TECHNISCHE UNIVERSITÄT WIEN
Vienna | Austria

FAKULTÄT FÜR !NFORMATIK
Faculty of Informatics

S&P SECURITY & PRIVACY GROUP

Anonymous Multi-Hop Locks for Blockchain Scalability and Interoperability

(https://eprint.iacr.org/2018/472.pdf)

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Motivation: Scalability Issues

- Bitcoin has a low transaction rate (~10 tx/sec)
  - Visa, in contrast, supports >10K tx/sec
- Scalability approaches:
  - On-chain (consensus layer or layer 1): e.g., Sharding
  - Off-chain (application layer or layer 2): e.g., Payment Channel Networks

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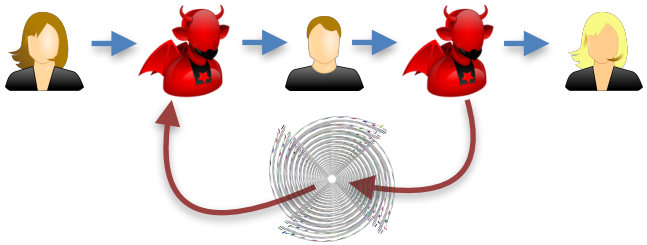
Lightning Network
(Bitcoin)

Raiden Network
(Ethereum)

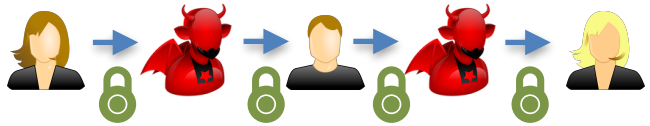
Many other research projects (Bolt, Z-Channels, Perun, etc.)

Contributions

The **Wormhole Attack**:
A novel attack on Payment Channel Network Security



AMHLs: A **new primitive** for secure + anonymous Payment Channel Networks

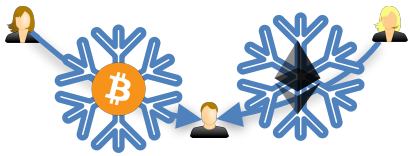


Concrete **constructions** of AMHLs that

… are efficient

… got implemented in Bitcoin's Lightning Network

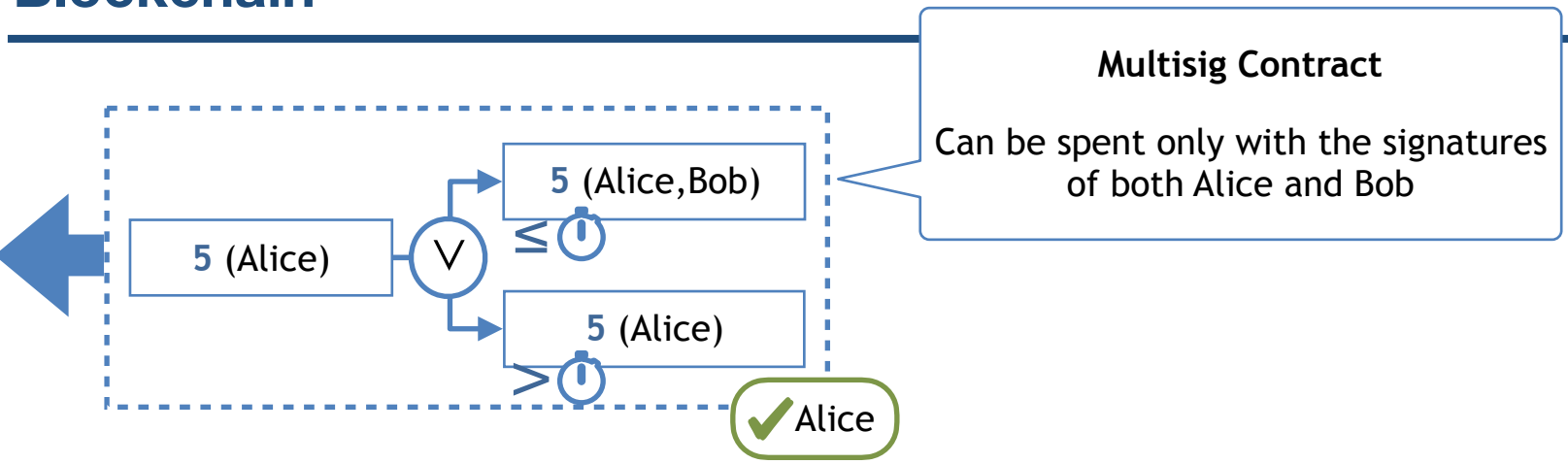
… enable inter-blockchain Payment Channels



