A Post-Quantum Round-Optimal Oblivious PRF from Isogenies

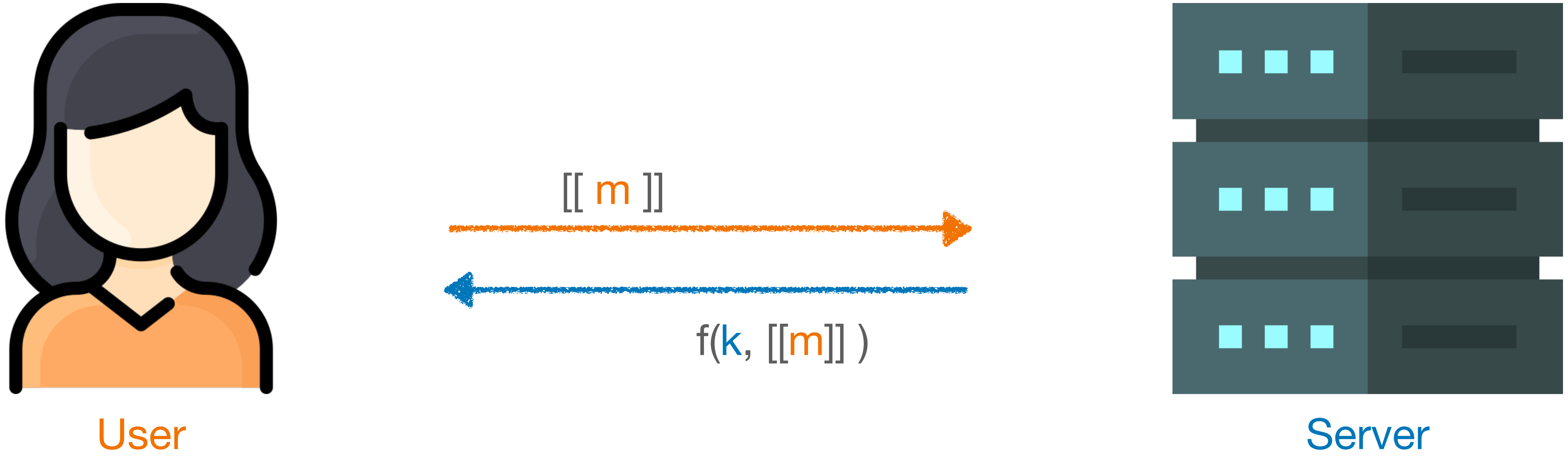
Andrea Basso

16th August, 2023
Selected Areas in Cryptography 2023

UNIVERSITY OF BIRMINGHAM

University of BRISTOL

Oblivious PRF



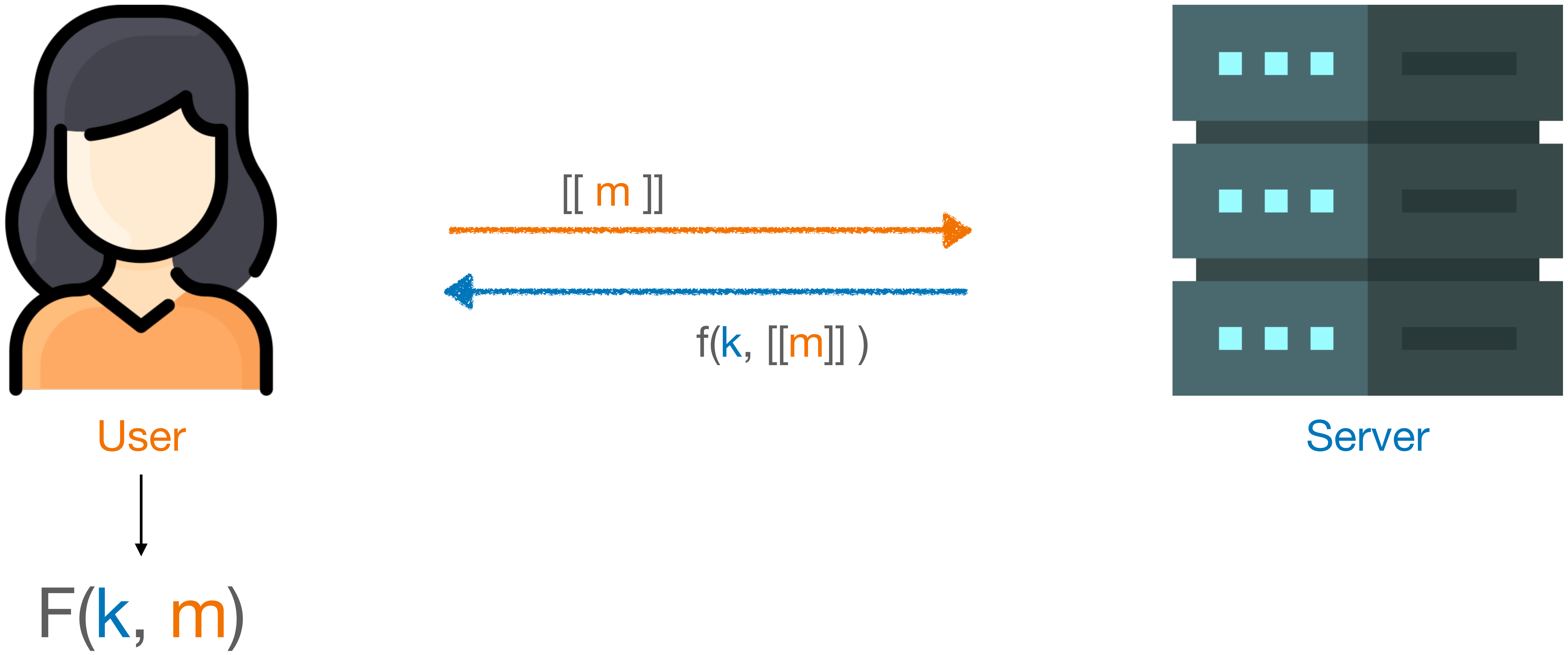
[[m]]

f(k, [[m]])

User

Server

Oblivious PRF



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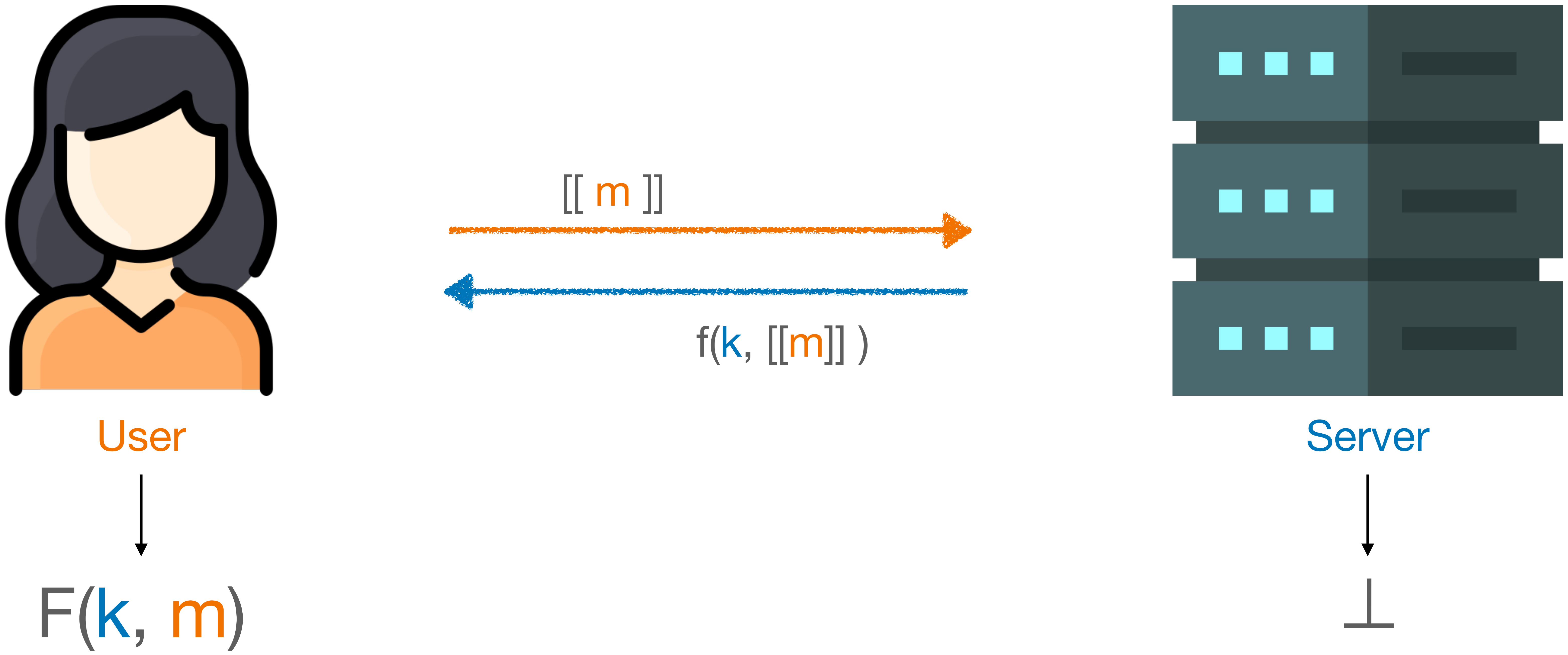


User

[[m]]

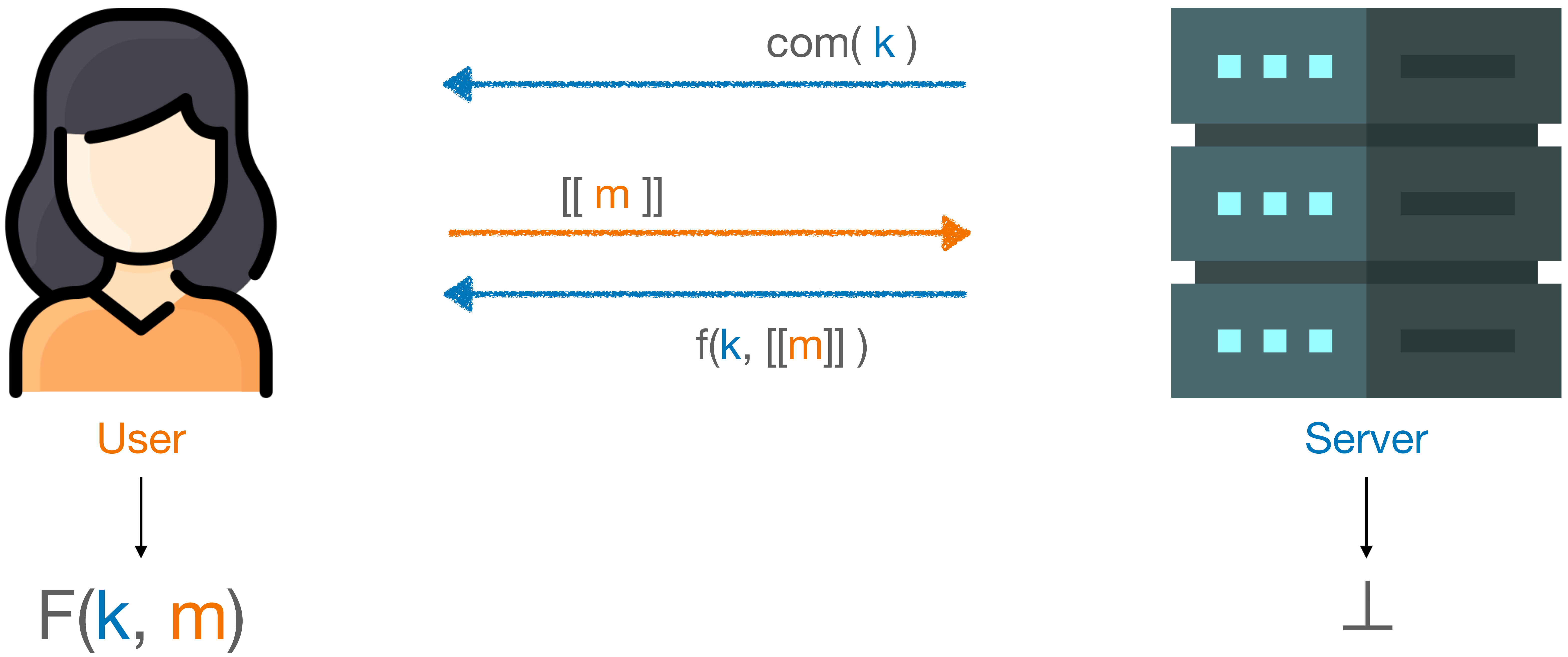
f(k, [[m]])

Server

$F(k, m)$

$\perp$

Oblivious PRF



com(k)

[[m]]

f(k, [[m]])

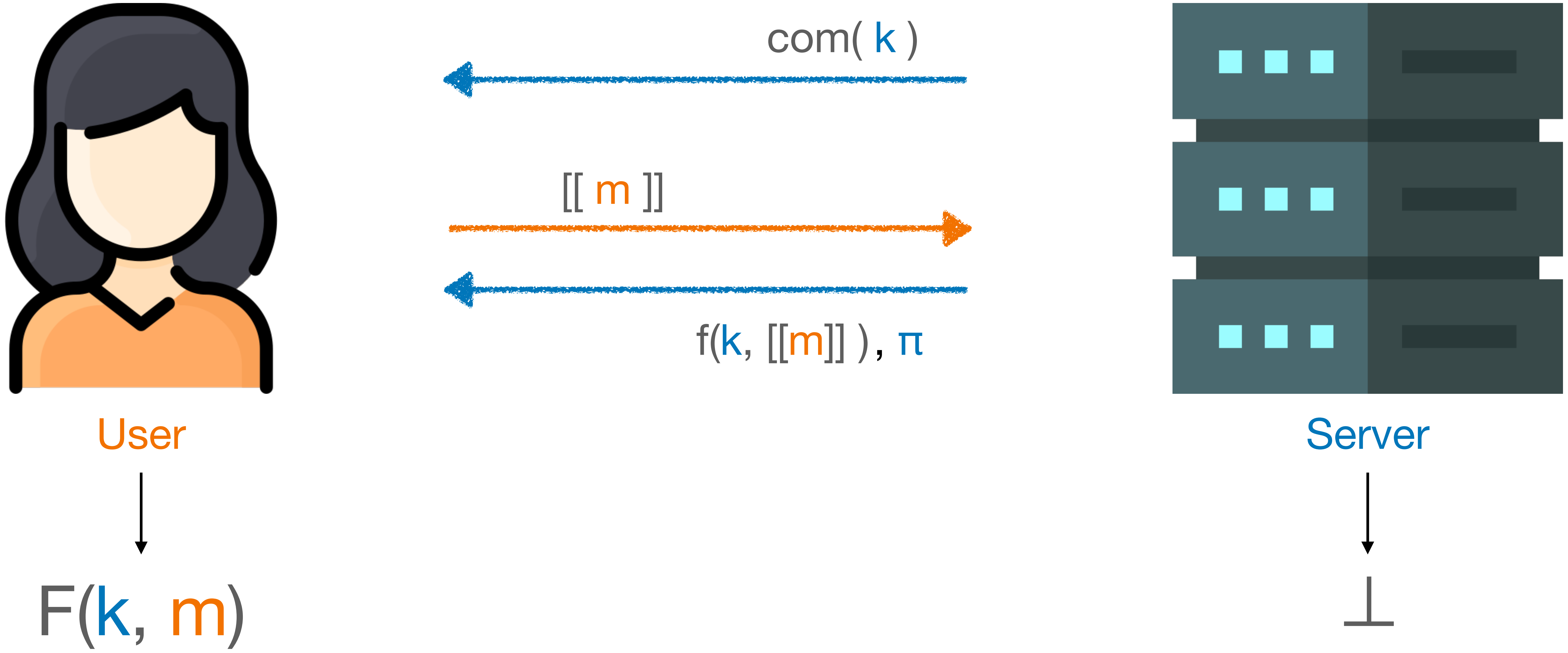
User

Server

F(k, m)

⊥

Oblivious PRF



com(k)

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f(k, [[m]]) , π

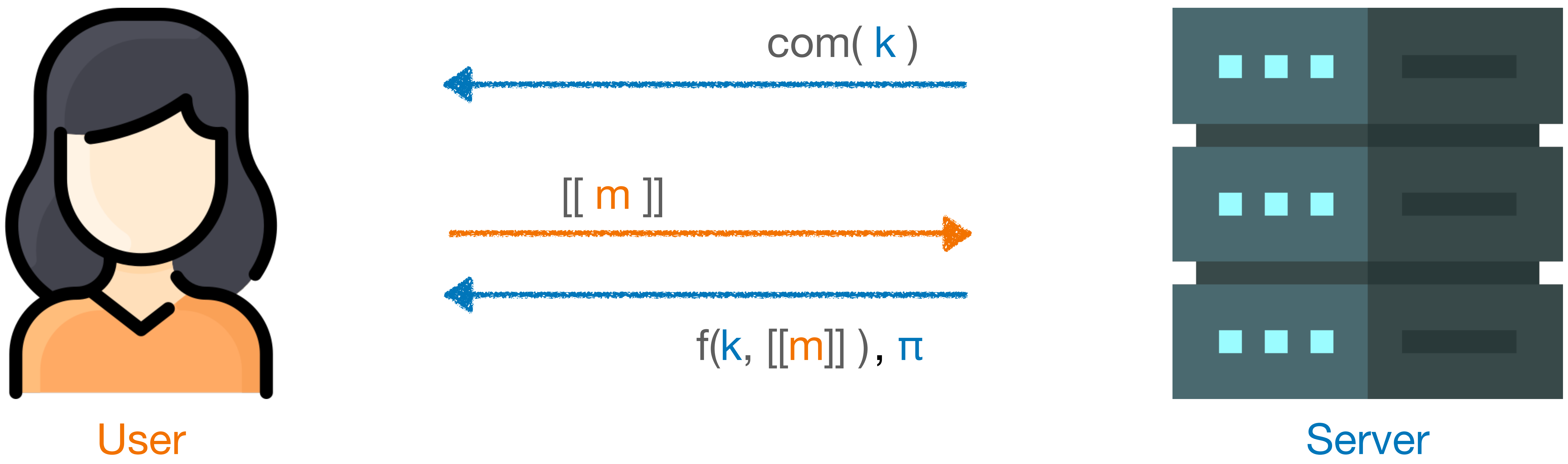
User

Server

F(k, m)

⊥

Oblivious PRF



com(k)

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f(k, [[m]]), π

User

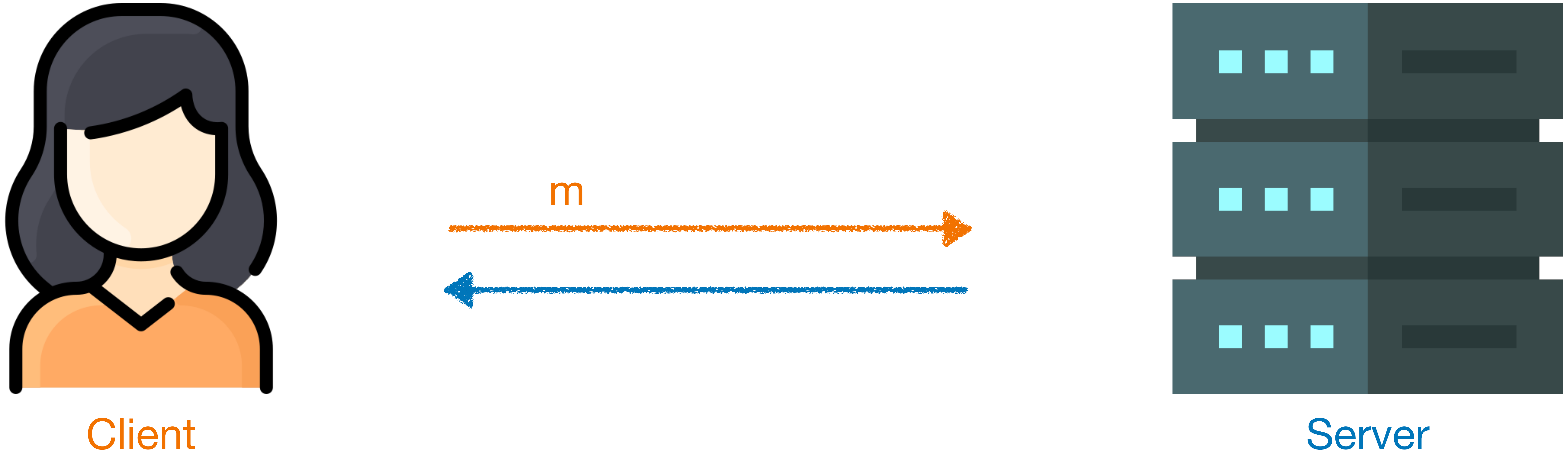
Server

$F(k, m)$

$\perp$

- Password-checking in Microsoft Edge
- OPAQUE
- Privacy pass
- Private-set intersection
- Adaptive OT
- ....

