Anonymous, Robust Post-Quantum Public Key Encryption

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Applied Cryptography Group
ETH Zurich

Joint work with Paul Grubbs and Kenneth G. Paterson

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

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From **Handbook of Applied Cryptography** (http://cacr.uwaterloo.ca/hac)**:**

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Cryptography is the study of mathematical techniques related to aspects of information security such as confidentiality, data integrity, entity authentication, and data origin authentication.

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- But it is much more than that!

Applications of Cryptography

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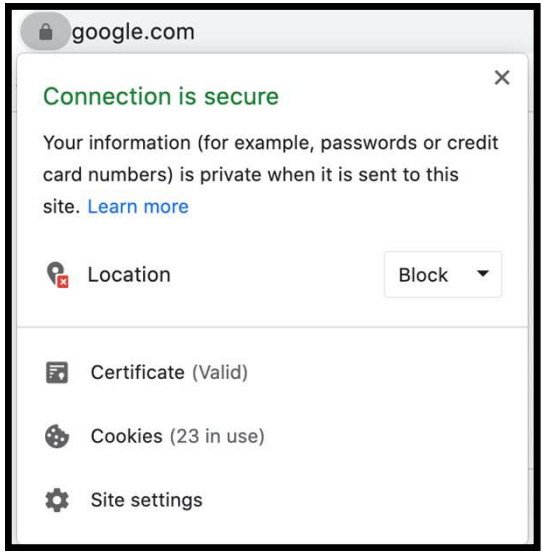
… and more!

Under the Hood



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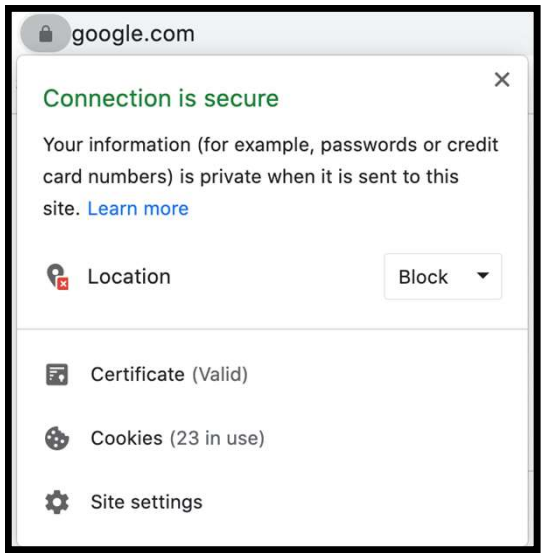
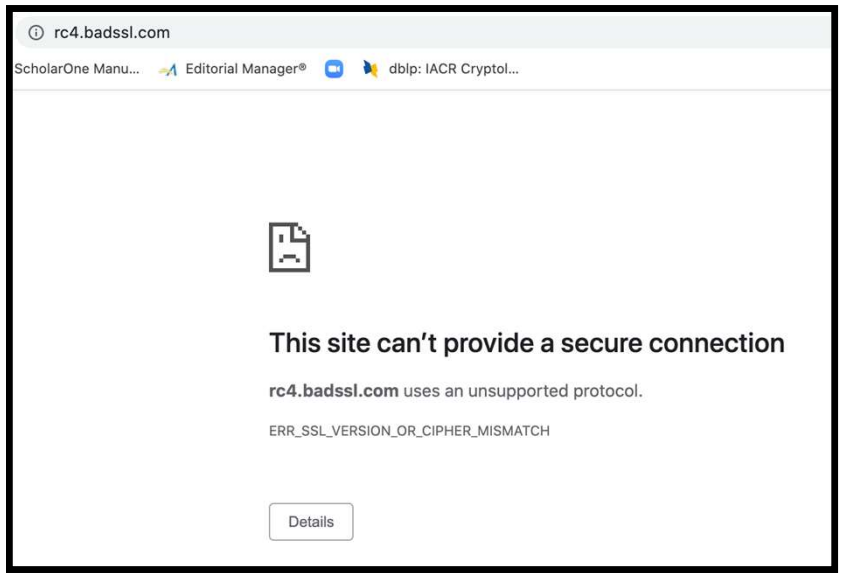
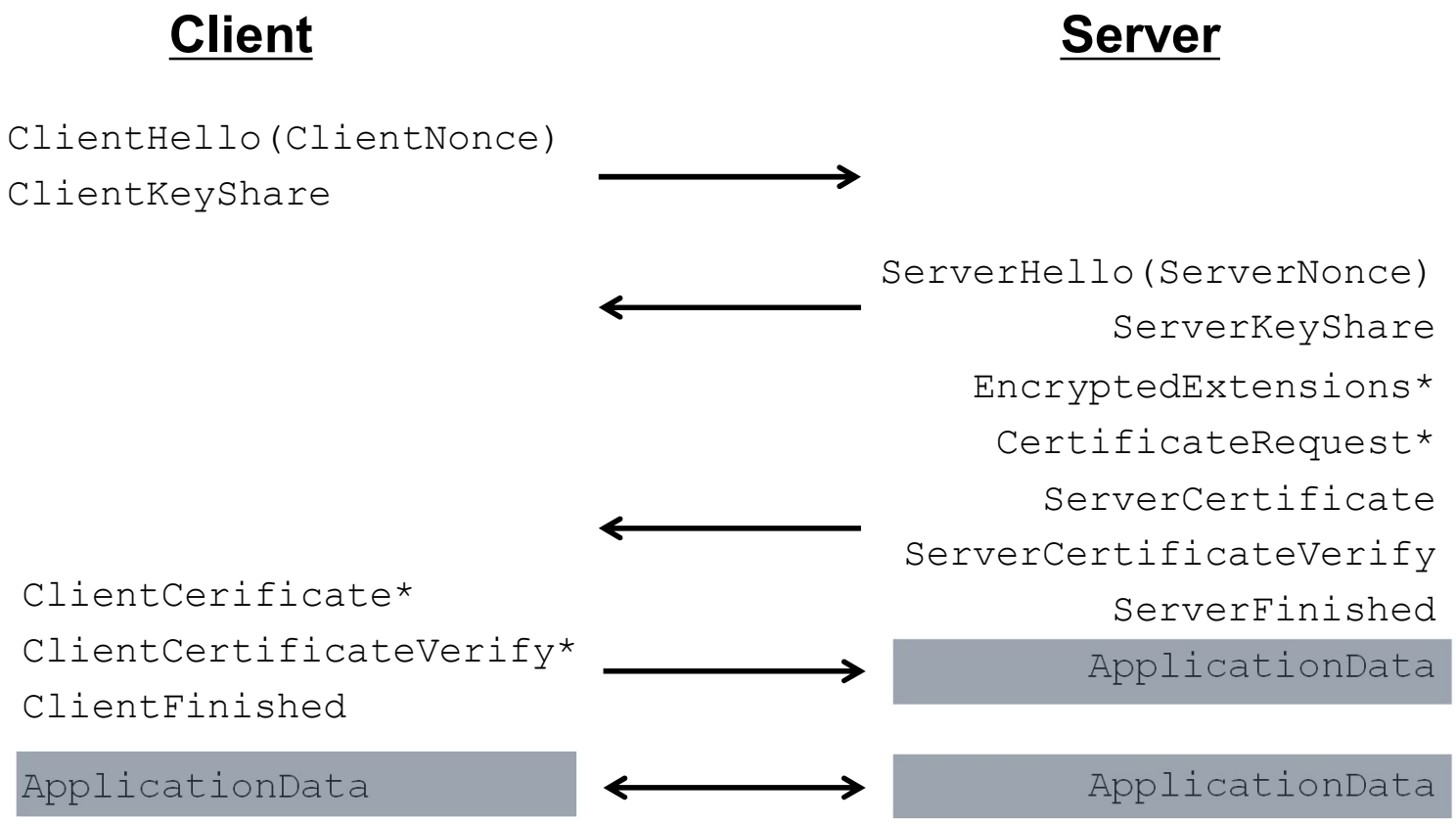




Under the Hood – the TLS 1.3 Handshake



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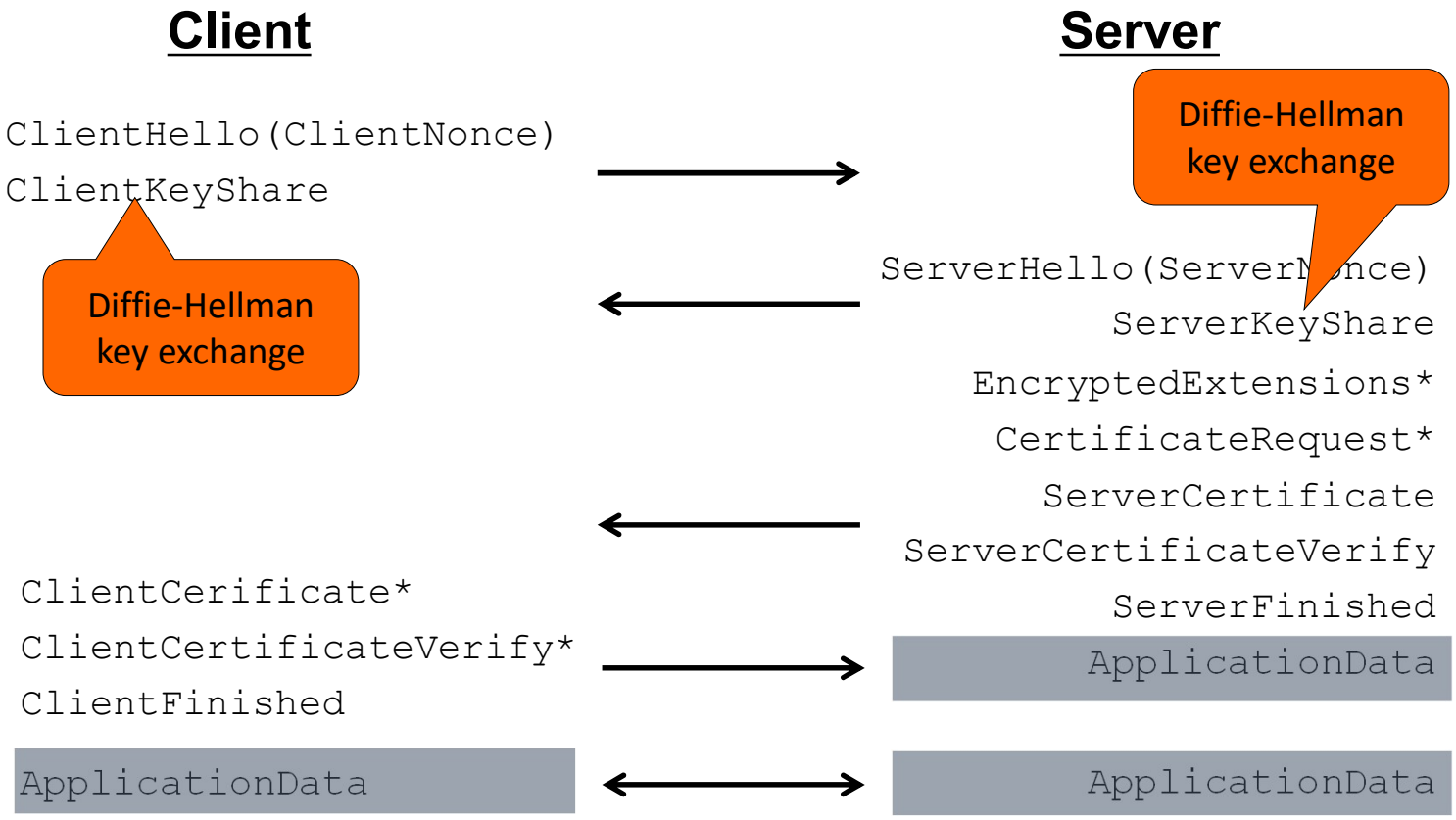

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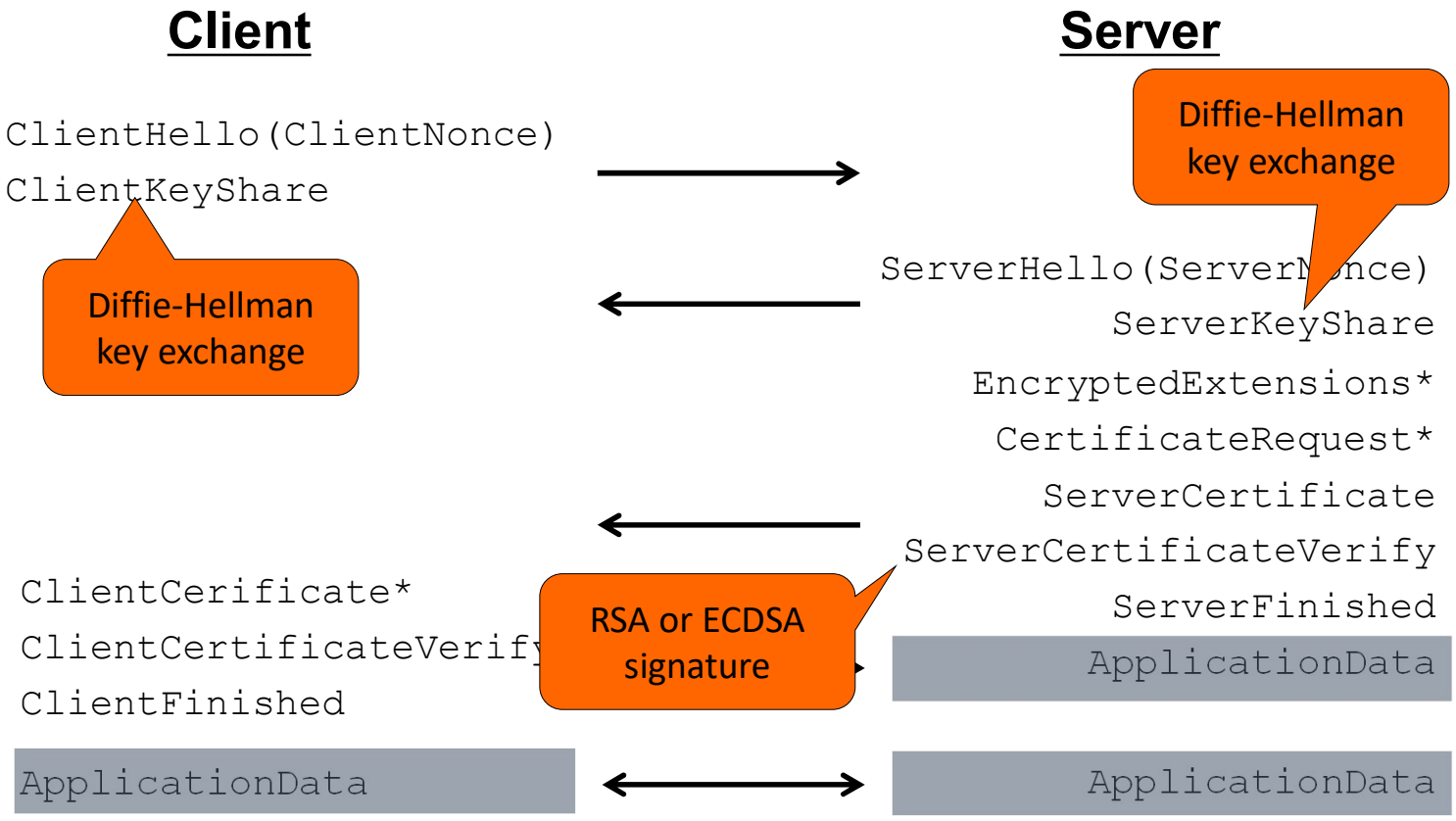
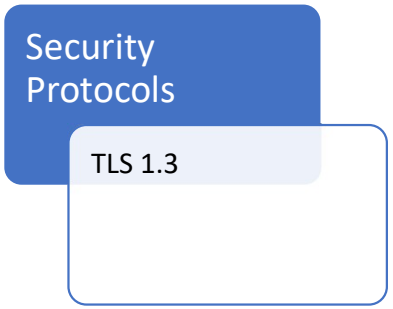


Bird’s-eye View



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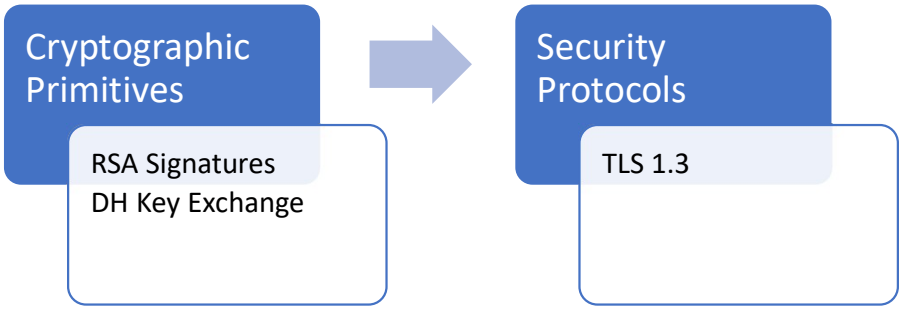