Background on Payment Channel Networks

Payment Channels: Open

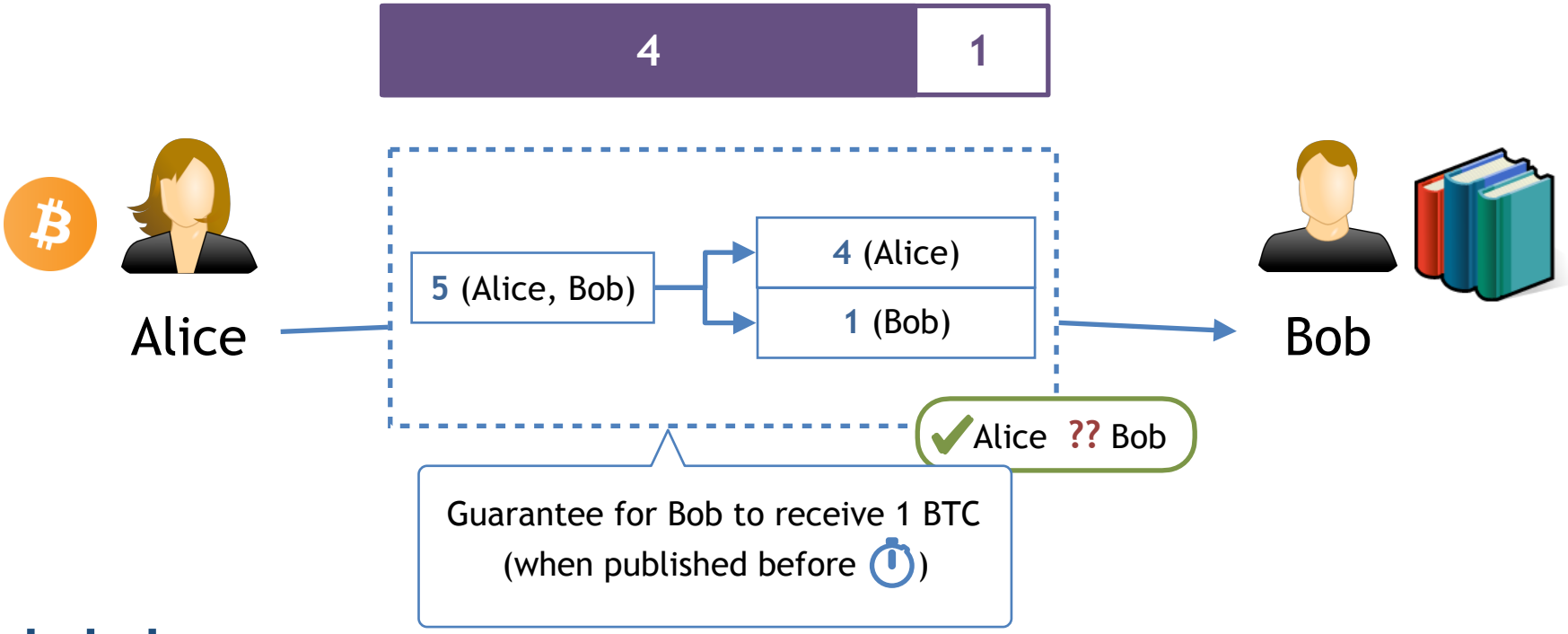
Blockchain



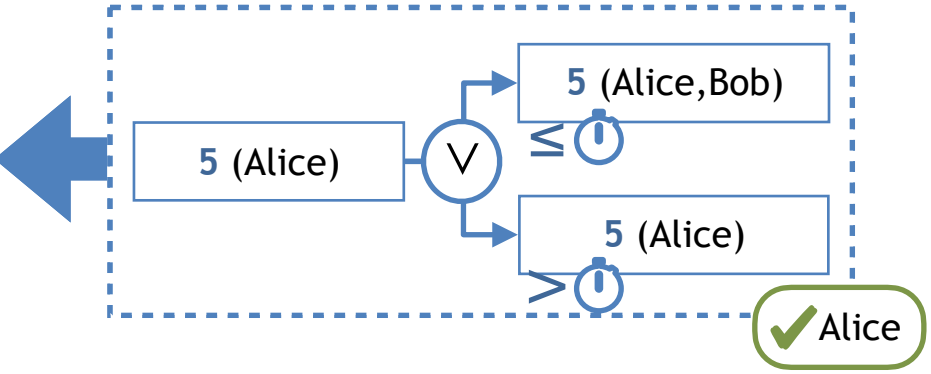
Multisig Contract

Can be spent only with the signatures of both Alice and Bob

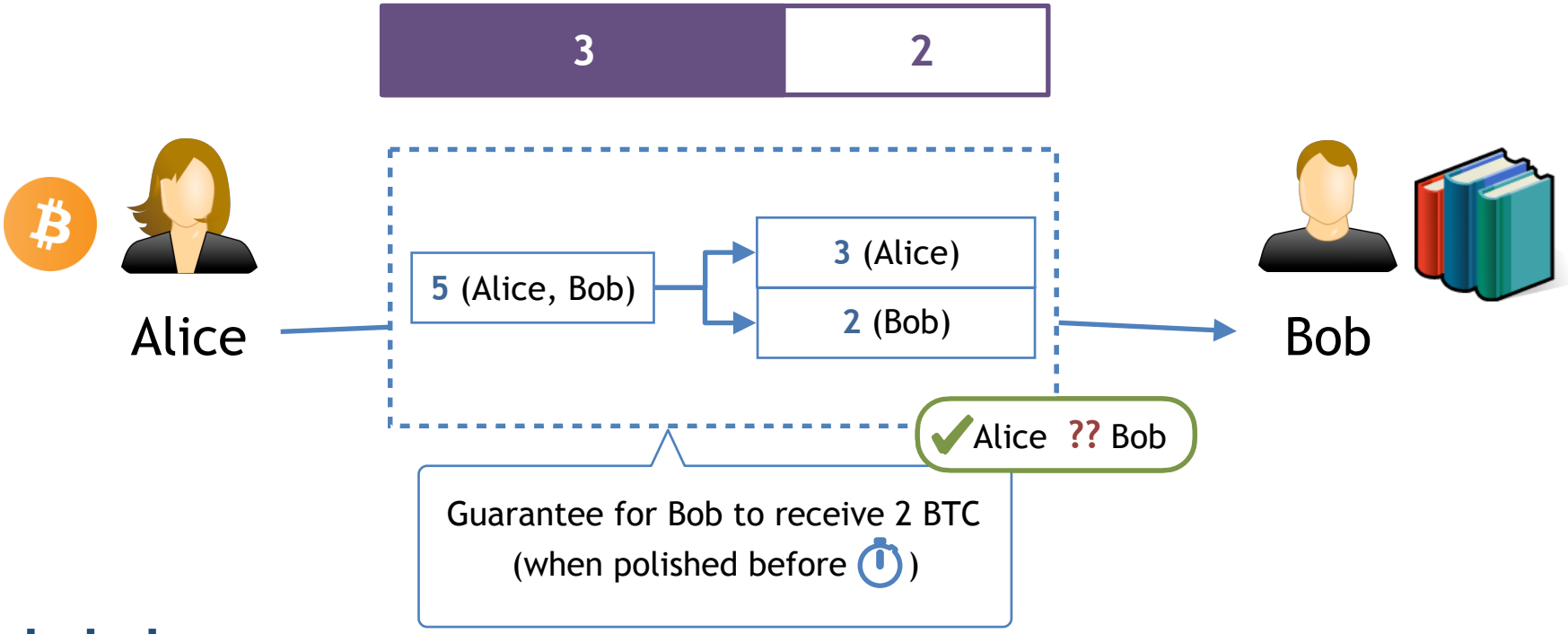
Payment Channels: Transactions



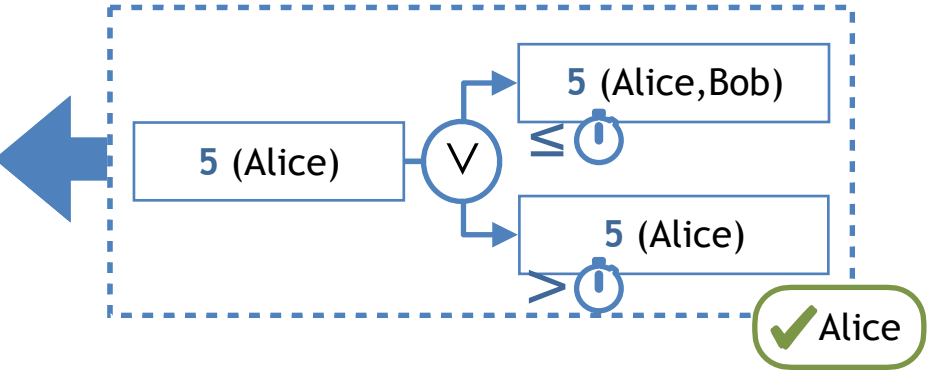
Blockchain



Payment Channels: Transactions

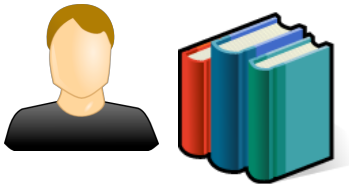


Blockchain



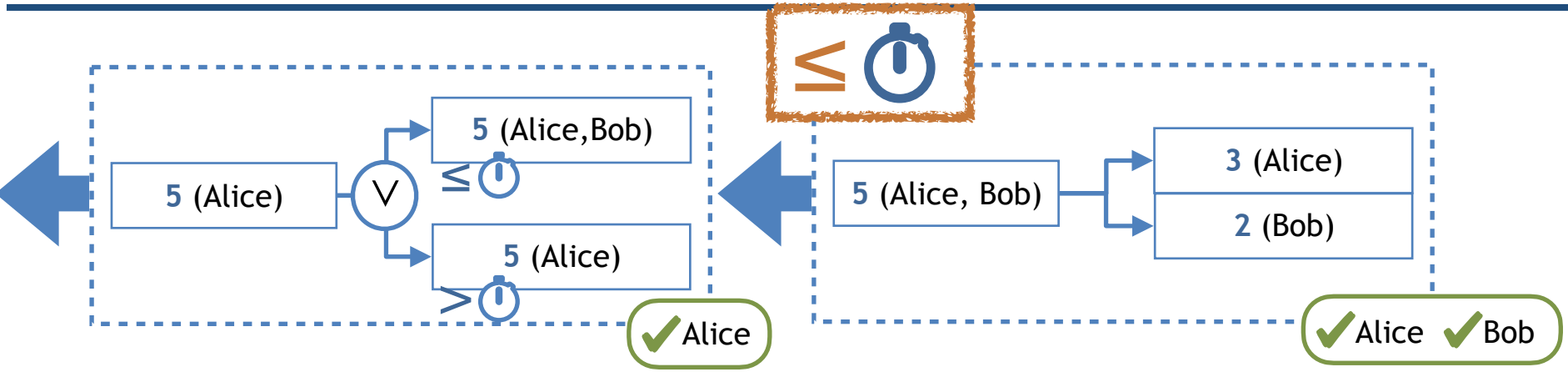
Payment Channels: Close

Alice

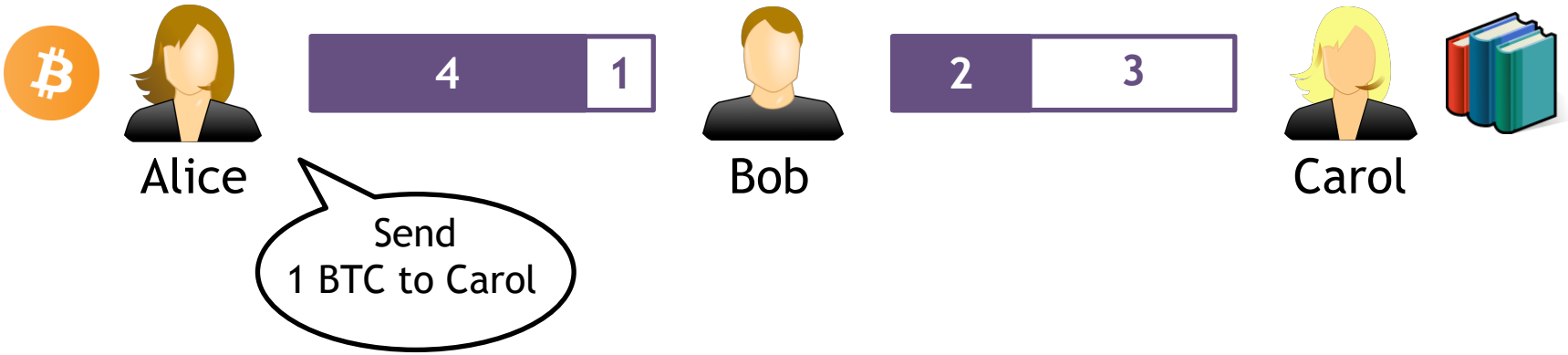


Bob

Blockchain



Payment Channel Networks



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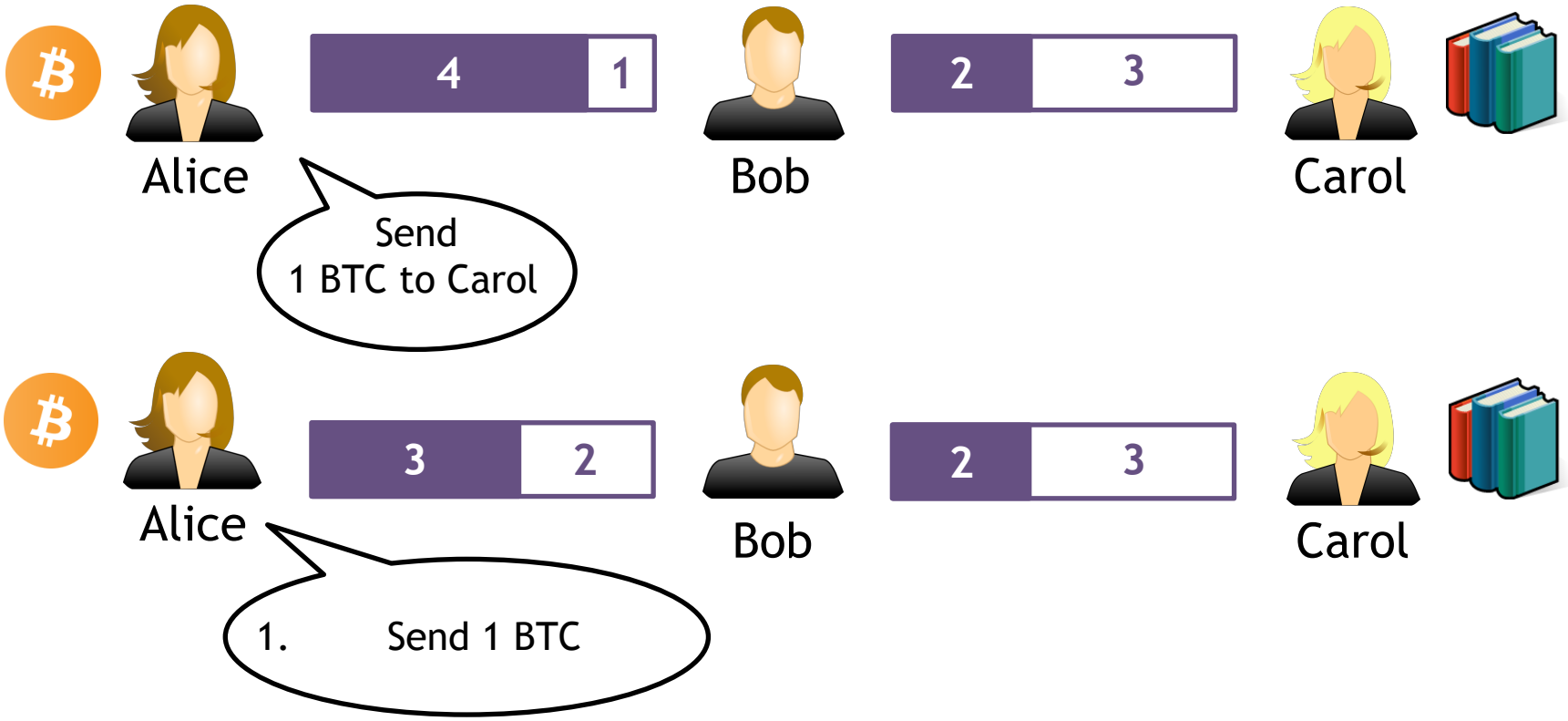

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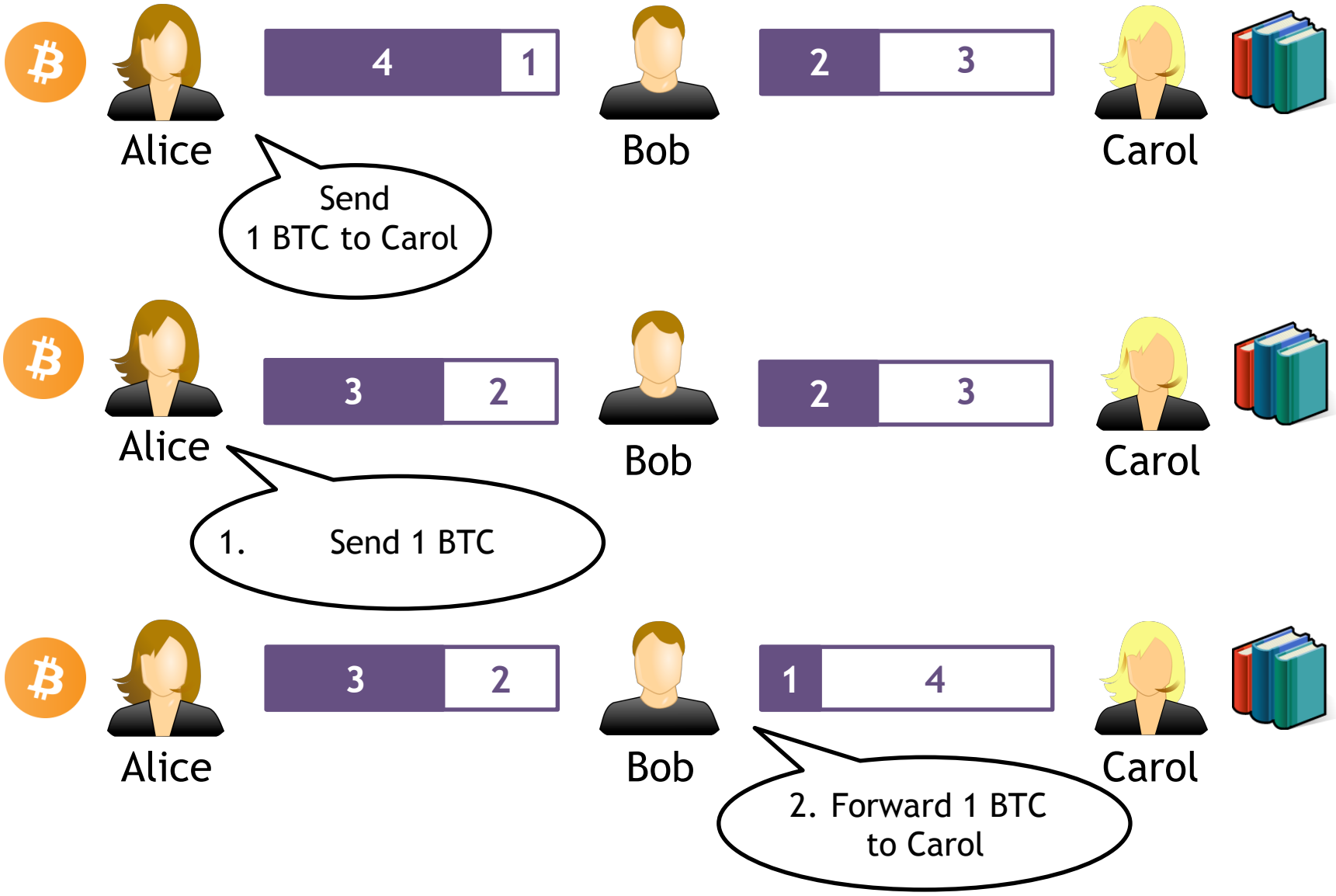

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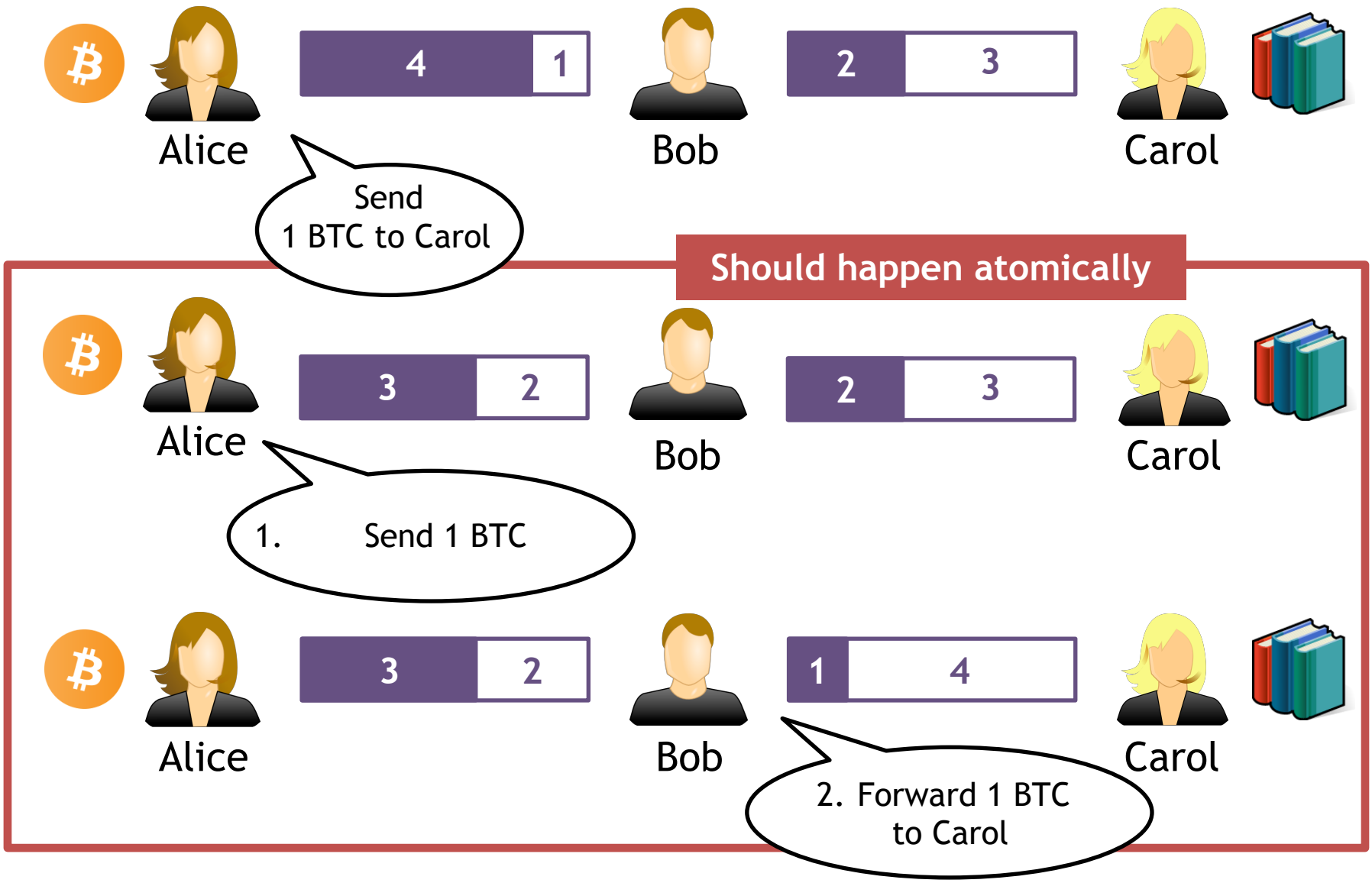

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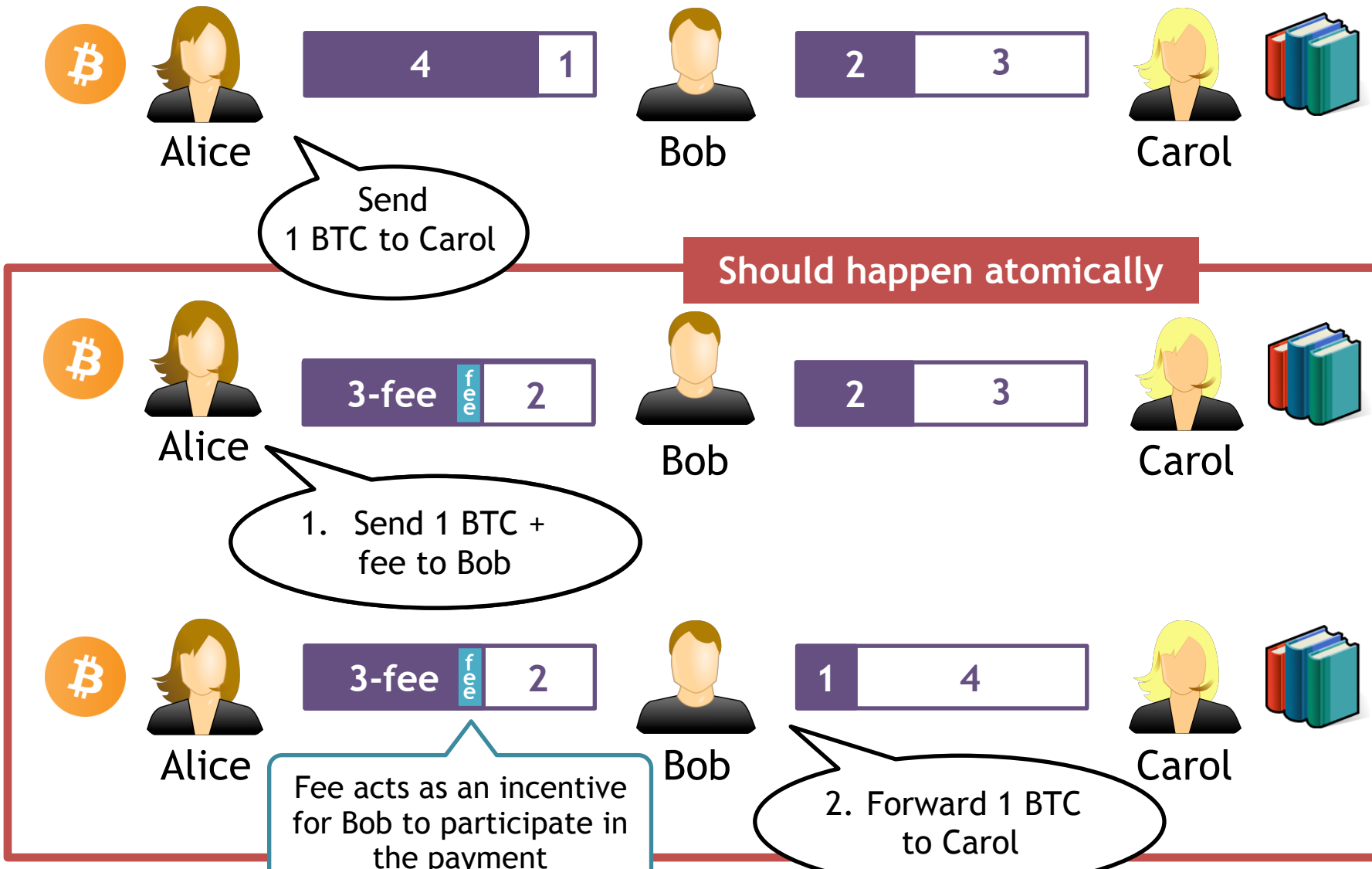
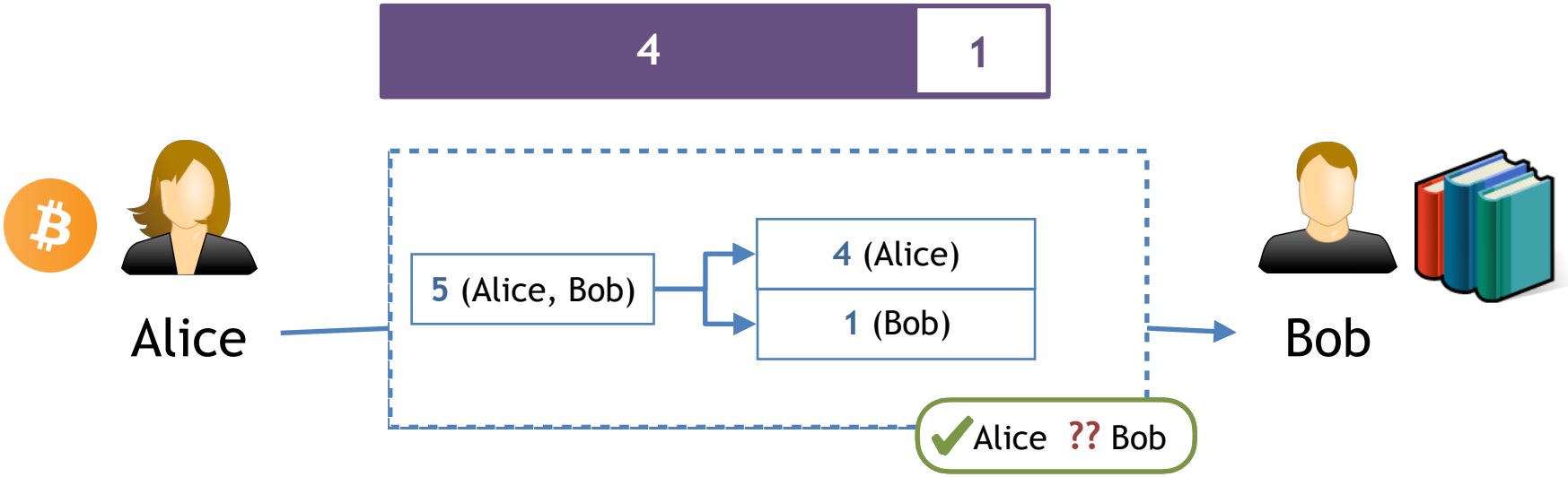