HashDH OPRF



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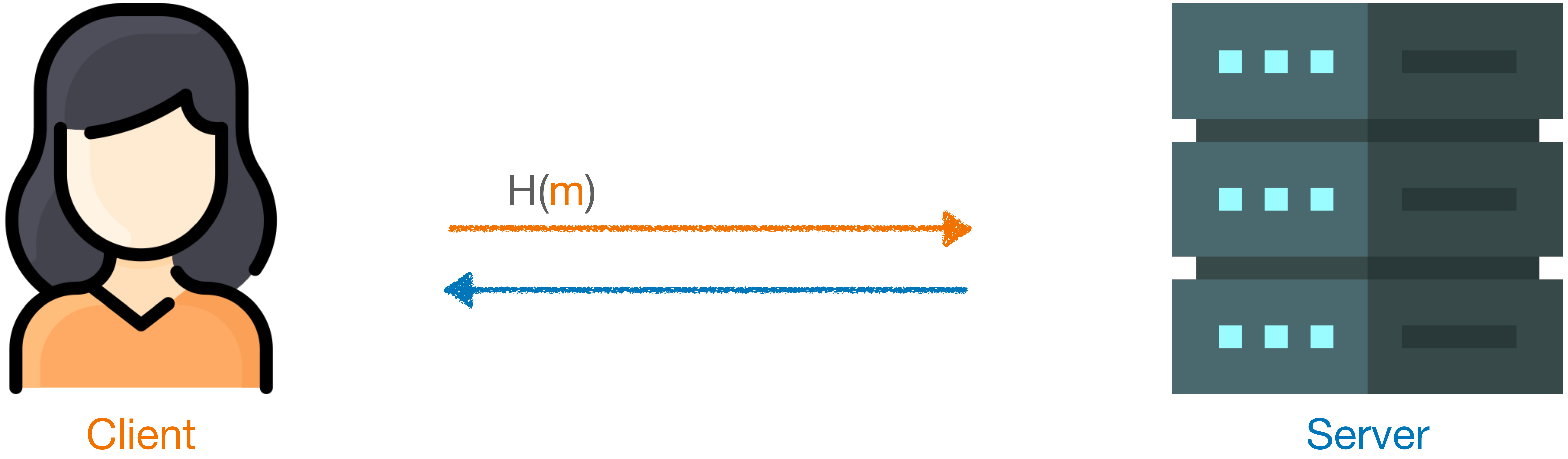

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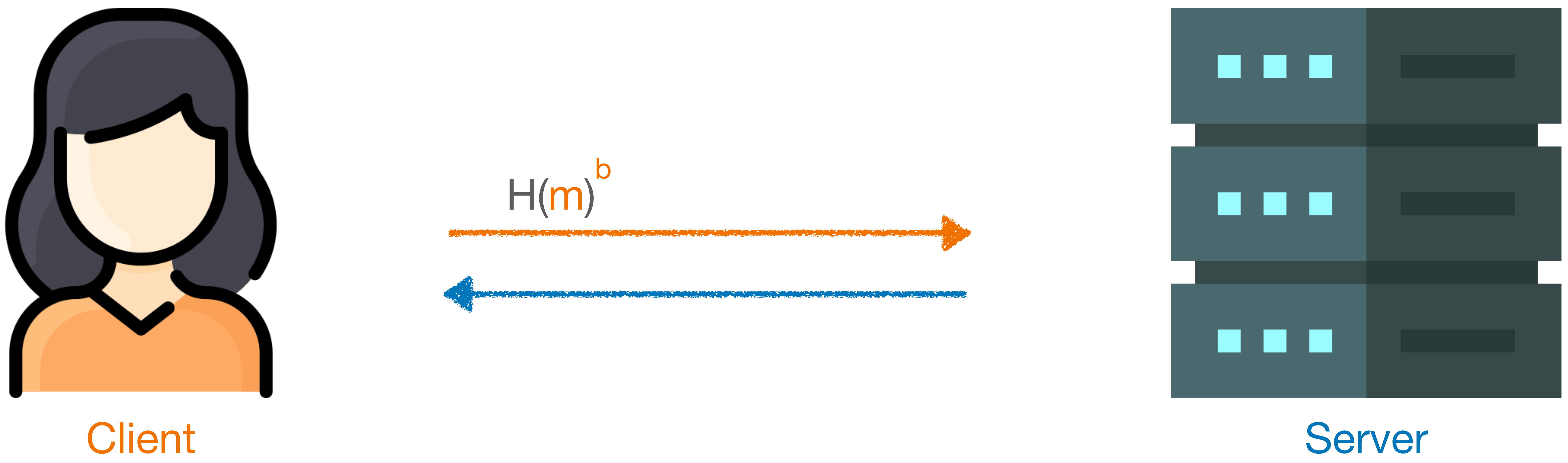
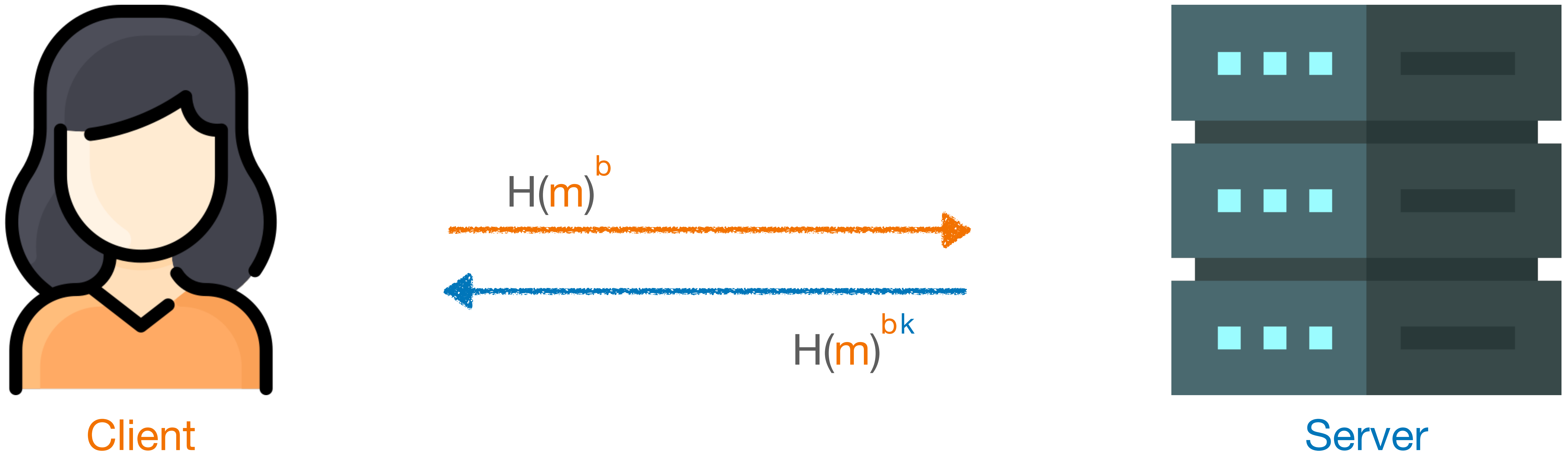


$H(m)^b$

Client

Server

HashDH OPRF



$H(m)^{b}$

$H(m)^{bk}$

Client

Server

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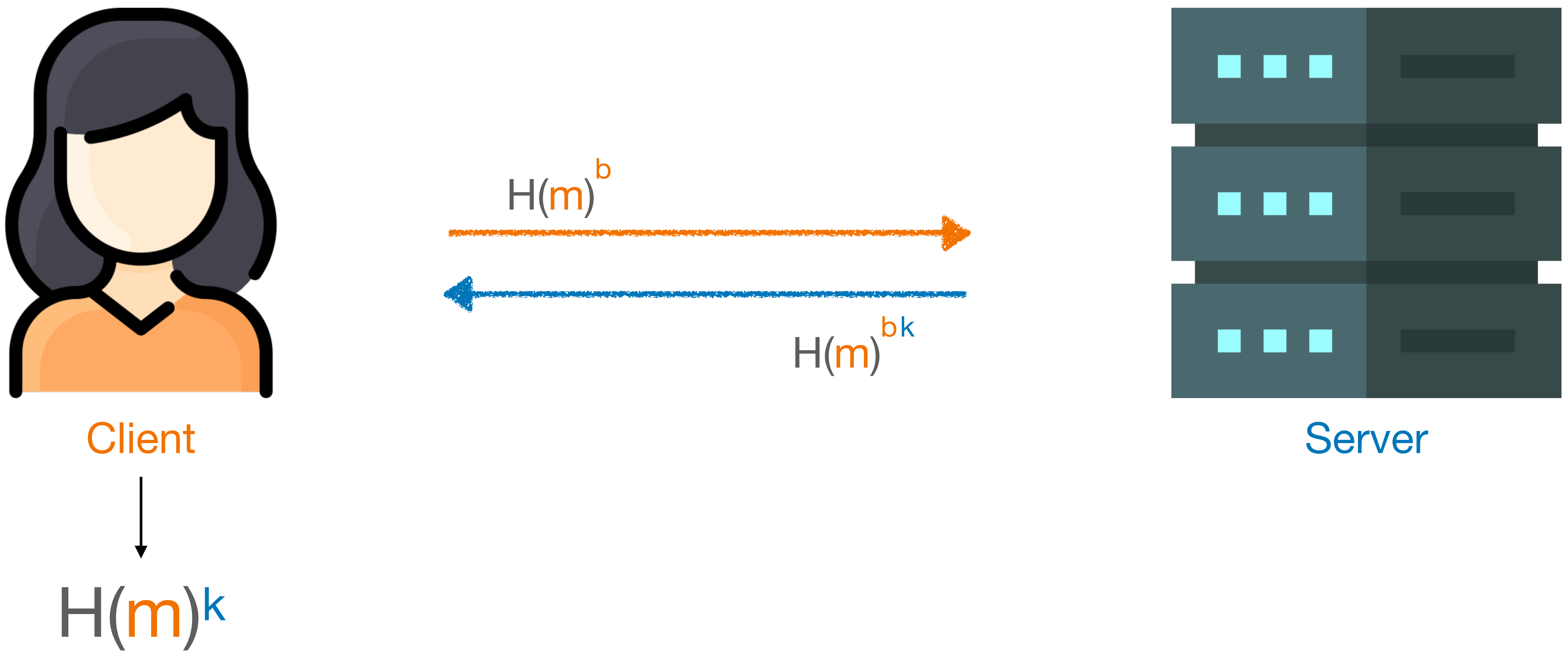

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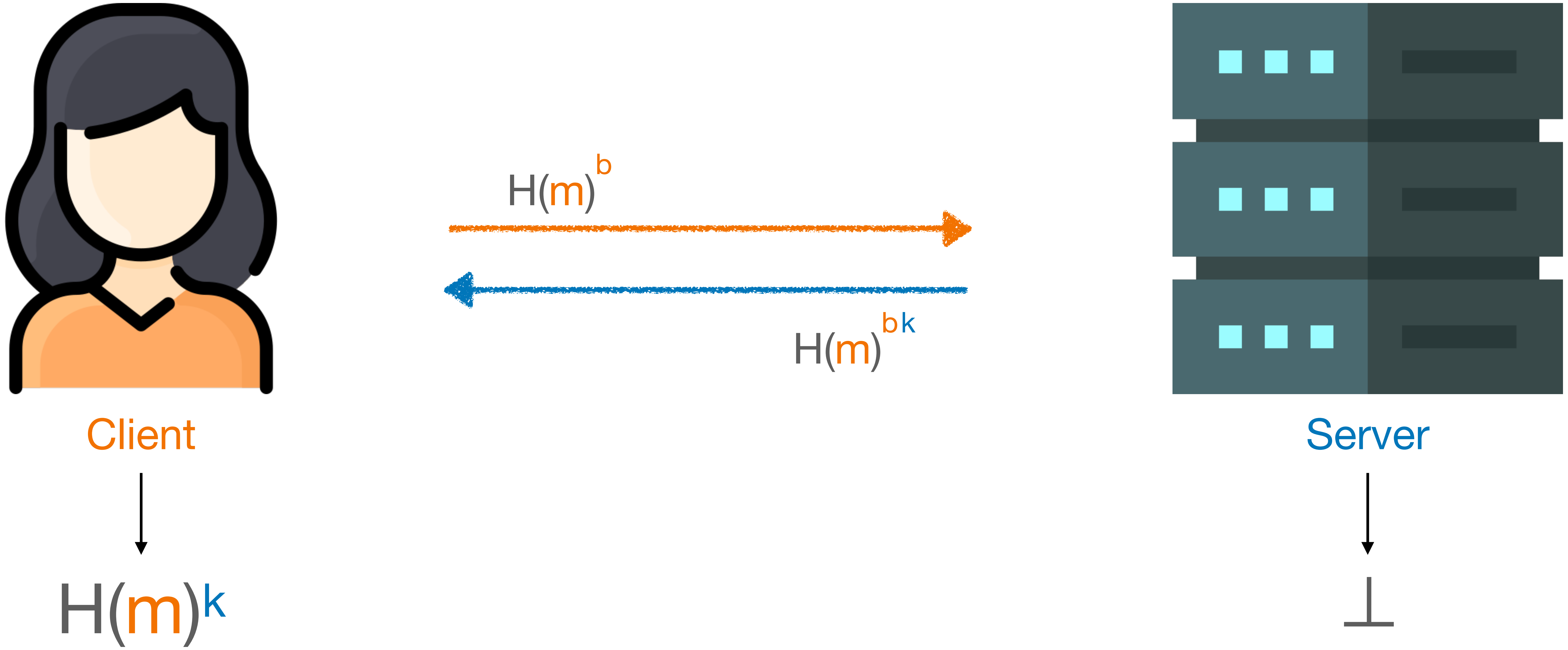

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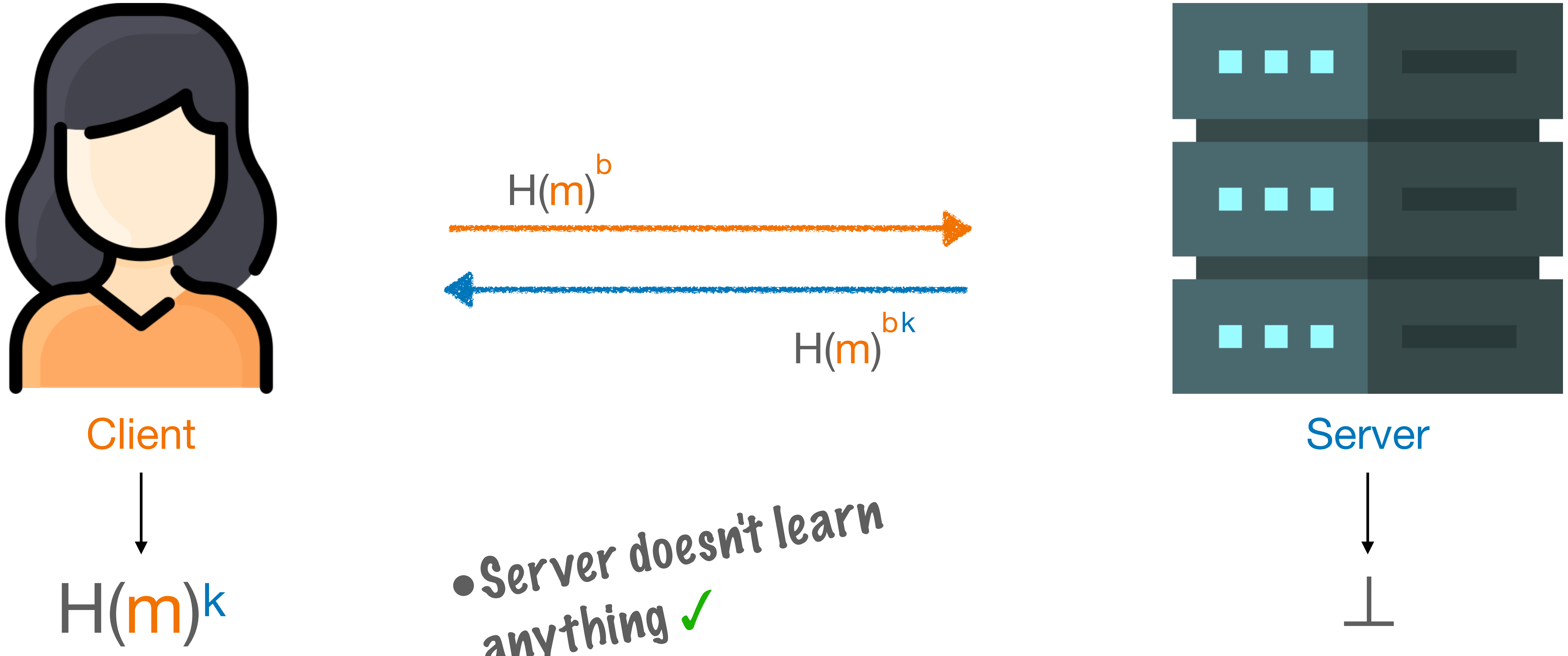
Client

Server

$H(m)^{k}$

$\perp$

HashDH OPRF



$H(m)^b$

$H(m)^{bk}$

Client

$H(m)^k$

Server

$\perp$

- Server doesn't learn anything ✓
- Output is deterministic ✓
- Client only learns one output ✓

Post-quantum OPRFs

- Generic MPC techniques →
  - many rounds (can’t be optimal)
- VOPRF based on lattices [ADDS19] →
  - round optimal
  - feasibility result (> 2^{40} bits of comms)
- VOPRF based on SIDH [BKW20] →
  - six rounds
  - broken by attack on PR and on SIDH
- OPRF based on CSIDH [BKW20] →
  - three rounds (OT required)
  - CSIDH parameters?

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The original OPRF [BKW20]

$$\begin{tikzcd}
E_0 \arrow[r, "m"] \arrow[d, "k"'] & E_m \arrow[d] \\
E_k \arrow[r] & E_{mk}
\end{tikzcd}$$

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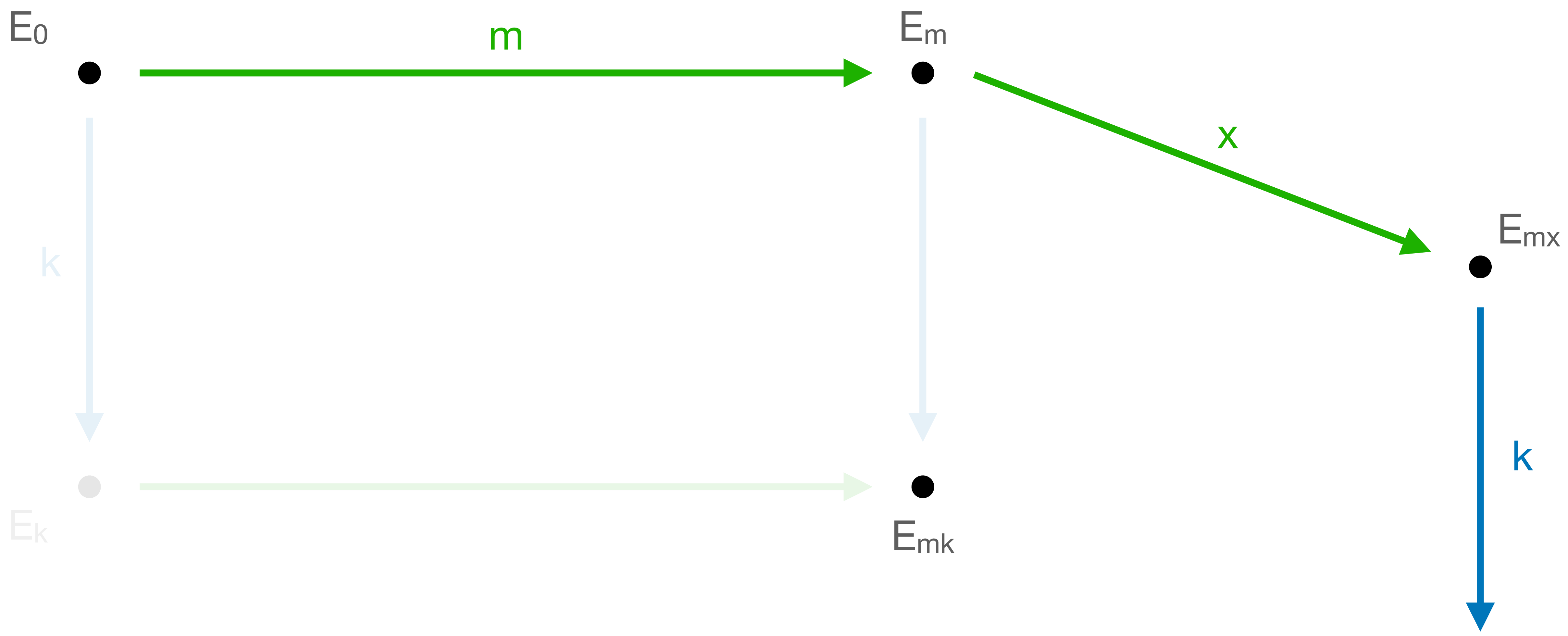

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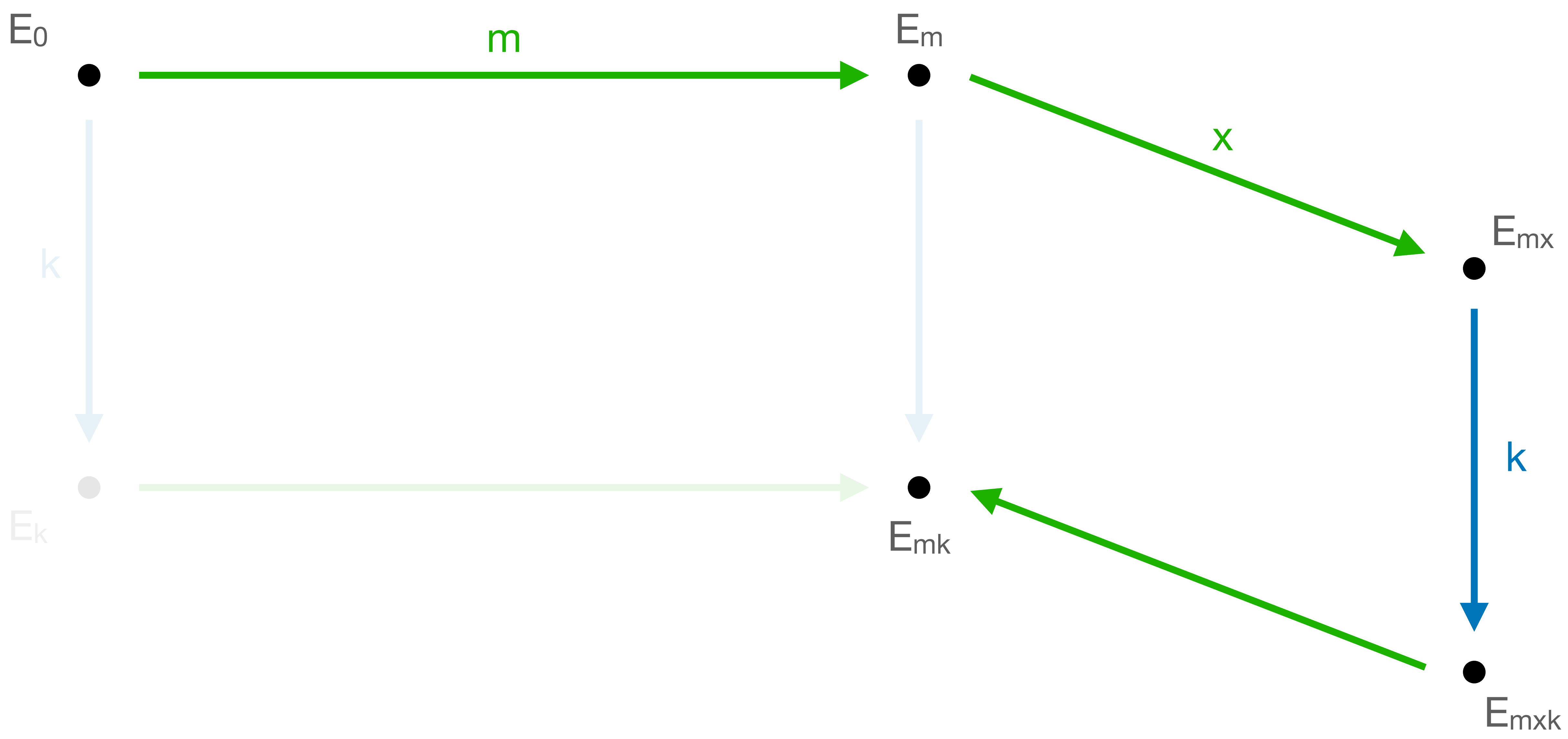

