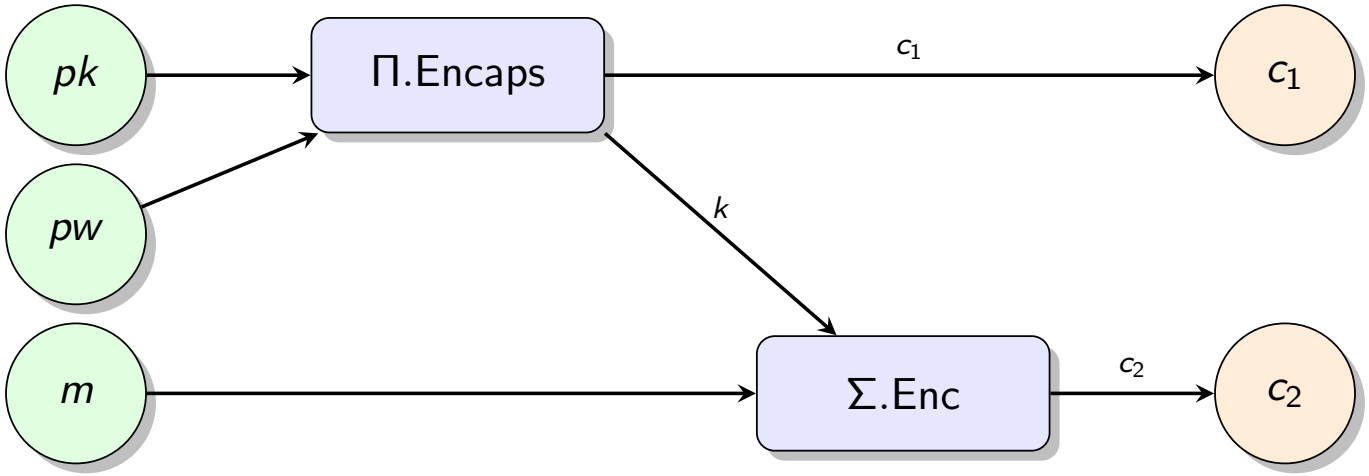

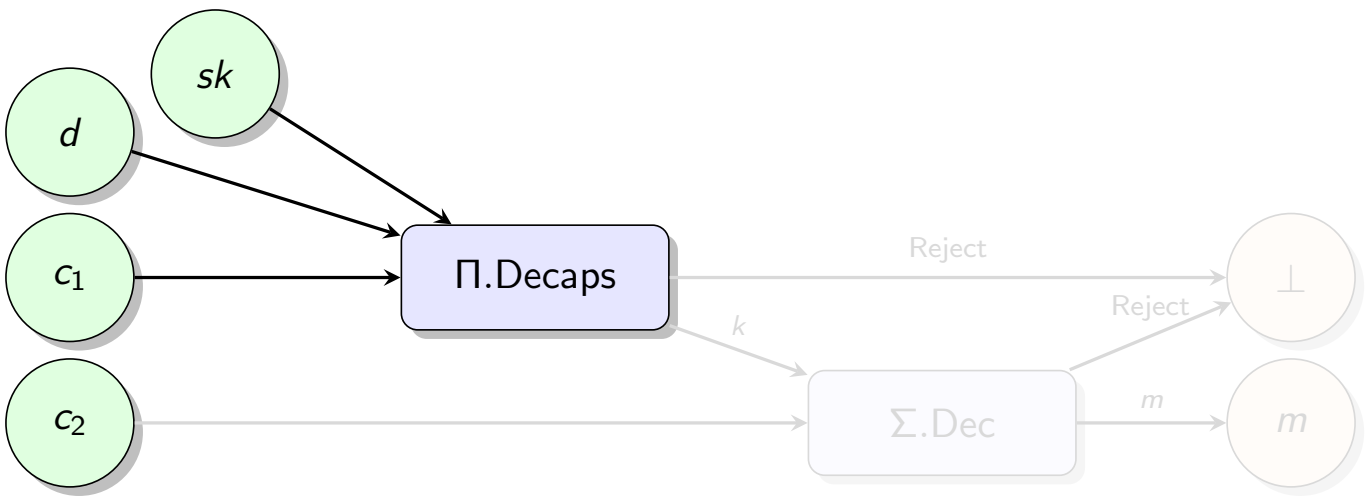

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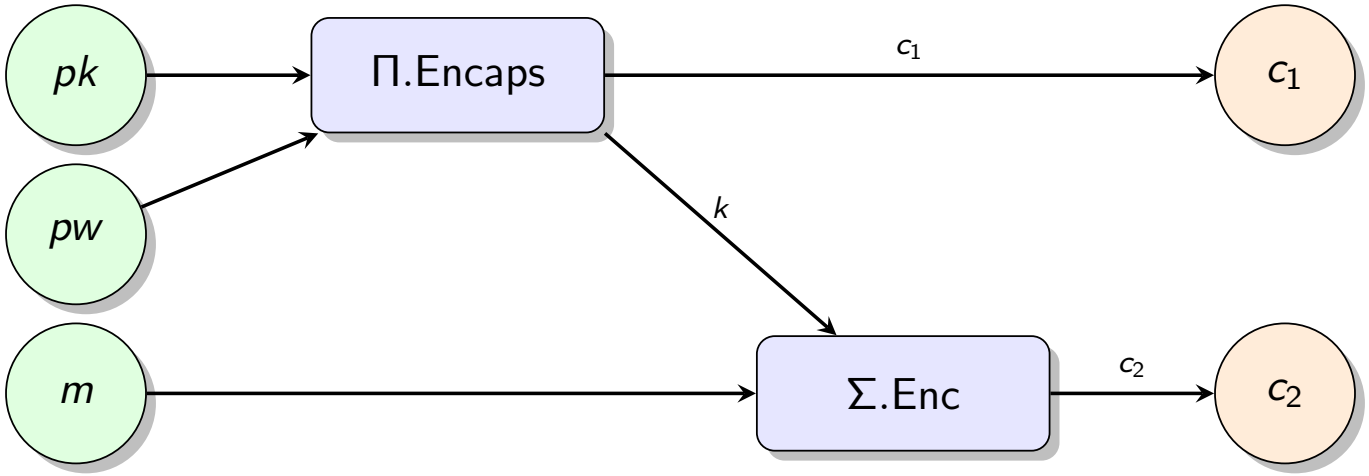