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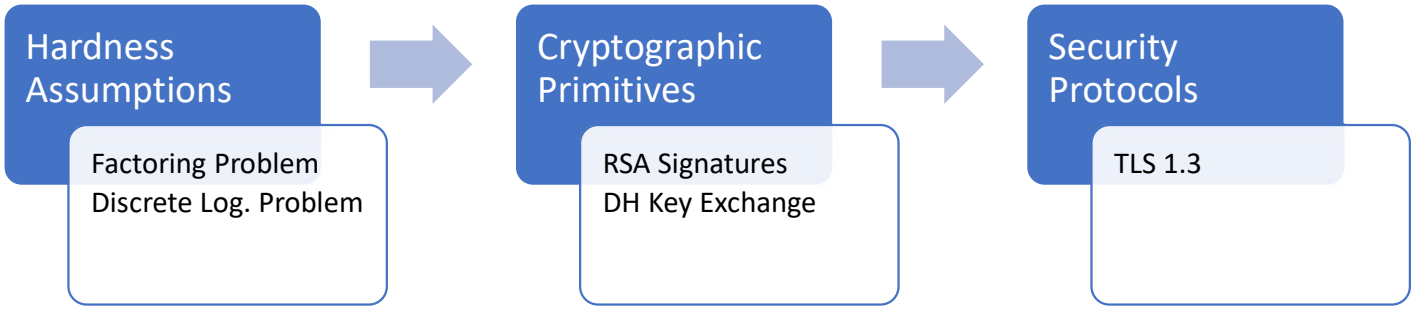

Enter Quantum Computing

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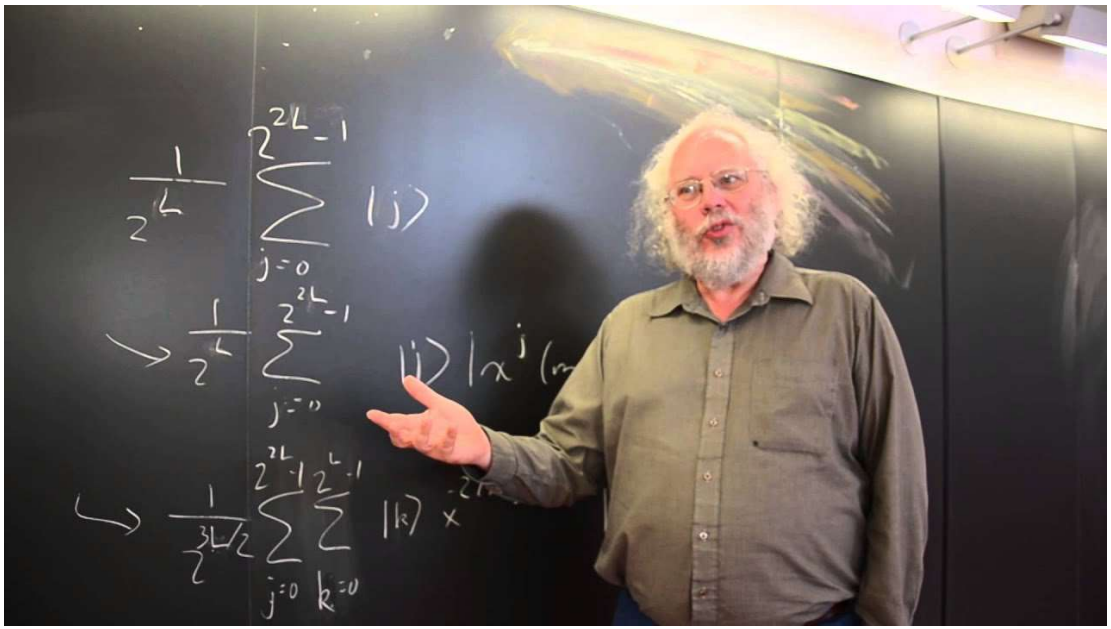


Enter Quantum Computing

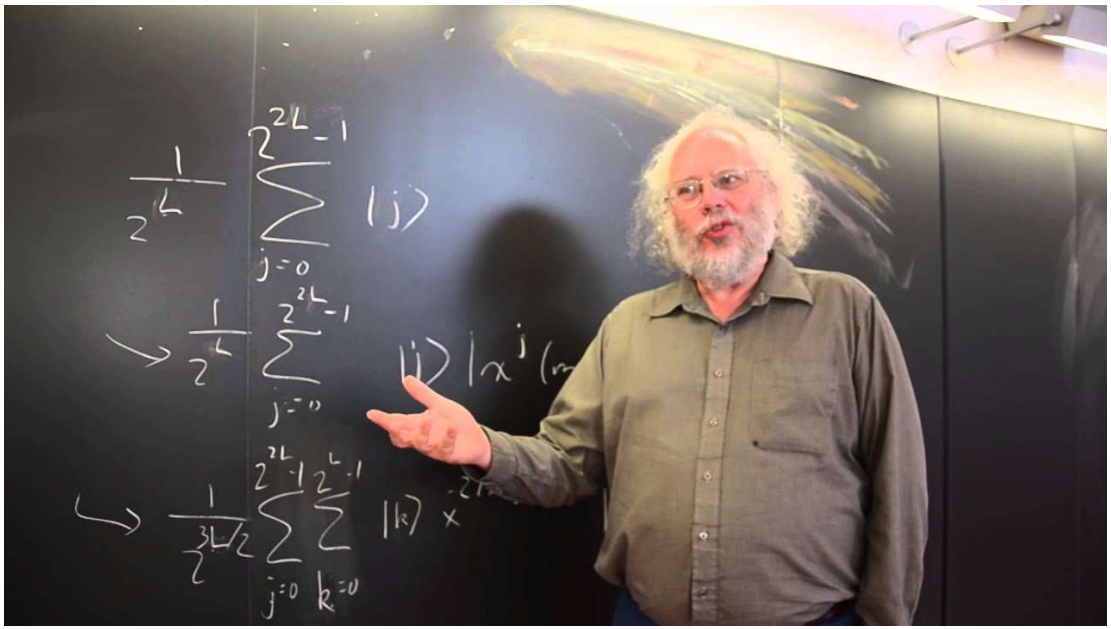
Polynomial-Time Algorithms for Prime Factorization and Discrete Logarithms on a Quantum Computer*

Peter W. Shor†

Abstract

A digital computer is generally believed to be an efficient universal computing device; that is, it is believed able to simulate any physical computing device with an increase in computation time by at most a polynomial factor. This may not be true when quantum mechanics is taken into consideration. This paper considers factoring integers and finding discrete logarithms, two problems which are generally thought to be hard on a classical computer and which have been used as the basis of several proposed cryptosystems. Efficient randomized algorithms are given for these two problems on a hypothetical quantum computer. These algorithms take a number of steps polynomial in the input size, e.g., the number of digits of the integer to be factored.

[FOCS'94]



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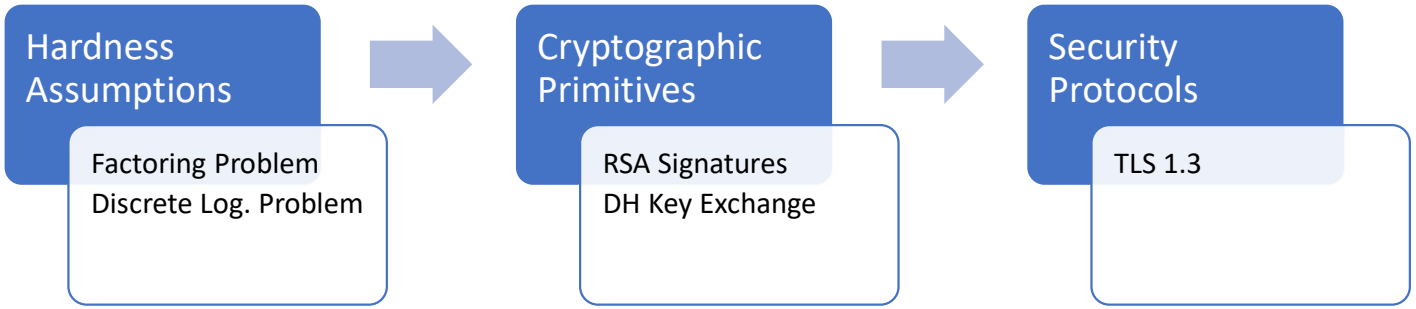

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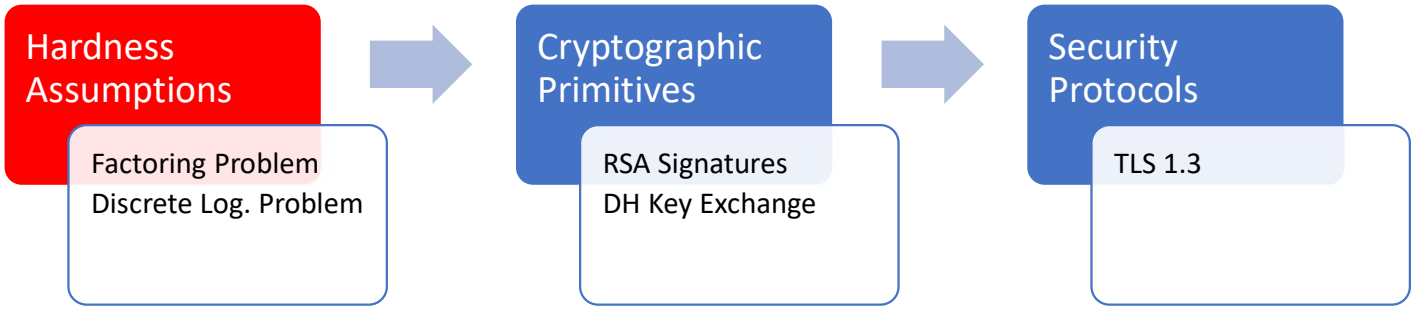

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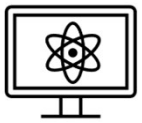

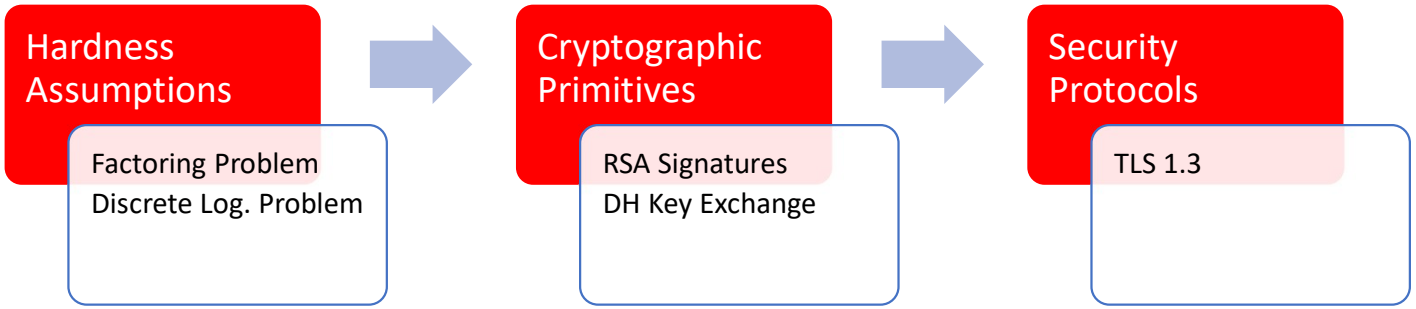

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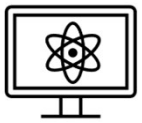


Hardness Assumptions

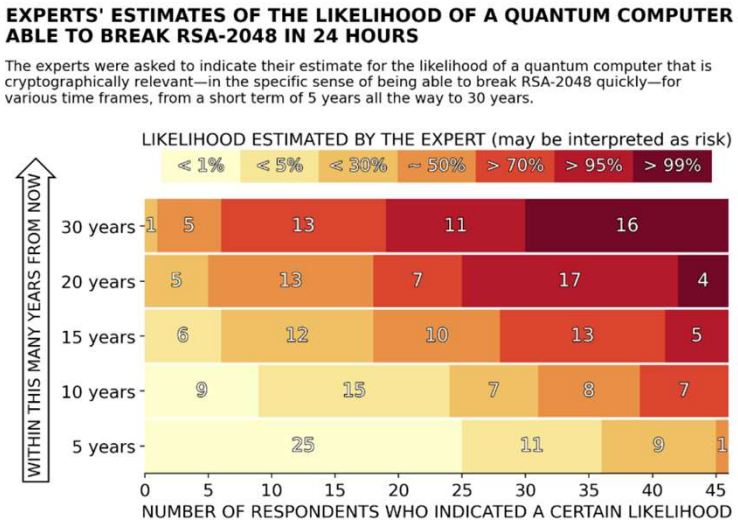
Factoring Problem
Discrete Log. Problem

Cryptographic Primitives

RSA Signatures
DH Key Exchange

Security Protocols

TLS 1.3



[Image: Global Risk Institute, 2021 Quantum Threat Timeline Report]

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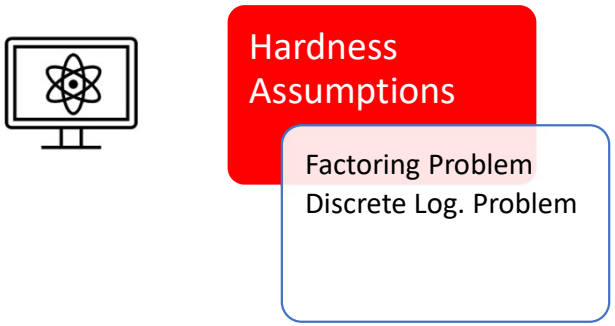

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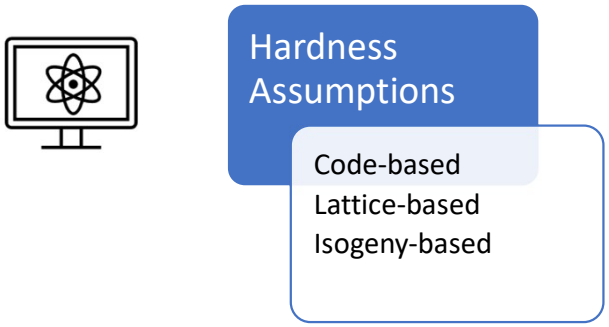

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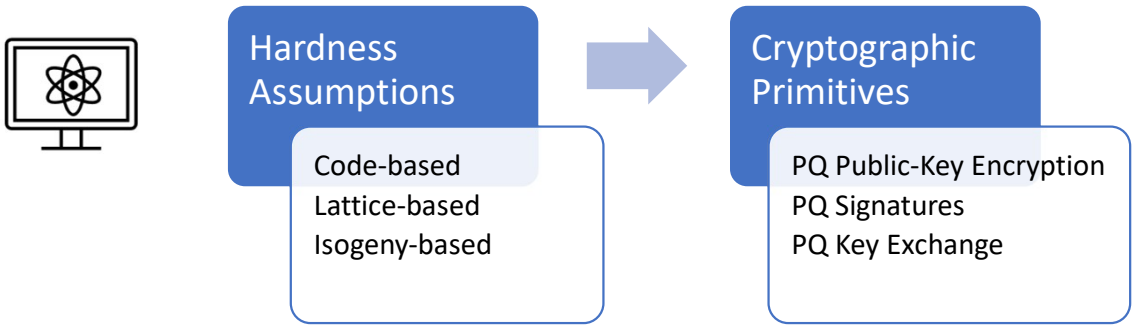

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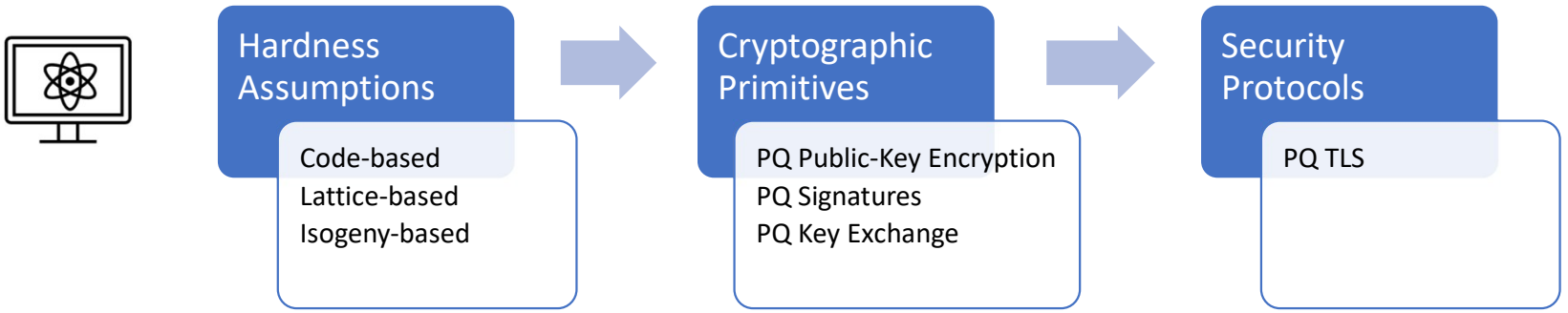