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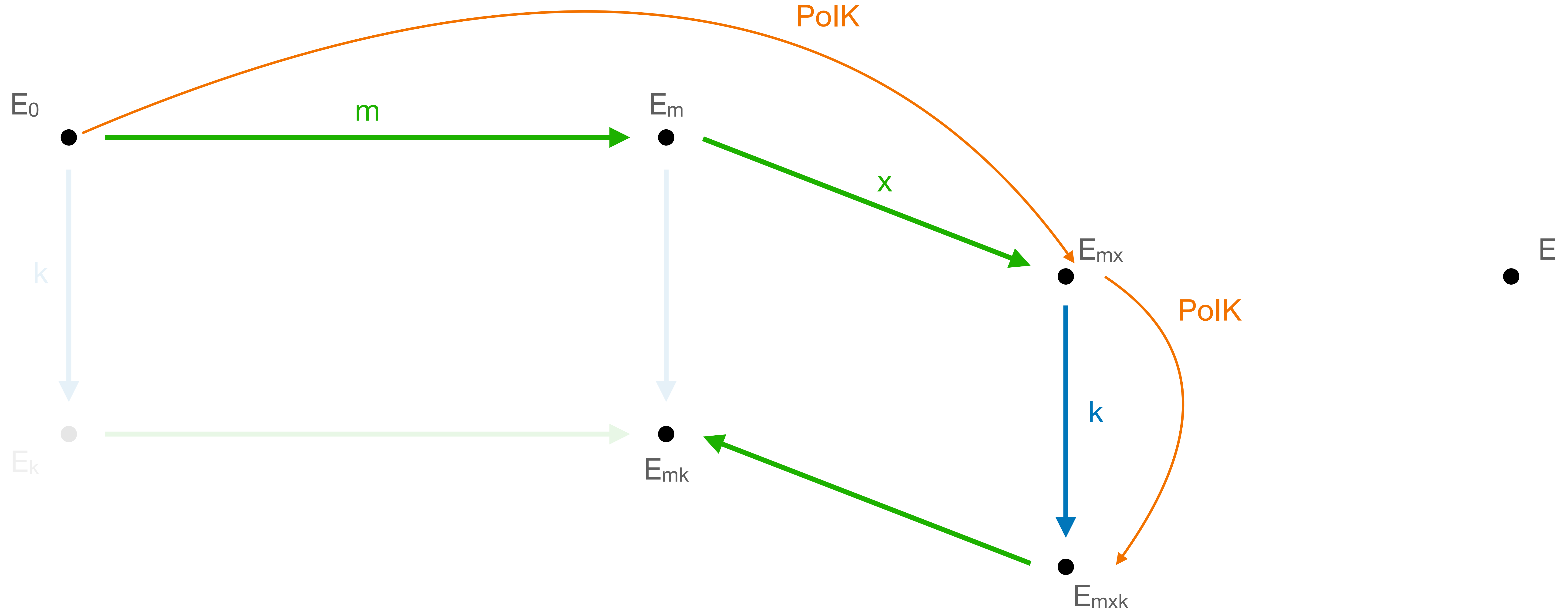

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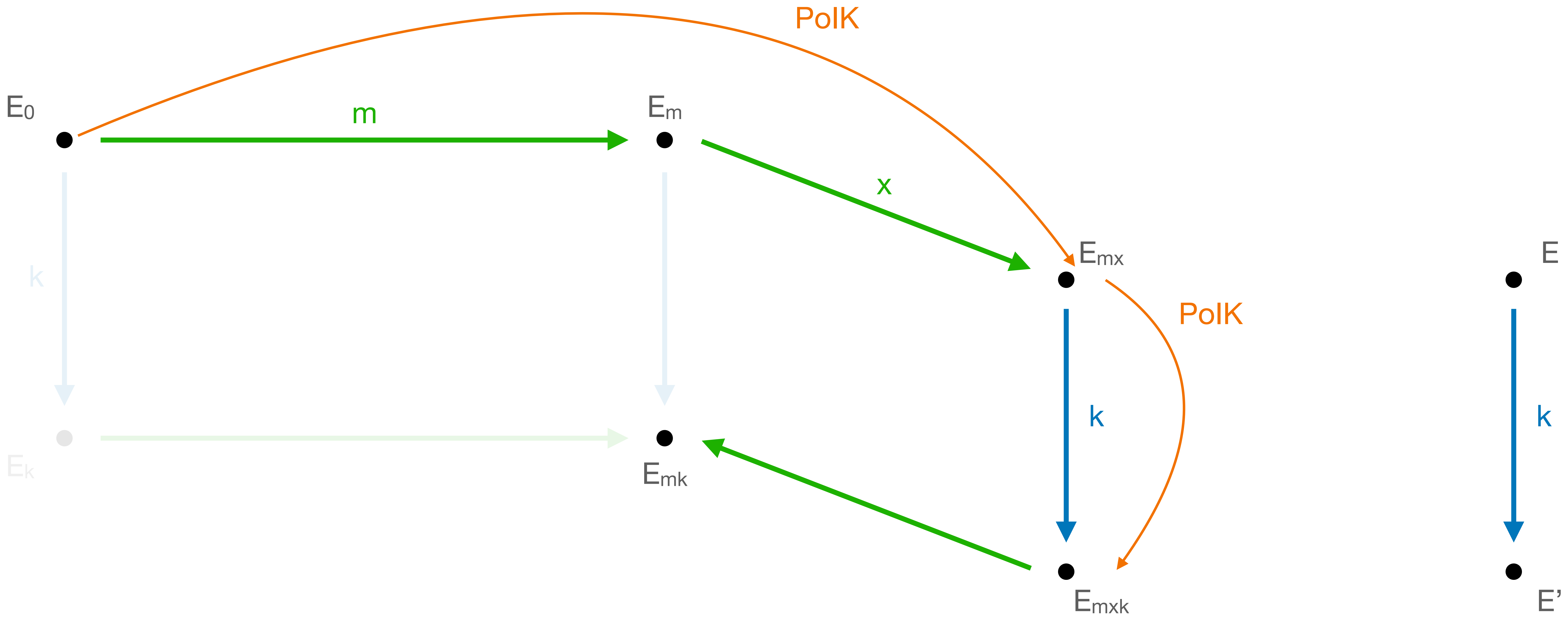

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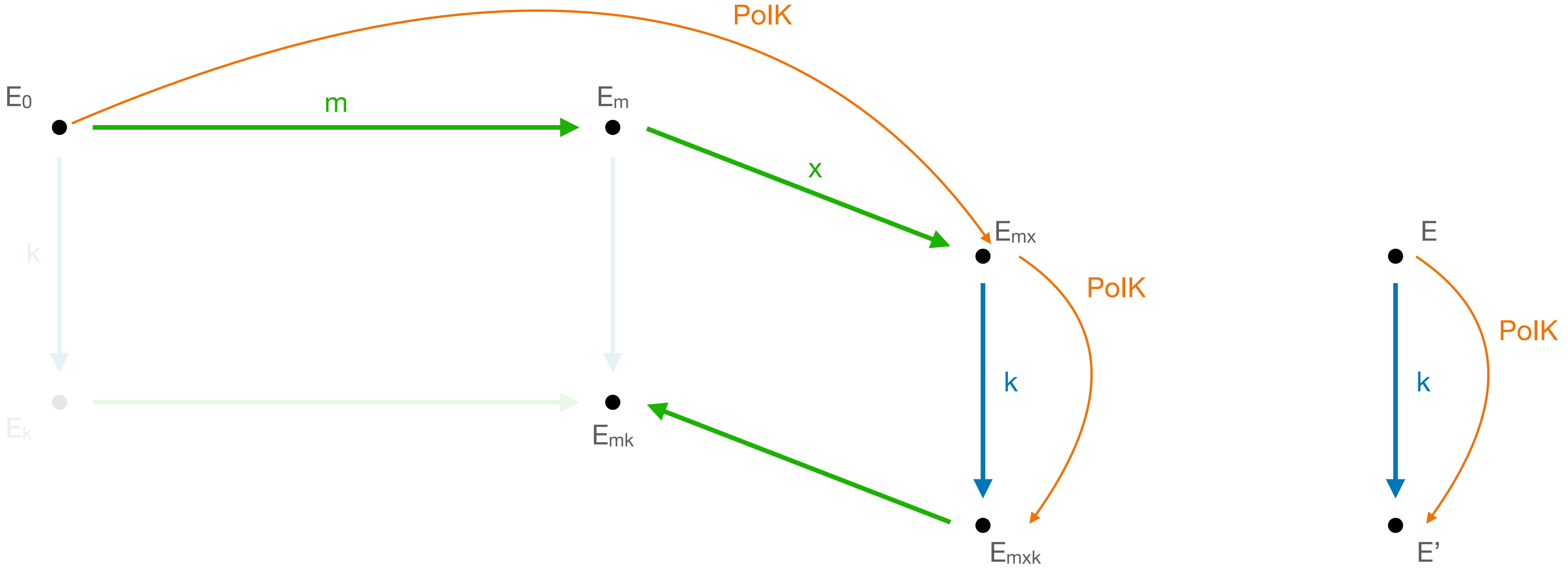

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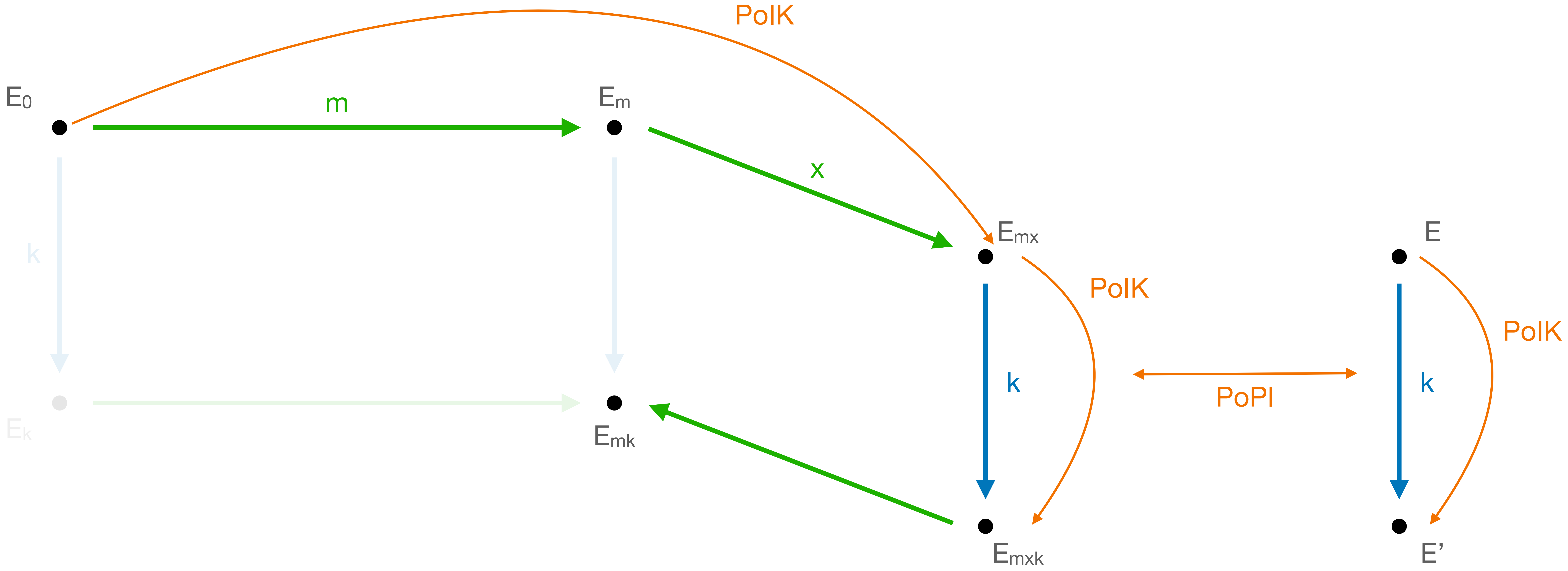

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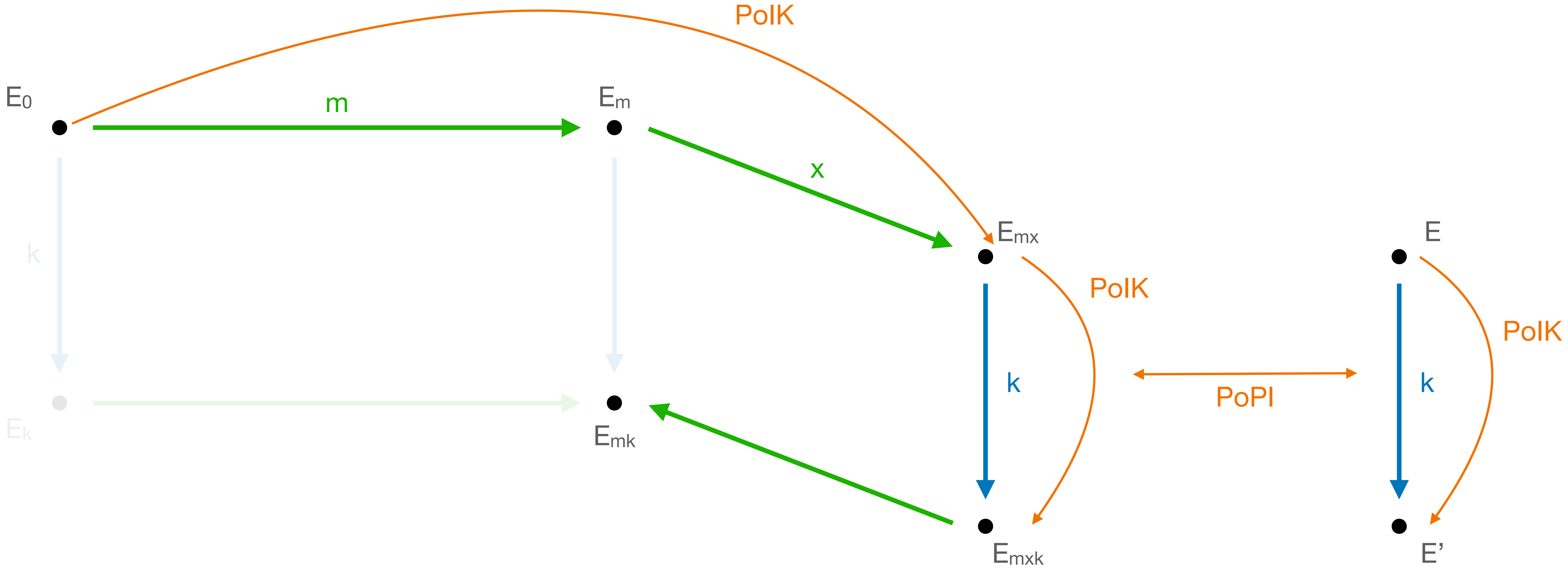
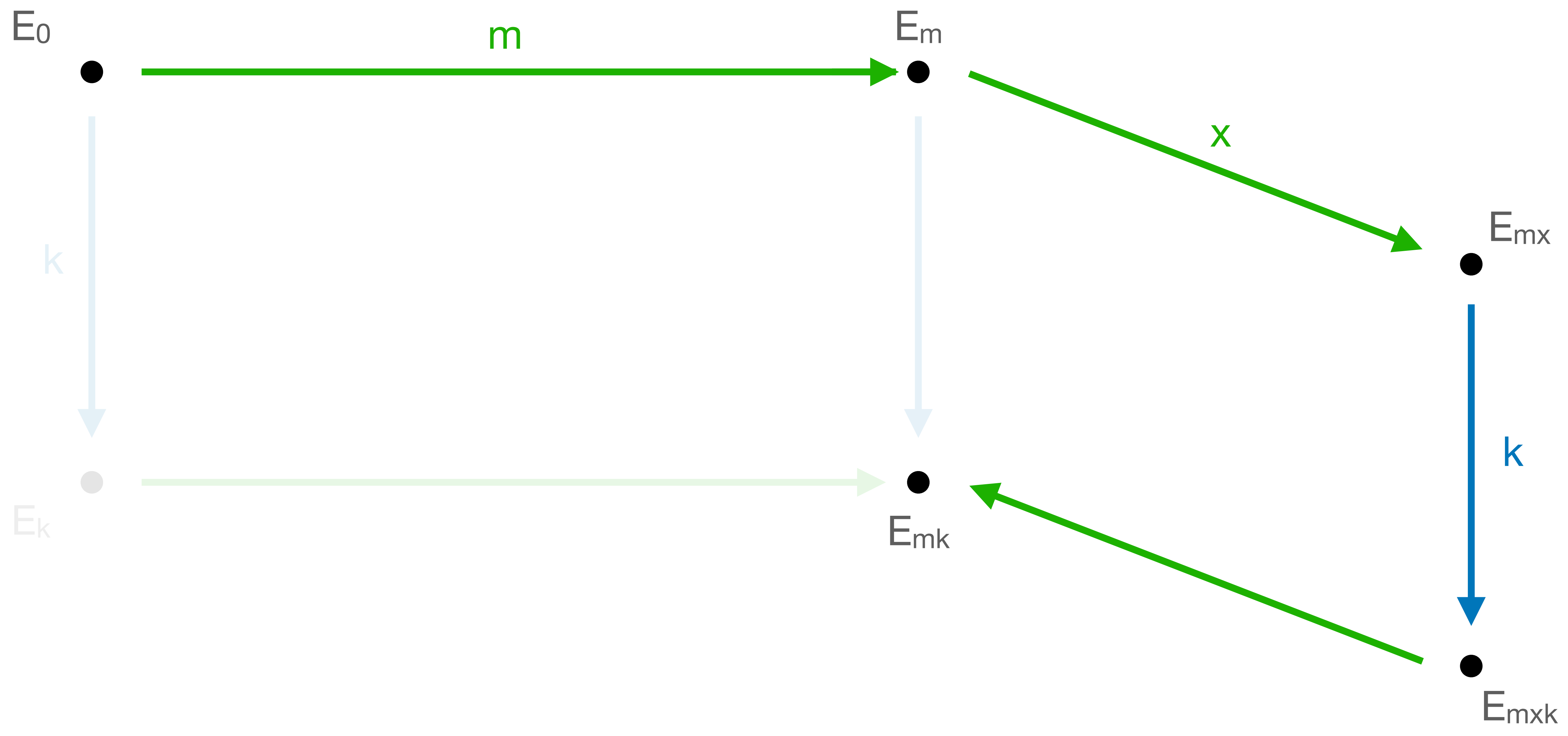


$$F(k, m) = H(m, j_{mk}, E')$$

Breaking pseudorandomness [BKMPS21]

Pseudorandomness: after n interactions, an attacker cannot generate n+1 PRF outputs



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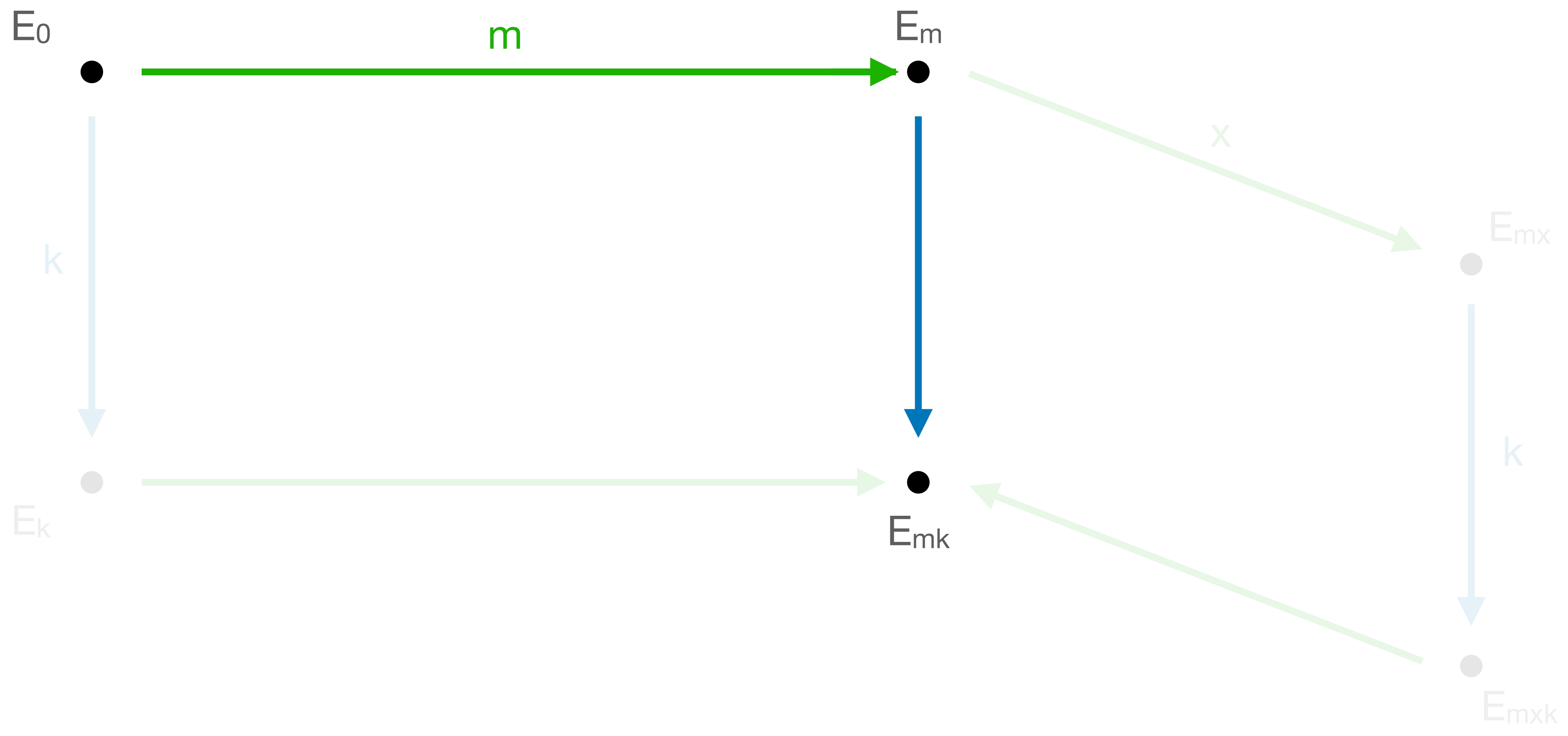