The Lightning Network (LN)

Payment Channels in the LN



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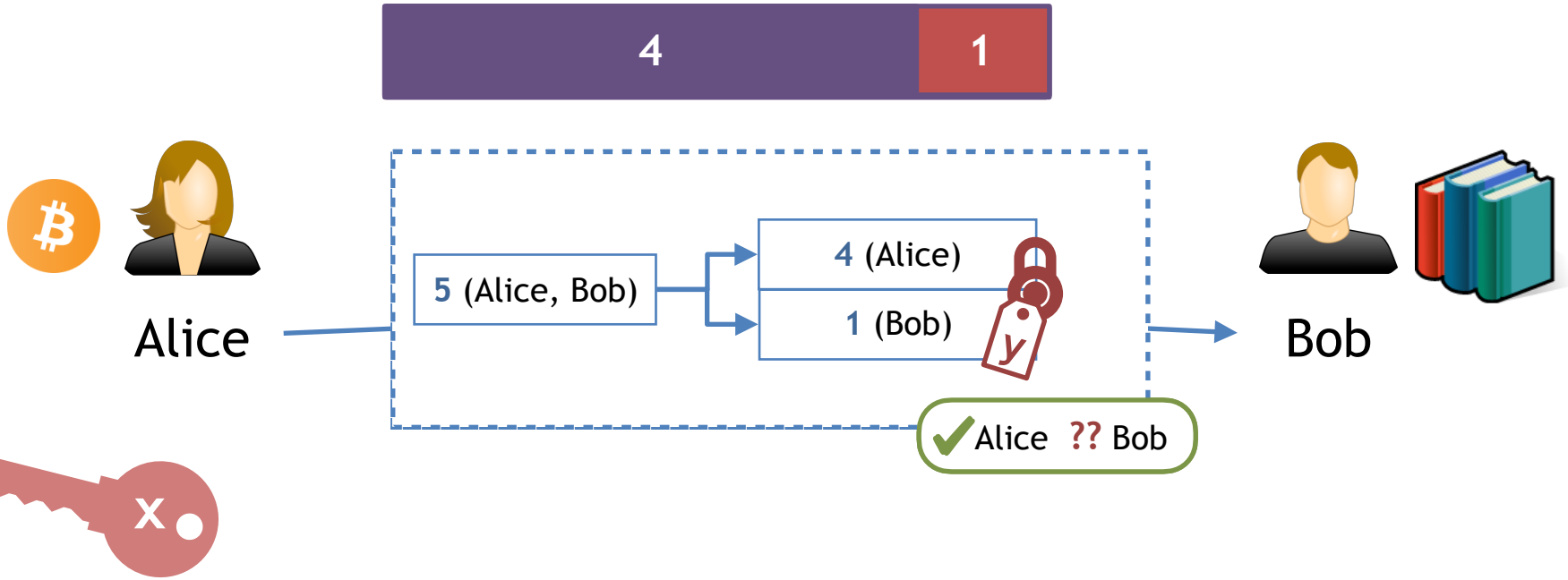

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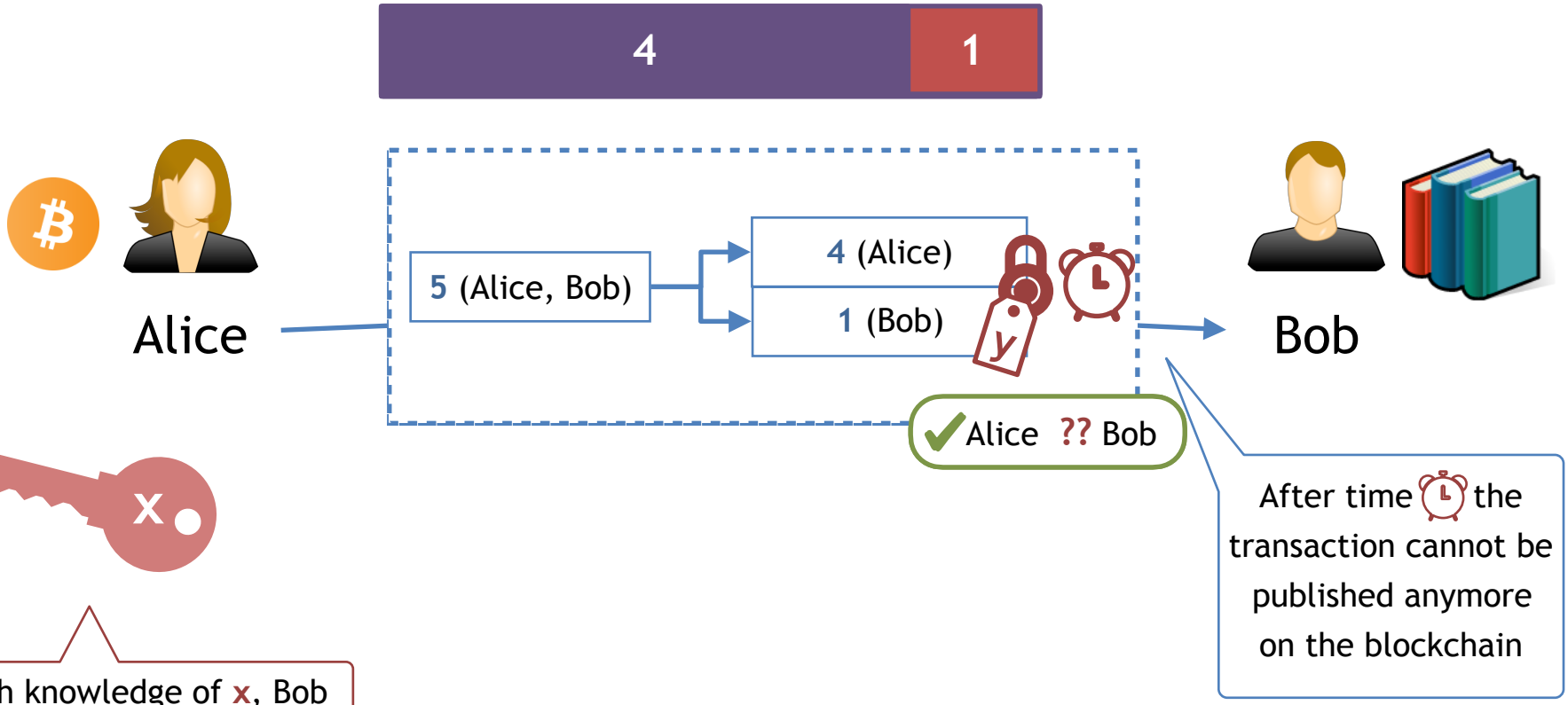

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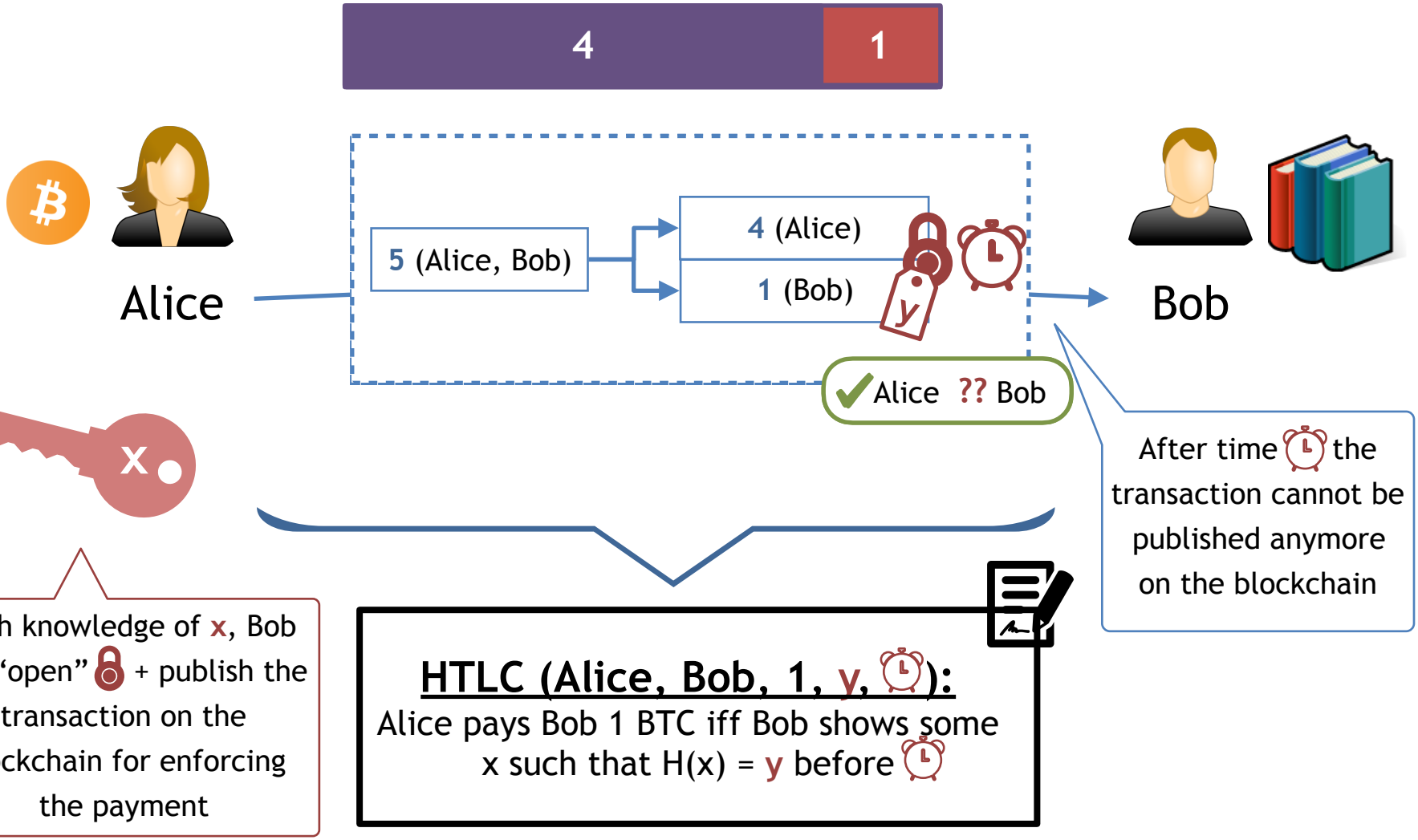
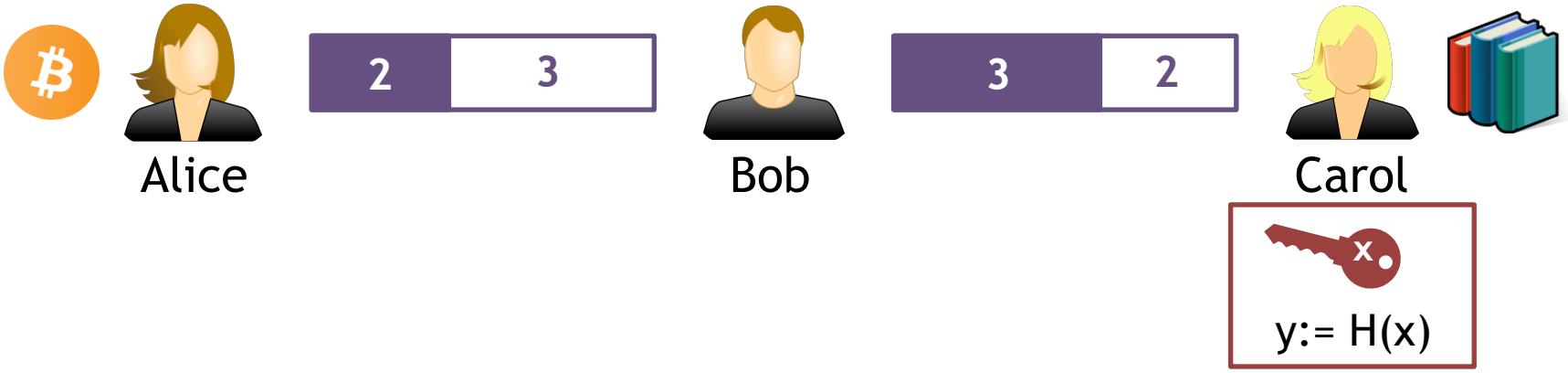


"Multi-hop-Lock"

HTLC for Multi-hop Payments



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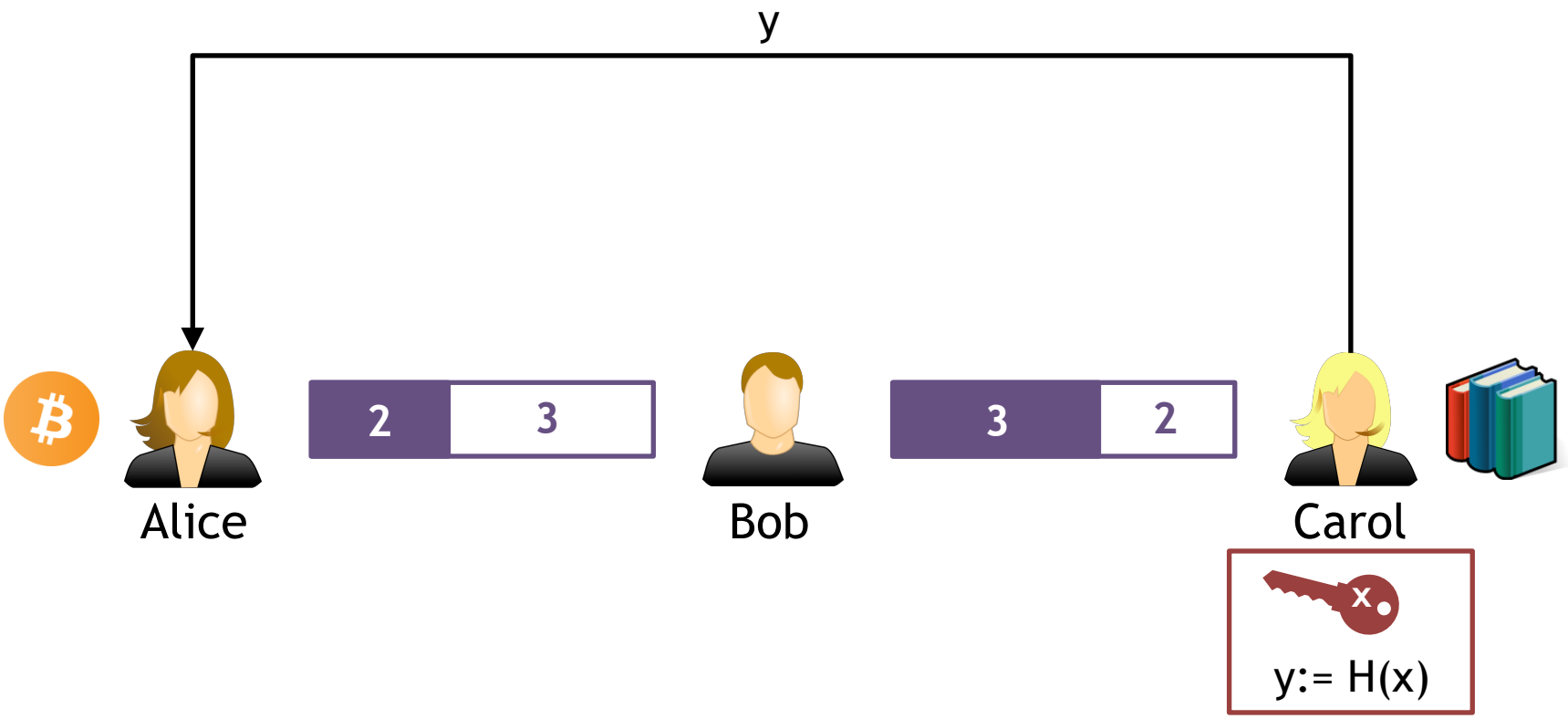