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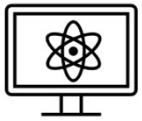
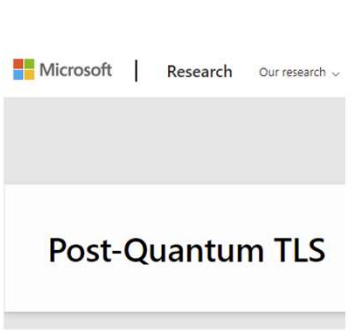
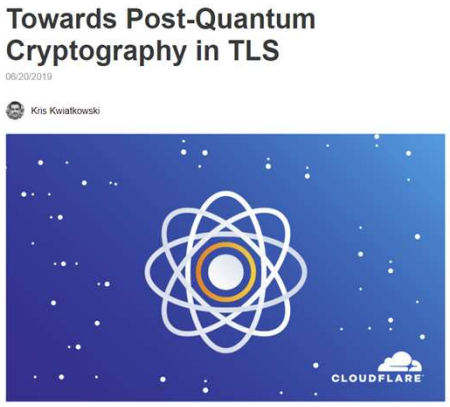


Hardness Assumptions
- Code-based
- Lattice-based
- Isogeny-based

Cryptographic Primitives
- PQ Public-Key Encryption
- PQ Signatures
- PQ Key Exchange

Security Protocols
- PQ TLS





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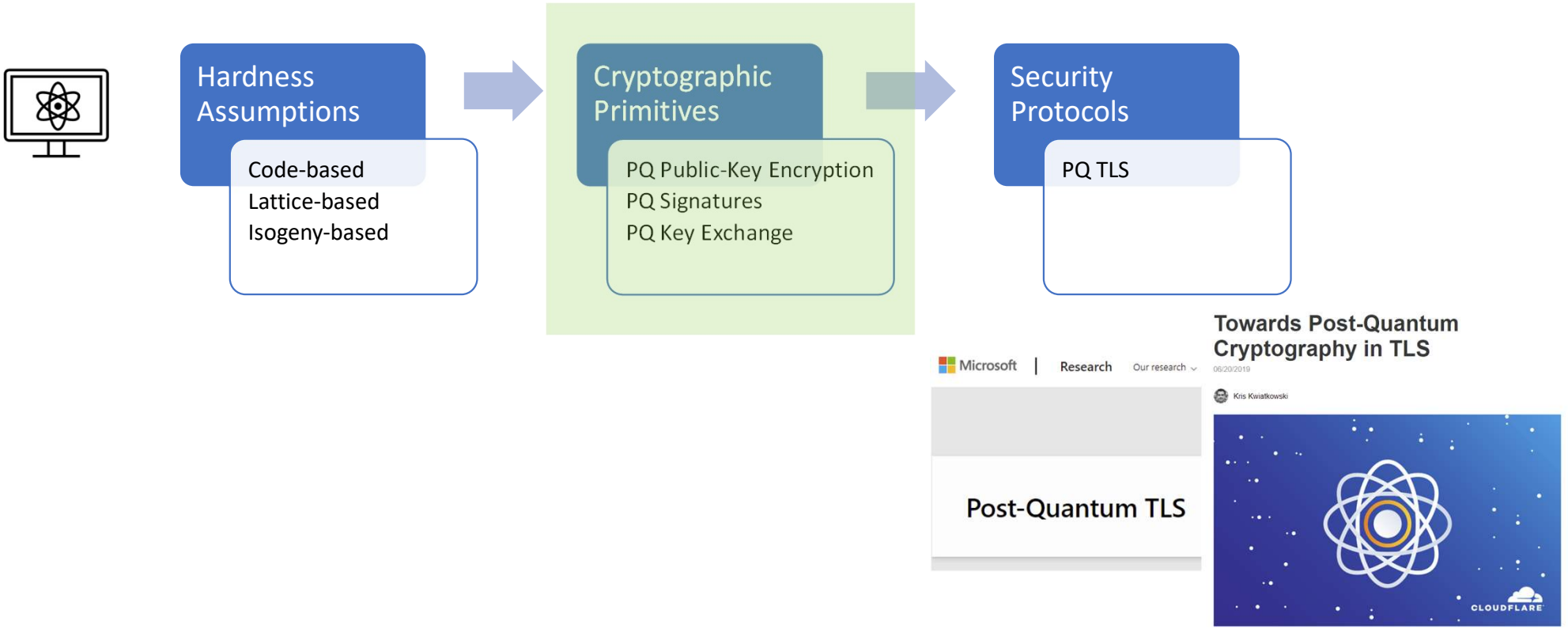

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NIST Kicks Off Effort to Defend Encrypted Data from Quantum Computer Threat

April 28, 2016

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Credit: Hanacek/NIST

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charles.boutin@nist.gov
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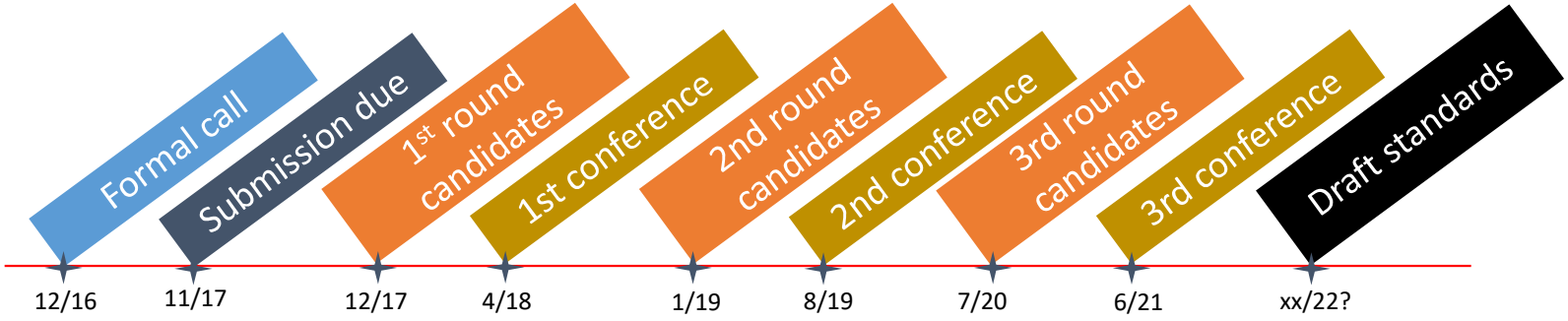

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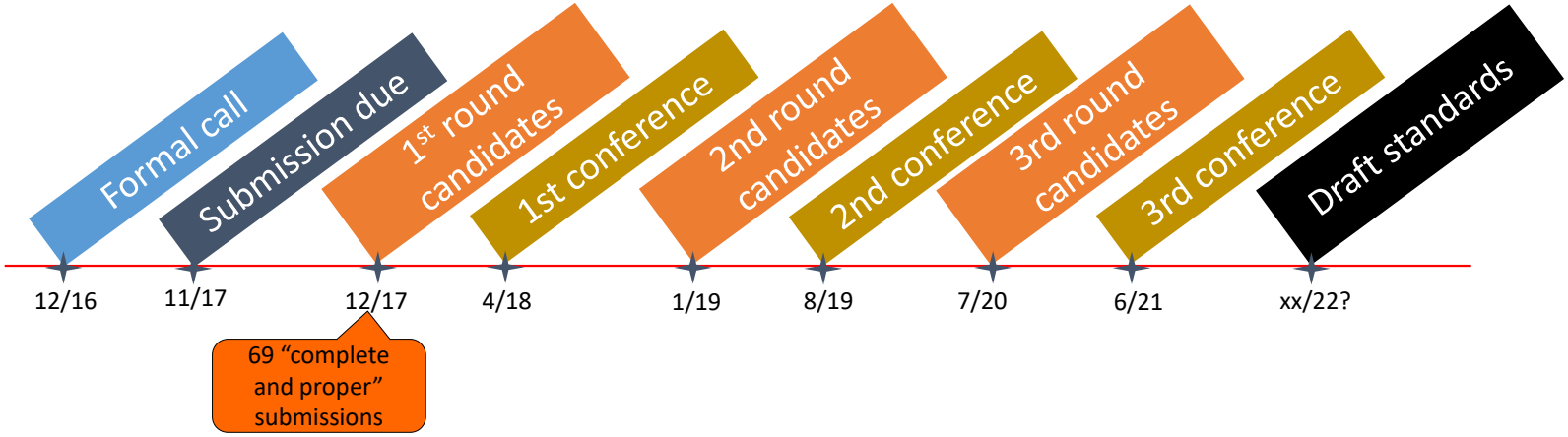

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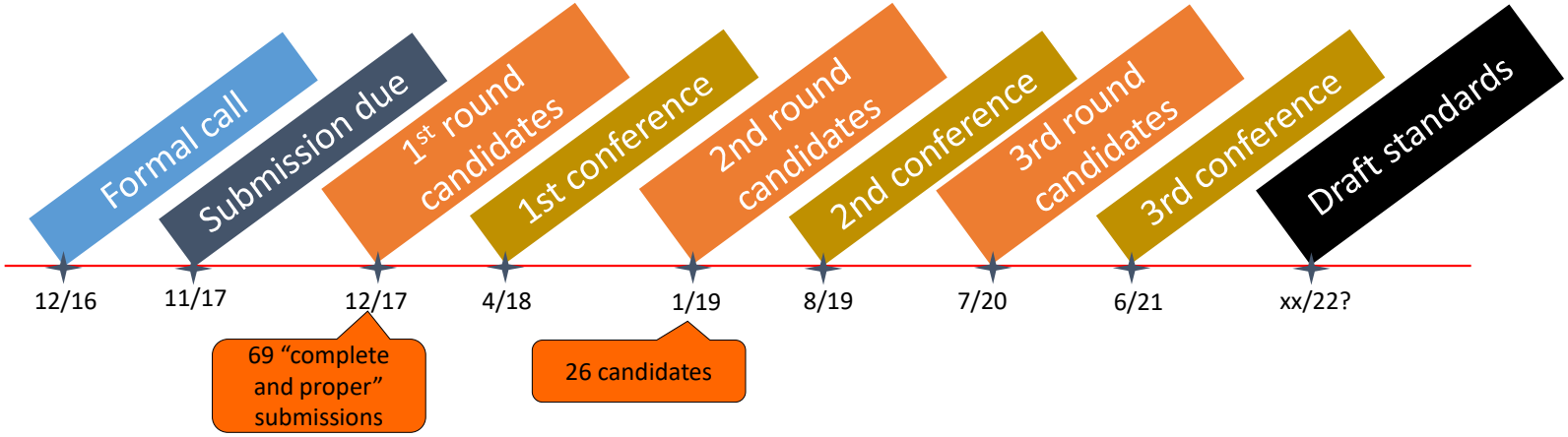

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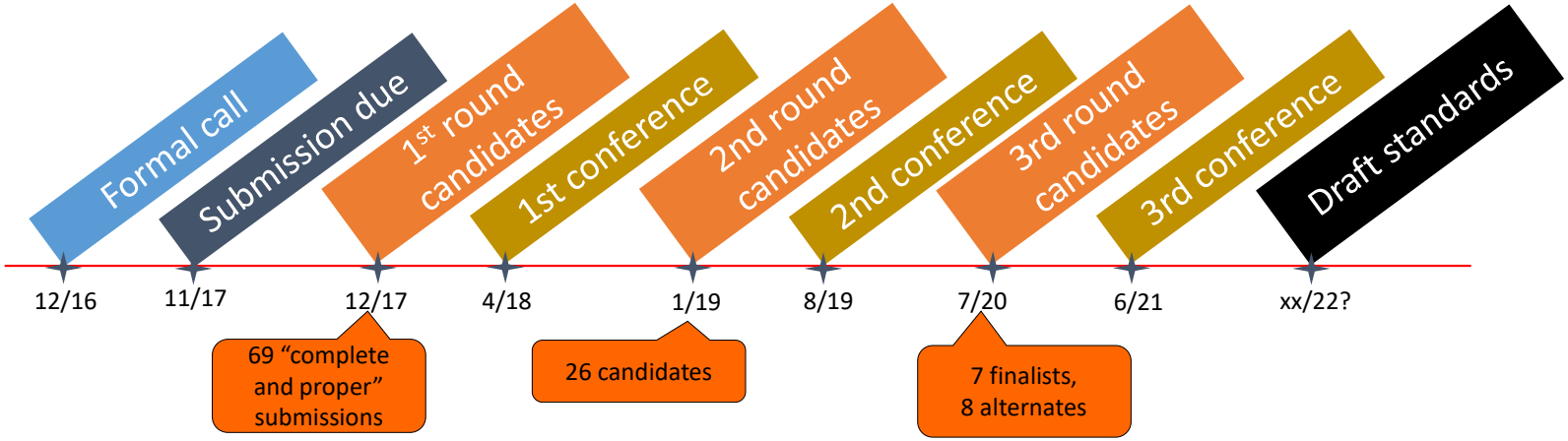

PQC and NIST

PQC Standardization Process: Third Round Candidate Announcement

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Classic McEliece:
conservative code-based cryptography

10 October 2020

Principal submitter

This submission is from the following team, listed in alphabetical order:

- Martin R. Albrecht, Information Security Group, Royal Holloway, University of London
- Daniel J. Bernstein, University of Illinois at Chicago and Ruhr University Bochum
- Tung Chou, Academia Sinica
- Carlos Cid, Royal Holloway, University of London and Simula UiB
- Jan Gilcher, ETH Zürich
- Tanja Lange, Eindhoven University of Technology
- Varun Maram, ETH Zürich
- Ingo von Maurich, self
- Rafael Misoczki, Google
- Ruben Niederhagen, University of Southern Denmark
- Kenneth G. Paterson, ETH Zürich
- Edoardo Persichetti, Florida Atlantic University
- Christiane Peters, self
- Peter Schwabe, Max Planck Institute for Security and Privacy & Radboud University
- Nicolas Sendrier, Inria
- Jakub Szefer, Yale University
- Cen Jung Tjhai, PQ Solutions Ltd.
- Martin Tomlinson, PQ Solutions Ltd. and University of Plymouth
- Wen Wang, Yale University

Public-Key Encryption (PKE)

Public-Key Encryption (PKE)

Alice

Bob

Public-Key Encryption (PKE)

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

Alice

Bob

Public-Key Encryption (PKE)

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

Key Generation

Alice

Bob

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

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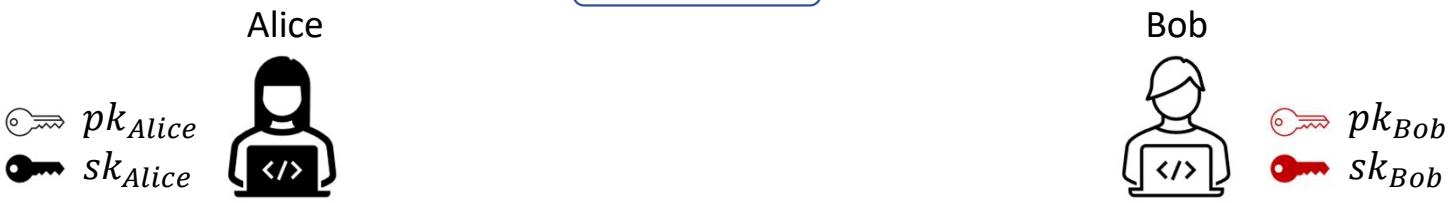

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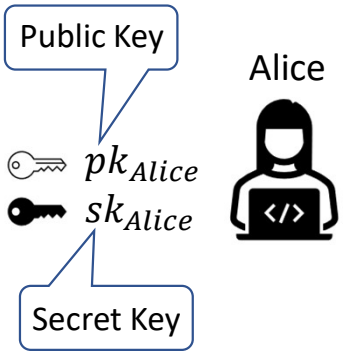

Alice

Bob

pk_{Bob}

sk_{Bob}

Public-Key Encryption (PKE)

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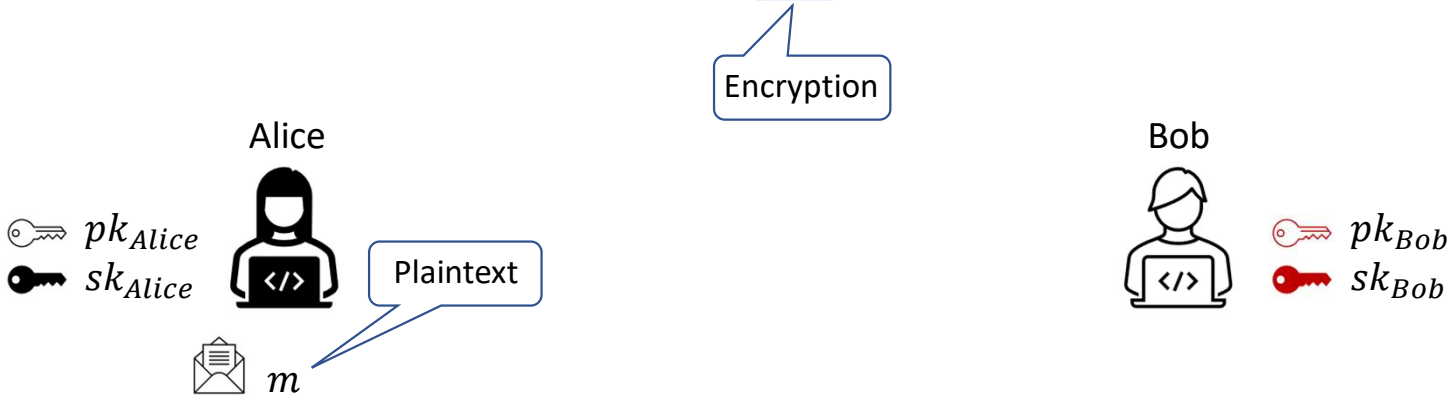