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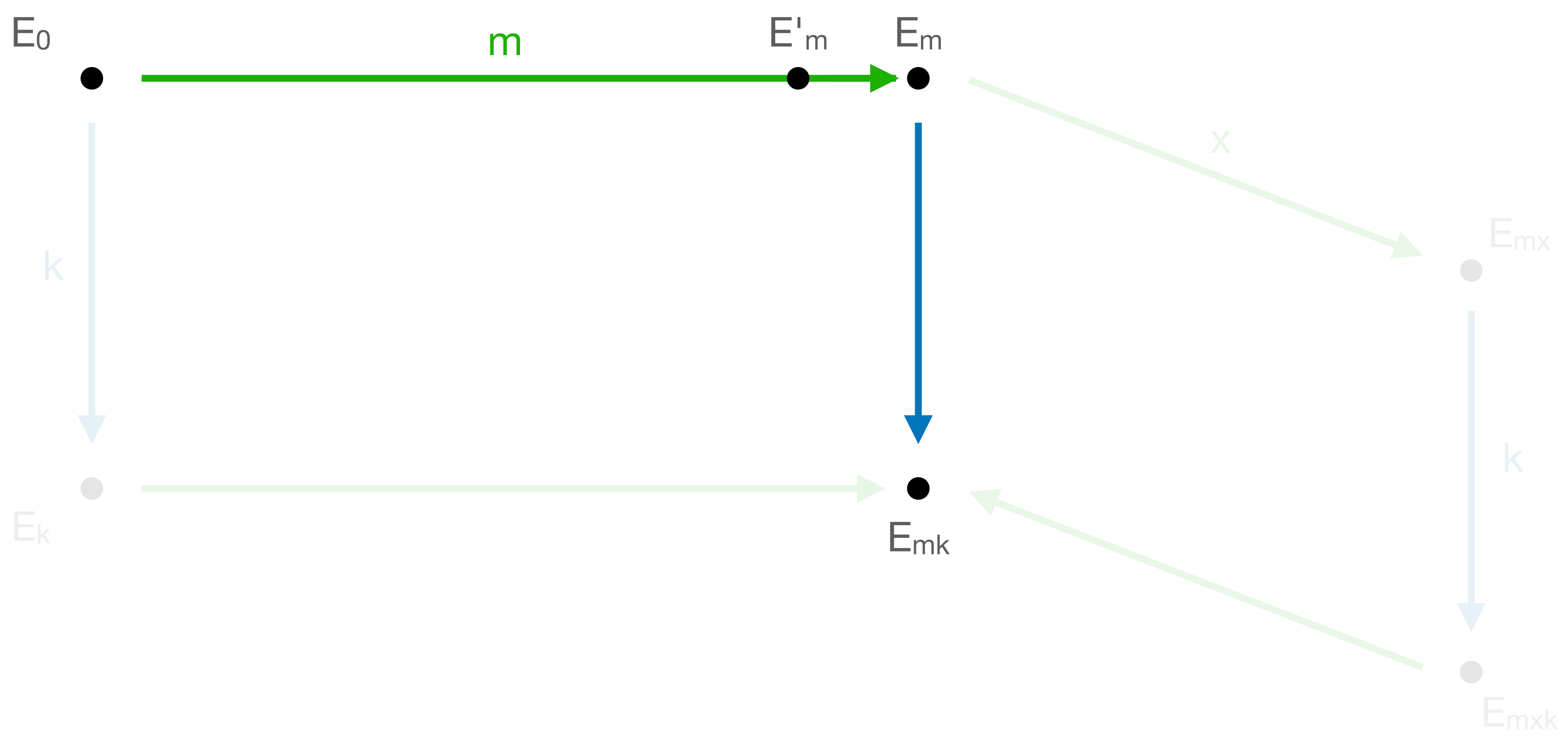

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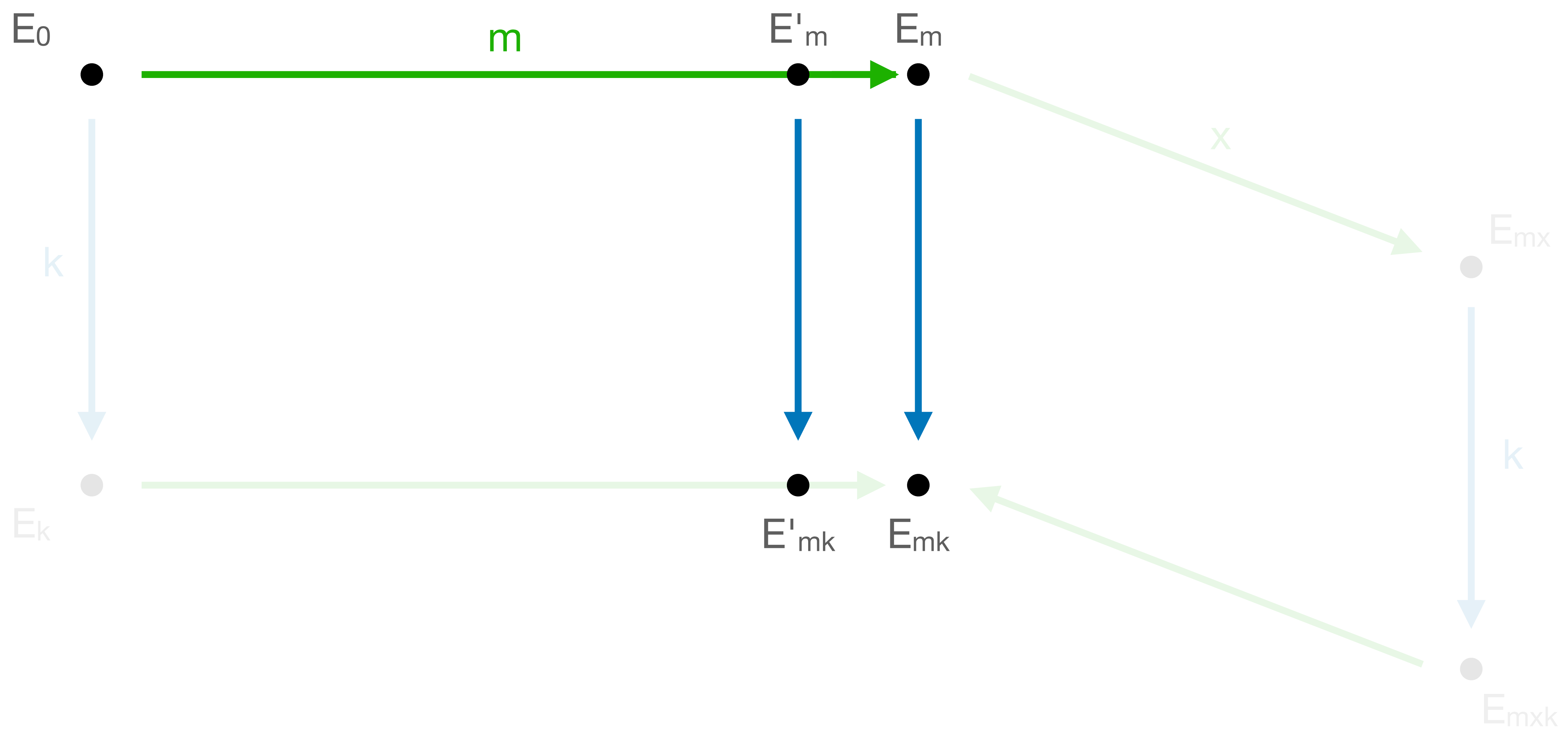

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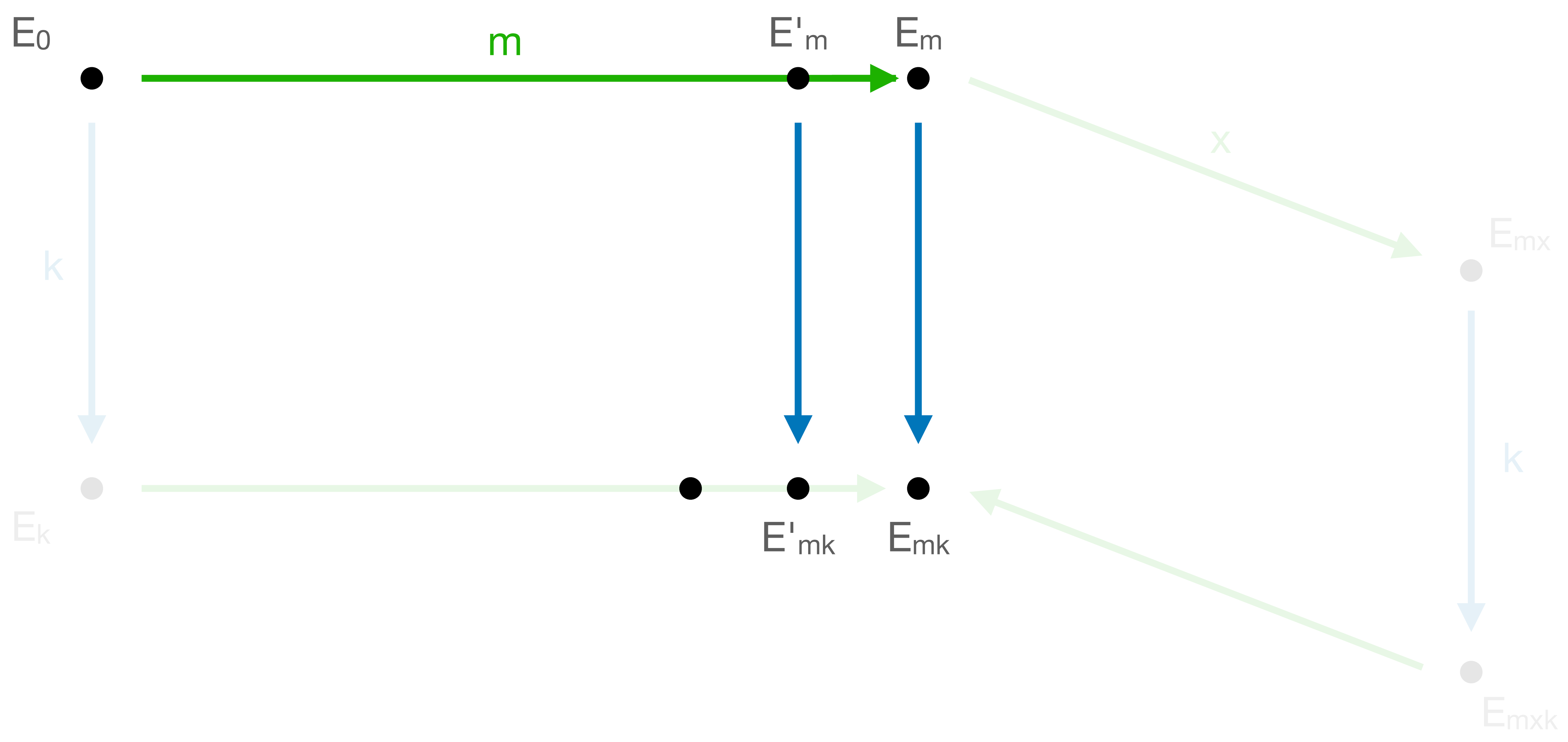

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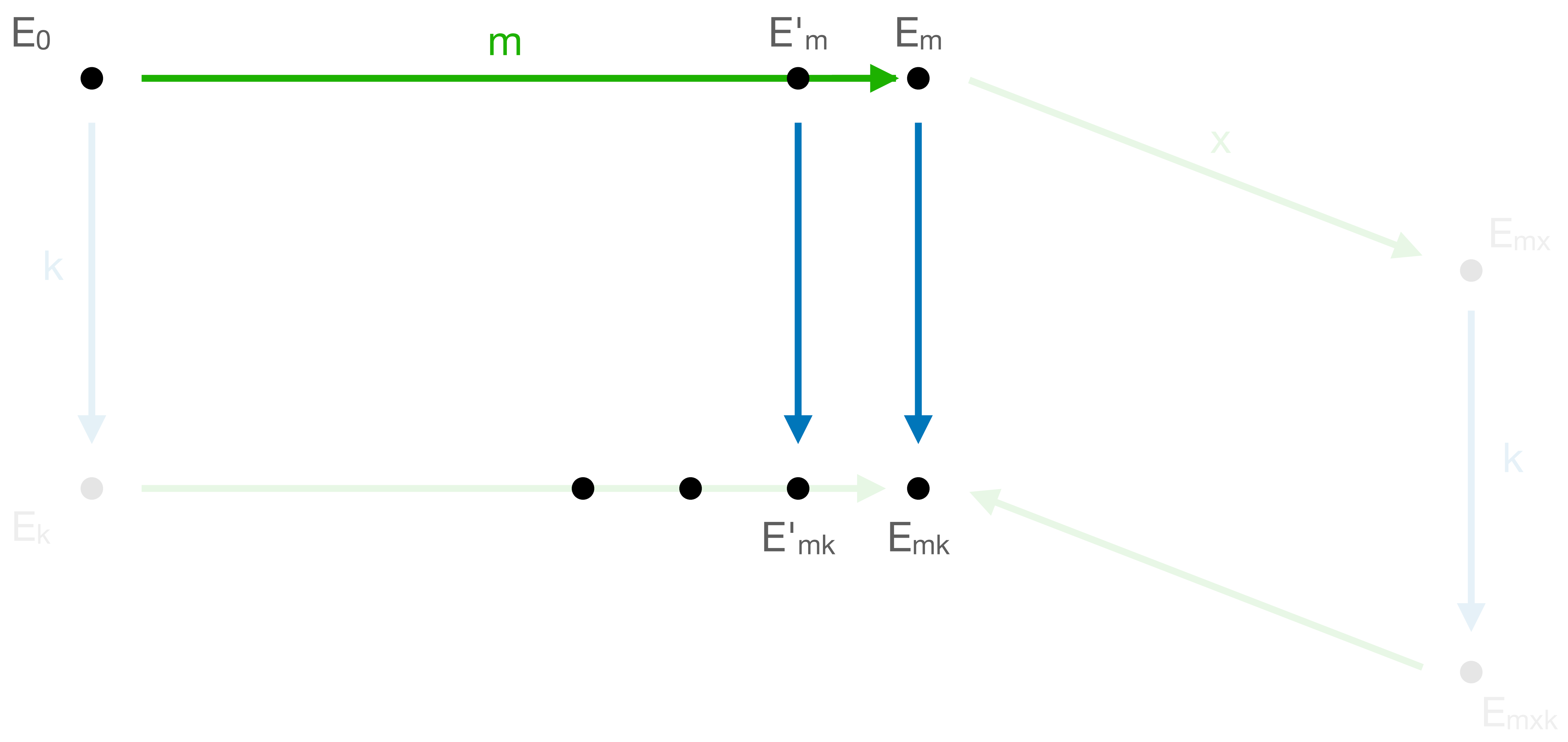

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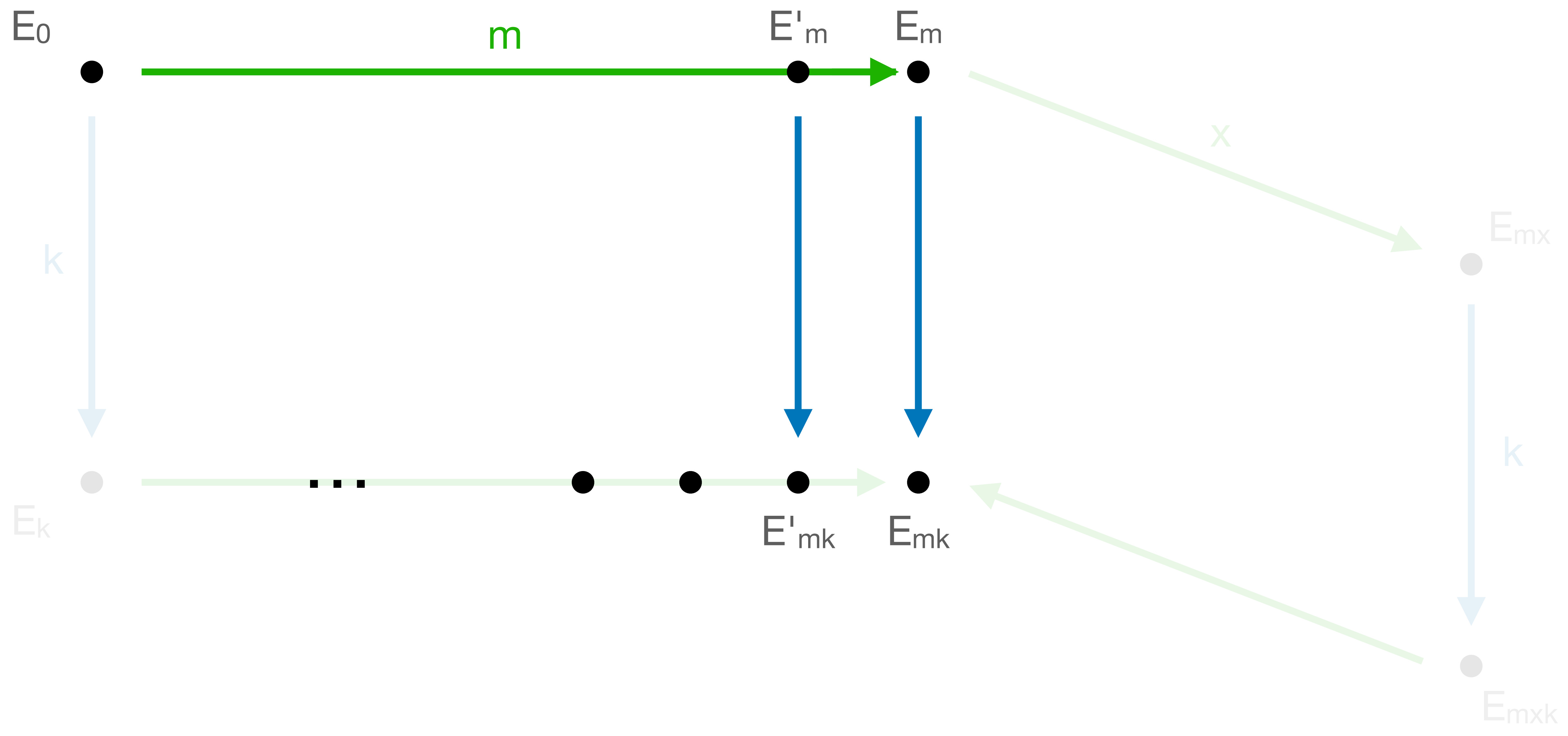

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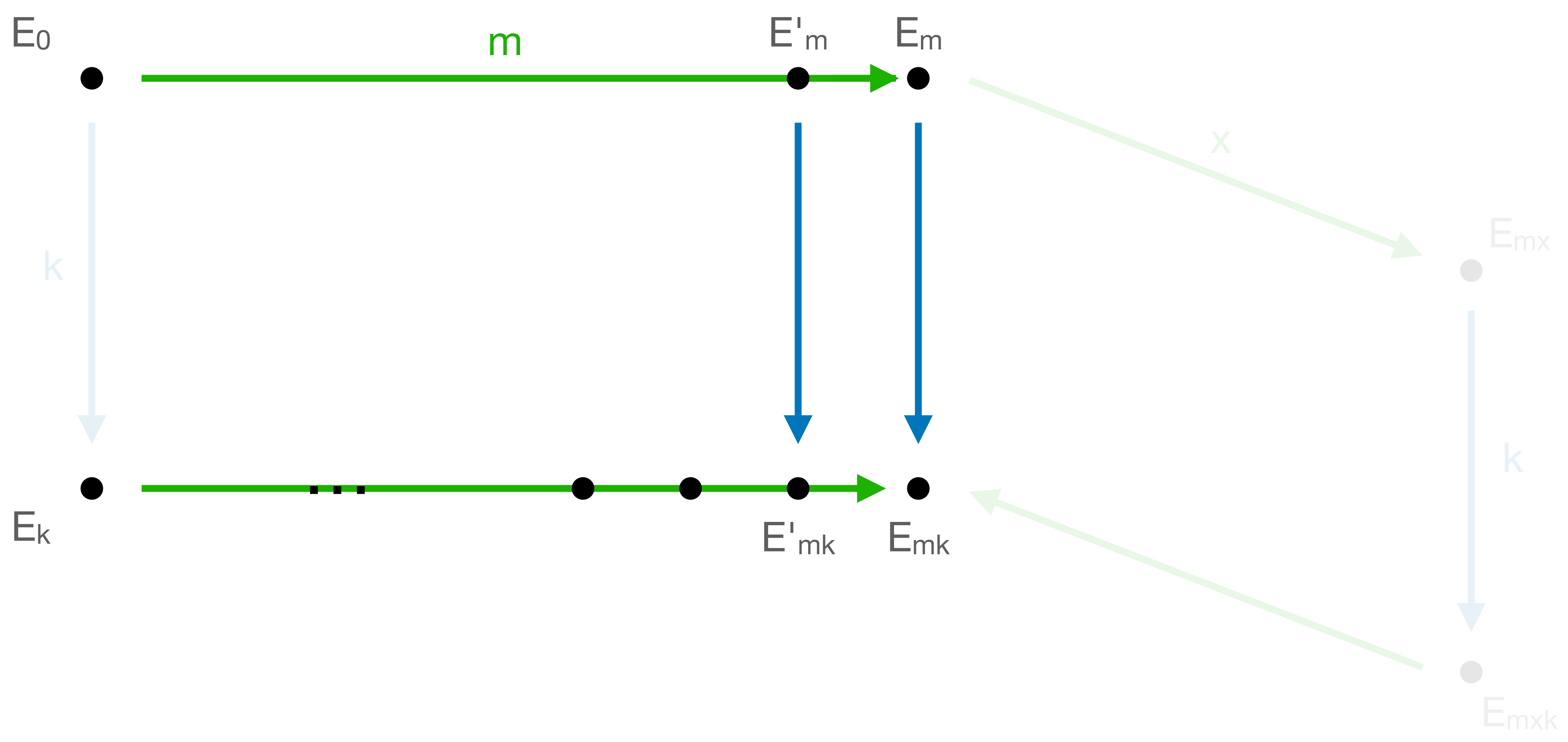