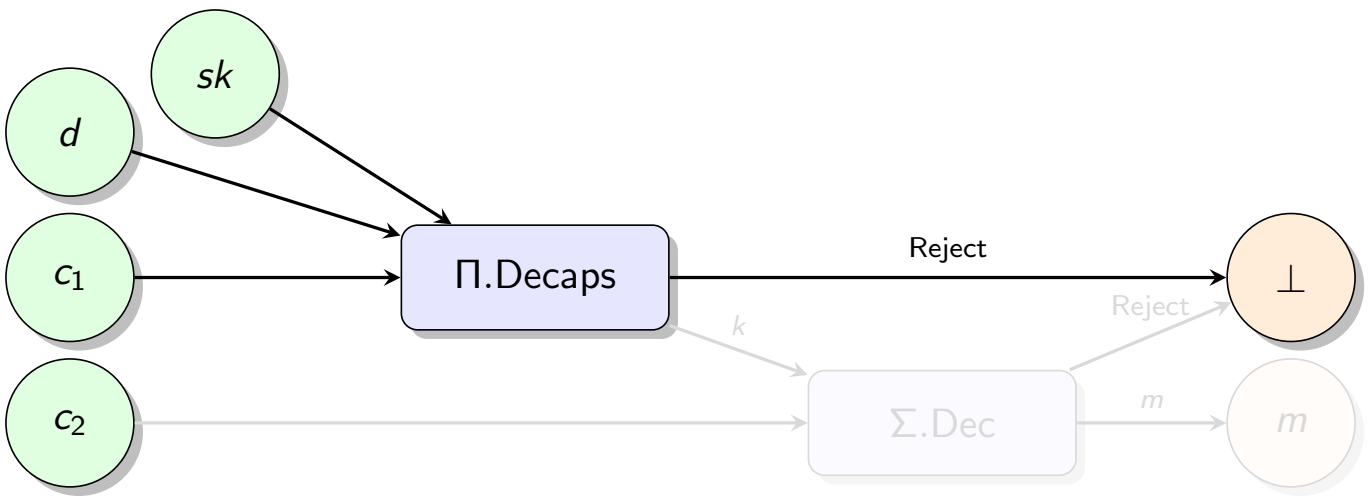

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