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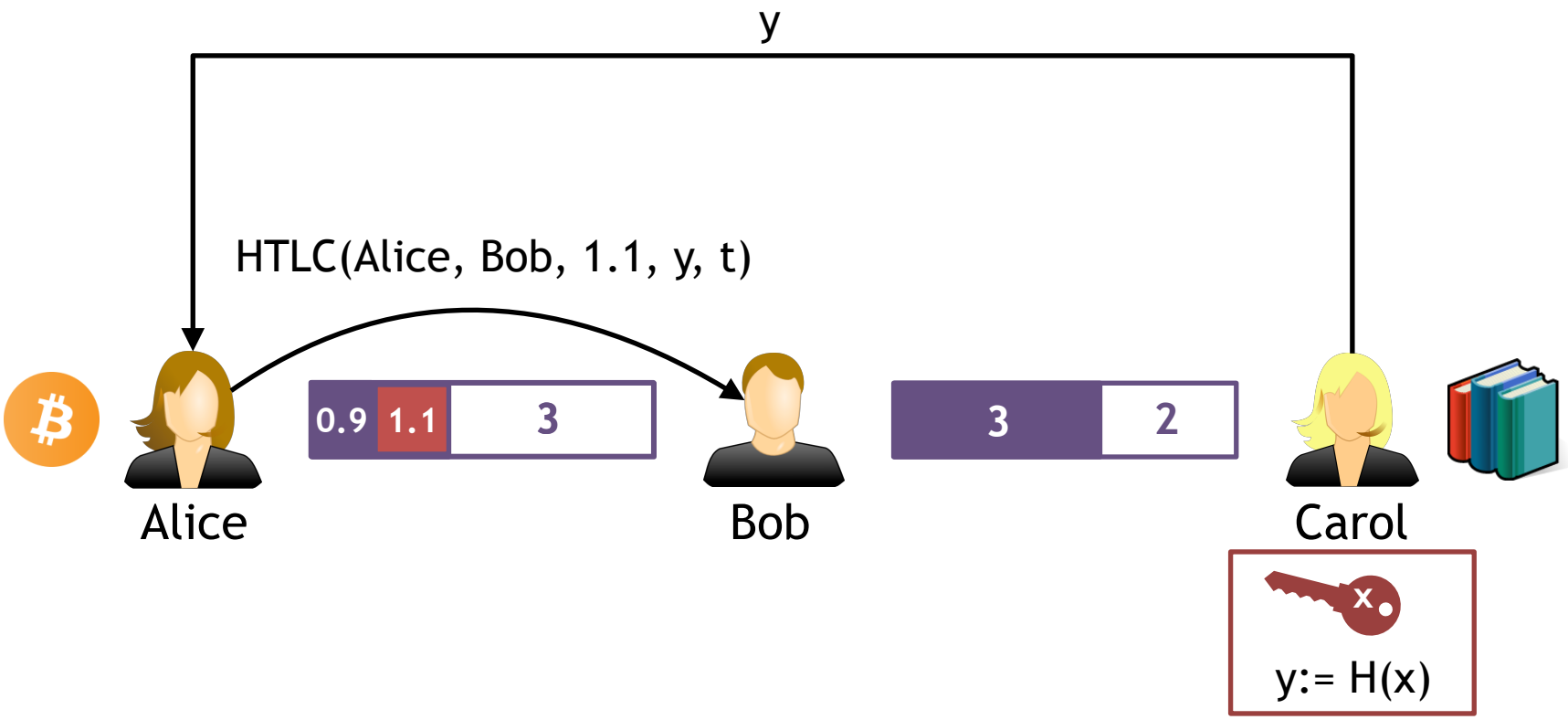

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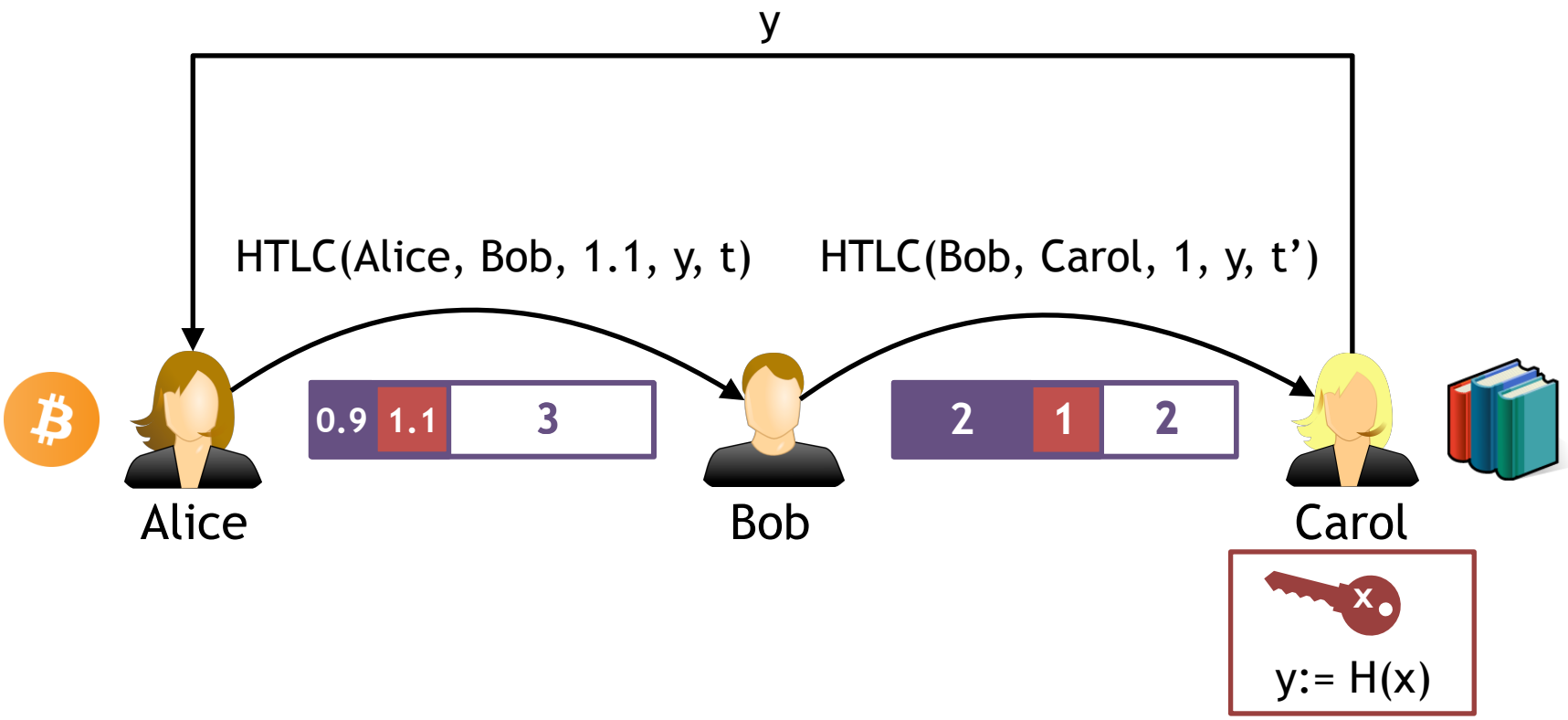

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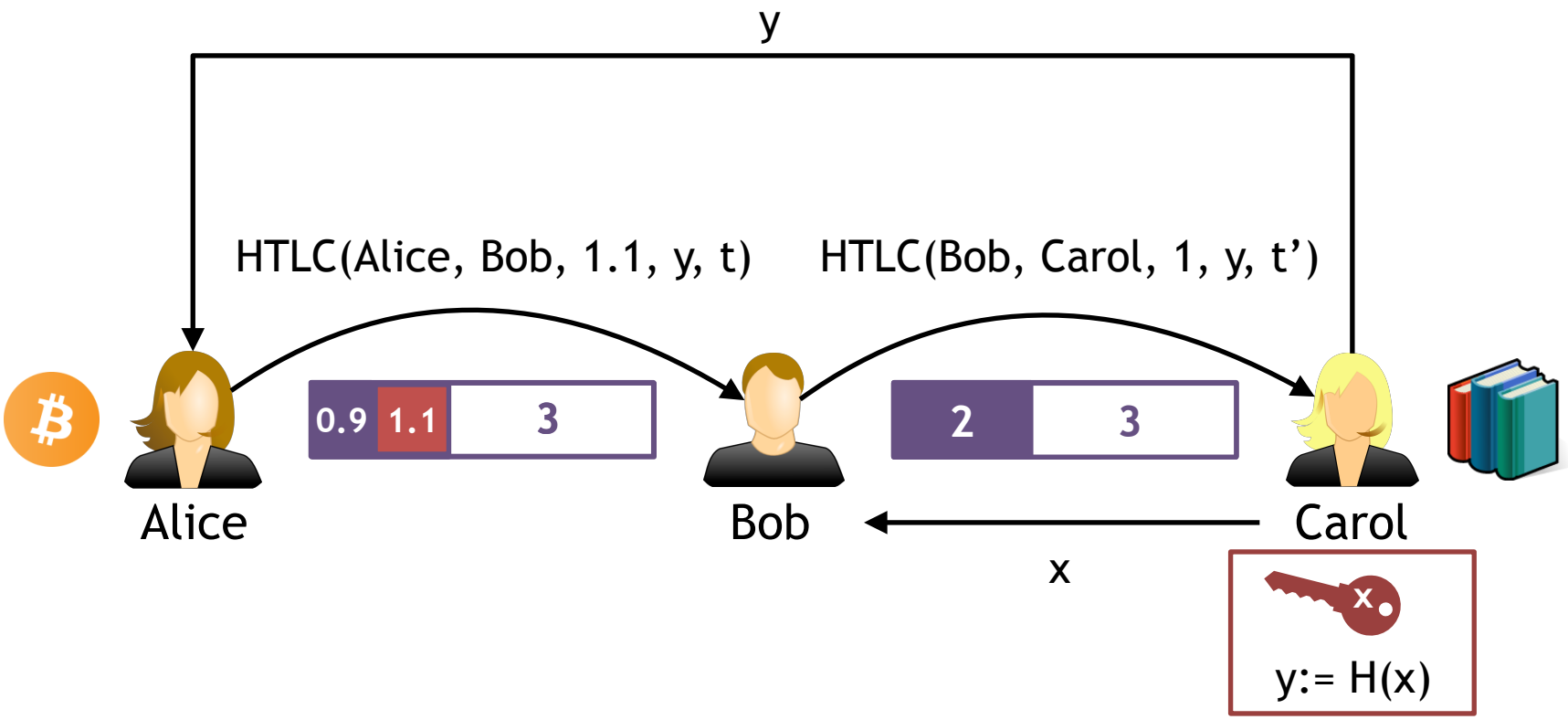

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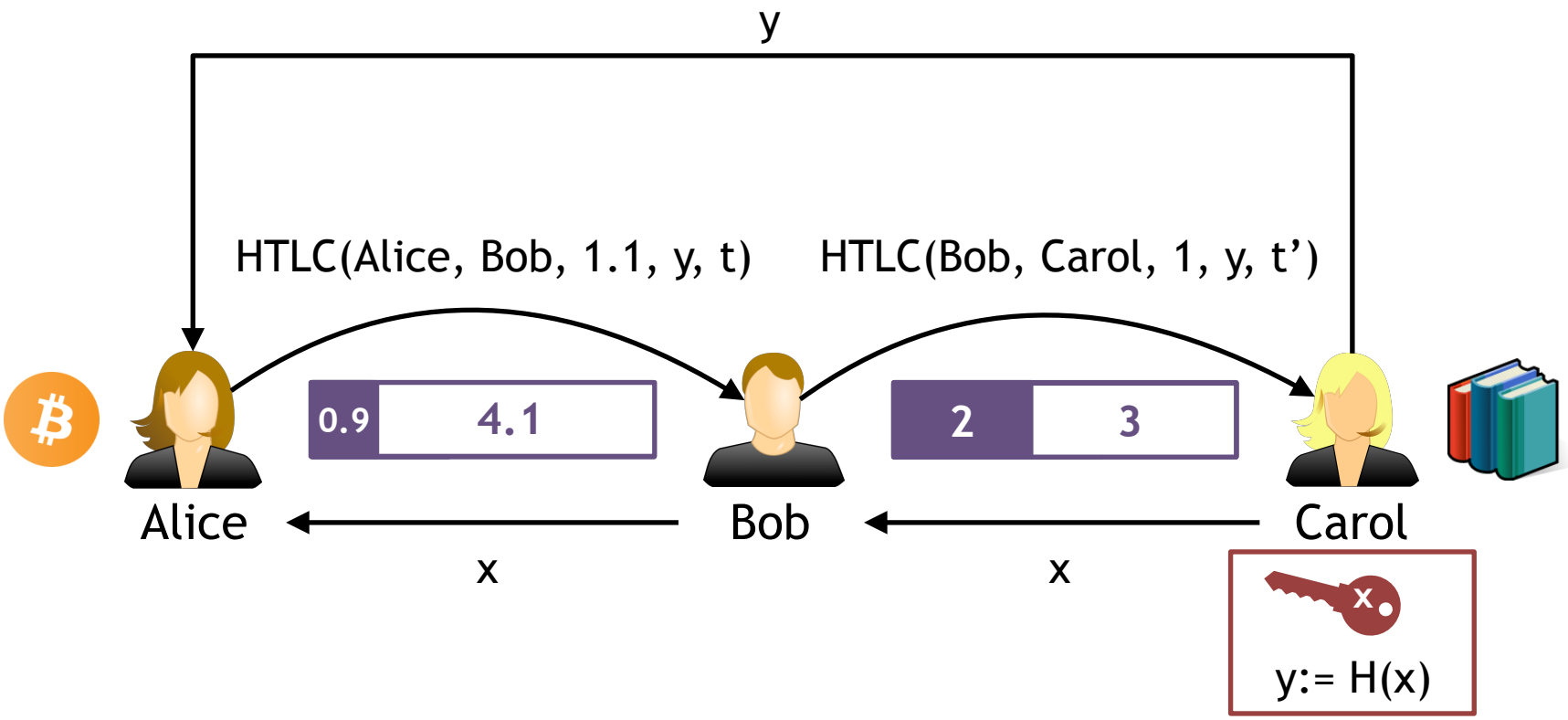

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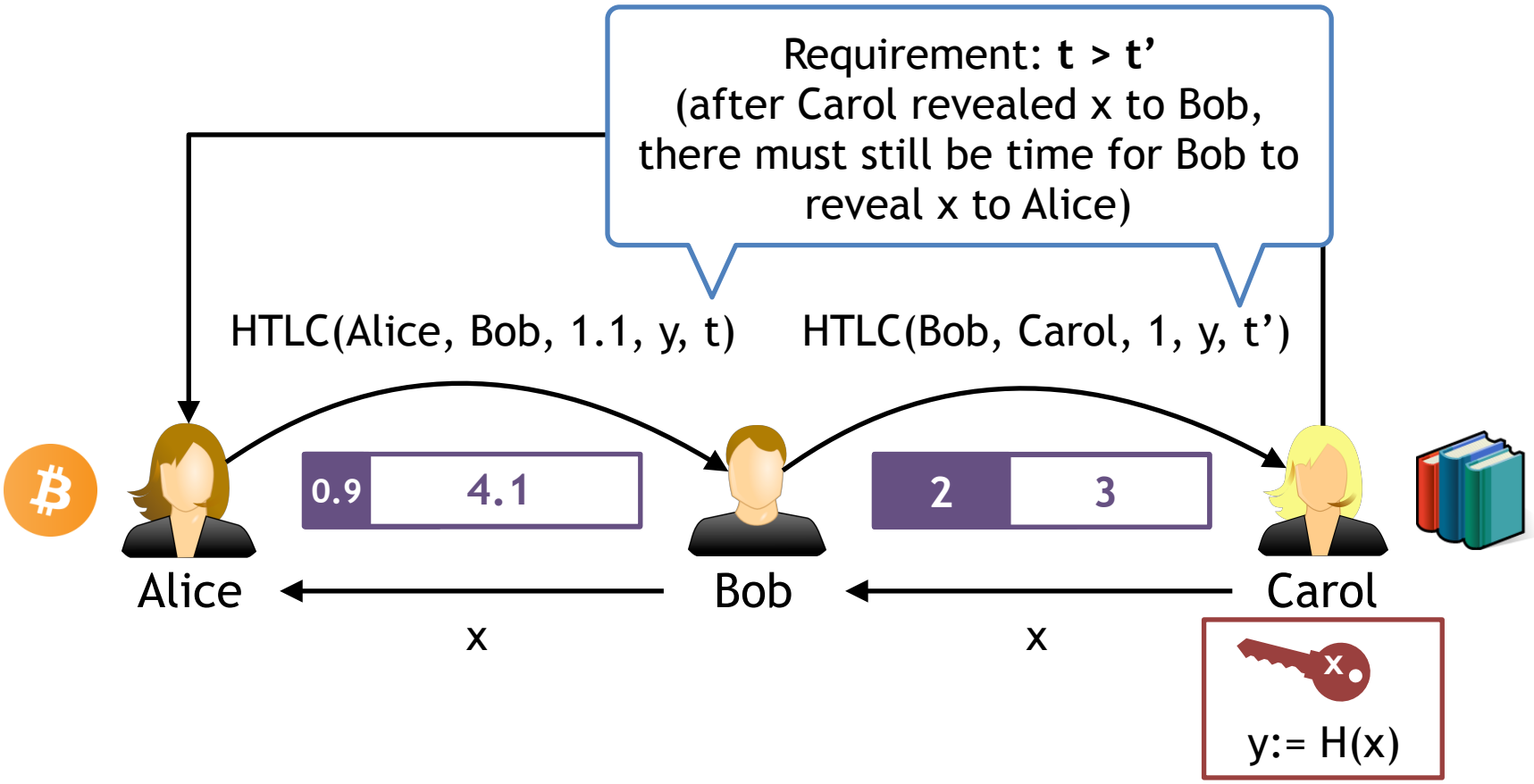

Security and Privacy Issues in Existing PCNs

Security + Privacy in PCNs

Are off-chain payments in PCNs secure?