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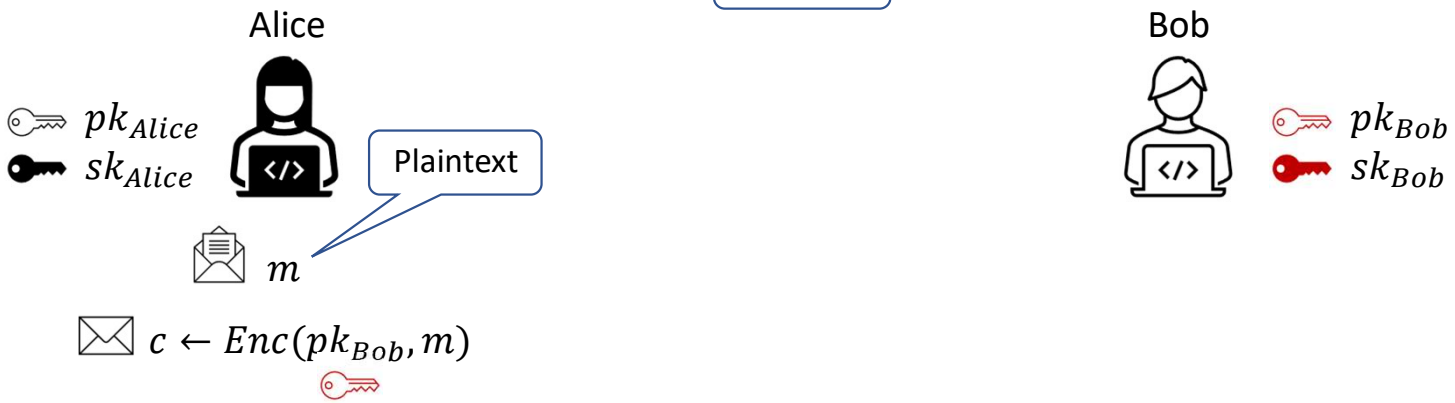
Encryption



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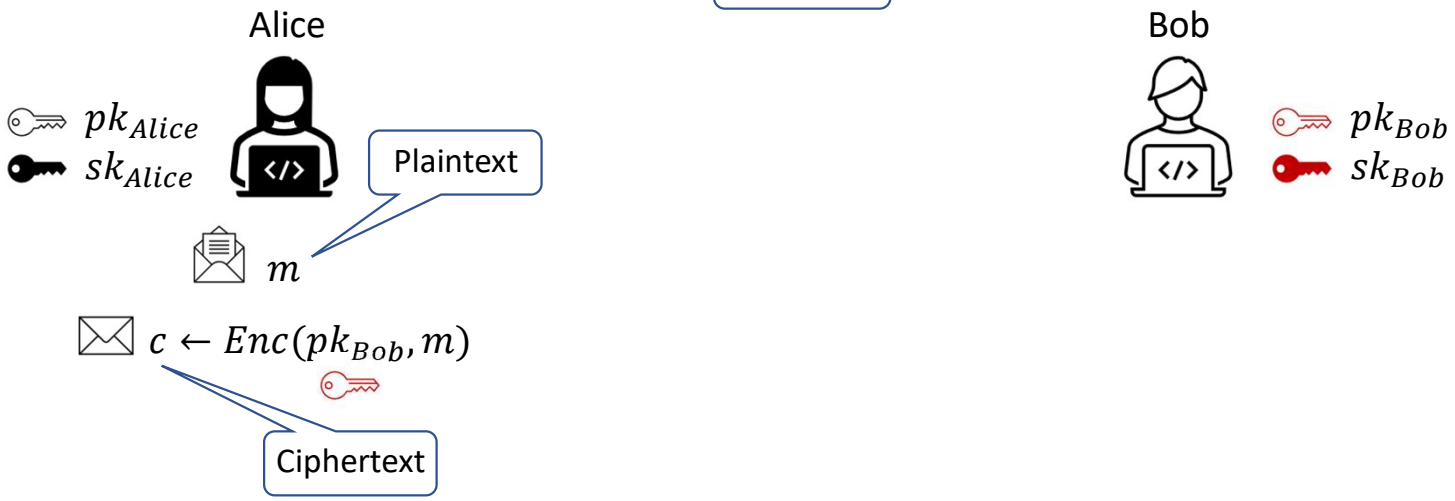

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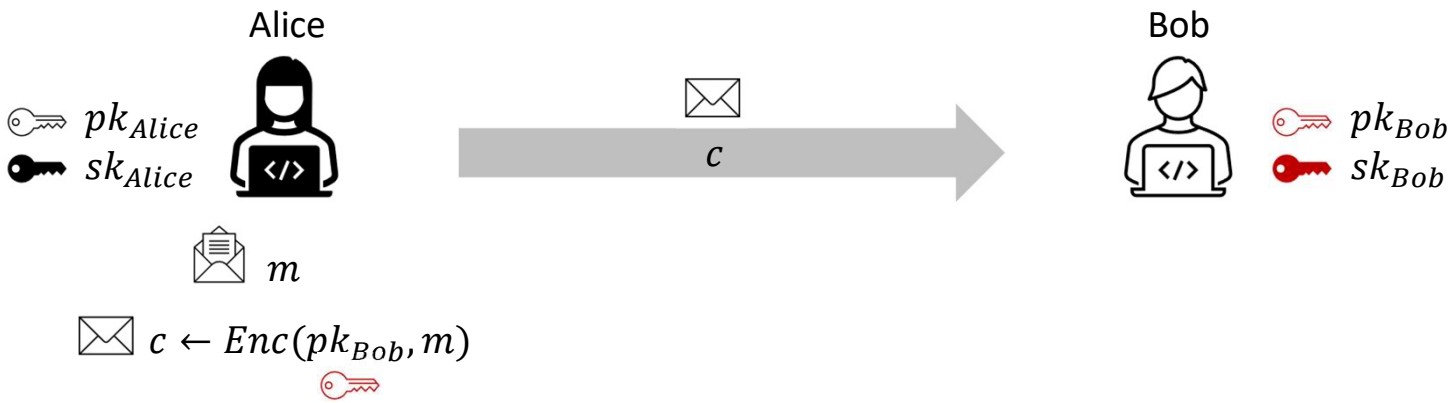

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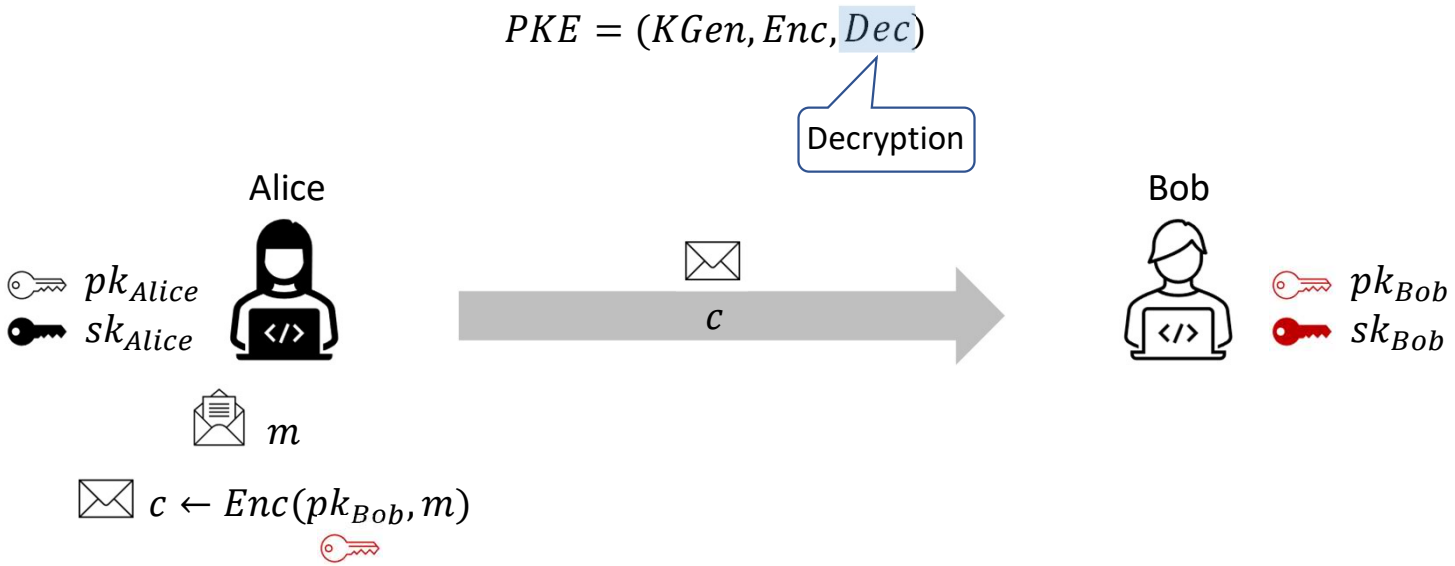

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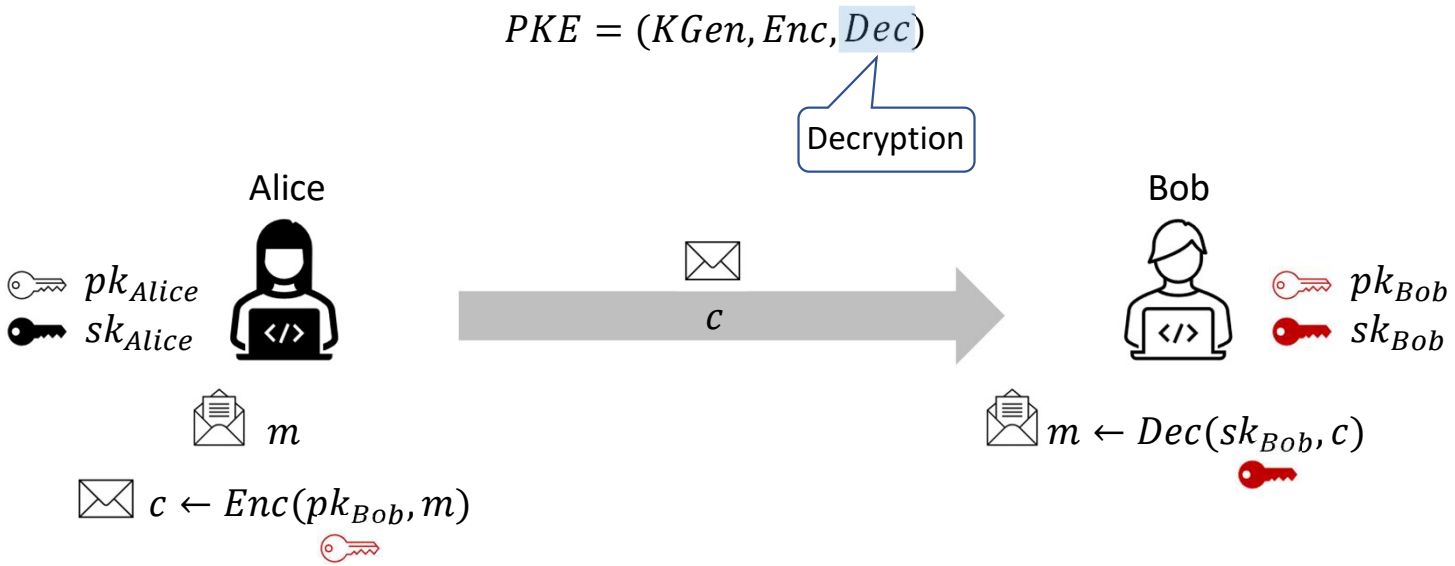

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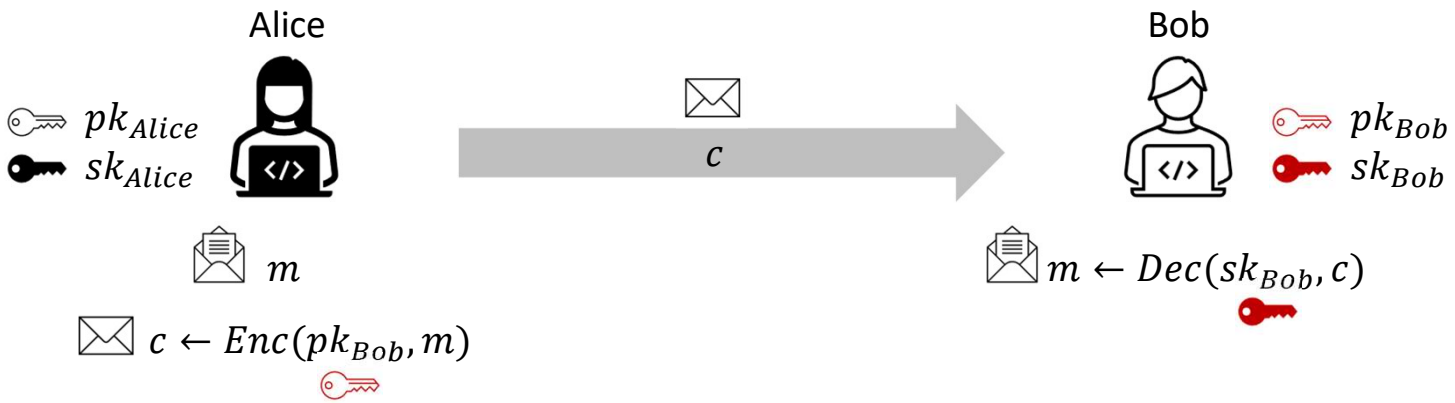
4.A.2 Security Definition for Encryption/Key-Establishment

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

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



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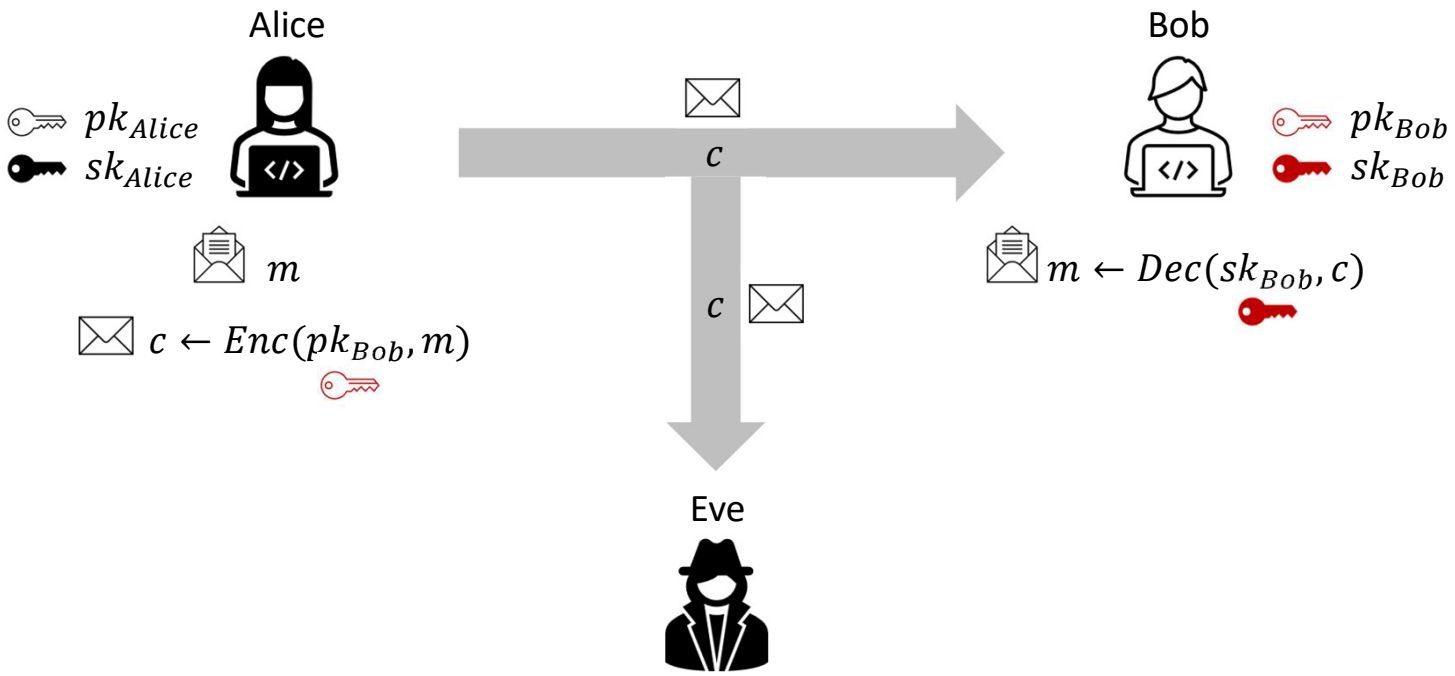