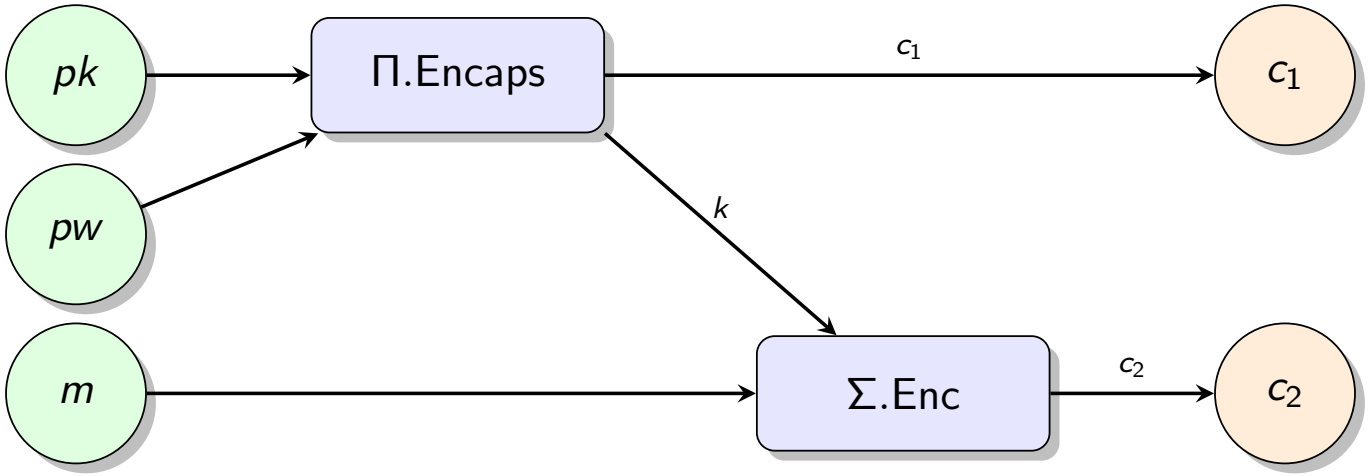
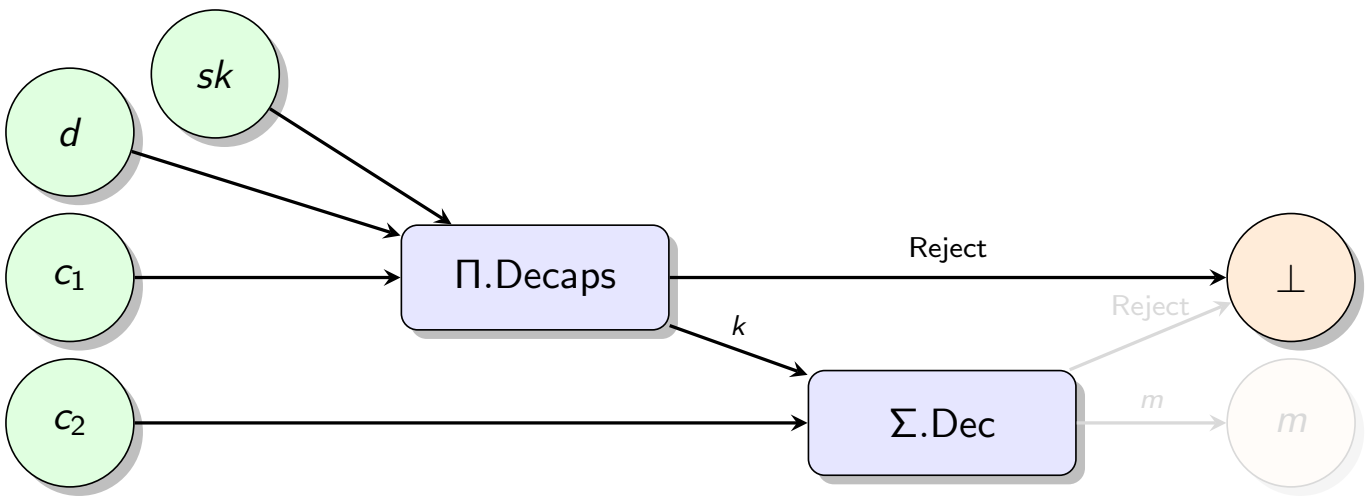