(No honest participant looses money!)

Are off-chain payments in PCNs privacy-preserving by default?

(individual payments are not recorded on the blockchain!)

Security + Privacy in PCNs

Are off-chain payments in PCNs secure?

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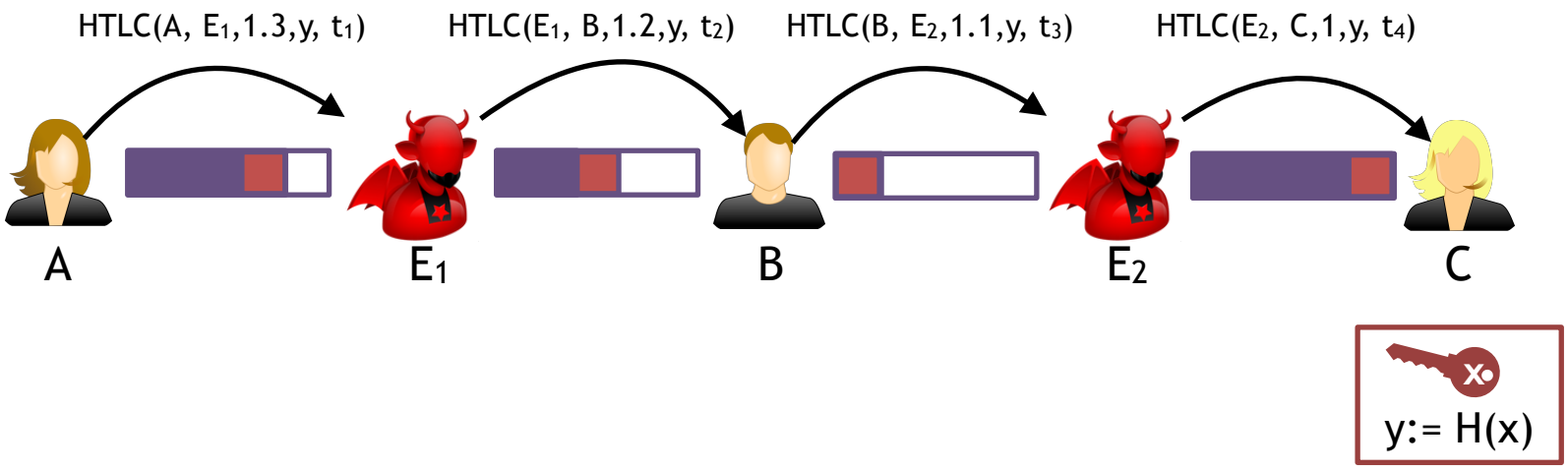
Security Issue: The Wormhole Attack



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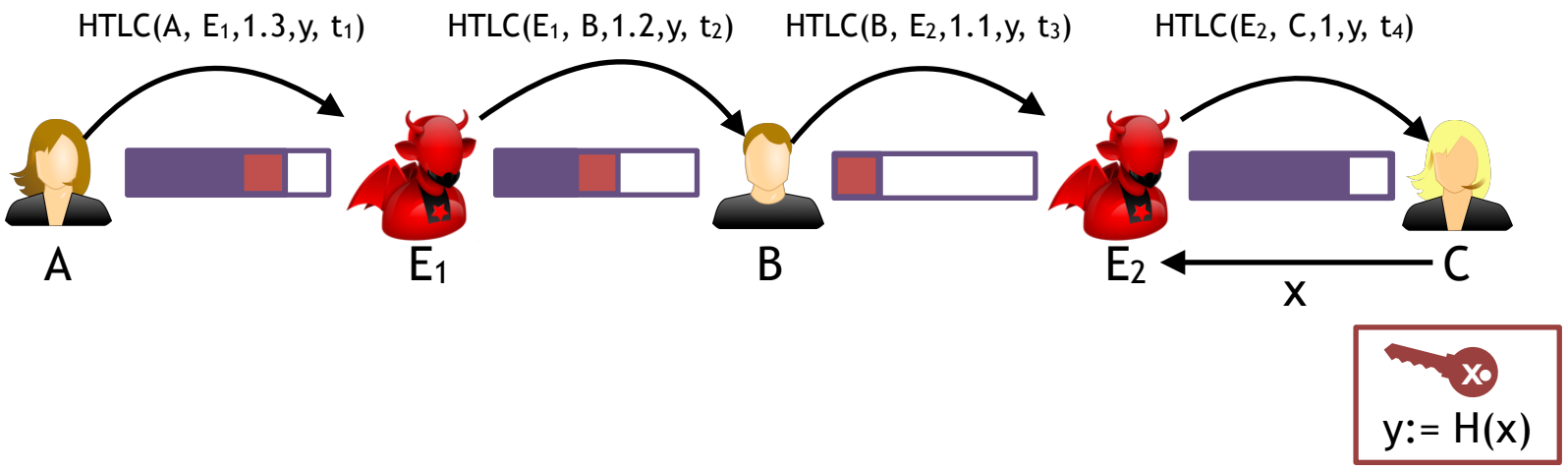

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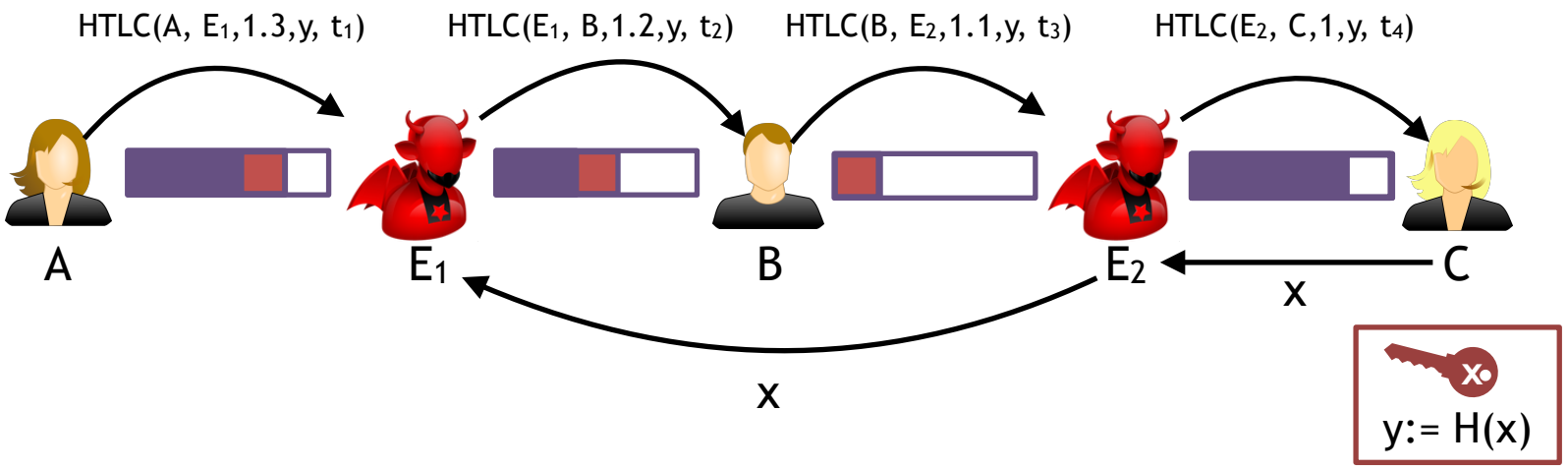

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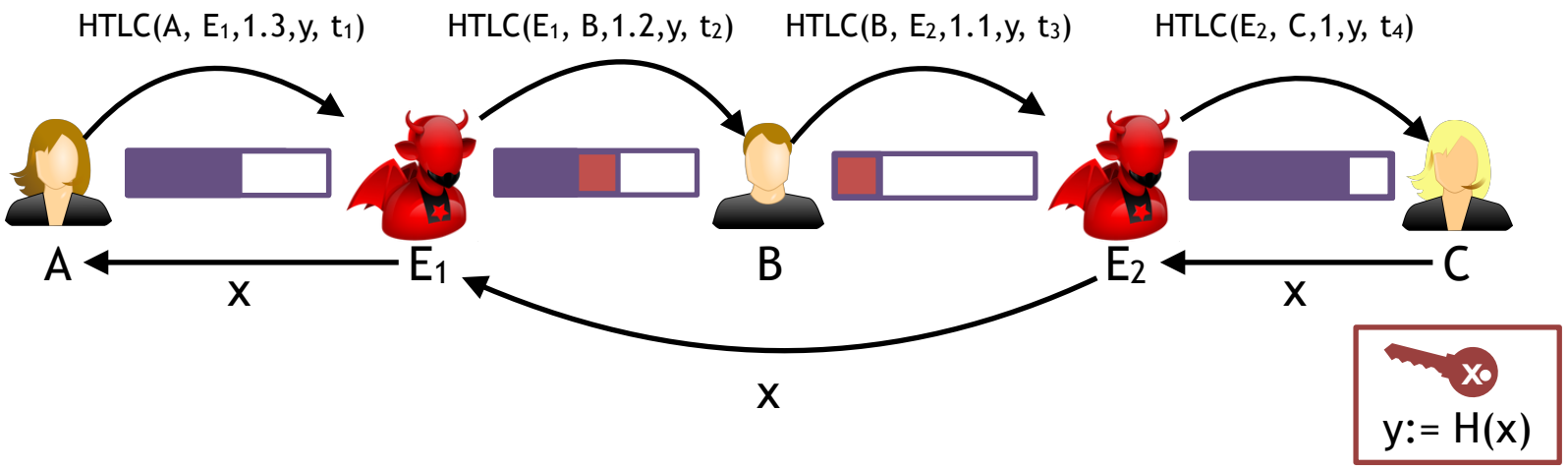

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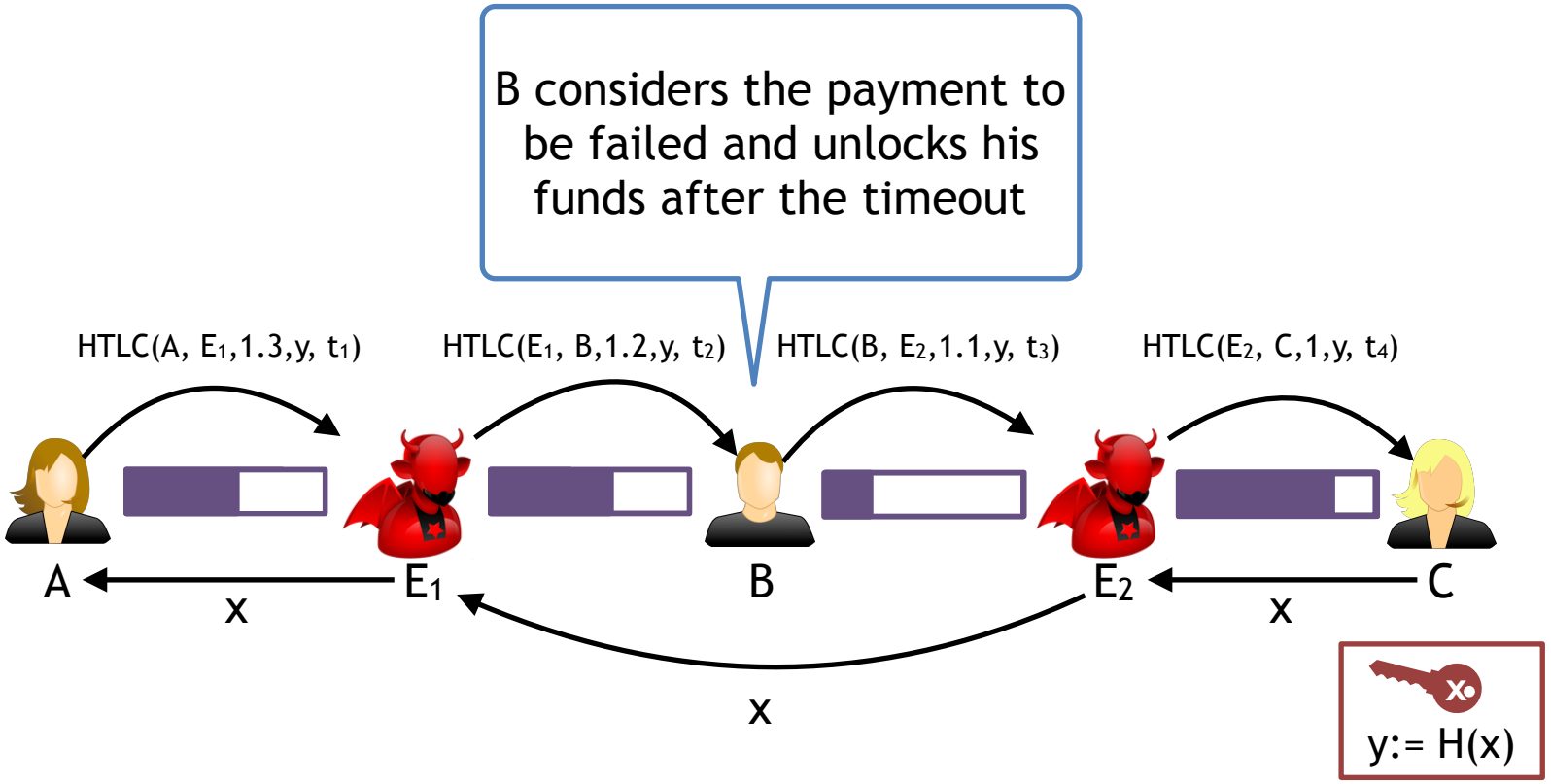