IND-CCA Security

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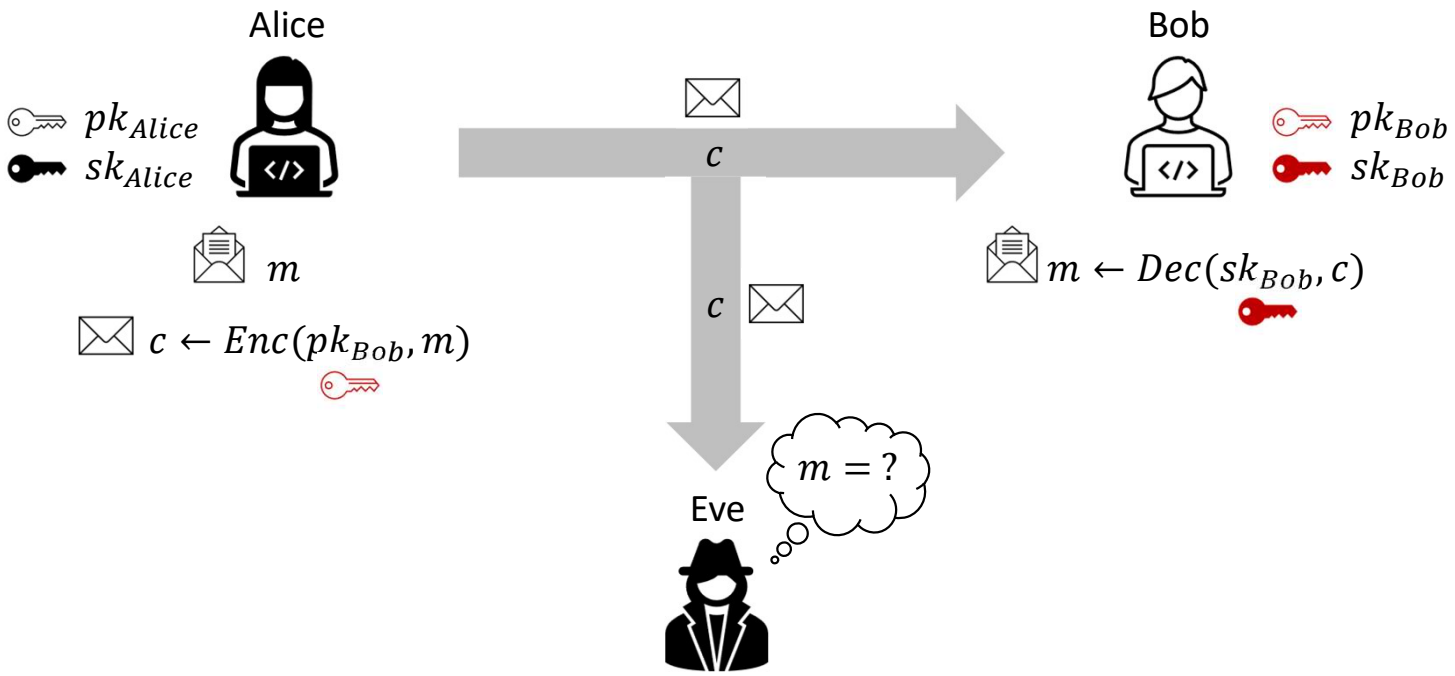
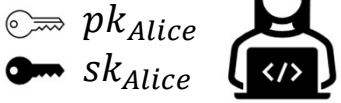


Anonymity

$PKE = (KGen, Enc, Dec)$

Alice



Bob

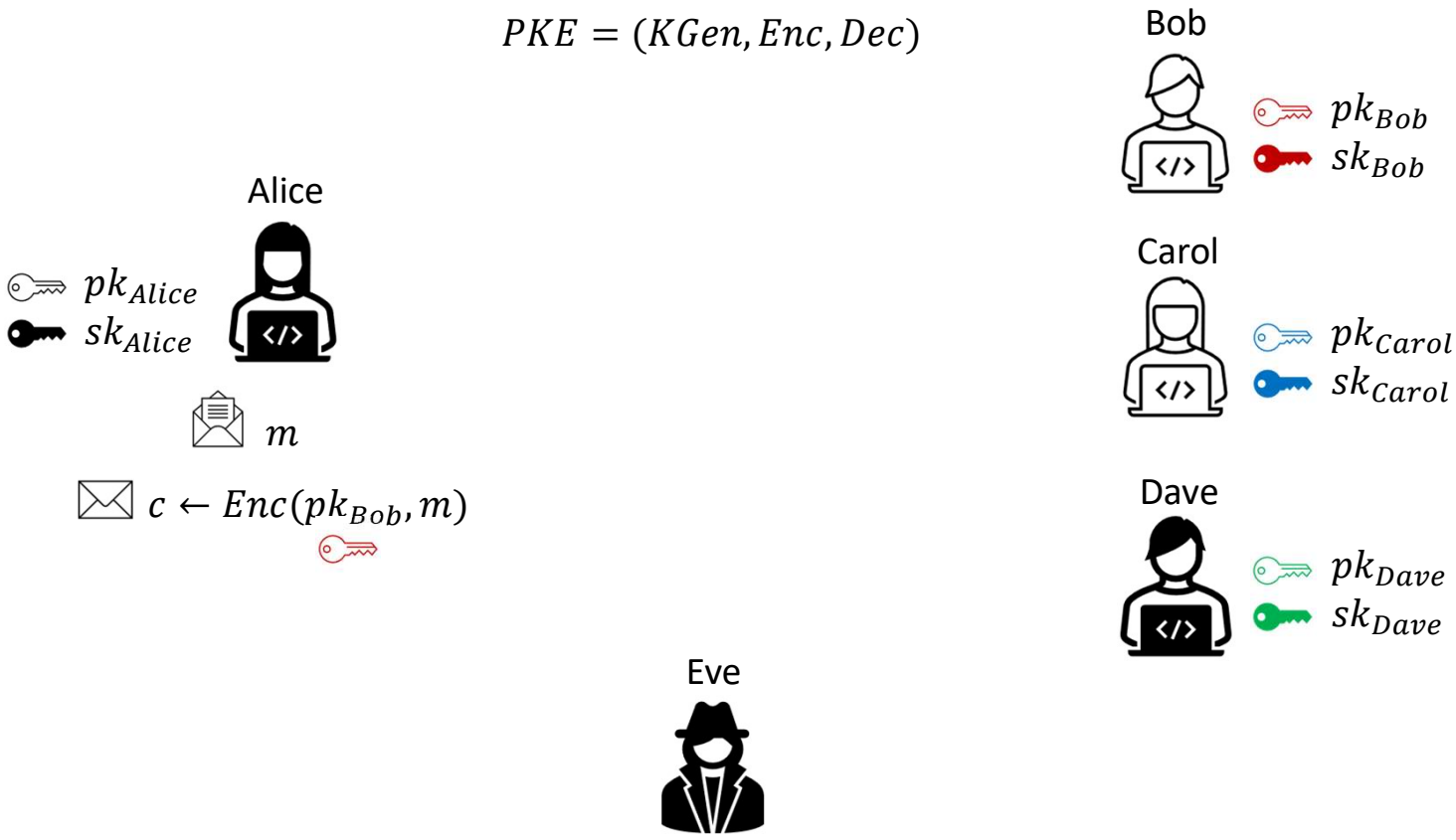
Carol

Dave

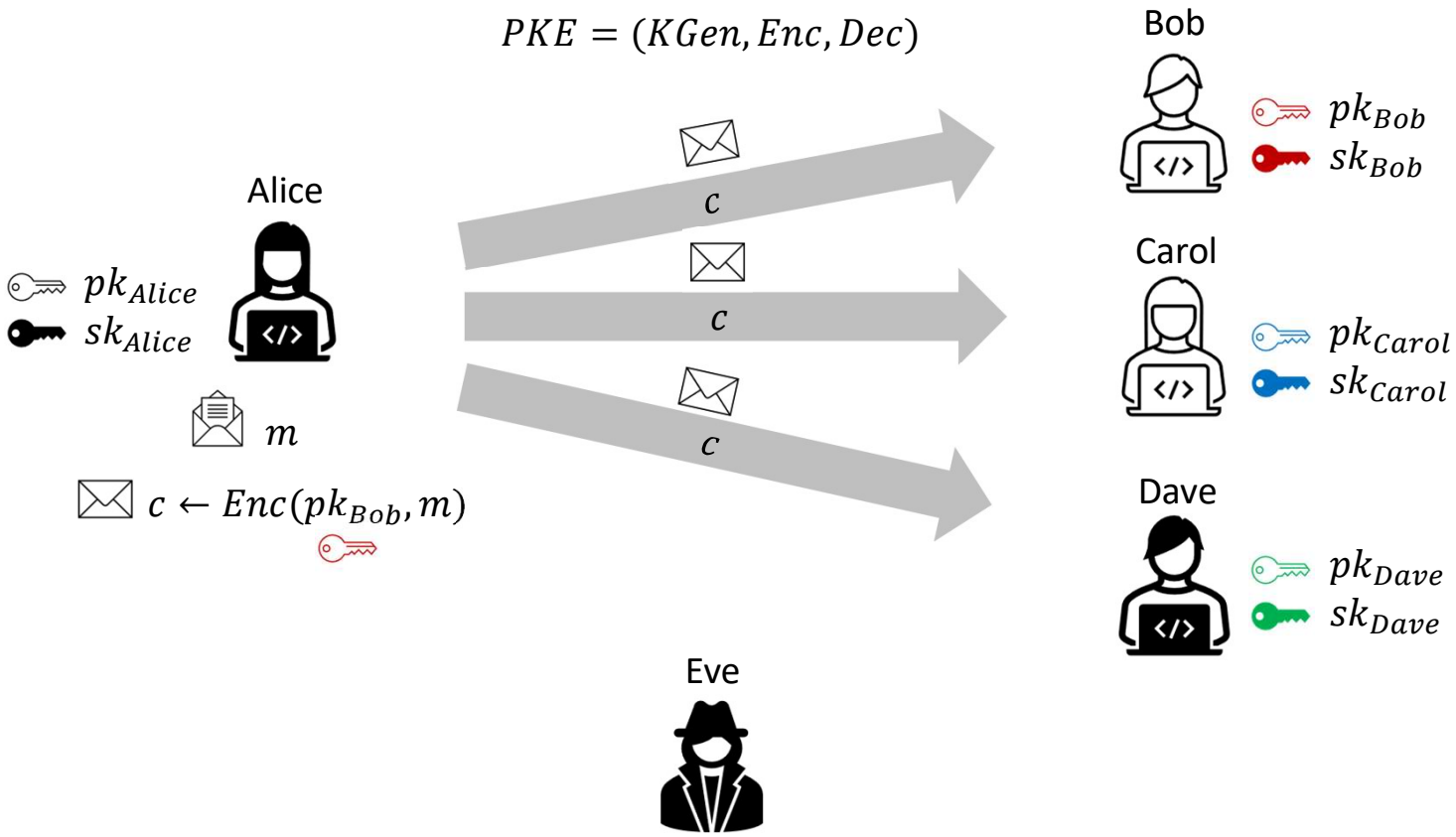
Eve

Anonymity

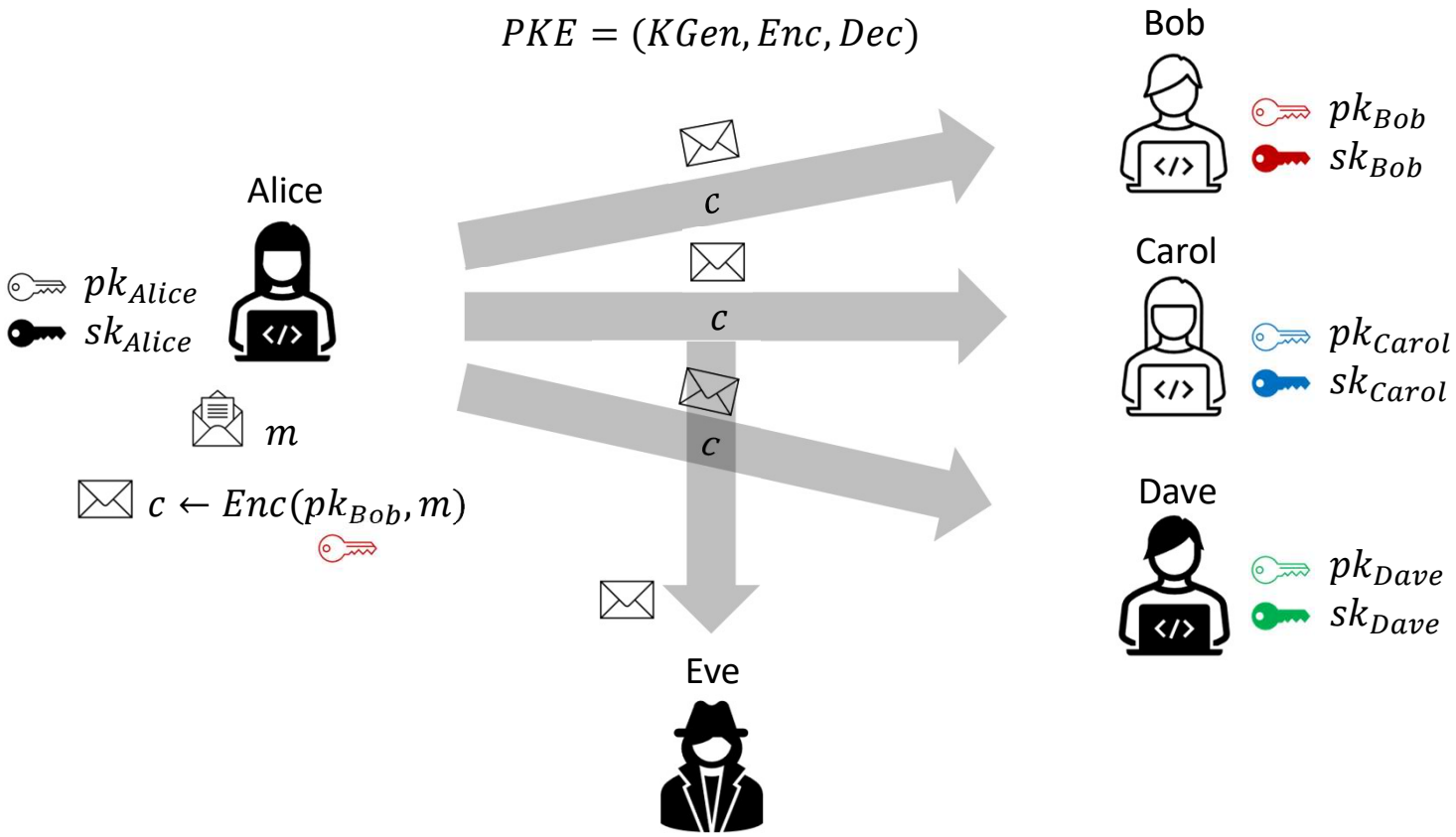
$PKE = (KGen, Enc, Dec)$



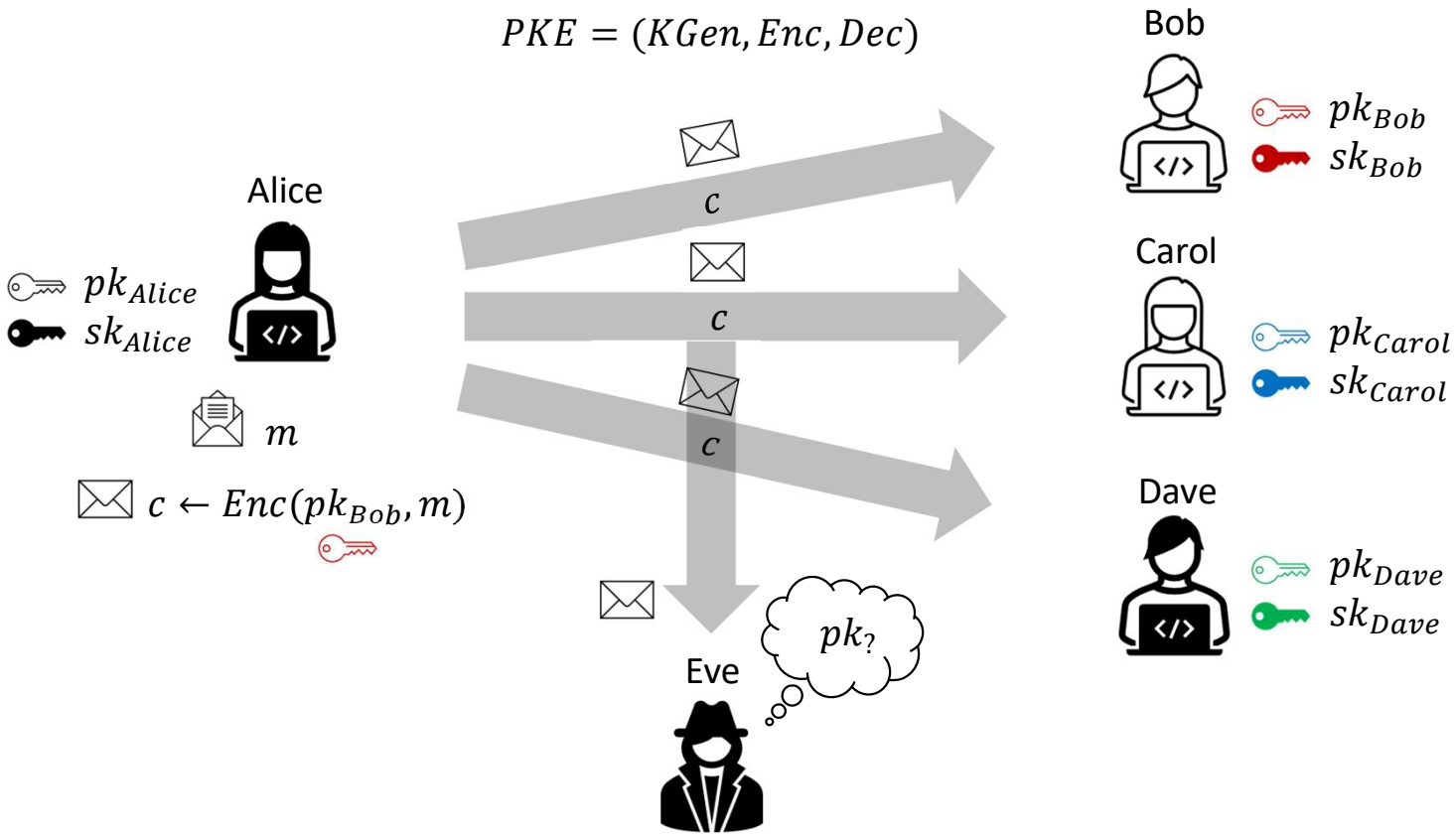
Anonymity


$PKE = (KGen, Enc, Dec)$
Alice
pk_{Alice}
sk_{Alice}
m
$c \leftarrow Enc(pk_{Bob}, m)$
c
c
c
Bob
pk_{Bob}
sk_{Bob}
Carol
pk_{Carol}
sk_{Carol}
Dave
pk_{Dave}
sk_{Dave}
Eve