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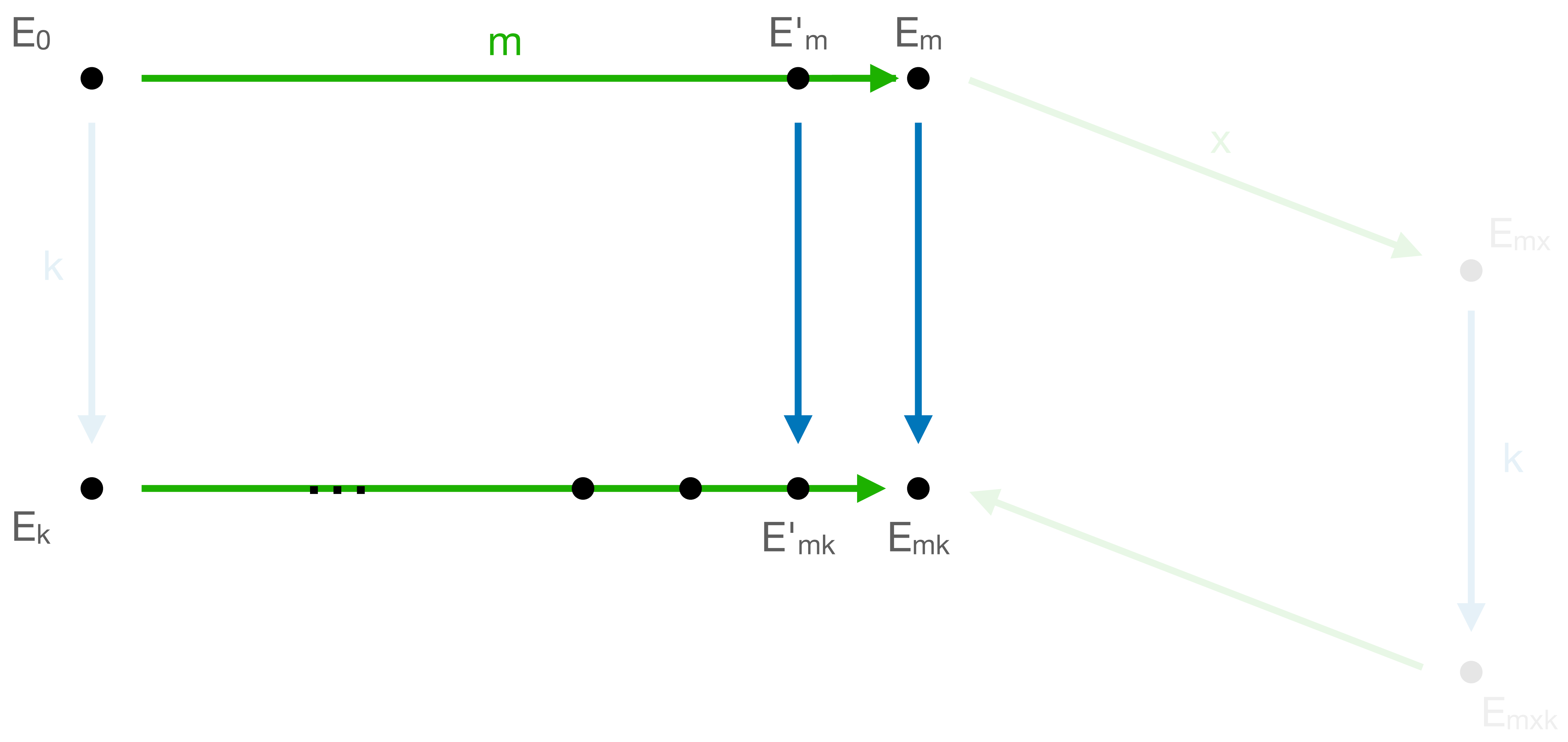

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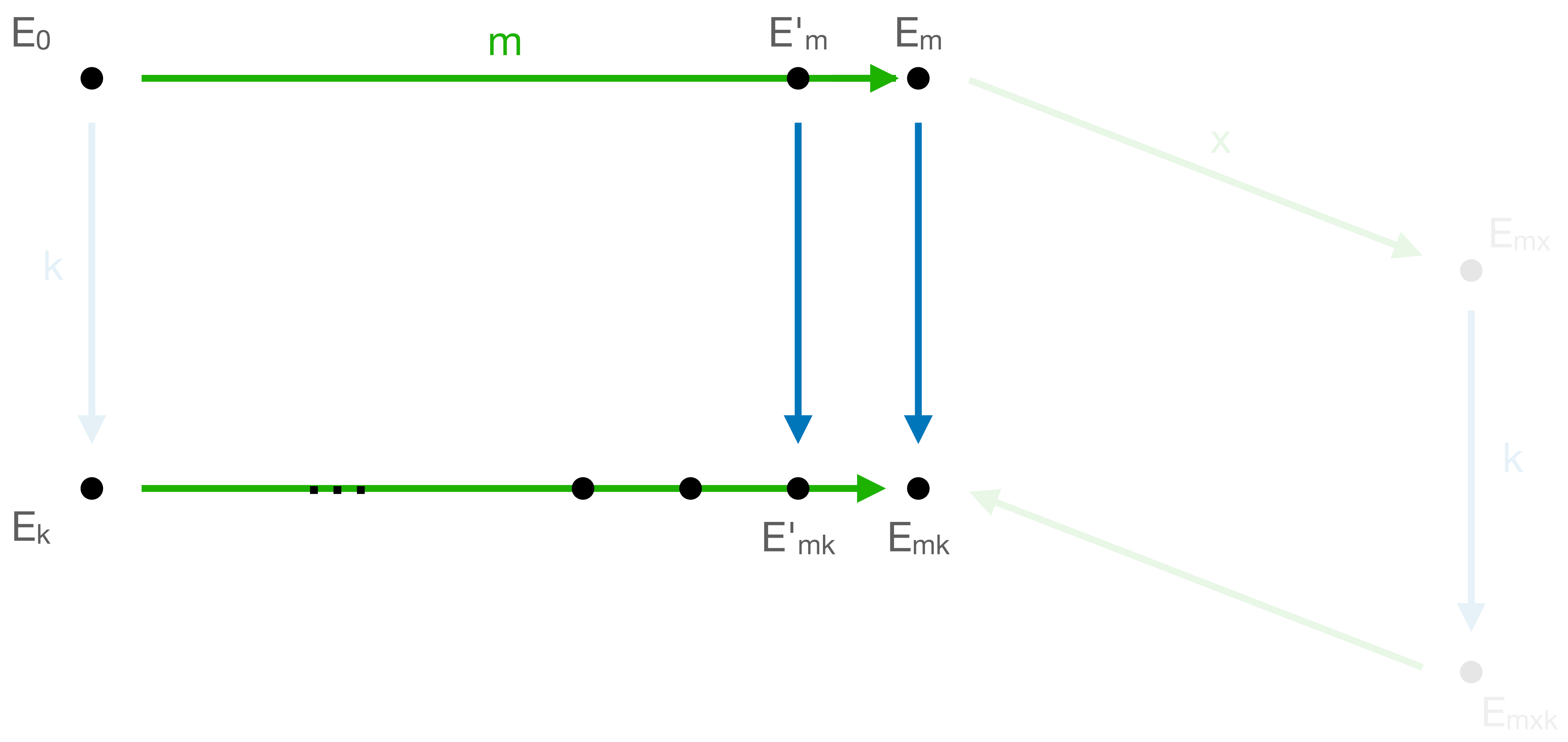
Part 2



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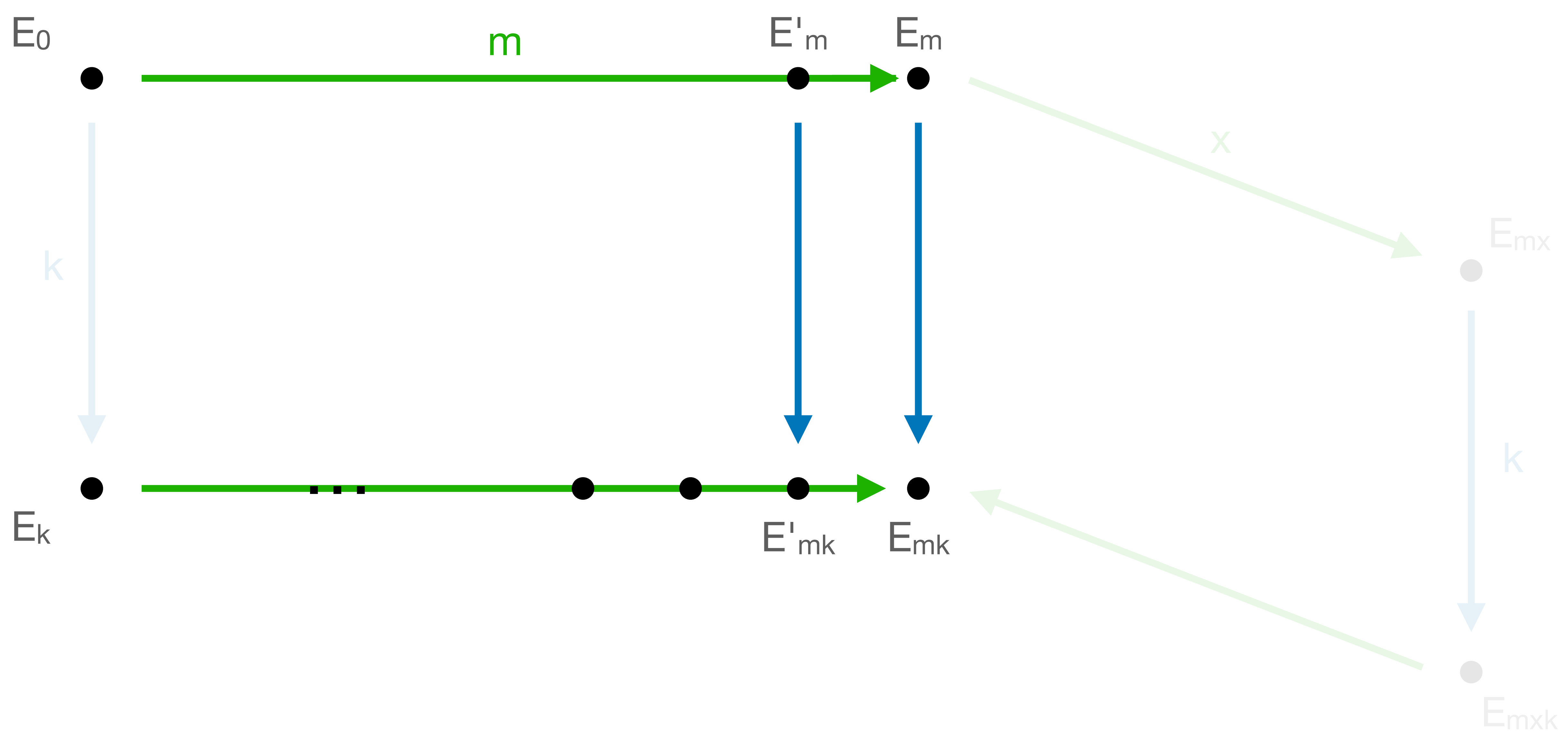

Part 2

- Repeat the attack 3 times

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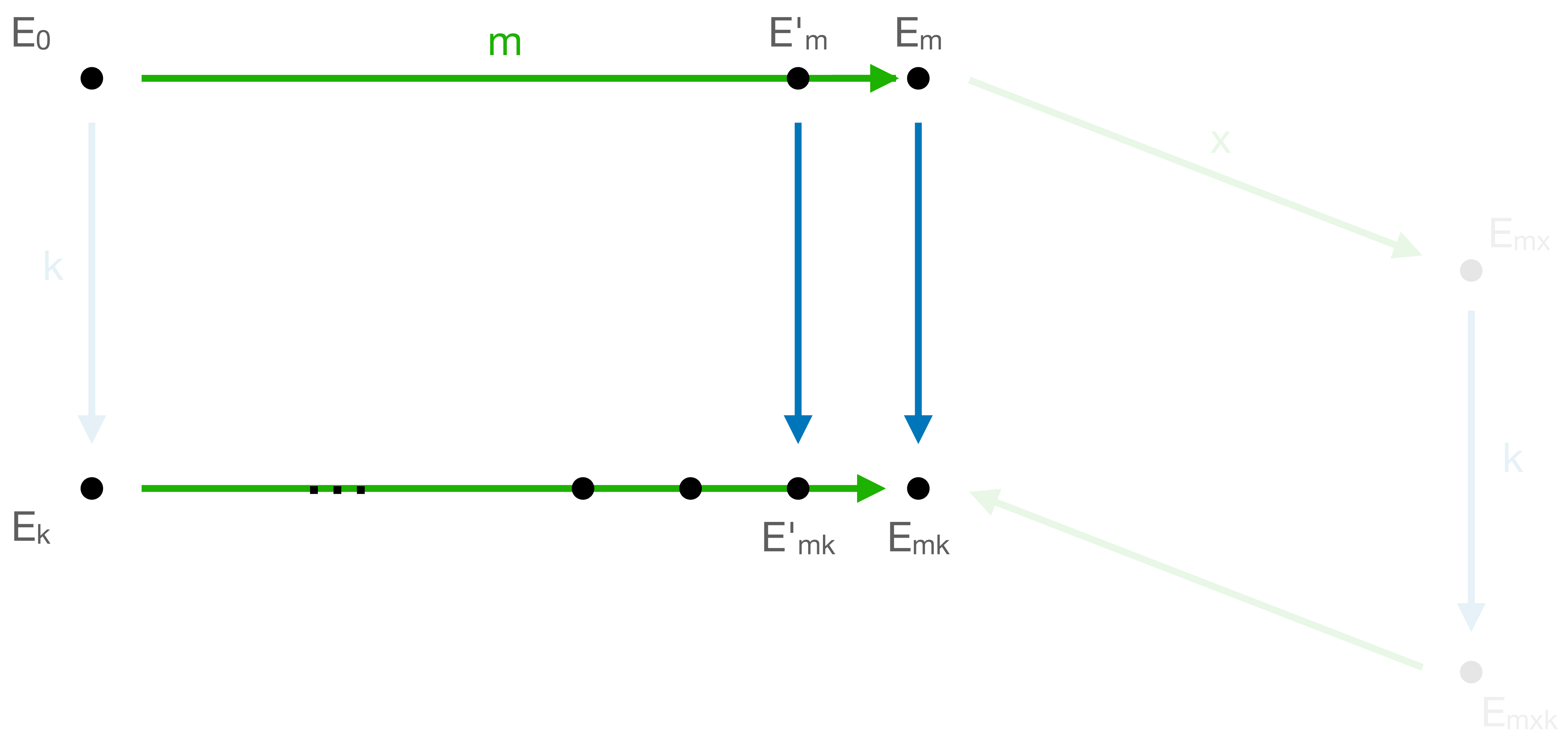

Part 2

- Repeat the attack 3 times
- Find a basis on E_k

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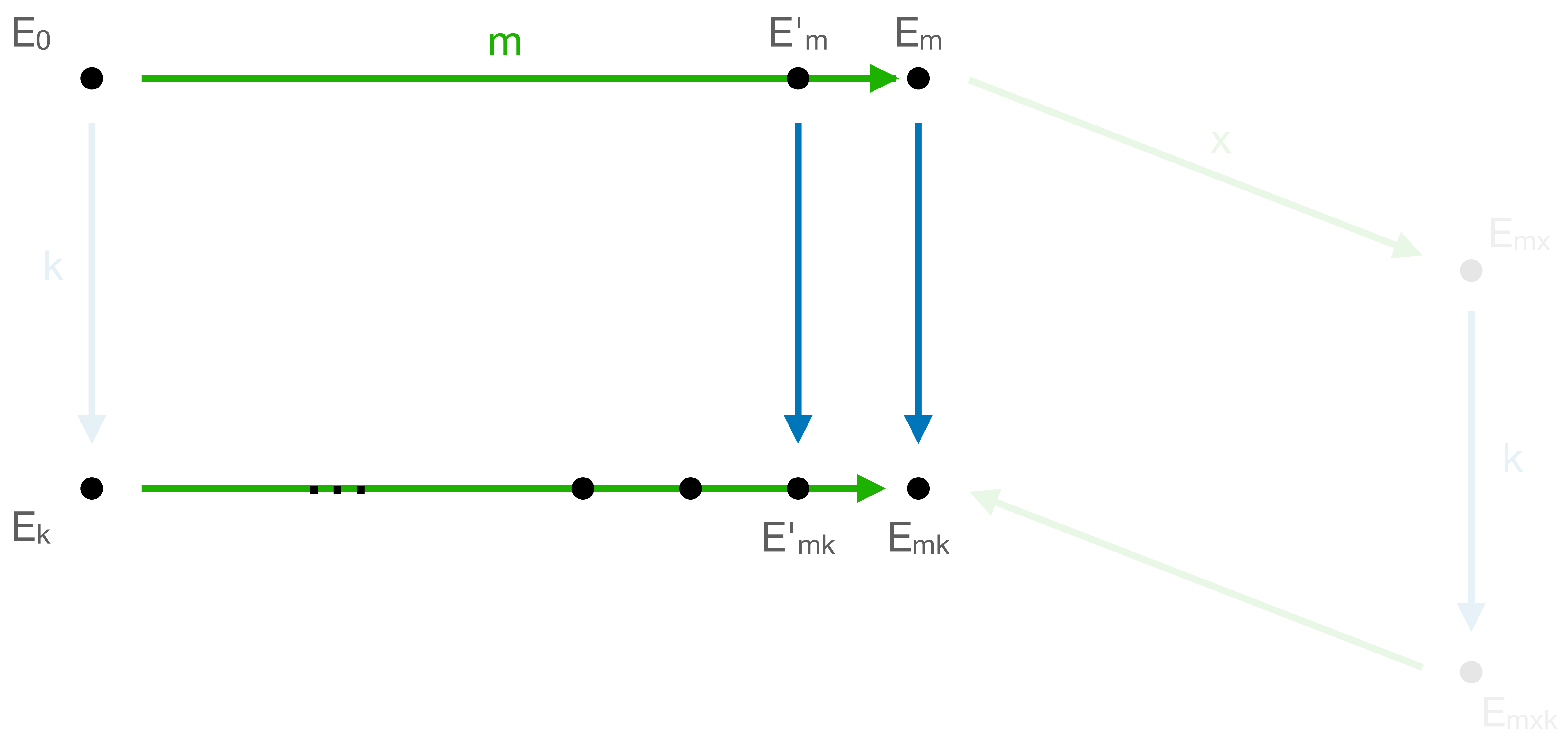

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- Repeat the attack 3 times
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- Evaluate the PRF on *any* message

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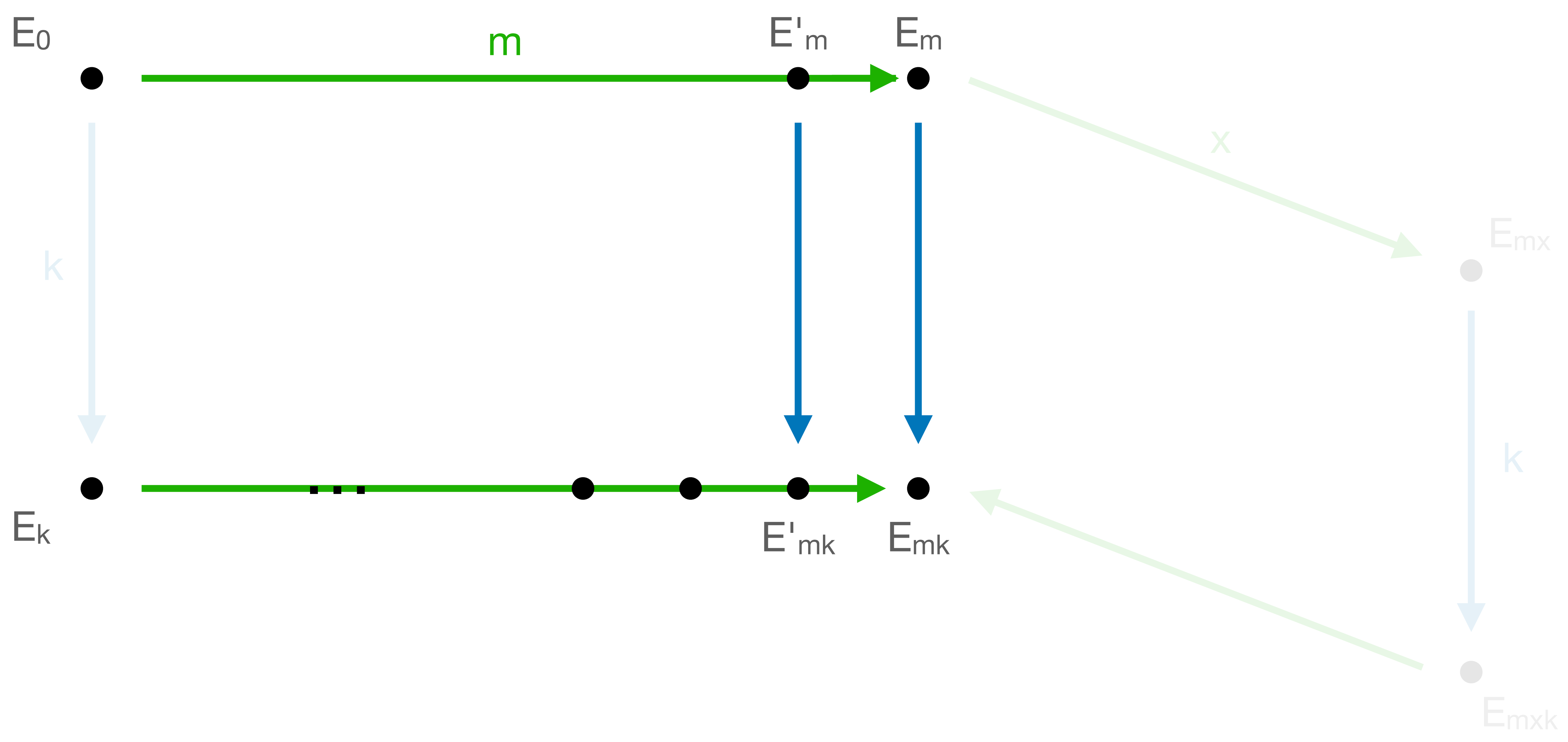

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The server can check the degree with the PoK!