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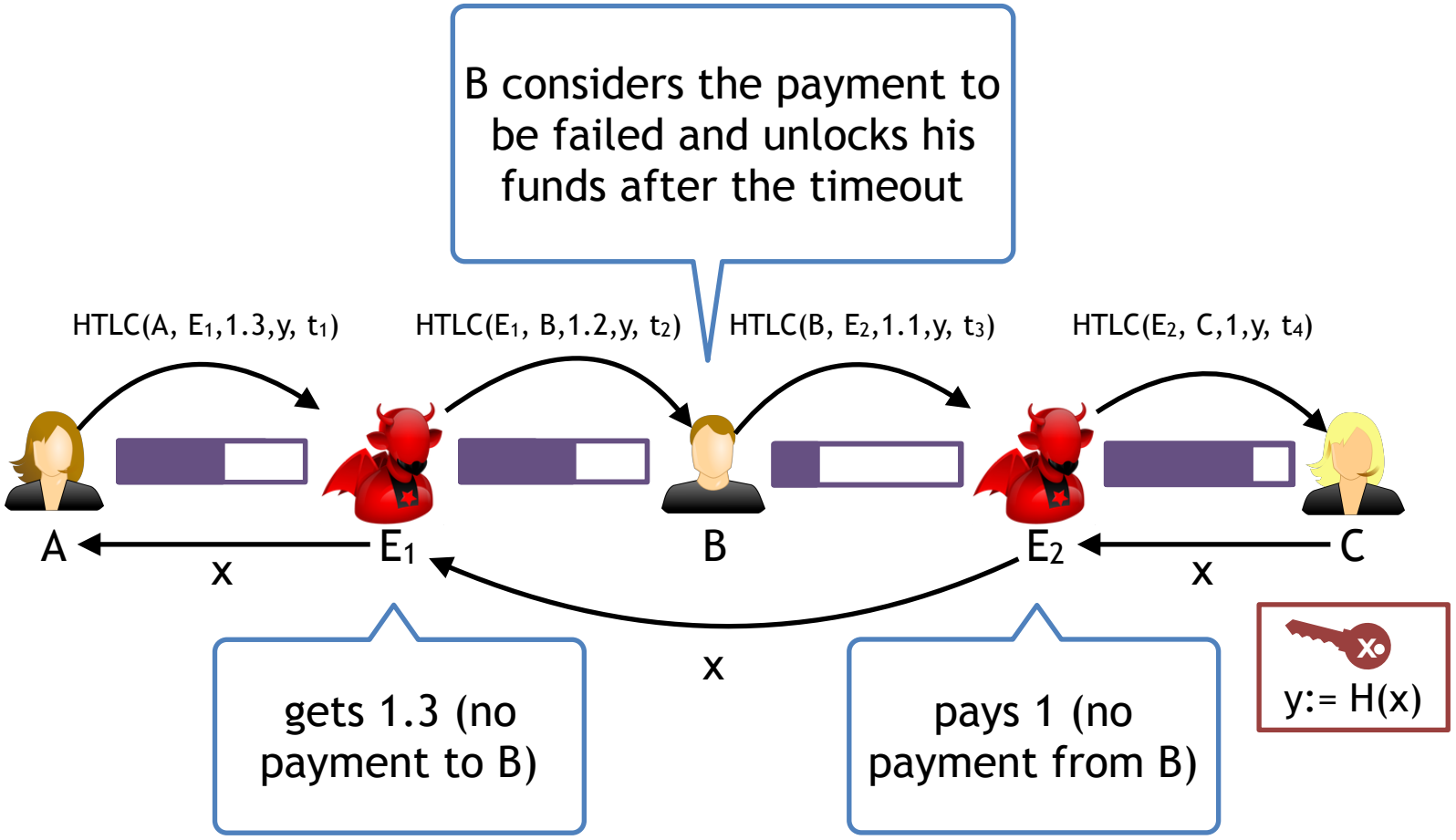
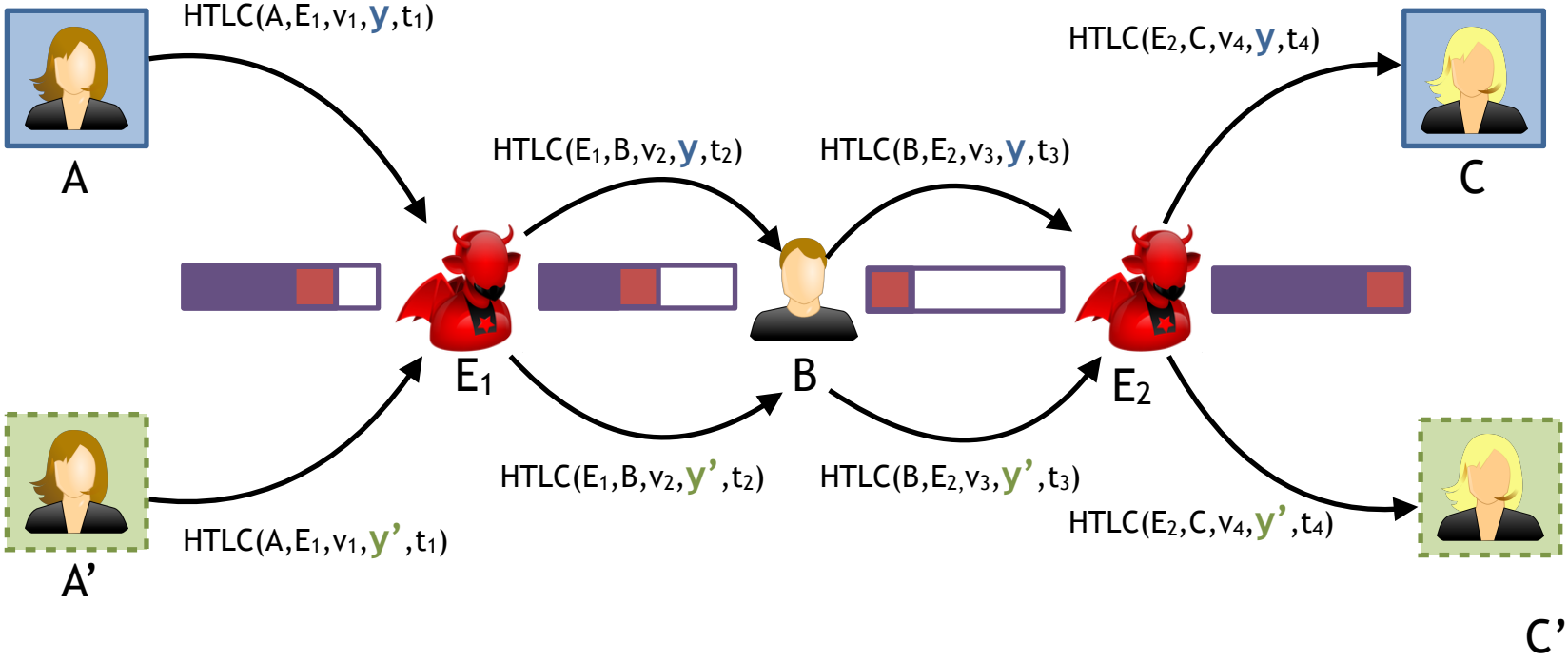


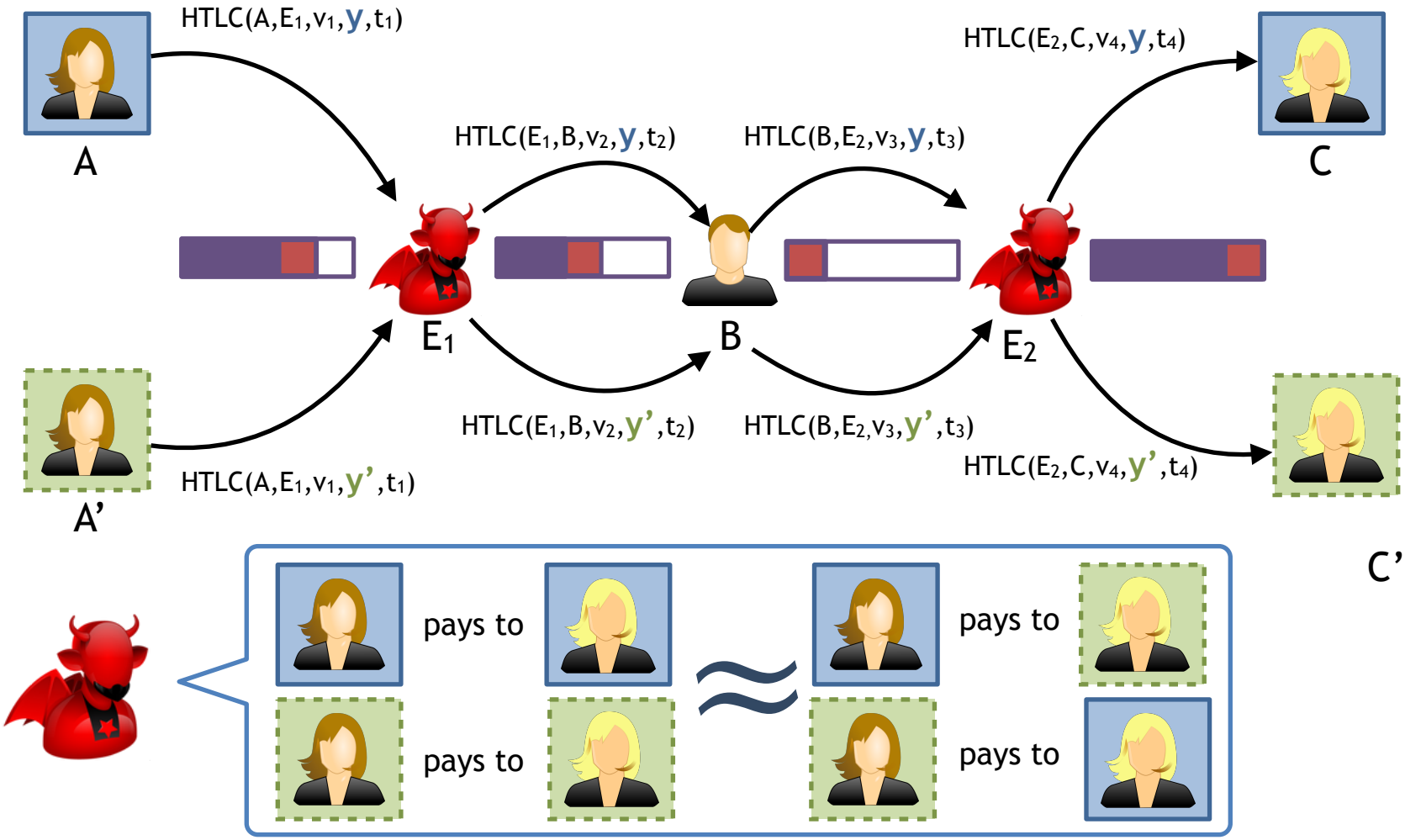
Attacker earns 0.3 BTC (own fees + B's fees)

Privacy Issues in HTLC-based Payments



Relationship Anonymity: On-path adversaries do not learn who pays to whom

Privacy Issues in HTLC-based Payments



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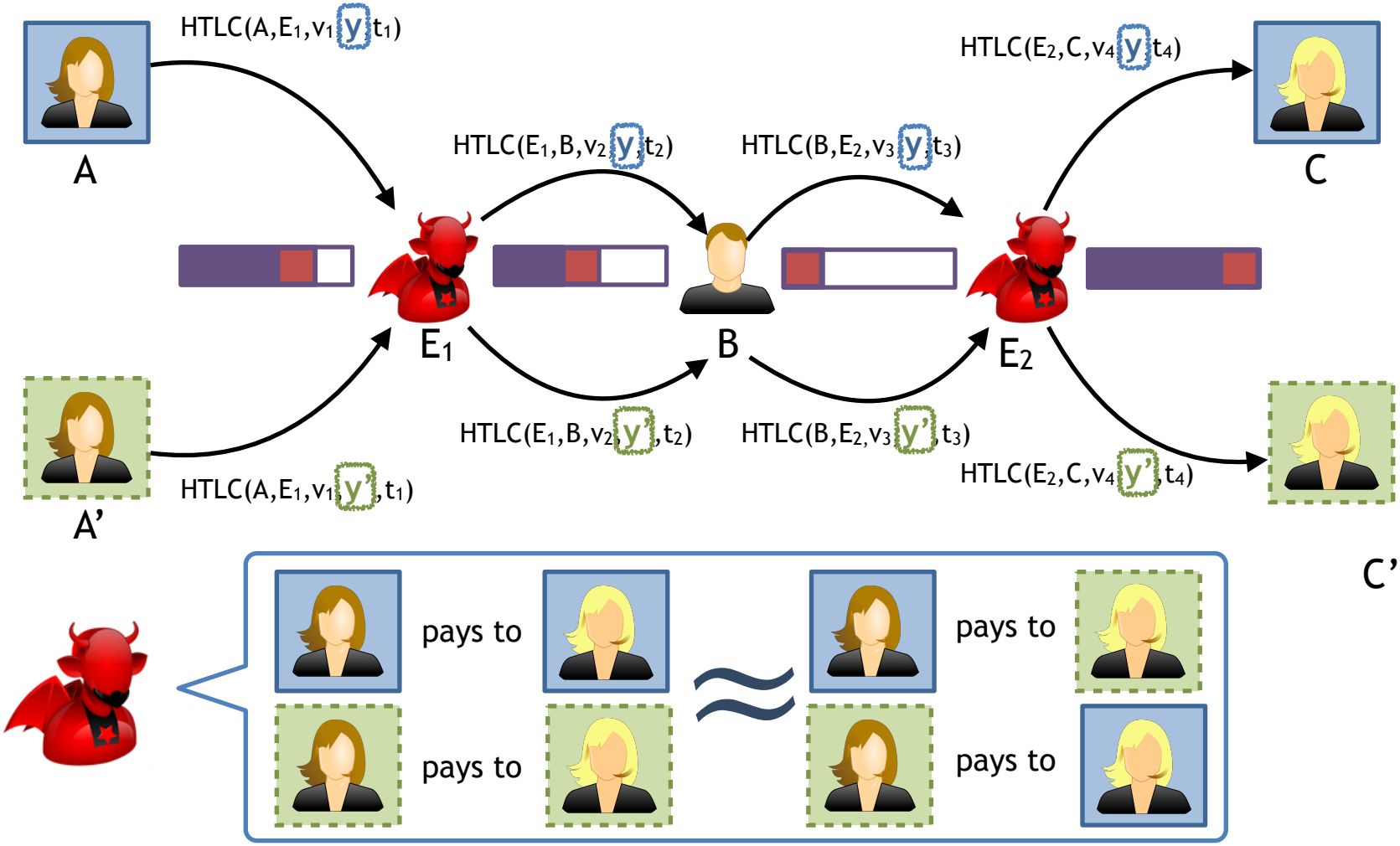

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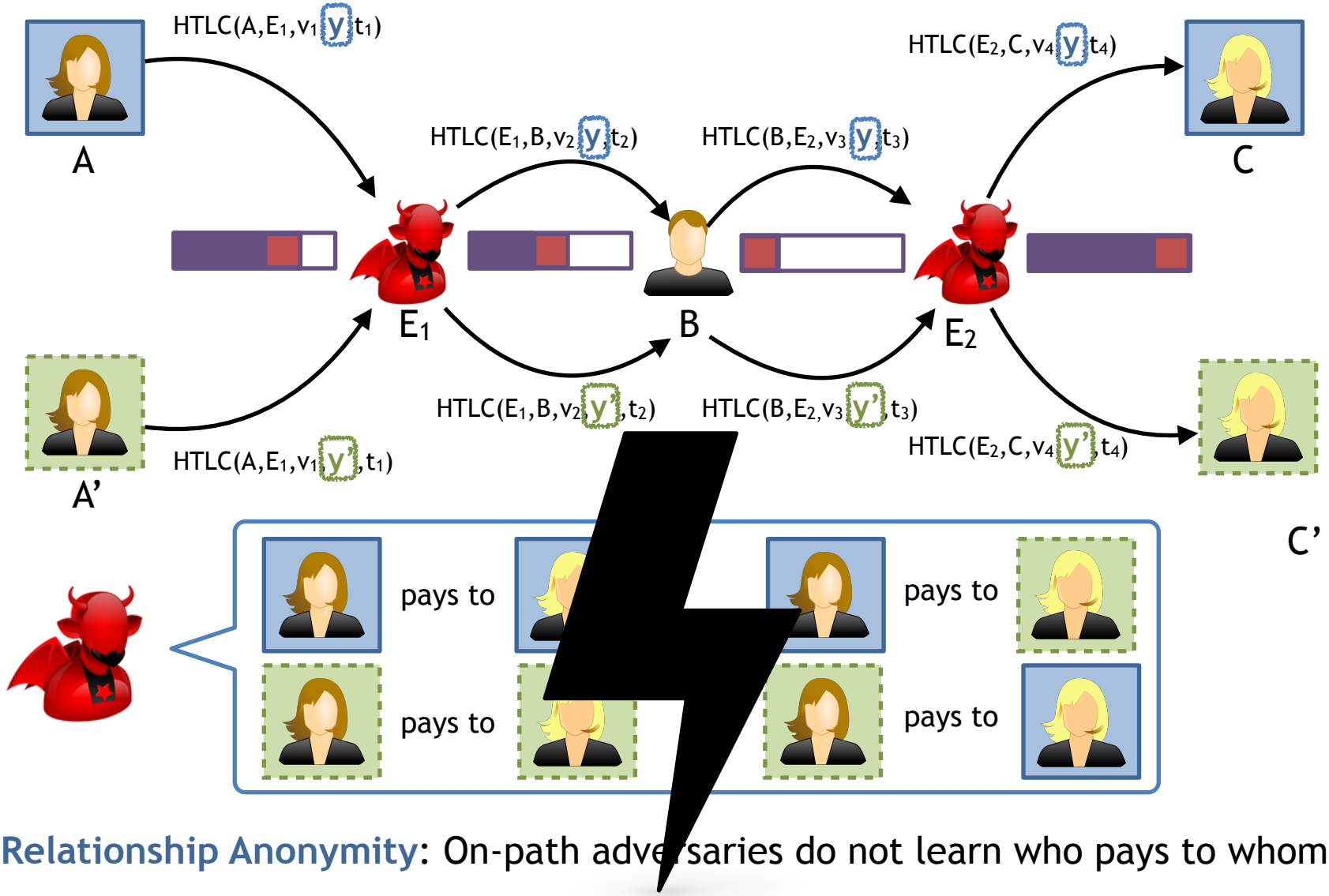
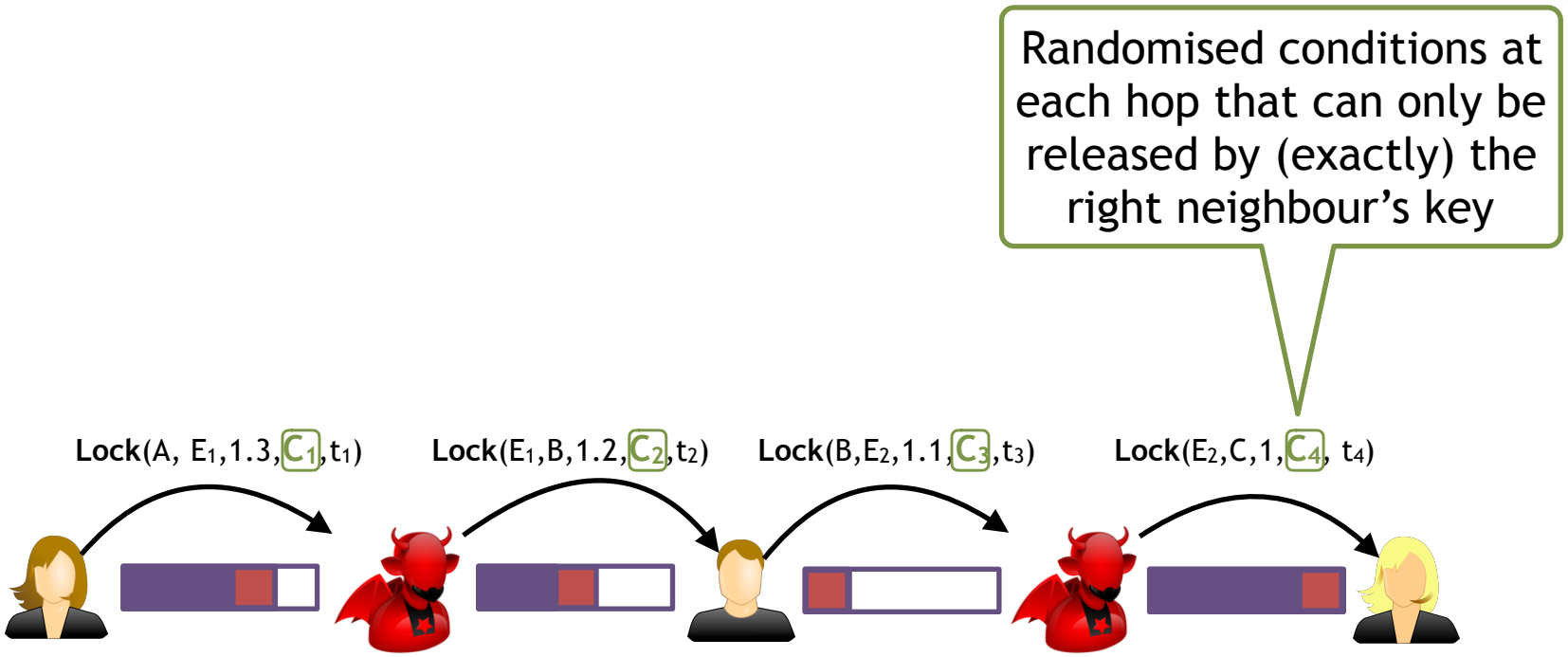