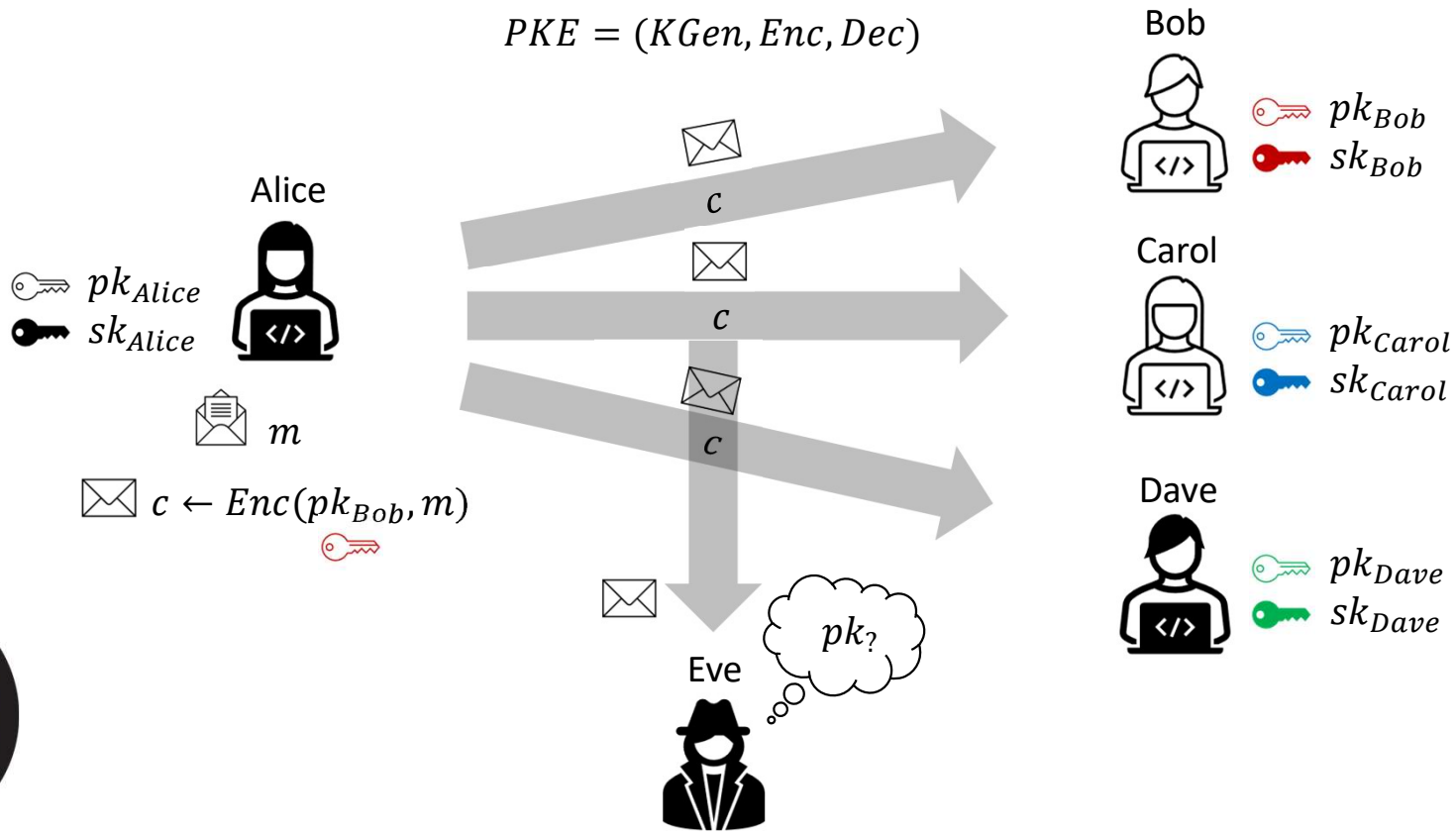
Anonymity


$PKE = (KGen, Enc, Dec)$
Alice
pk_{Alice}
sk_{Alice}
m
$c \leftarrow Enc(pk_{Bob}, m)$
c
c
c
Bob
pk_{Bob}
sk_{Bob}
Carol
pk_{Carol}
sk_{Carol}
Dave
pk_{Dave}
sk_{Dave}
Eve

Anonymity


$PKE = (KGen, Enc, Dec)$
Alice
pk_{Alice}
sk_{Alice}
m
$c \leftarrow Enc(pk_{Bob}, m)$
c
c
c
Bob
pk_{Bob}
sk_{Bob}
Carol
pk_{Carol}
sk_{Carol}
Dave
pk_{Dave}
sk_{Dave}
Eve
$pk_?$

Anonymity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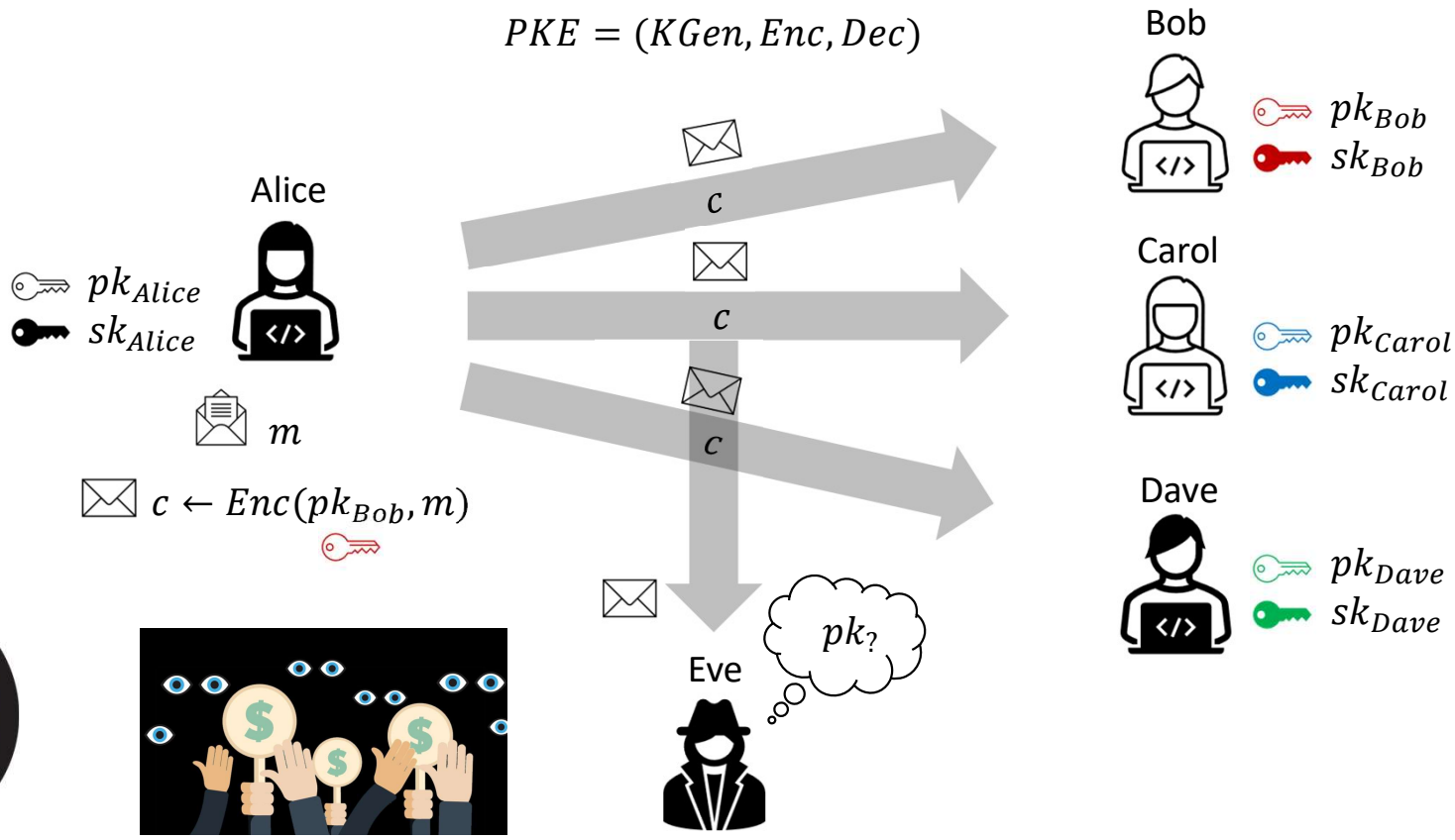
Alice
pk_{Alice}
sk_{Alice}
m
$c \leftarrow Enc(pk_{Bob}, m)$
c
c
c
Bob
pk_{Bob}
sk_{Bob}
Carol
pk_{Carol}
sk_{Carol}
Dave
pk_{Dave}
sk_{Dave}
Eve
$pk_?$

Anonymity


$PKE = (KGen, Enc, Dec)$
Alice
pk_{Alice}
sk_{Alice}
m
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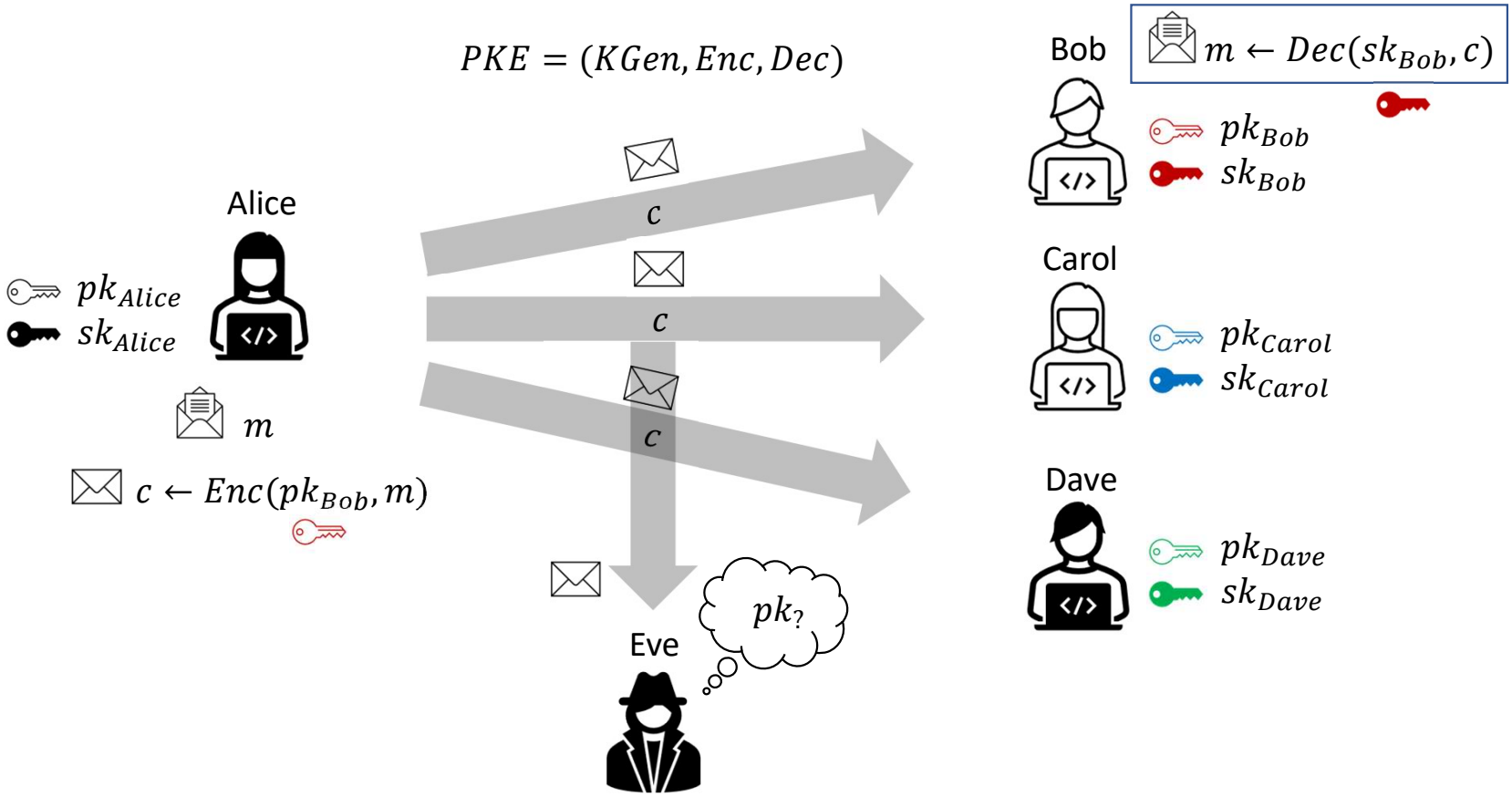
c
c
c
Bob
pk_{Bob}
sk_{Bob}
Carol
pk_{Carol}
sk_{Carol}
Dave
pk_{Dave}
sk_{Dave}
Eve
$pk_?$

Anonymity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Alice
pk_{Alice}
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m
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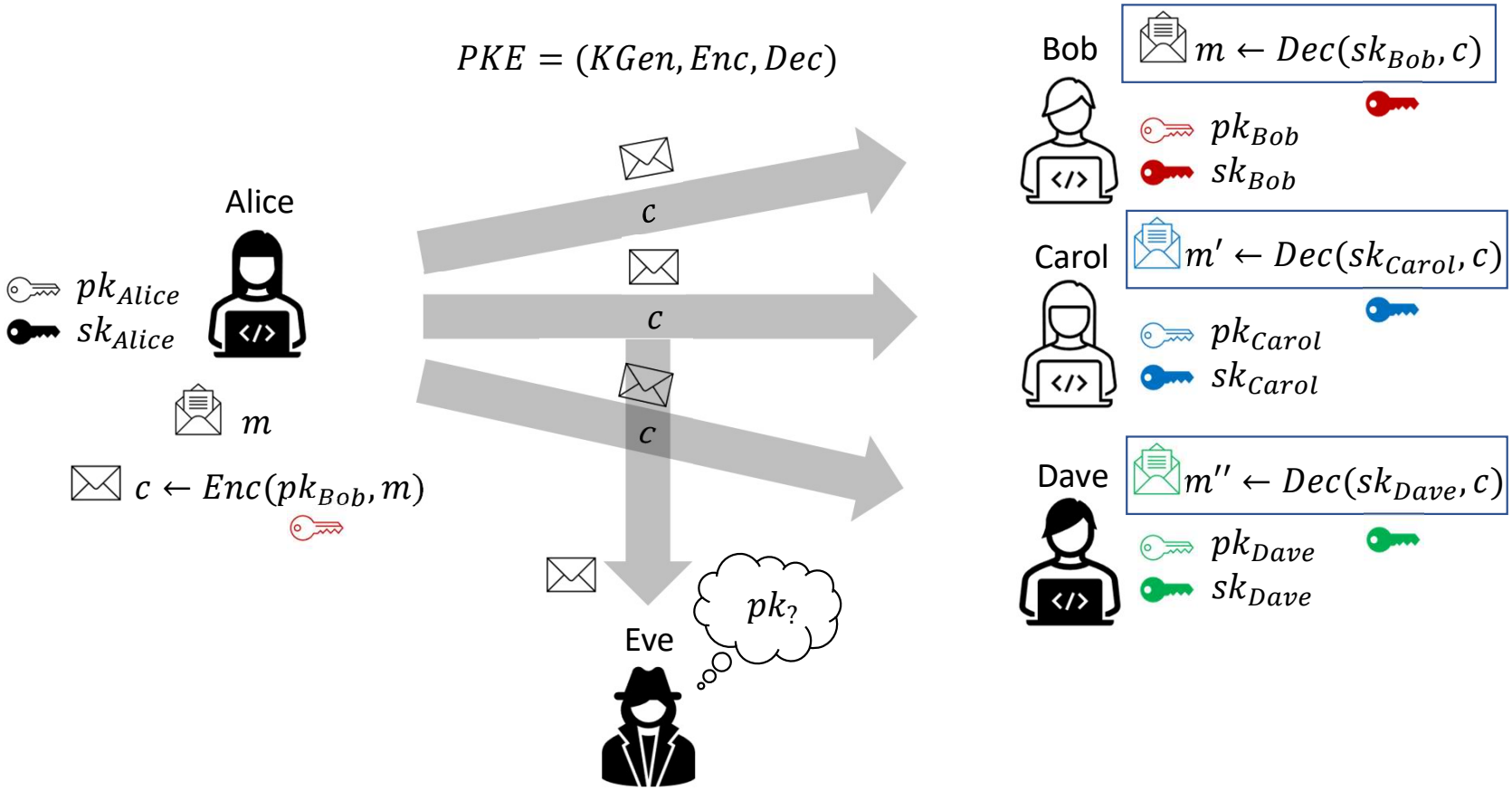
c
c
c
Eve
$pk_?$
Bob
$m \leftarrow Dec(sk_{Bob}, c)$
pk_{Bob}
sk_{Bob}
Carol
pk_{Carol}
sk_{Carol}
Dave
pk_{Dave}
sk_{Dave}