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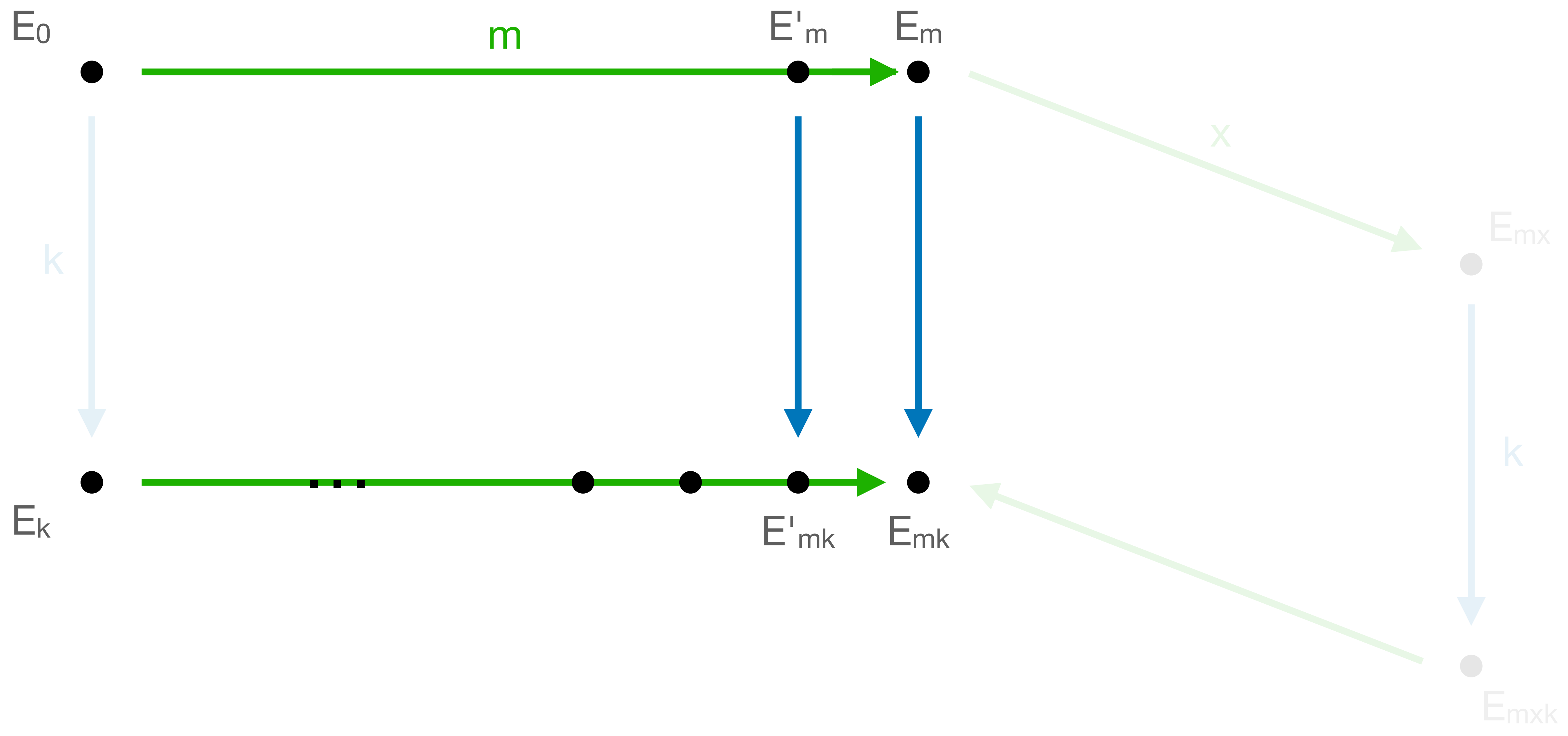

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Actual complexity: sub-exponential

Countermeasures?

It seems hard to prevent an attacker from recovering a basis on E_k

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Ensure that the client submits valid message isogenies

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The protocol is oblivious

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Use dynamic values for server’s computations

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$p > 2^{16,000}$

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$p > 2^{16,000}$

Idea: make the basis on E_k not enough for an attack

An efficient countermeasure

[BKW20]

An efficient countermeasure

$$\begin{tikzcd} E_0 \arrow[r, "\mathrm{Ker} = <P + H(m)Q>"] & E_m \end{tikzcd}$$

[BKW20]

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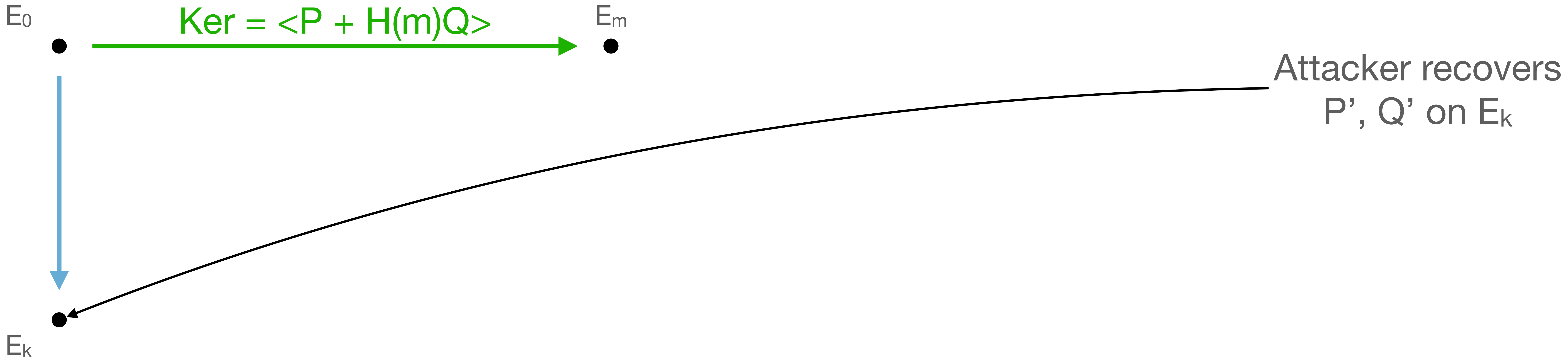

Attacker recovers
P’, Q’ on E_k

An efficient countermeasure

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$$\begin{tikzcd}
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Attacker recovers P', Q' on E_k

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Can evaluate the PRF on any message

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$\downarrow$

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Our countermeasure

An efficient countermeasure

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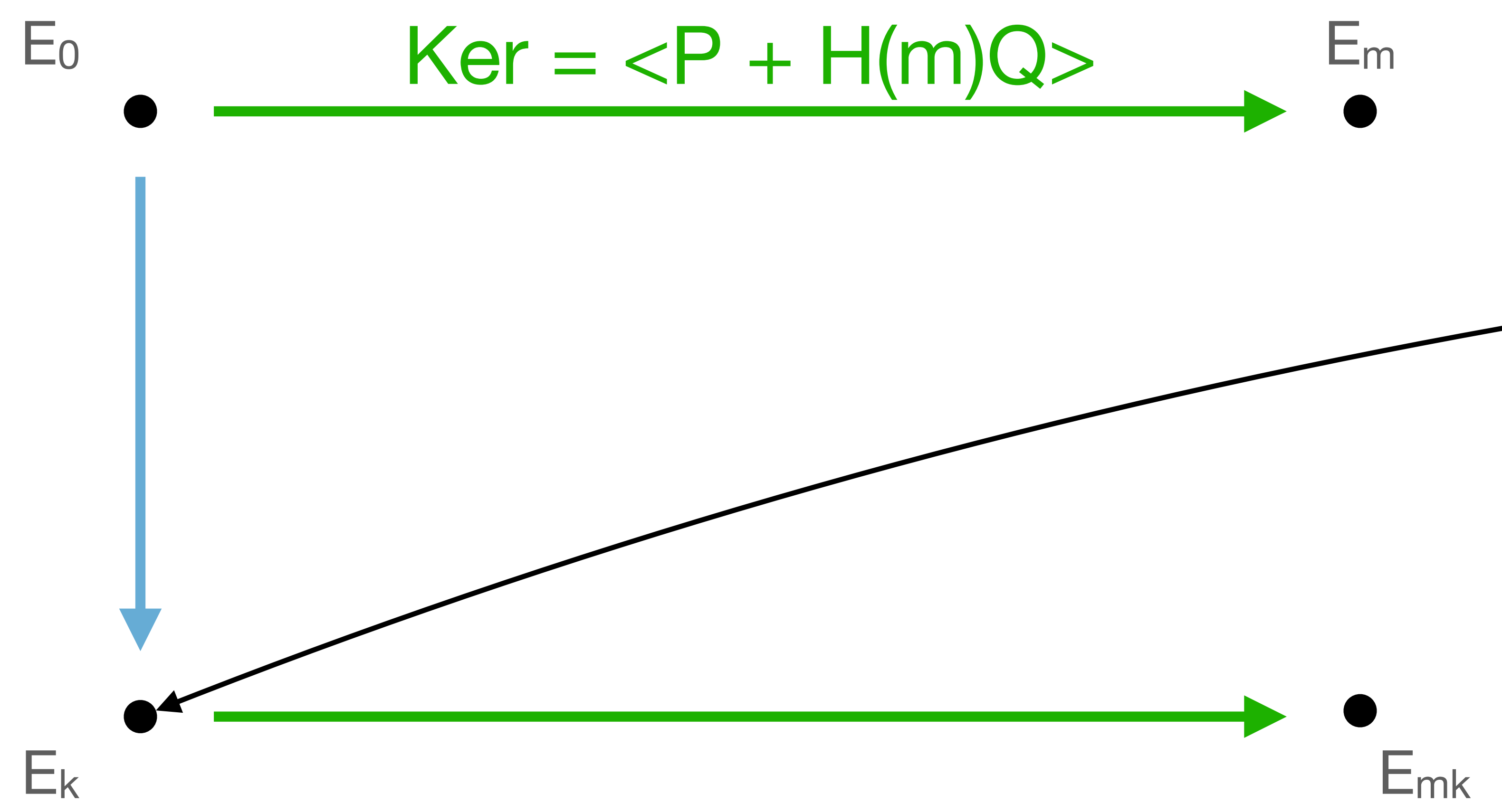

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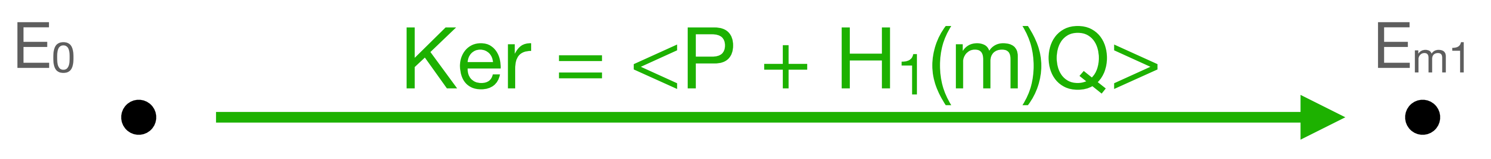

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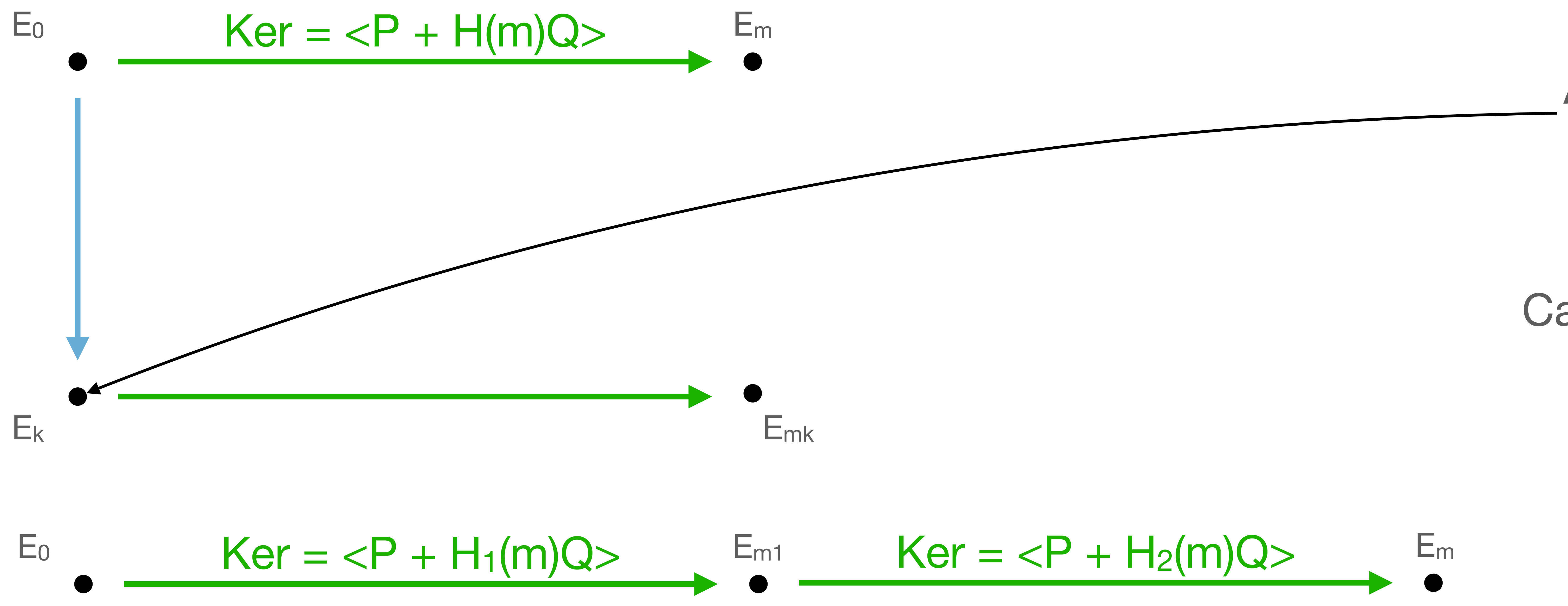
E_0
$\text{Ker} = \langle P + H(m)Q \rangle$
E_m
E_k
E_{mk}
E_0
$\text{Ker} = \langle P + H_1(m)Q \rangle$
E_{m1}
$\text{Ker} = \langle P + H_2(m)Q \rangle$
E_m

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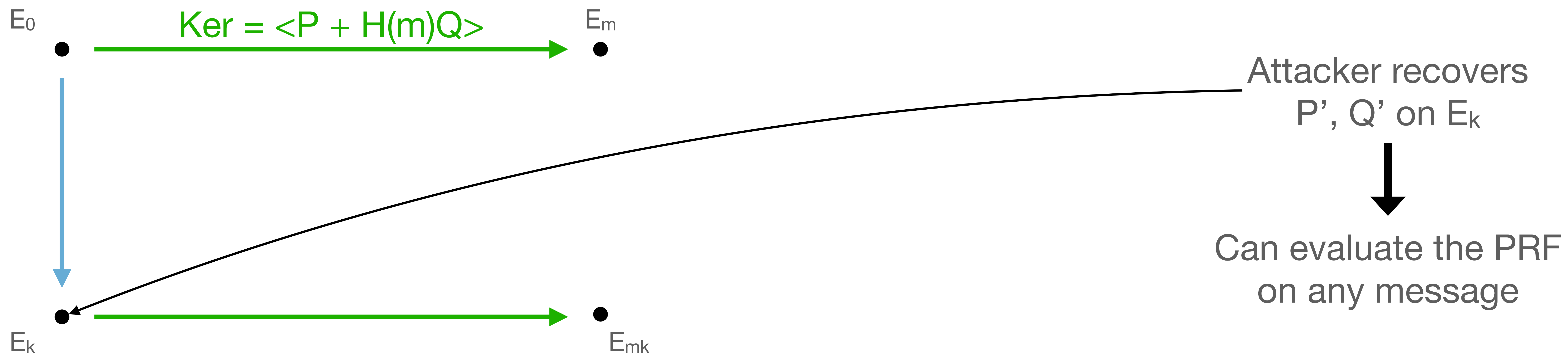

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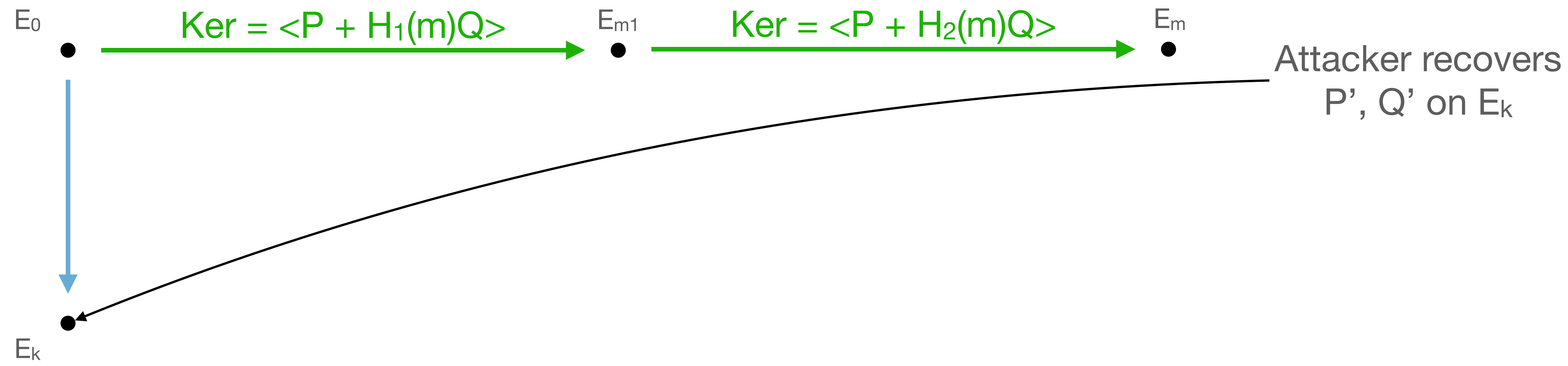

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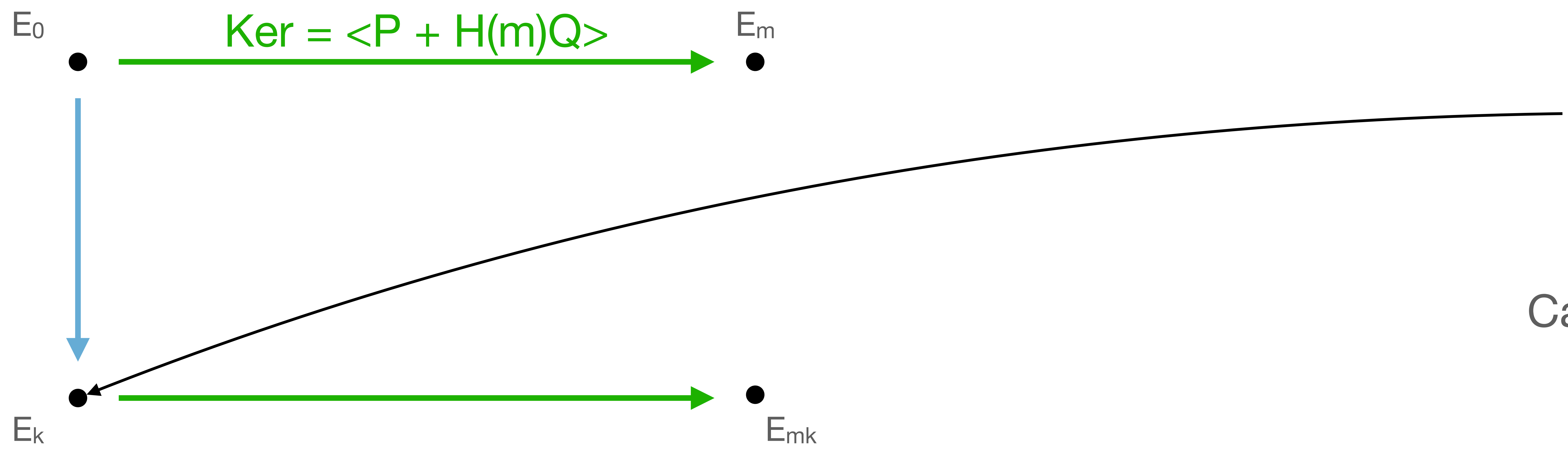

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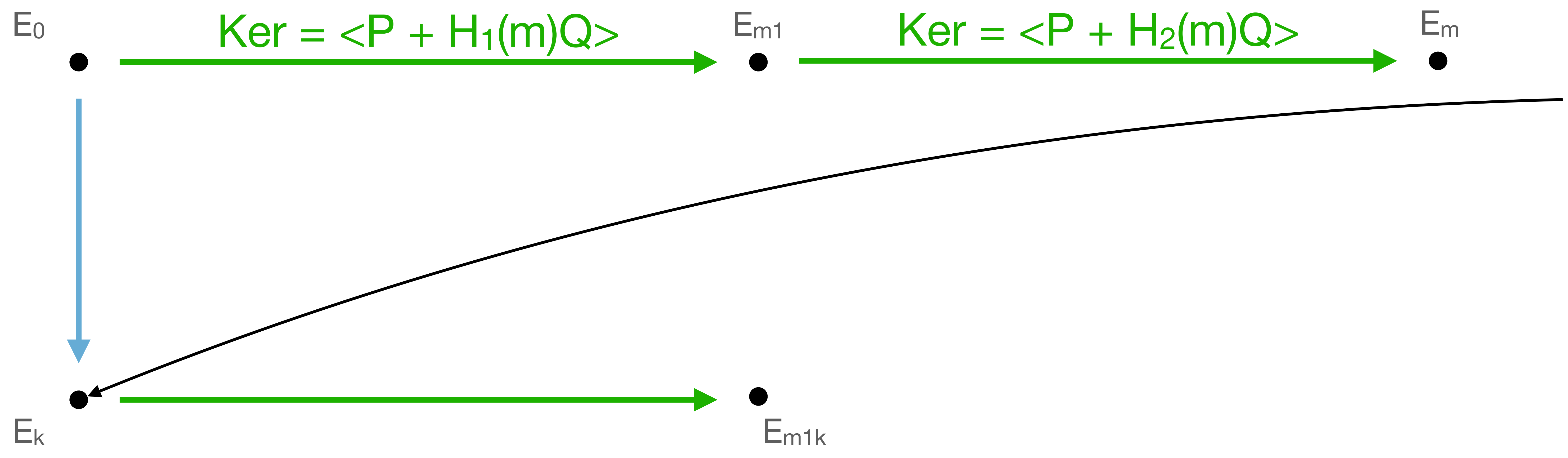
Can evaluate the PRF on any message

Our countermeasure



Attacker recovers P', Q' on E_k

Can only evaluate the first half

One more attack to prevent

The SIDH attacks fully break the BKW OPRF

One more attack to prevent

The SIDH attacks fully break the BKW OPRF

Need to introduce SIDH countermeasures

One more attack to prevent

The SIDH attacks fully break the BKW OPRF

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Longer isogenies

One more attack to prevent

The SIDH attacks fully break the BKW OPRF

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Longer isogenies

❌

only works for one party

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Masked-degree isogenies
[Mor22,FMP23]

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Longer isogenies

❌

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Masked-degree isogenies [Mor22,FMP23]

❌

hard to build proofs

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The SIDH attacks fully break the BKW OPRF

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Longer isogenies

❌

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Masked-degree isogenies [Mor22,FMP23]

❌

hard to build proofs

Masked torsion points [Fou22,FMP23]