Relationship Anonymity: On-path adversaries do not learn who pays to whom

Solving Security and Privacy Issues in Payment Channel Networks

Solving Security + Privacy Issues



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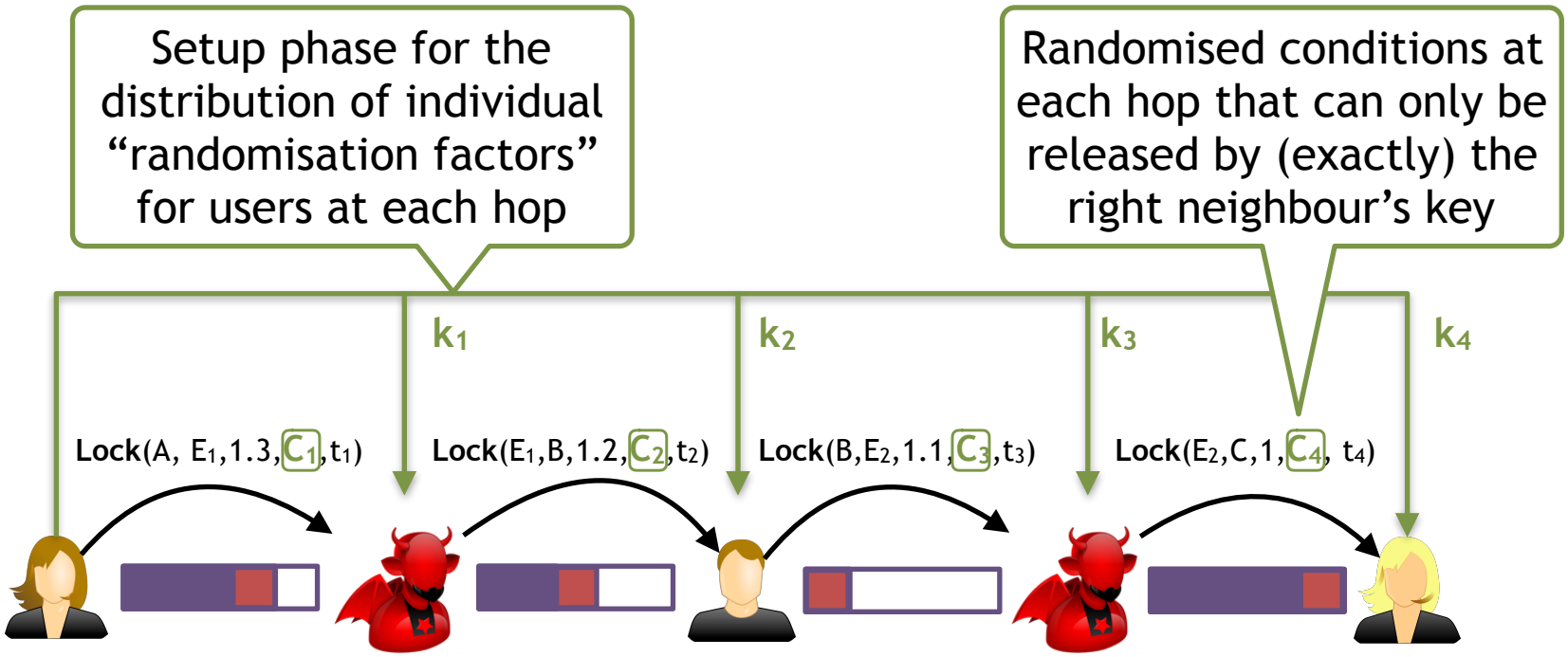

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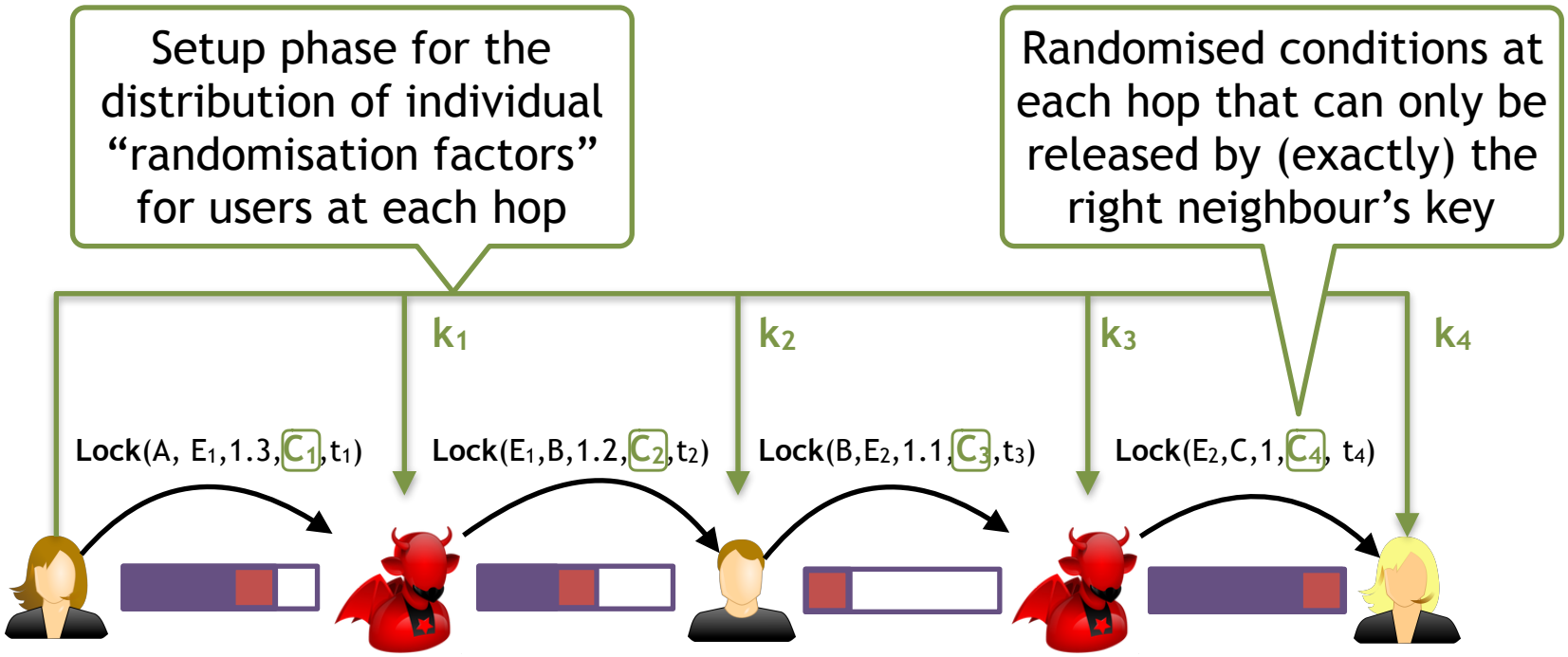
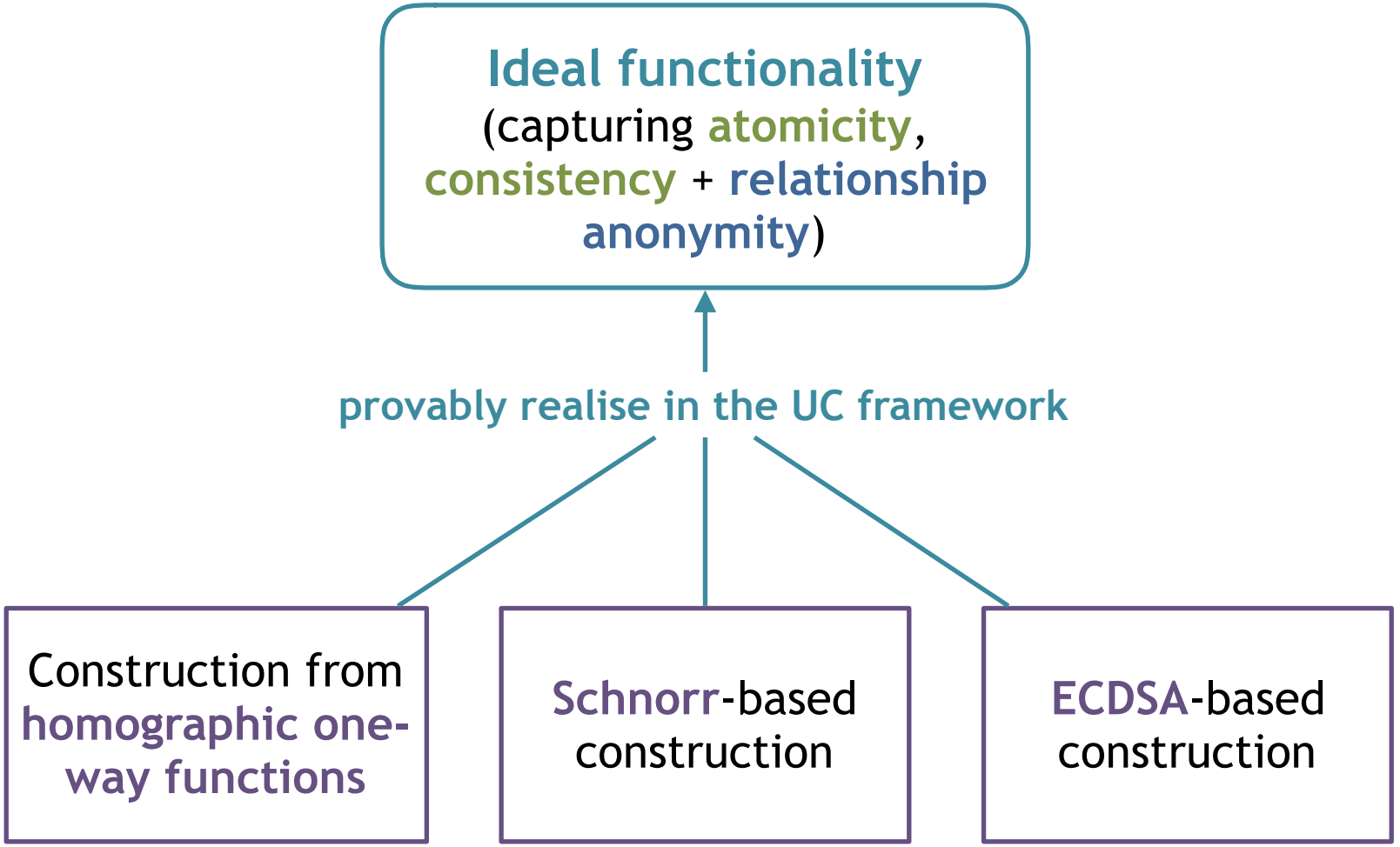


Desired Properties

1. **Atomicity**:
   If a user's right lock gets opened, he can open his left lock
2. **Consistency**:
   A user can open his left lock only if his right lock was released
3. **Relationship Anonymity**:
   A user learns about no other participant of the payment path than his direct neighbours

No coin loss	No Wormhole Attacks	Privacy

Anonymous Multi-hop-Locks (AMHL)



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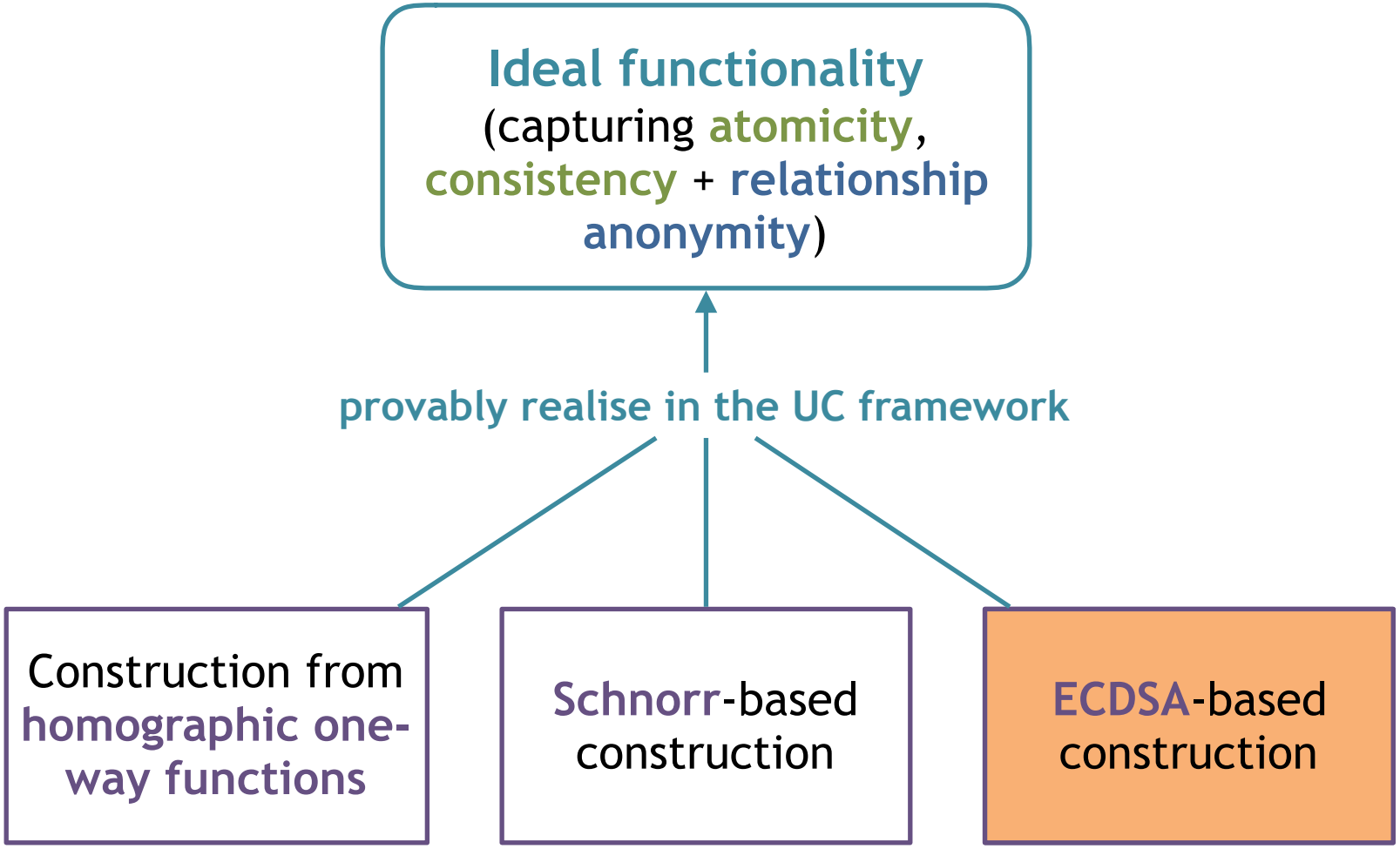