Anonymity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Alice
pk_{Alice}
sk_{Alice}
m
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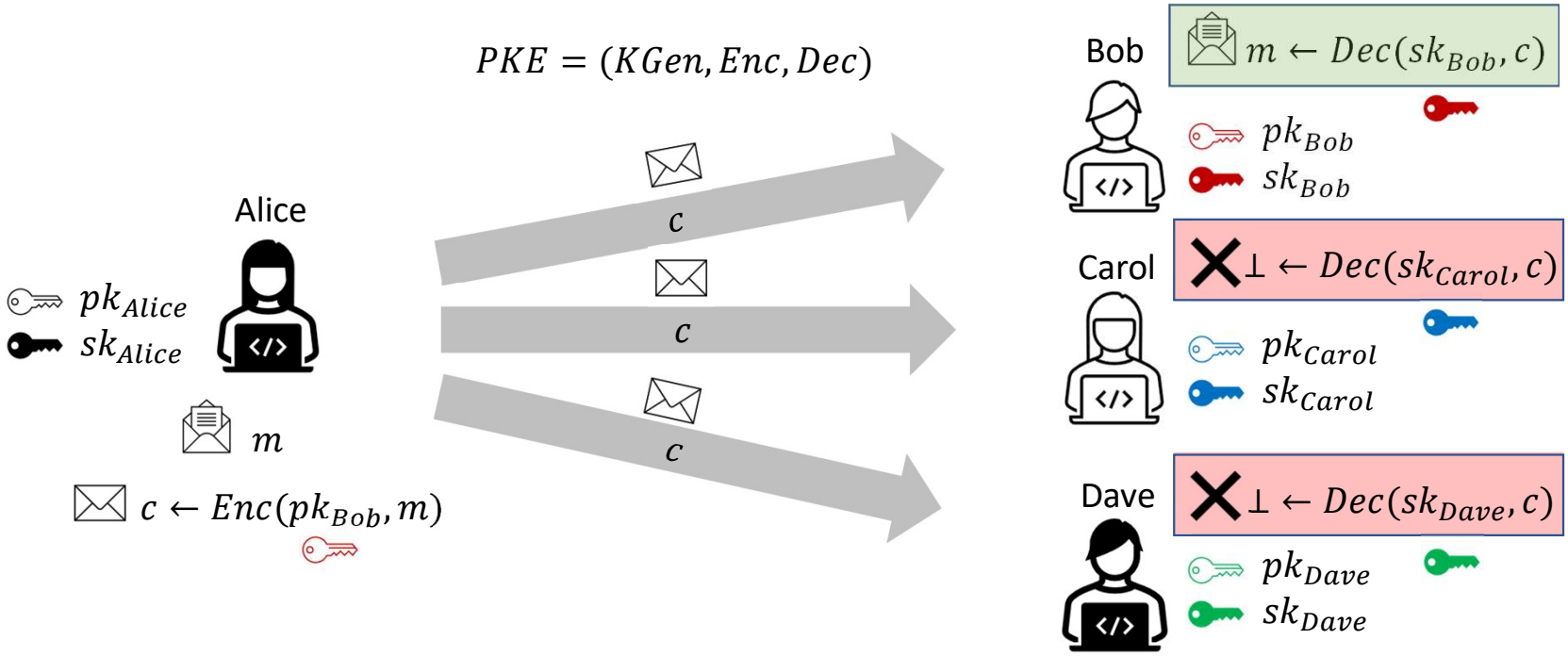
c
c
c
Eve
$pk_?$
Bob
$m \leftarrow Dec(sk_{Bob}, c)$
pk_{Bob}
sk_{Bob}
Carol
$m' \leftarrow Dec(sk_{Carol}, c)$
pk_{Carol}
sk_{Carol}
Dave
$m'' \leftarrow Dec(sk_{Dave}, c)$
pk_{Dave}
sk_{Dave}

Robustness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m
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c
c
c
Bob
$m \leftarrow Dec(sk_{Bob}, c)$
pk_{Bob}
sk_{Bob}
Carol
$\perp \leftarrow Dec(sk_{Carol}, c)$
pk_{Carol}
sk_{Carol}
Dave
$\perp \leftarrow Dec(sk_{Dave}, c)$
pk_{Dave}
sk_{Dave}

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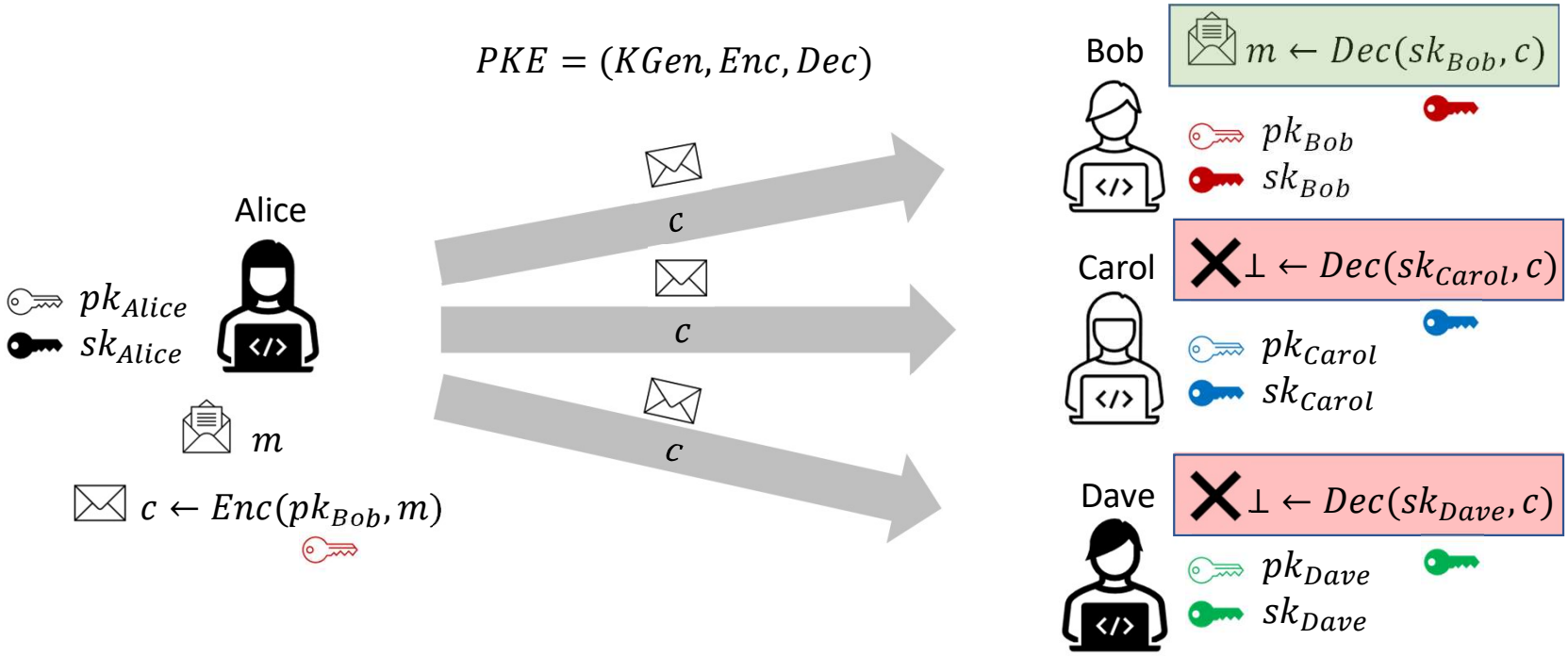

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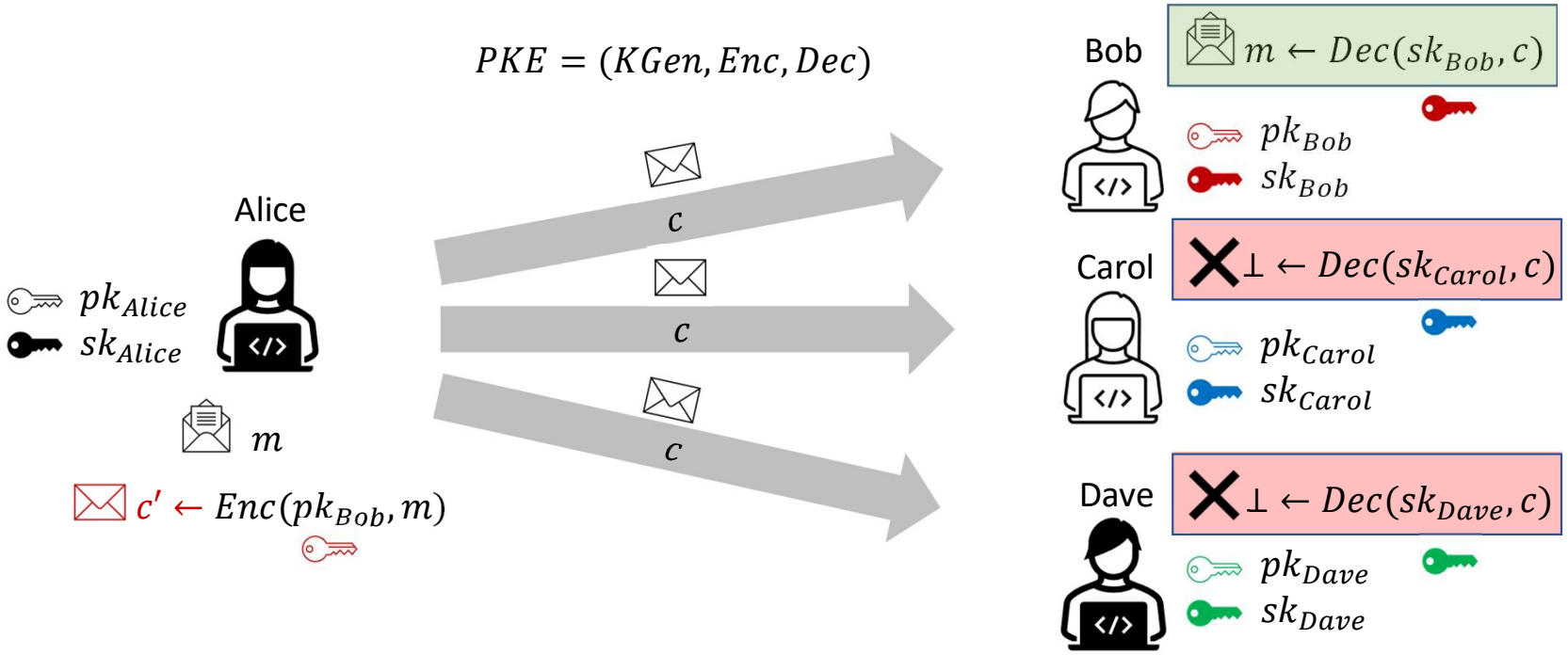

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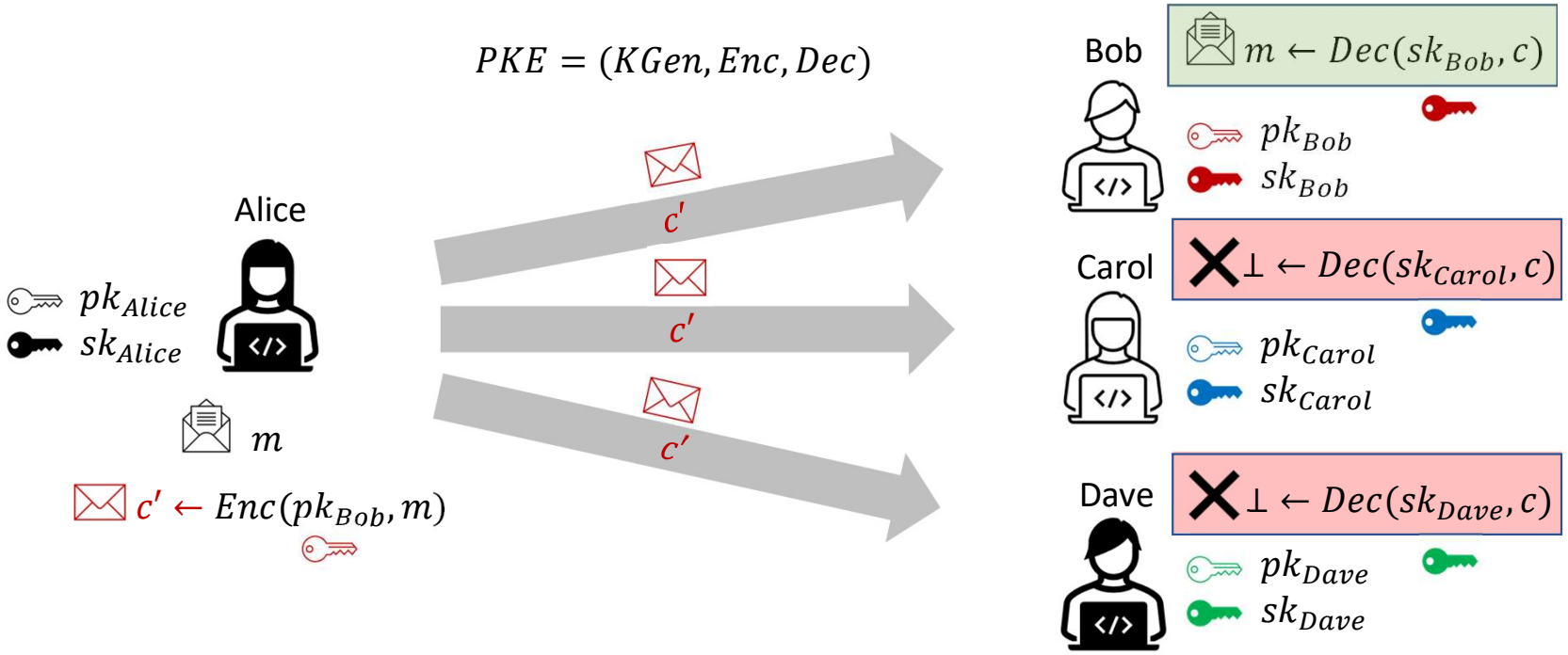