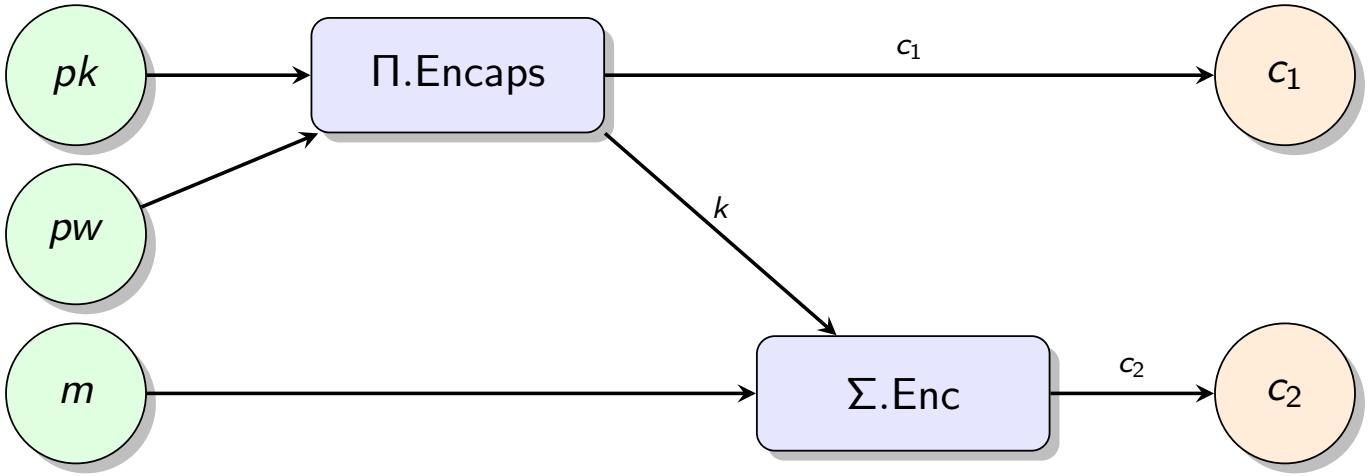
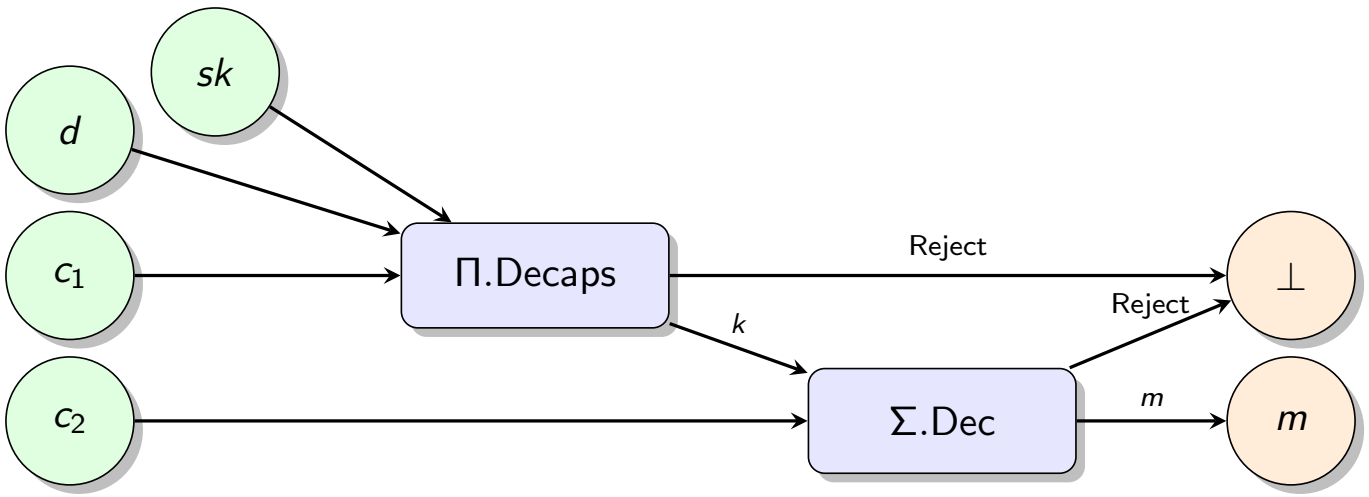