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The SIDH attacks fully break the BKW OPRF

Need to introduce SIDH countermeasures

Longer isogenies

❌

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[Mor22,FMP23]

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Masked torsion points
[Fou22,FMP23]

✅

it works

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it works

needs new PoIK

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only works for one party

Masked-degree isogenies [Mor22,FMP23]

❌

hard to build proofs

Masked torsion points [Fou22,FMP23]

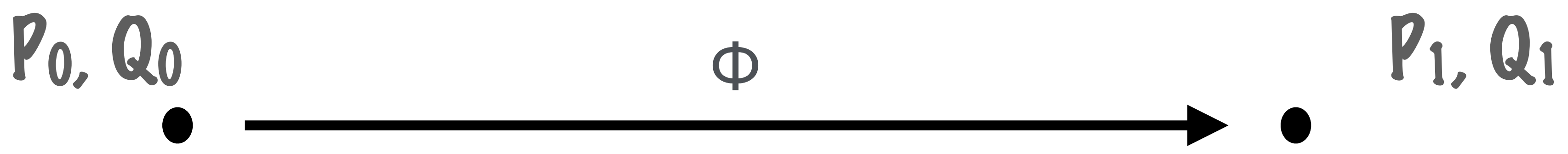
✅

it works

needs new PoIK

$p \approx 2^{6000}$

PolK with masked torsion



PolK with masked torsion

$$\begin{tikzcd}P_0, Q_0 \arrow[r, "\phi"] & {[a]P_1, [a]Q_1}\end{tikzcd}$$

PolK with masked torsion

$$\begin{tikzcd} \overset{P_0, Q_0}{\bullet} \arrow[r, "\phi"] \arrow[d] & \overset{[a]P_1, [a]Q_1}{\bullet} \\ \bullet \arrow[r] & \bullet \arrow[u] \end{tikzcd}$$

PoIK with masked torsion

$$\begin{tikzcd}
P_0, Q_0 \arrow[r, "\phi"] \arrow[d] & {[a]P_1, [a]Q_1} \\
\bullet \arrow[r] & \bullet \arrow[u]
\end{tikzcd}$$

challenges from {-1, 0, 1}

PoIK with masked torsion

$$\begin{tikzcd}
P_0, Q_0 \arrow[r, "\phi"] \arrow[d] & {[a]P_1, [a]Q_1} \\
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\end{tikzcd}$$

challenges from $\{-1, 0, 1\}$

soundness error = 2/3
⇒ need 1.7λ repetitions

PoIK with masked torsion

$$\begin{tikzcd}
P_0, Q_0 \arrow[r, "\phi"] \arrow[d] & {[a]P_1, [a]Q_1} \\
P_2, Q_2 \arrow[r] & \bullet \arrow[u]
\end{tikzcd}$$

challenges from {-1, 0, 1}

soundness error = 2/3

⇒ need 1.7λ repetitions

PoIK with masked torsion

$$\begin{tikzcd}
P_0, Q_0 \arrow[r, "\phi"] \arrow[d] & {[a]P_1, [a]Q_1} \\
P_2, Q_2 \arrow[r] & P_3, Q_3 \arrow[u]
\end{tikzcd}$$

challenges from $\{-1, 0, 1\}$

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PoIK with masked torsion

$$\begin{tikzcd}
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P_2, Q_2 \arrow[r] & P_3, Q_3 \arrow[u]
\end{tikzcd}$$

$a = a_1 \times a_2 \times a_3$

challenges from $\{-1, 0, 1\}$

soundness error = 2/3
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PoIK with masked torsion

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\end{tikzcd}$$

$a = a_1 \times a_2 \times a_3$

challenges from {-1, 0, 1}

soundness error = 2/3

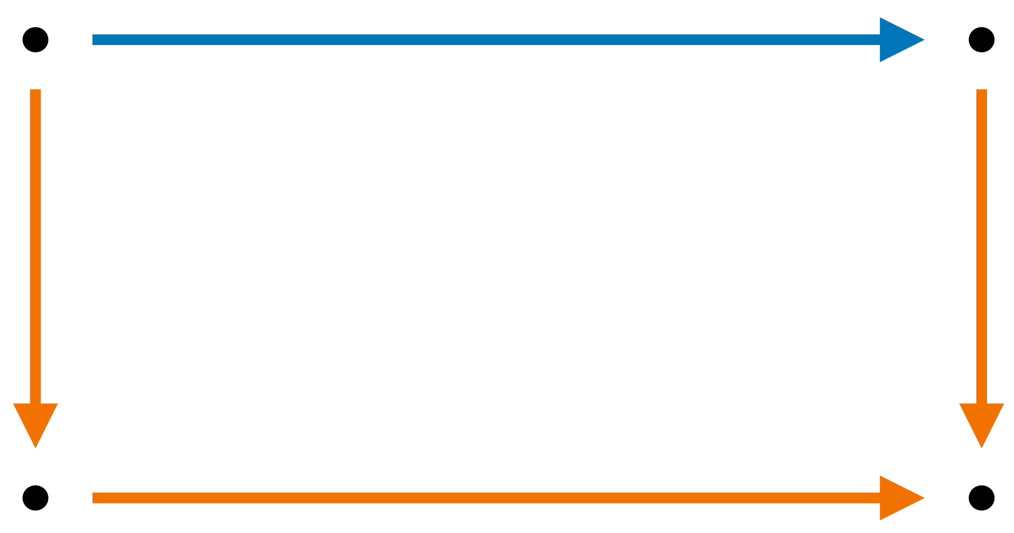
$\Rightarrow$ need 1.7λ repetitions

$p \approx \operatorname{ord} P, Q \times \deg \Phi \times \deg \rightarrow$

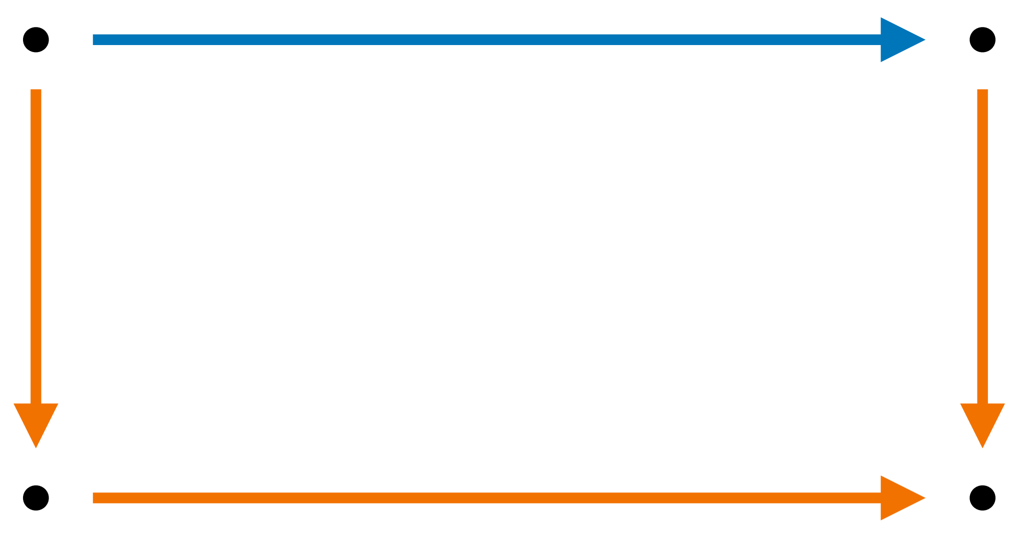
$\approx 2^{9000}$

Verifiability

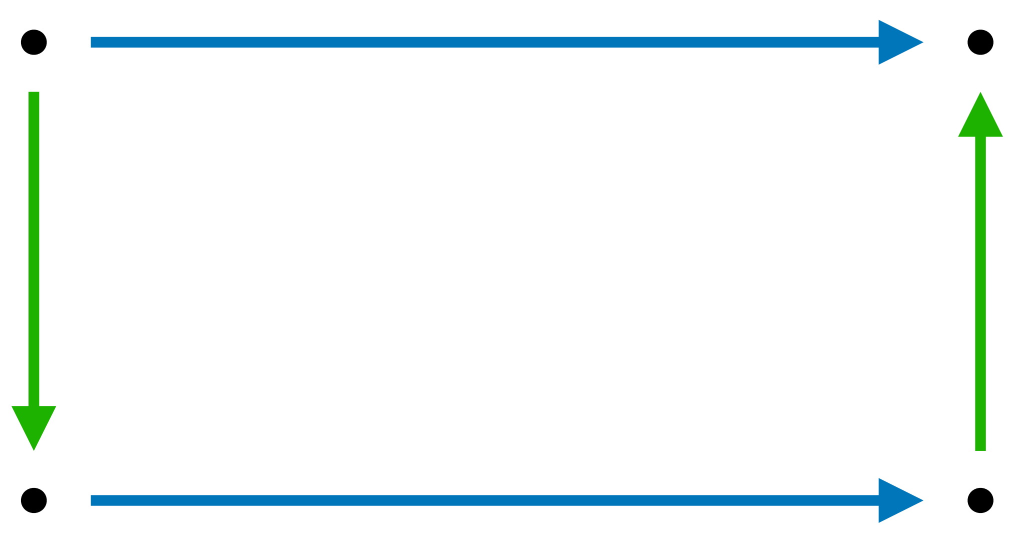
[BKW20] uses 3 proofs:



Server’s isogeny



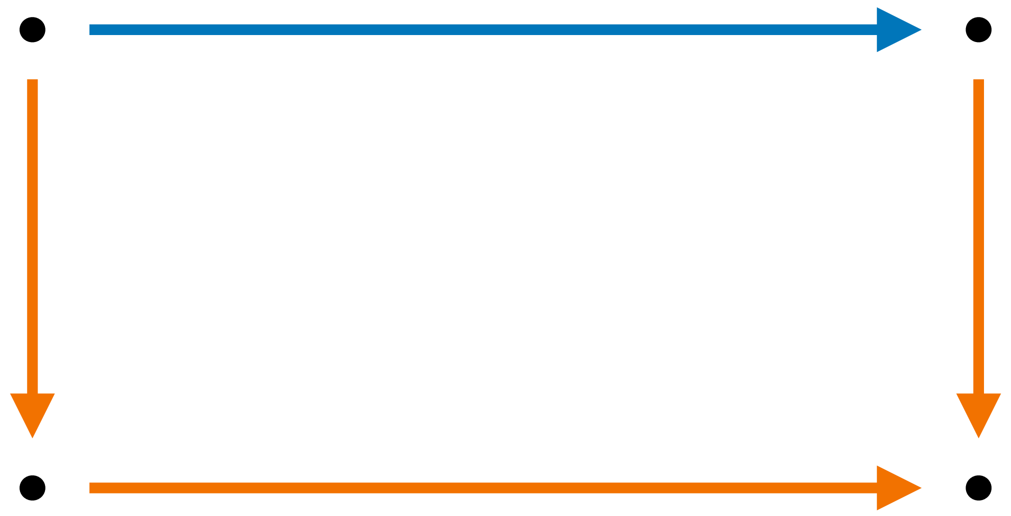
Server’s commitment



Isogeny is parallel
to commitment

Verifiability

[BKW20] uses 3 proofs:



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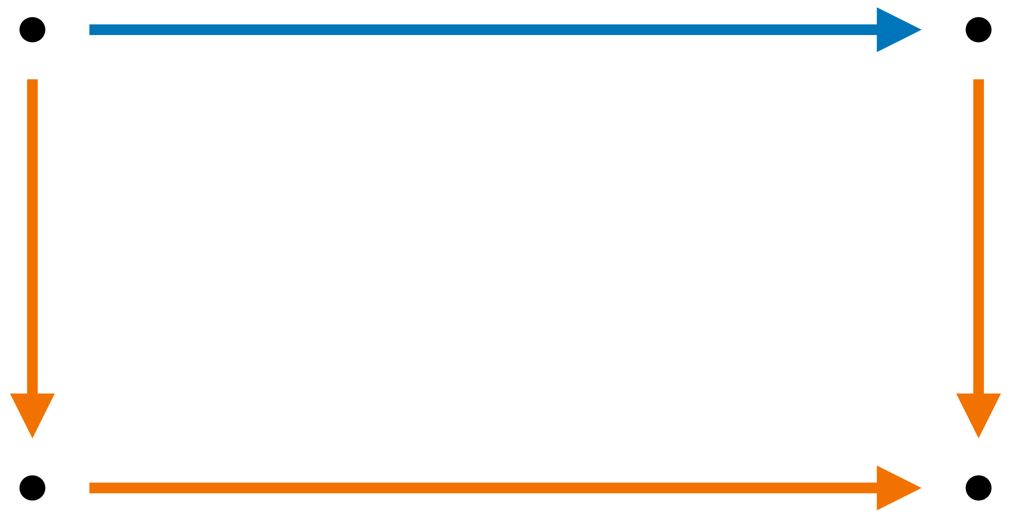
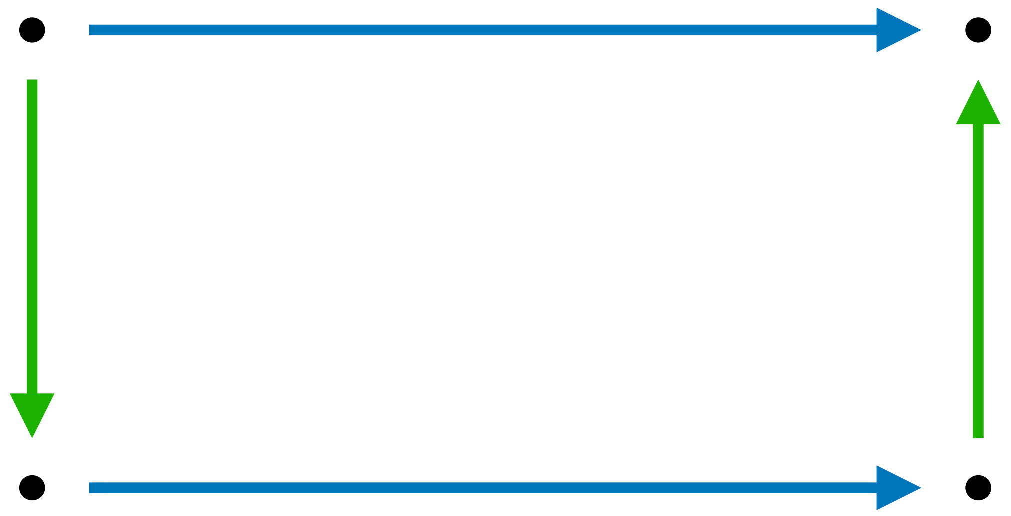


Server’s commitment

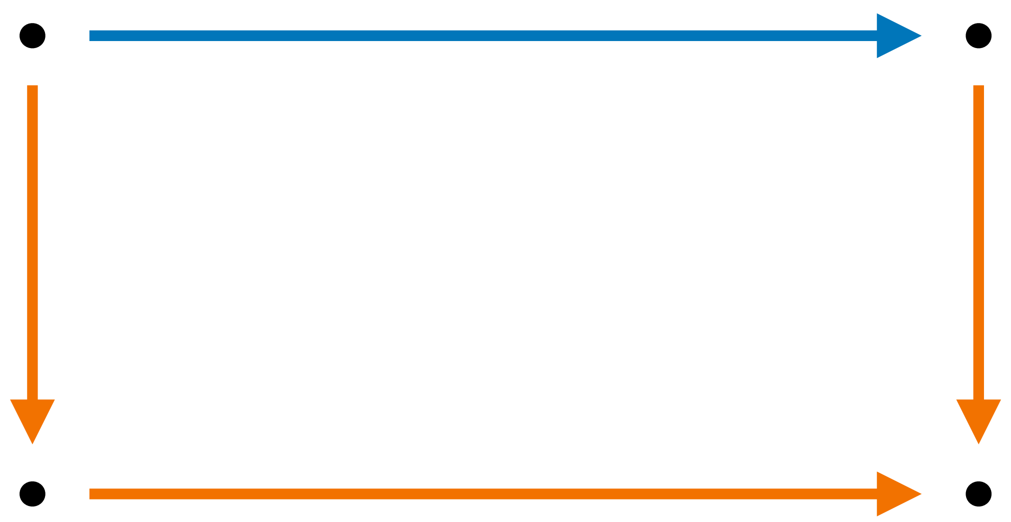


Isogeny is parallel
to commitment

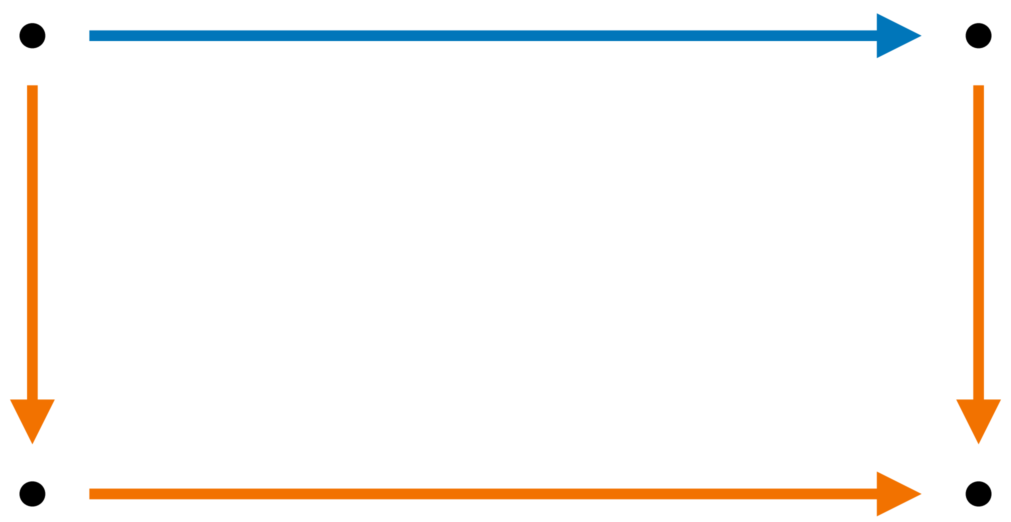
Interactive (5 rounds)

Verifiability

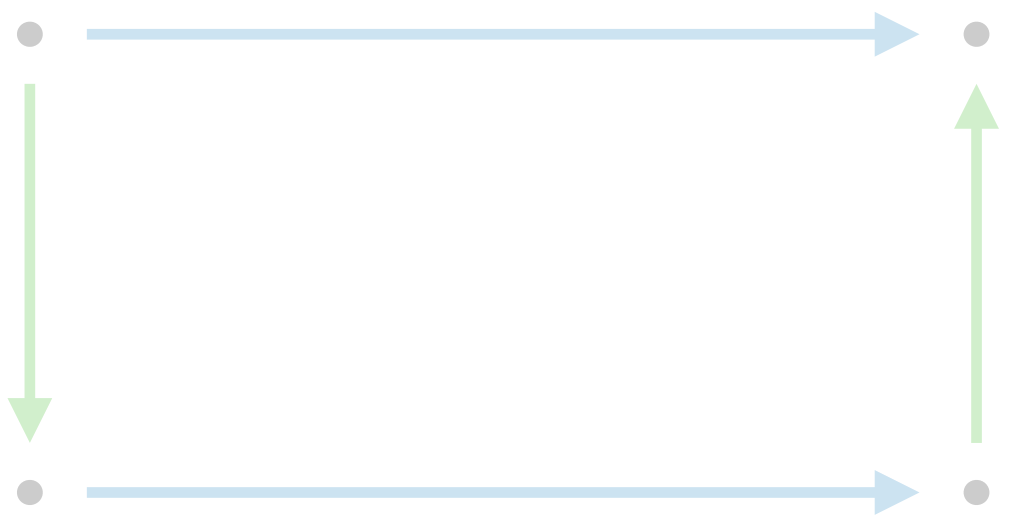
[BKW20] uses 3 proofs:



Server’s isogeny



Server’s commitment



Isogeny is parallel
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Interactive (5 rounds)

Verifiability

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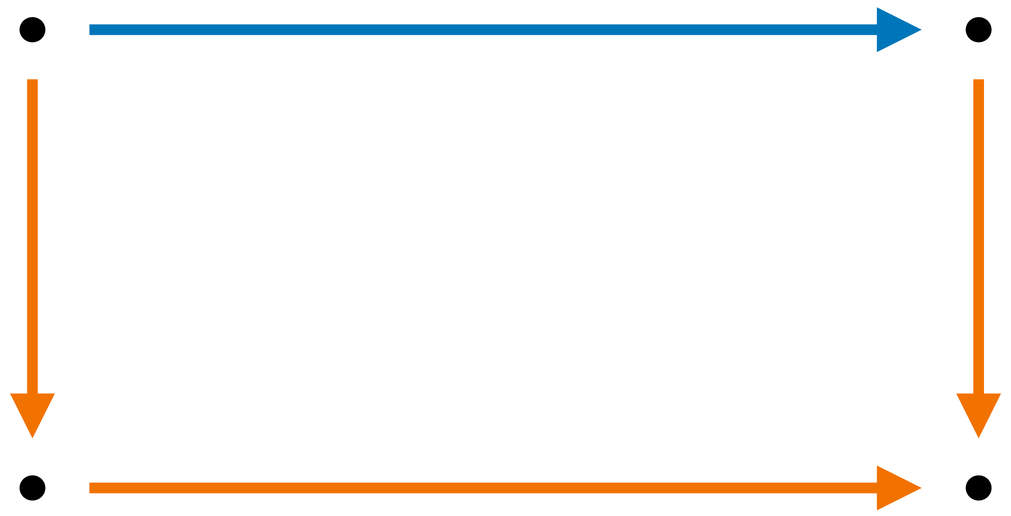
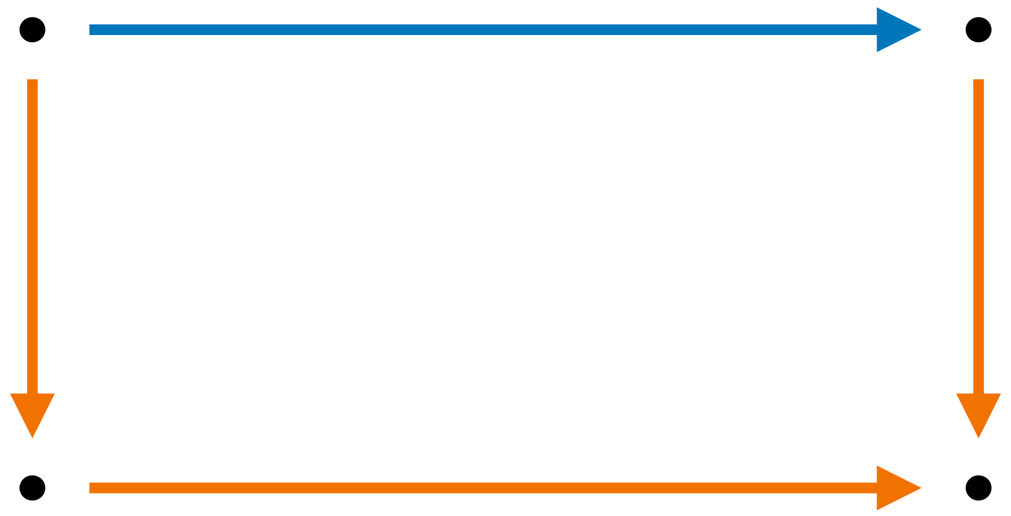
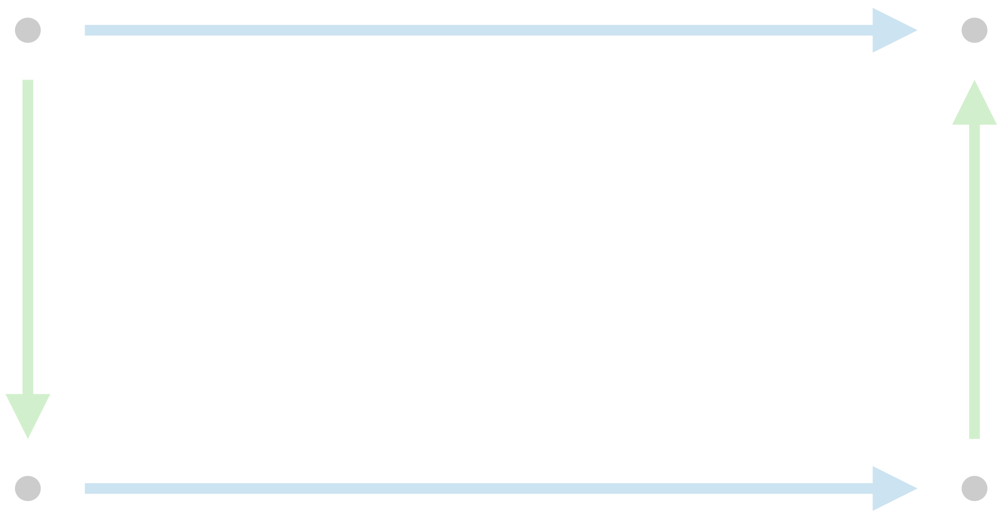