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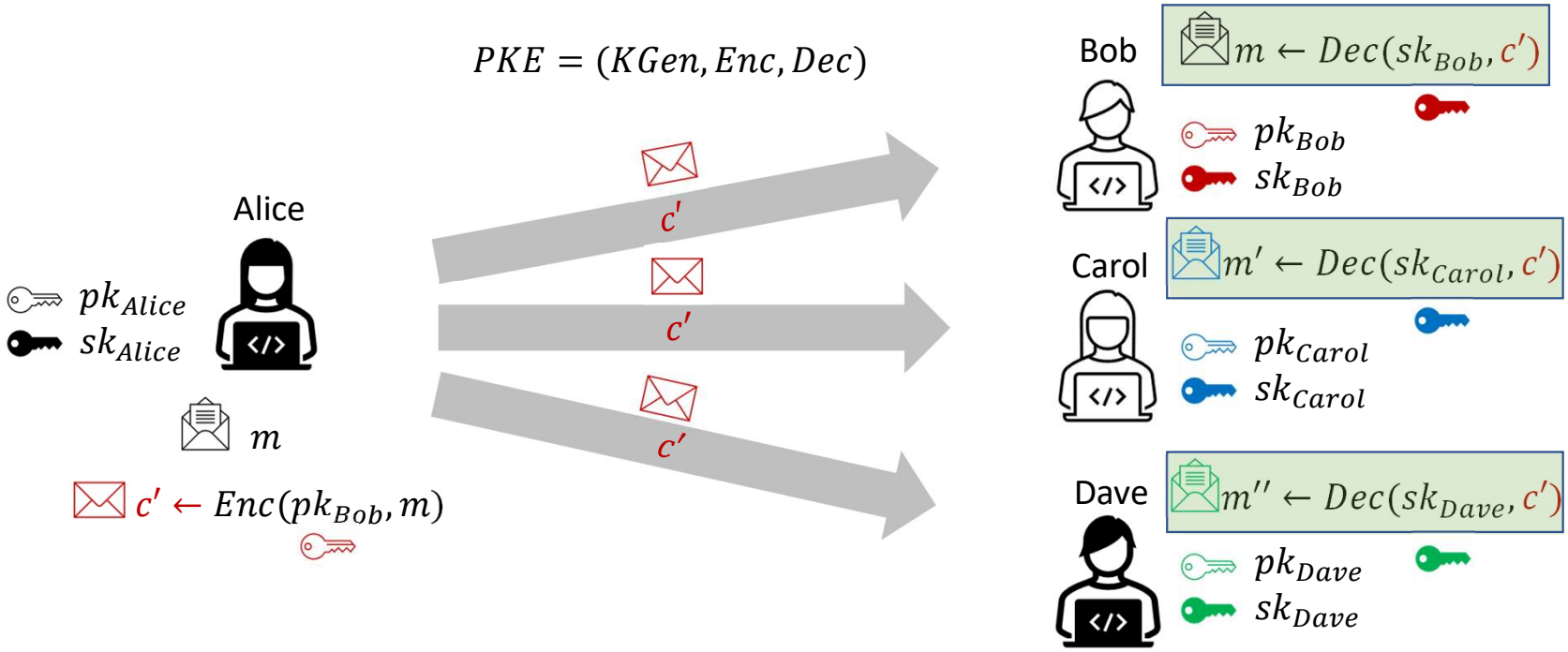

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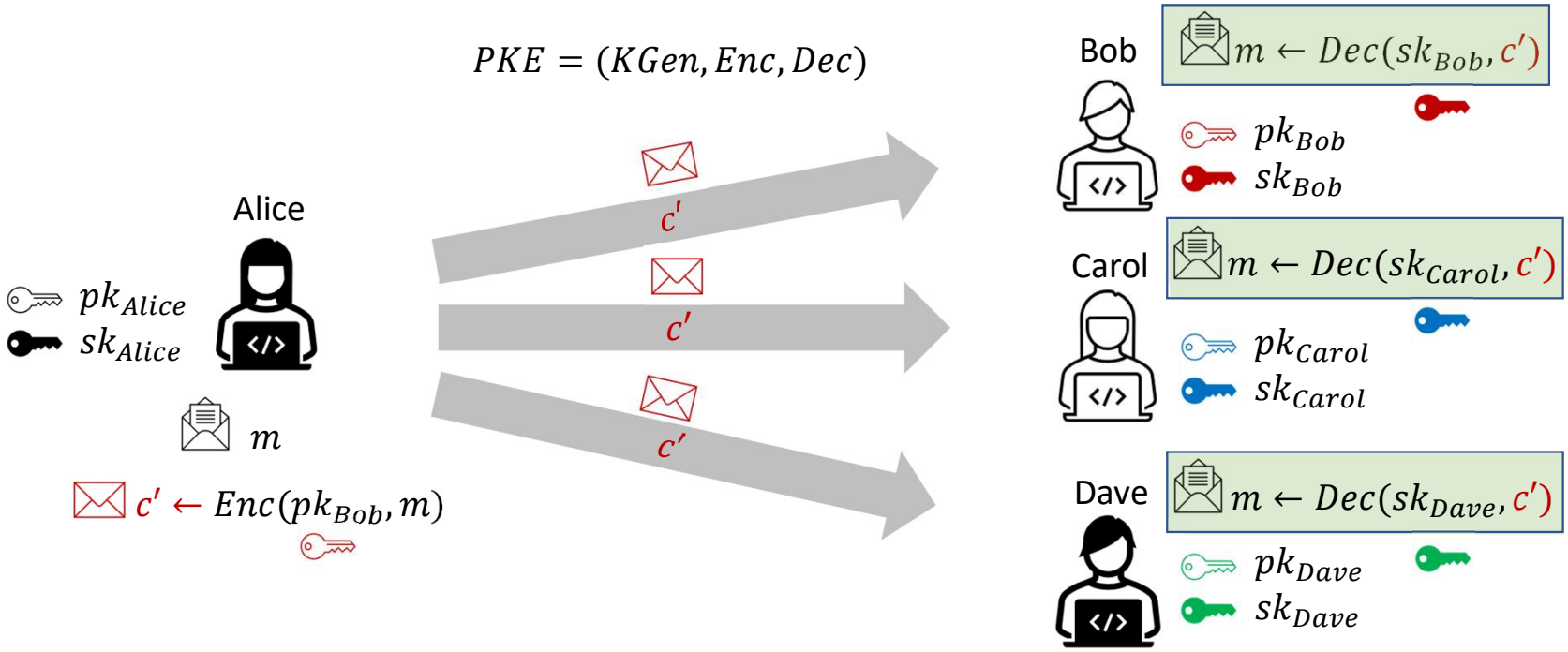

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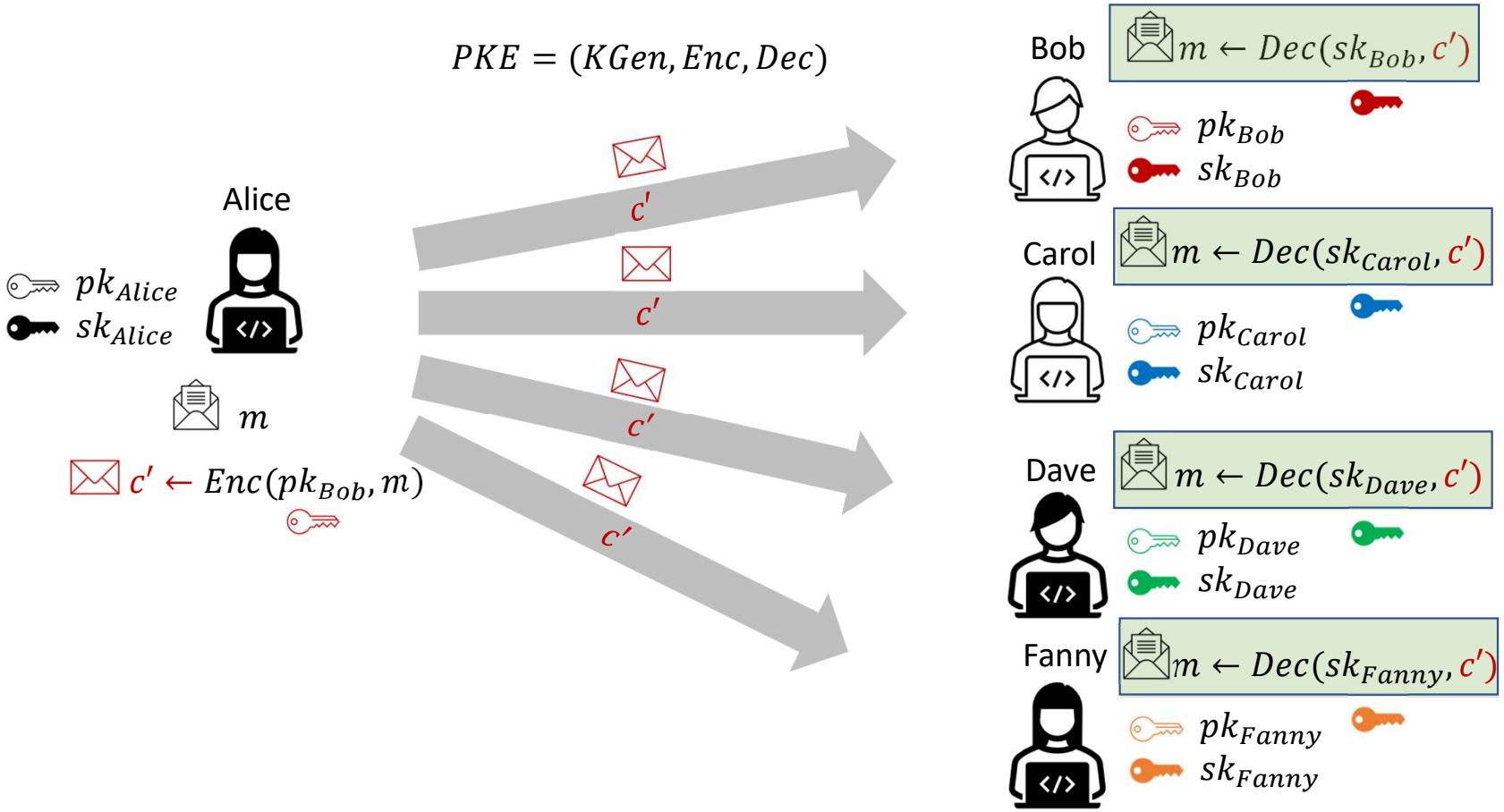

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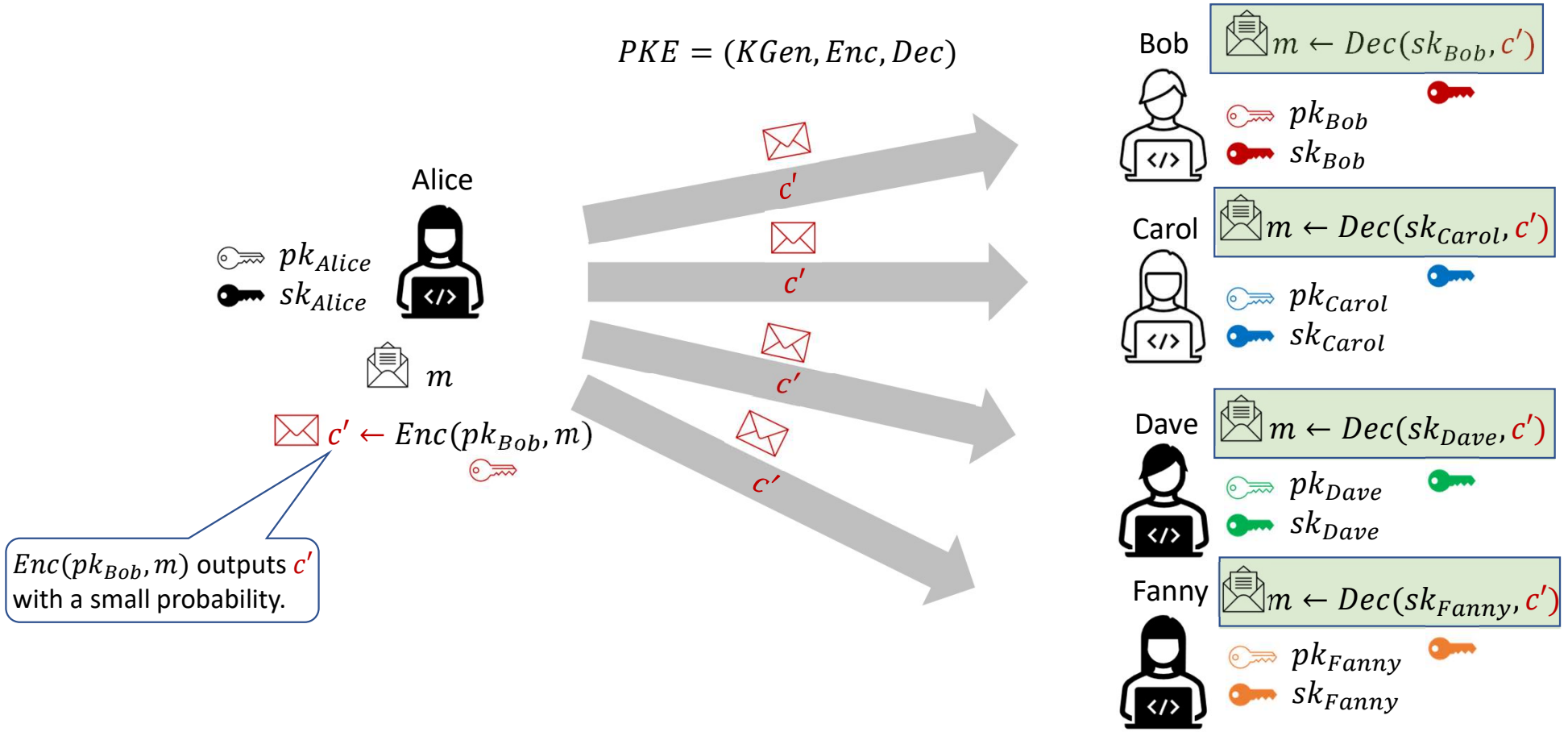

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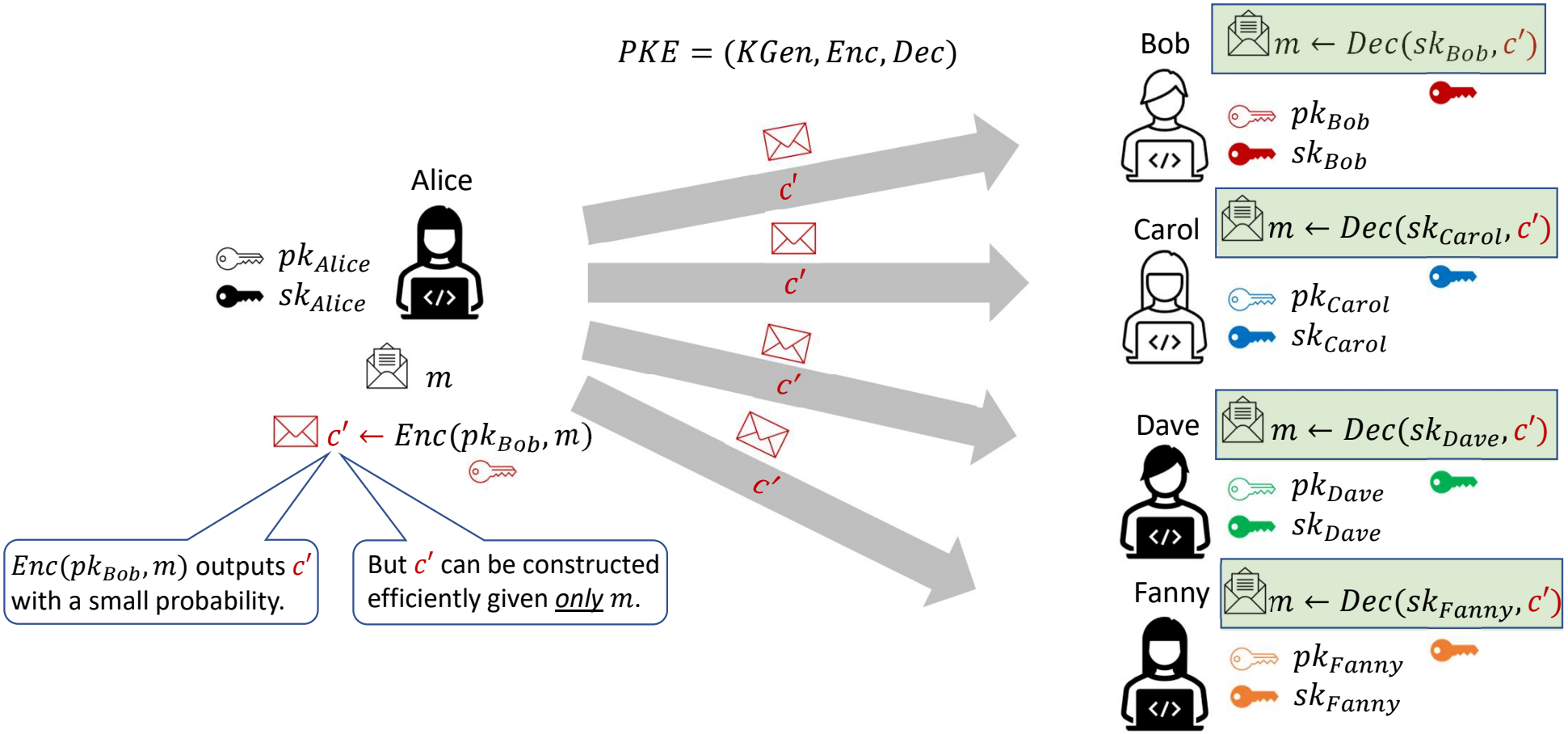

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  - But we identified barriers towards proving anonymity of these two schemes.
  - Interestingly, these same barriers also imply that the "level" of IND-CCA security offered by these schemes is overestimated by their respective teams.

- FrodoKEM does result in anonymous and robust PKE schemes.

[Xag21]: Keita Xagawa. *Anonymity of NIST PQC Round 3 KEMs,* EUROCRYPT 2022. [https://eprint.iacr.org/2021/1323.pdf]