Generic Construction From PAKEM and DEM





Proved Security

PAKEM	**DEM**	**PAHE**
Insider-CCA	IND-CCA	Insider-CCA
Outsider/Insider-Auth	INT-CTXT	Outsider-Auth

Table: Security assumptions of the construction and corresponding security.

PAHE Property	Reduction
Insider-CCA	$\mathrm{Adv}^{(q_d,q_c)\text{-Insider-CCA}}_{\mathcal{A},\mathrm{PAHE}} \leq \mathrm{Adv}^{(q_d,q_c)\text{-Insider-CCA}}_{\mathcal{B},\Pi}(\lambda) + q_c \cdot \mathrm{Adv}^{\text{IND-CCA}}_{\mathcal{C},\Sigma}$
Outsider-Auth	$\mathrm{Adv}^{(q_e,q_d,q_c)\text{-Outsider-Auth}}_{\mathcal{A},\mathrm{PAHE}} \leq \mathrm{Adv}^{(q_e,q_c)\text{-Insider-Auth}}_{\mathcal{B},\Pi} + \mathrm{Adv}^{\text{INT-CTXT}}_{\mathcal{C},\Sigma}$

Table: Security reduction bounds for PAHE security.

Why Not Insider-Auth?

Achieving **Insider-Auth security** by directly composing a PAKEM and a DEM as **black boxes is impossible**.

- The adversary is given both sk (PAKEM) and d.
- It obtains a valid ciphertext (c_1, c_2) from the encryption oracle.
- Using sk, it decapsulates c_1 and recovers the symmetric key k.
- It uses k to compute a new ciphertext c_2' for a message of its choice.
- The resulting (c_1, c_2') is a fresh valid ciphertext.

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Problem

The PAKEM ciphertext c_1 is **independent of the message**.

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Future Work Direction

Limitations:

- Security is define for two user setting
- PAHE is not Insider-Auth secure

Future Work:

- Replace the password by a biometric template
- Propose a direct construction of PAHE that is Insider-Auth secure
- Define the multi-user security and prove the security