Server’s isogeny



Server’s commitment

Run together

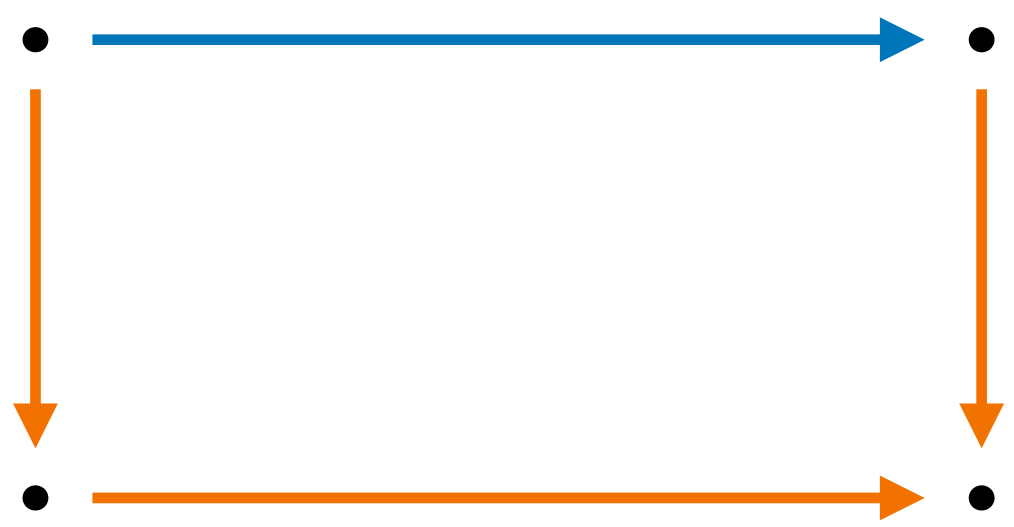


Isogeny is parallel
to commitment

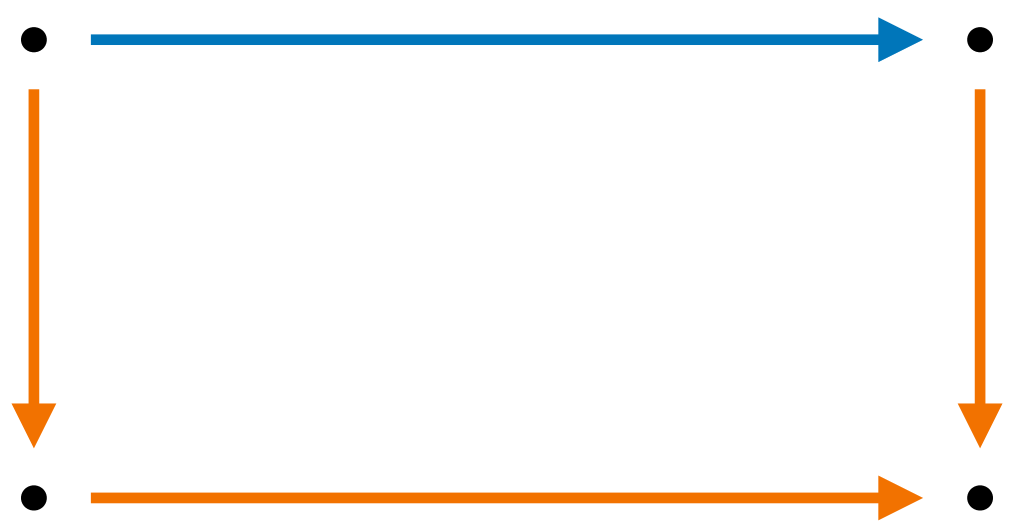
Interactive (5 rounds)

Verifiability

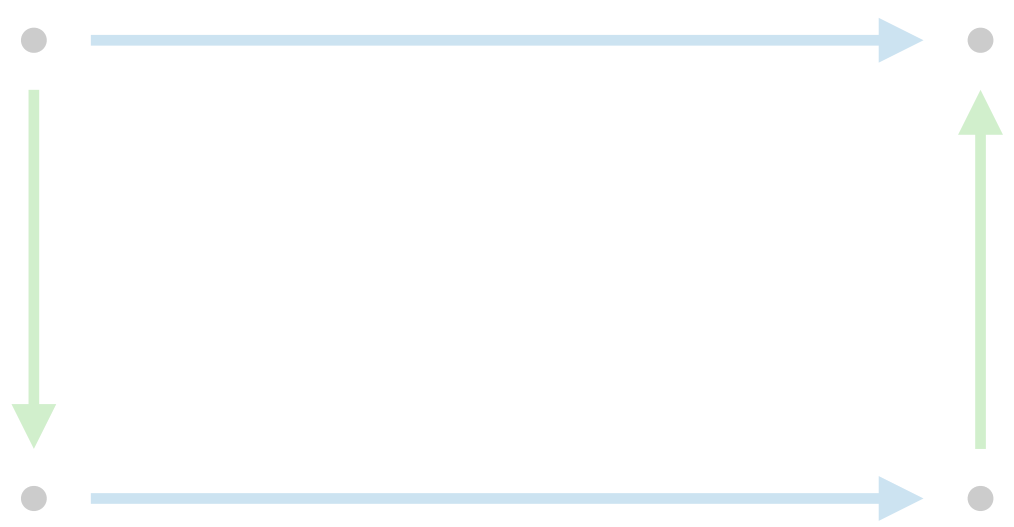
[BKW20] uses 3 proofs:



Server’s isogeny



Server’s commitment



Isogeny is parallel
to commitment

Run together

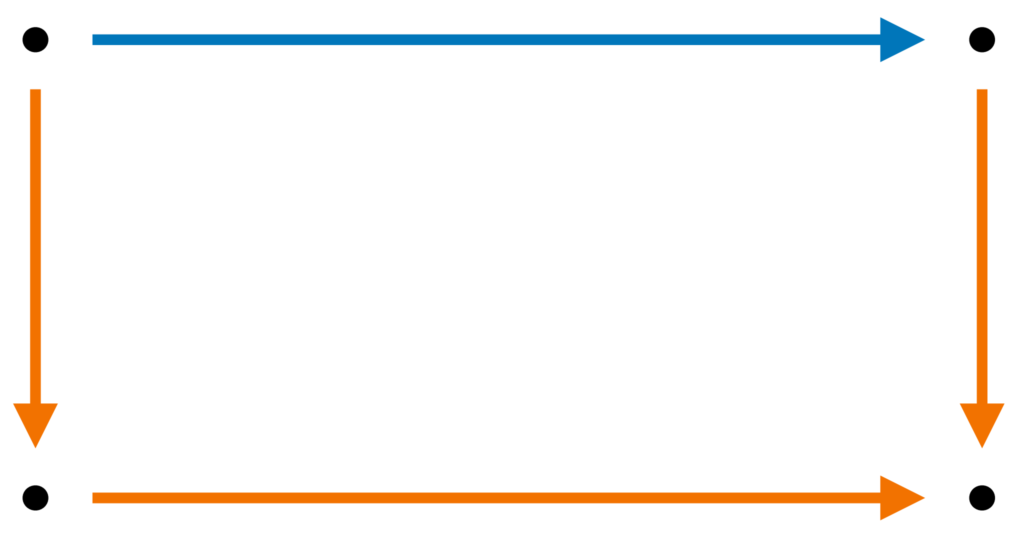
↓

Prove “parallelness" when
revealing horizontal isogeny

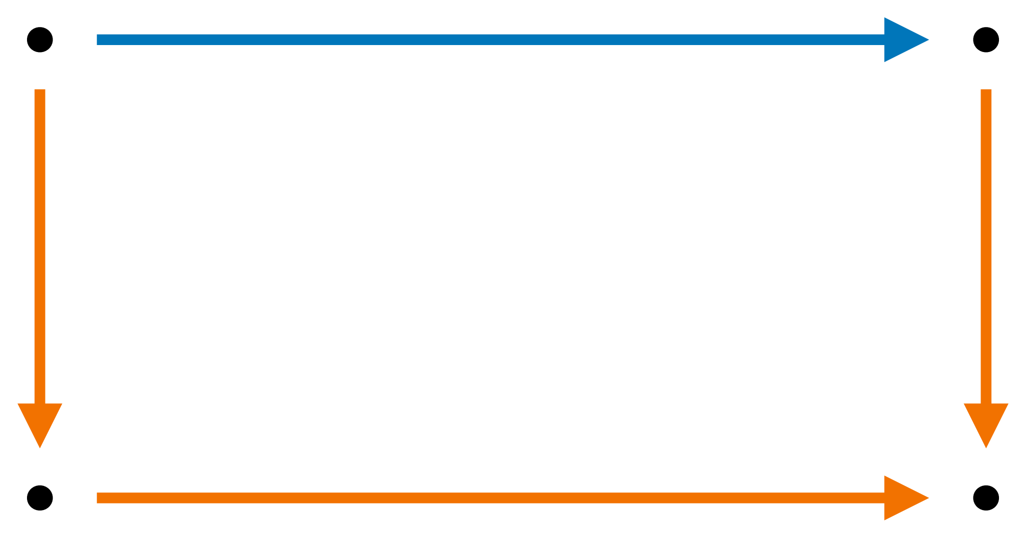
Interactive (5 rounds)

Verifiability

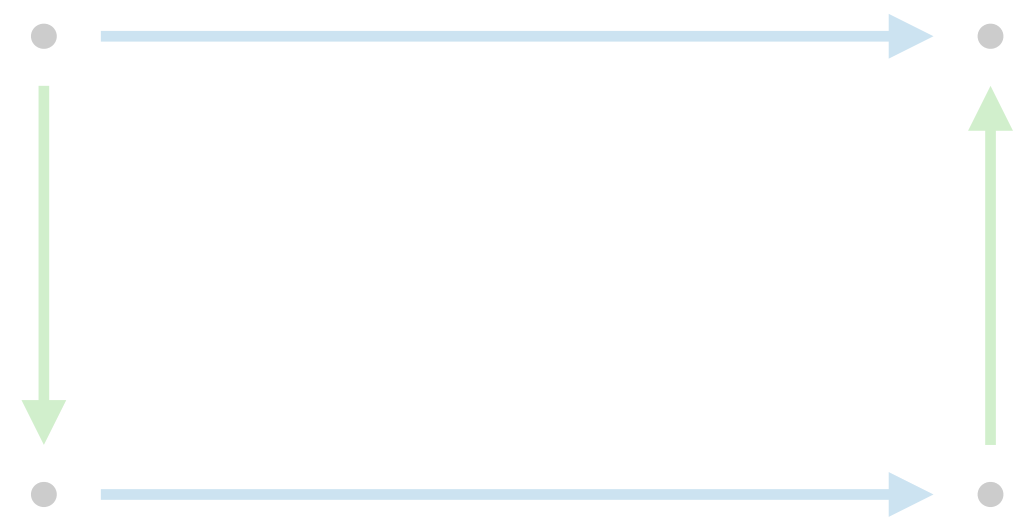
[BKW20] uses 3 proofs:



Server’s isogeny



Server’s commitment



Isogeny is parallel
to commitment

Interactive (5 rounds)

Run together

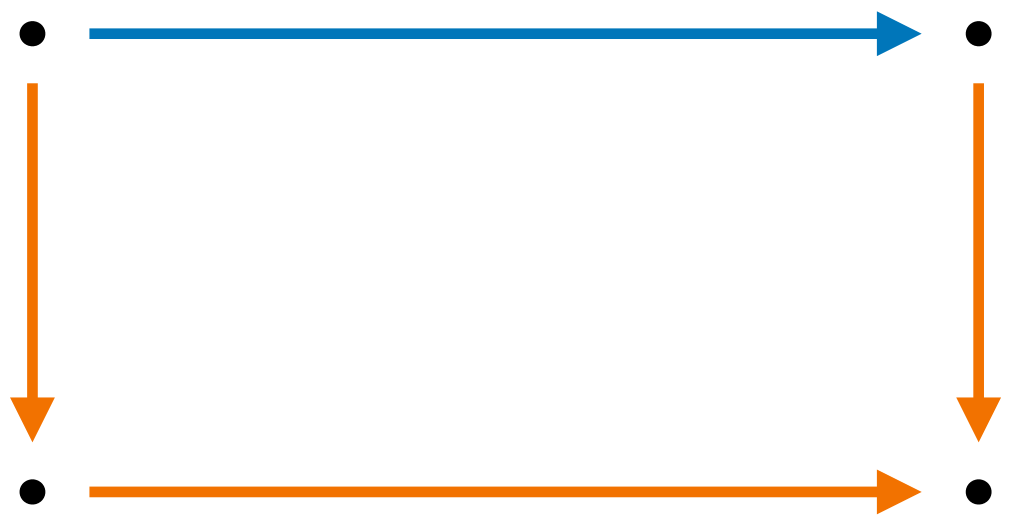
↓

Prove “parallelness" when
revealing horizontal isogeny

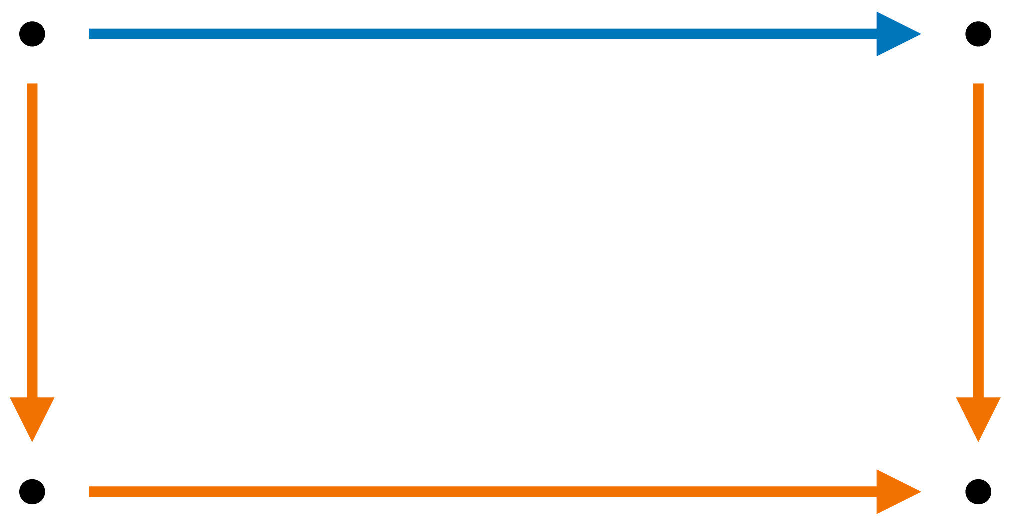
Non-interactive

Verifiability

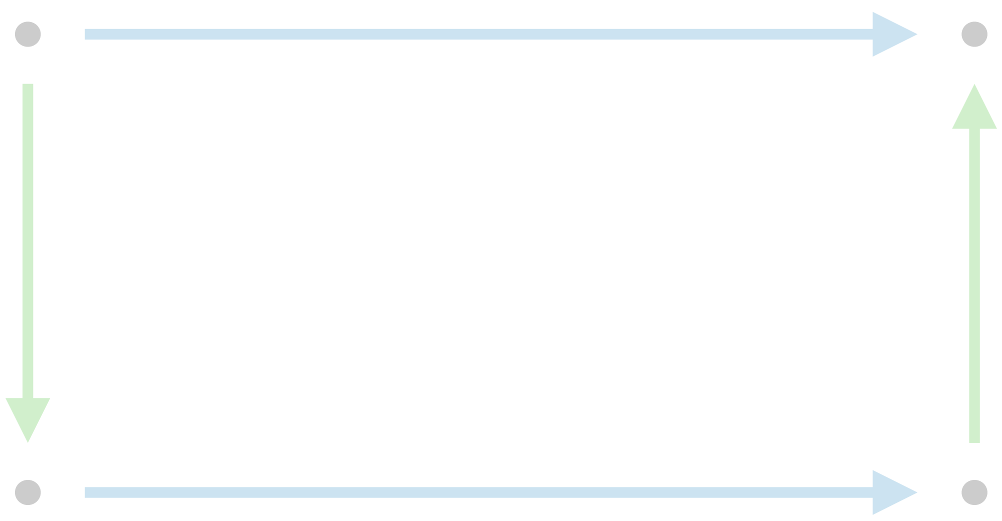
[BKW20] uses 3 proofs:



Server's isogeny



Server's commitment



Isogeny is parallel
to commitment

Run together

↓

Prove "parallelness" when
revealing horizontal isogeny

Non-interactive

Saves computations

Interactive (5 rounds)

Putting it all together

Putting it all together

- One-more unpredictability countermeasure

Putting it all together

- One-more unpredictability countermeasure

more efficient than original

new security assumption

Putting it all together

- One-more unpredictability countermeasure

more efficient than original

new security assumption

- Integrated SIDH countermeasures

Putting it all together

- One-more unpredictability countermeasure

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- Integrated SIDH countermeasures

novel proof of isogeny knowledge

prime is still large

Putting it all together

- One-more unpredictability countermeasure

more efficient than original

new security assumption

- Integrated SIDH countermeasures

novel proof of isogeny knowledge

prime is still large

- New PoPI

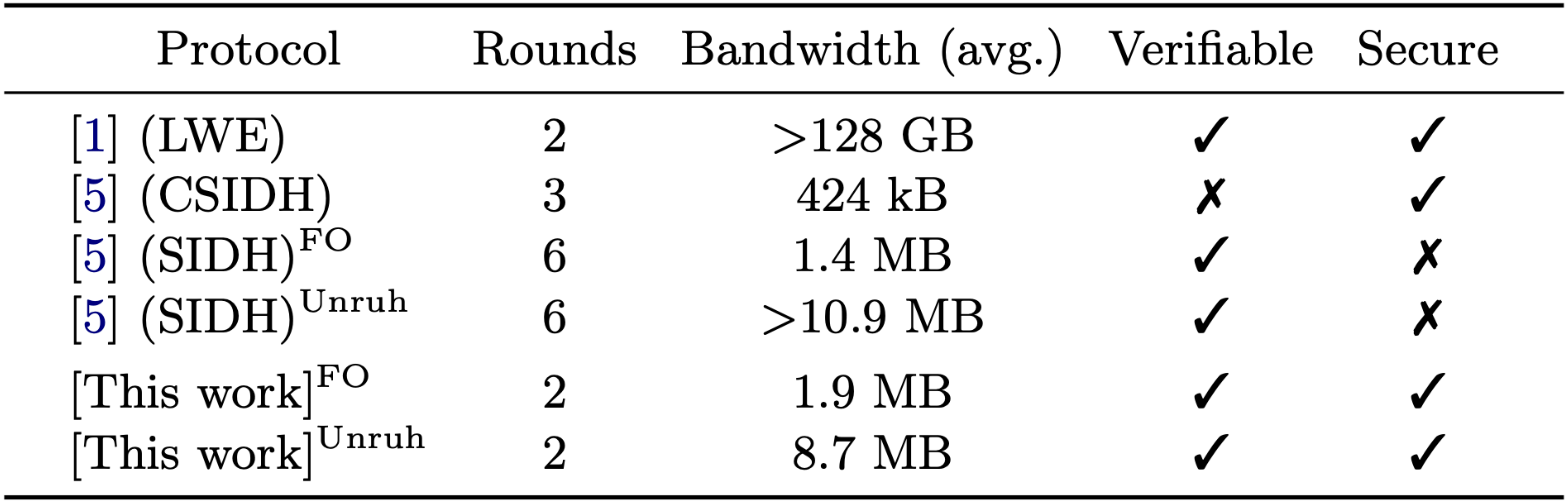
Putting it all together

- One-more unpredictability countermeasure more efficient than original new security assumption

- Integrated SIDH countermeasures novel proof of isogeny knowledge prime is still large

- New PoPI more efficient than original round optimal

Results



Protocol	Rounds	Bandwidth (avg.)	Verifiable	Secure
[1] (LWE)	2	>128 GB	✓	✓
[5] (CSIDH)	3	424 kB	✗	✓
[5] (SIDH)$^{\mathrm{FO}}$	6	1.4 MB	✓	✗
[5] (SIDH)$^{\mathrm{Unruh}}$	6	>10.9 MB	✓	✗
[This work]$^{\mathrm{FO}}$	2	1.9 MB	✓	✓
[This work]$^{\mathrm{Unruh}}$	2	8.7 MB	✓	✓