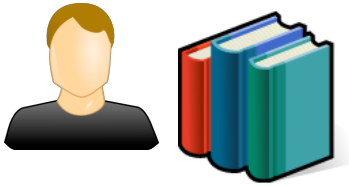
ECDSA-based Secure PCNs

Scriptless Scripts

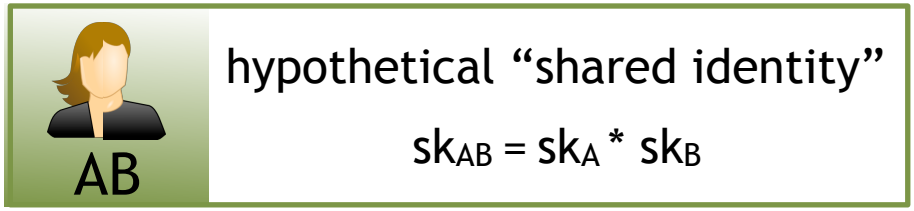
Scriptless Scripts

5

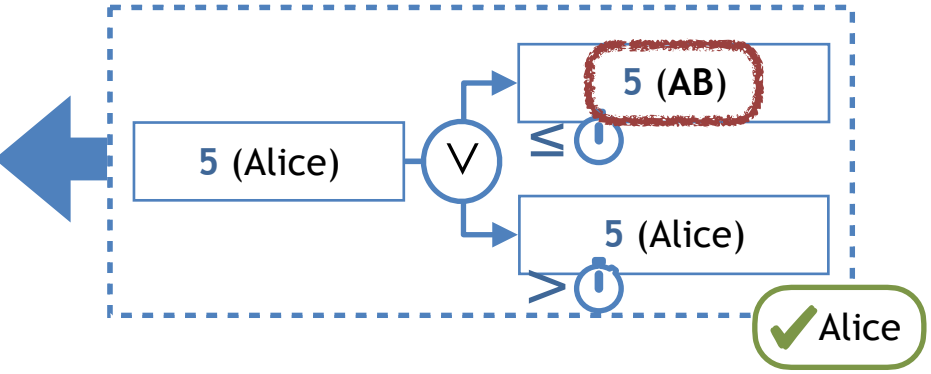
Alice
(sk_A)



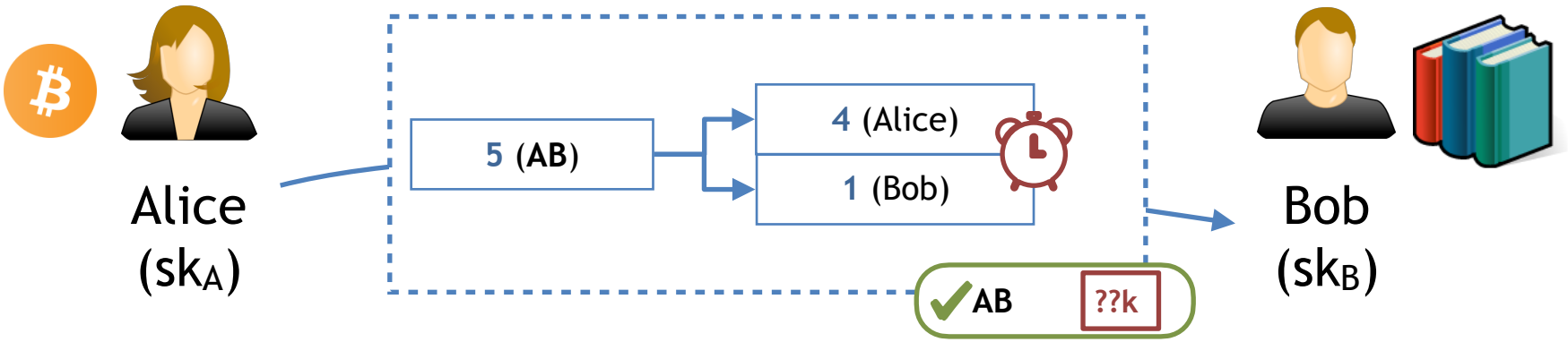
Bob
(sk_B)



Blockchain



Scriptless Scripts



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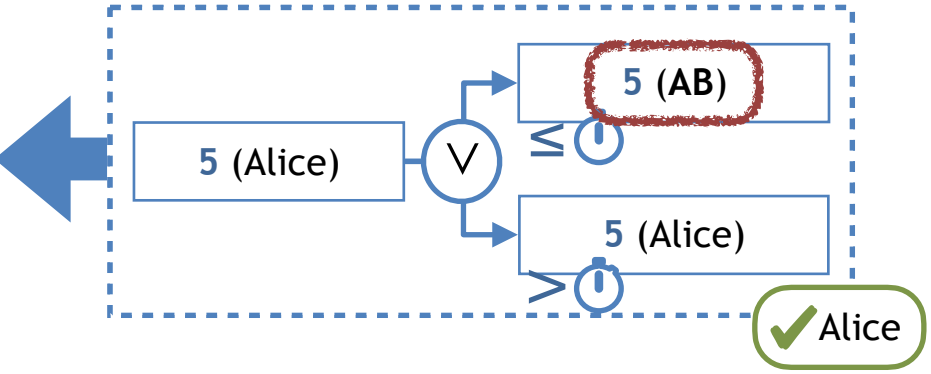
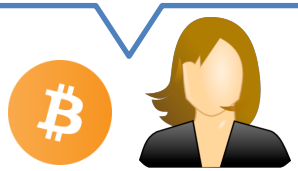


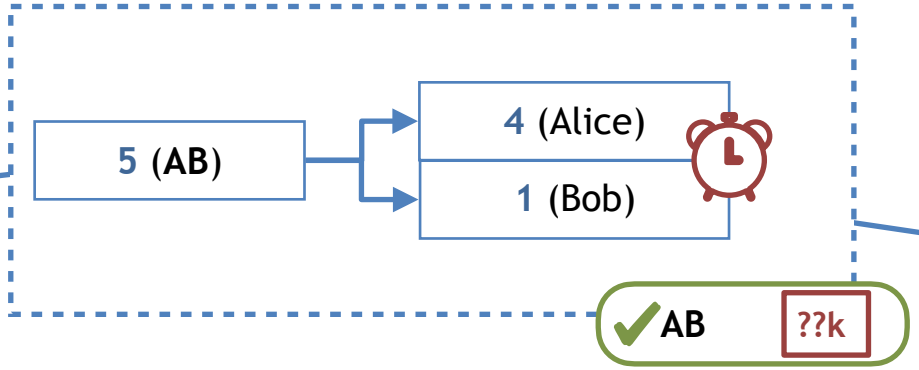
Scriptless Scripts

Alice gets sufficient information for producing a "half signature" that can be completed knowing secret **k**

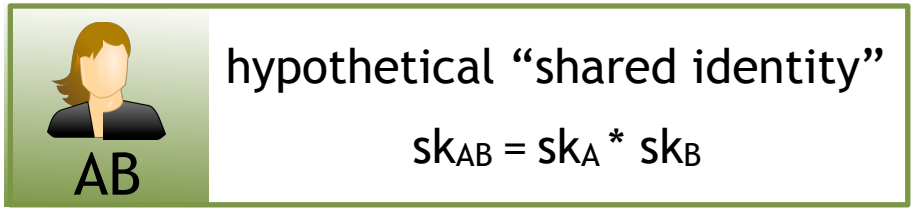
Bob gets sufficient information for checking that the "half signature" can be completed to a valid signature given **k**



Alice
(sk_A)



Bob
(sk_B)



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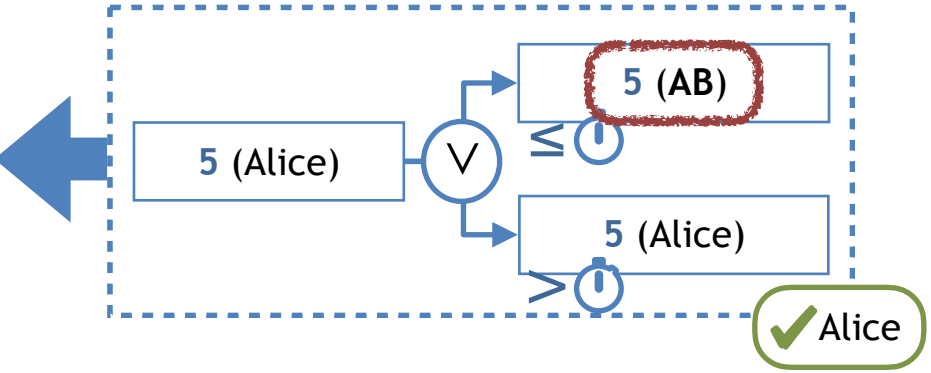
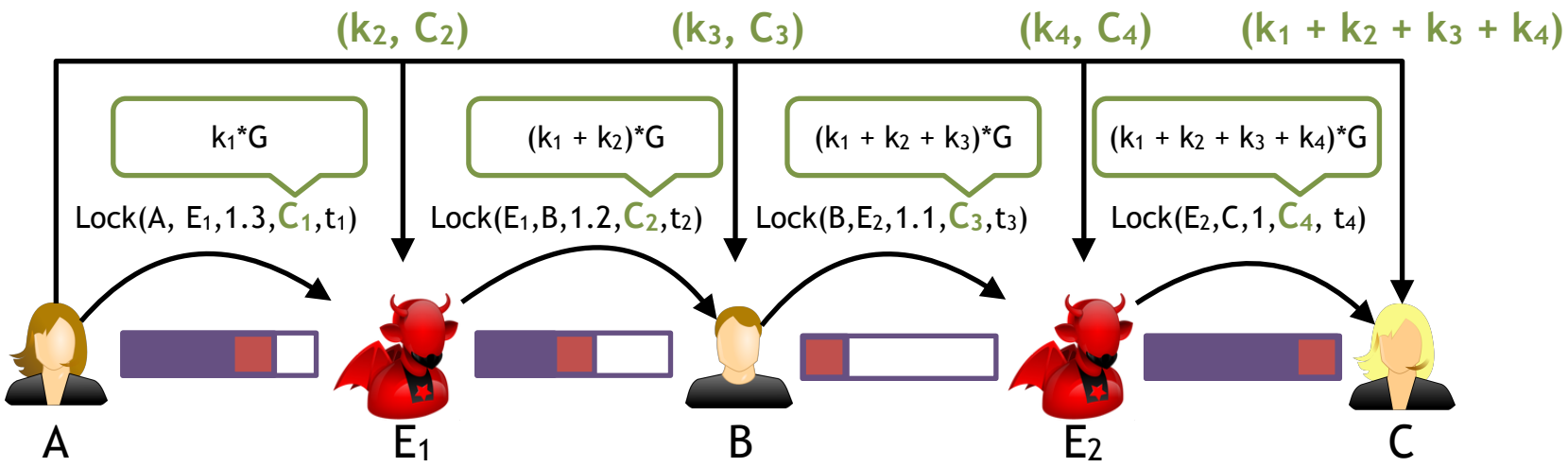


Extension to Multi-hop Locks



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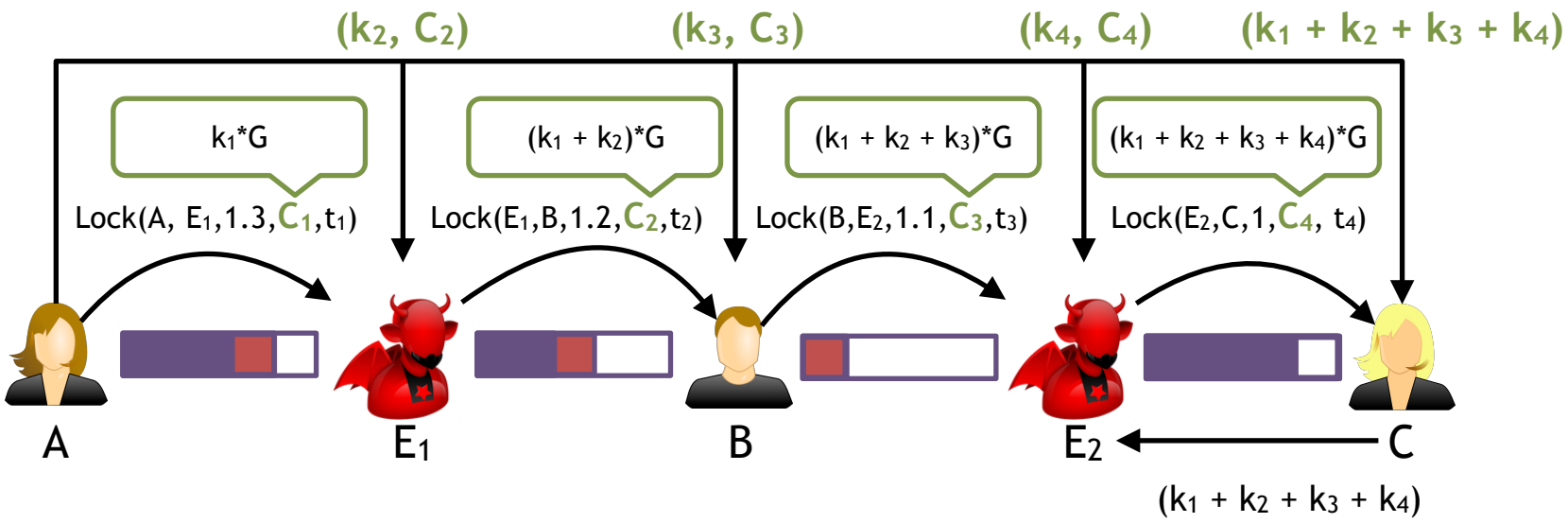
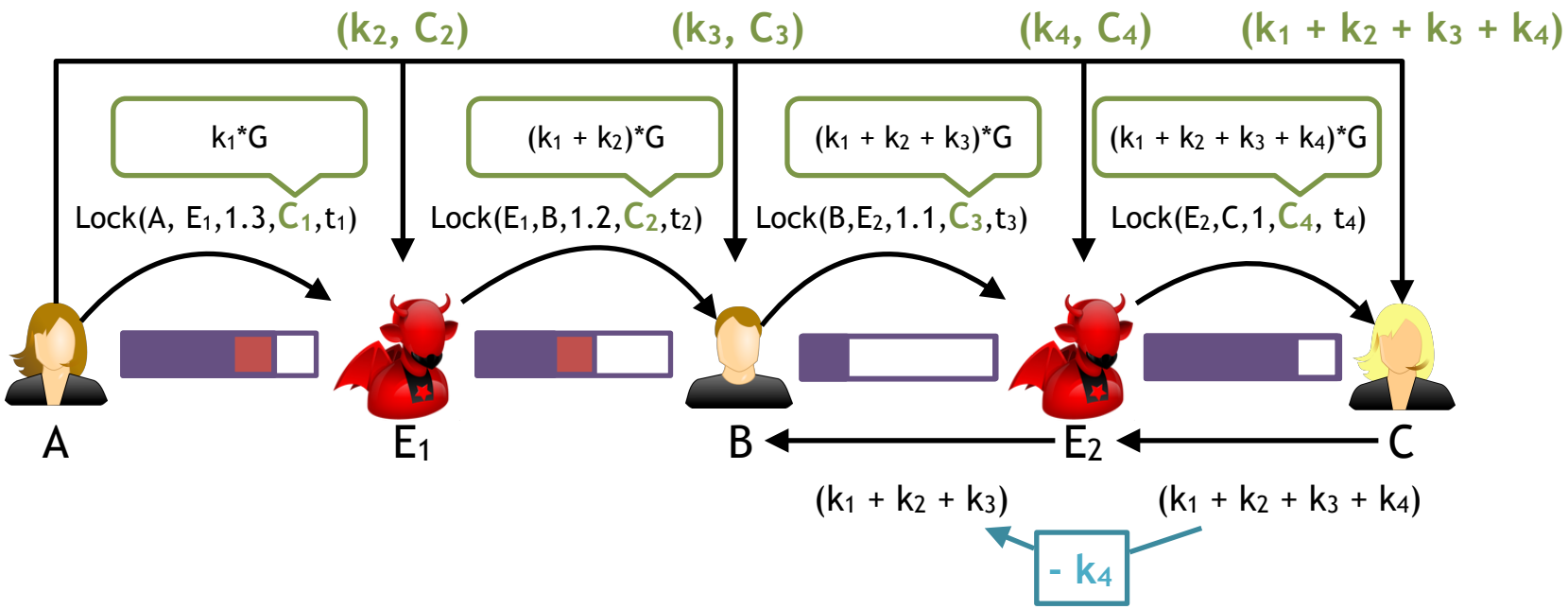
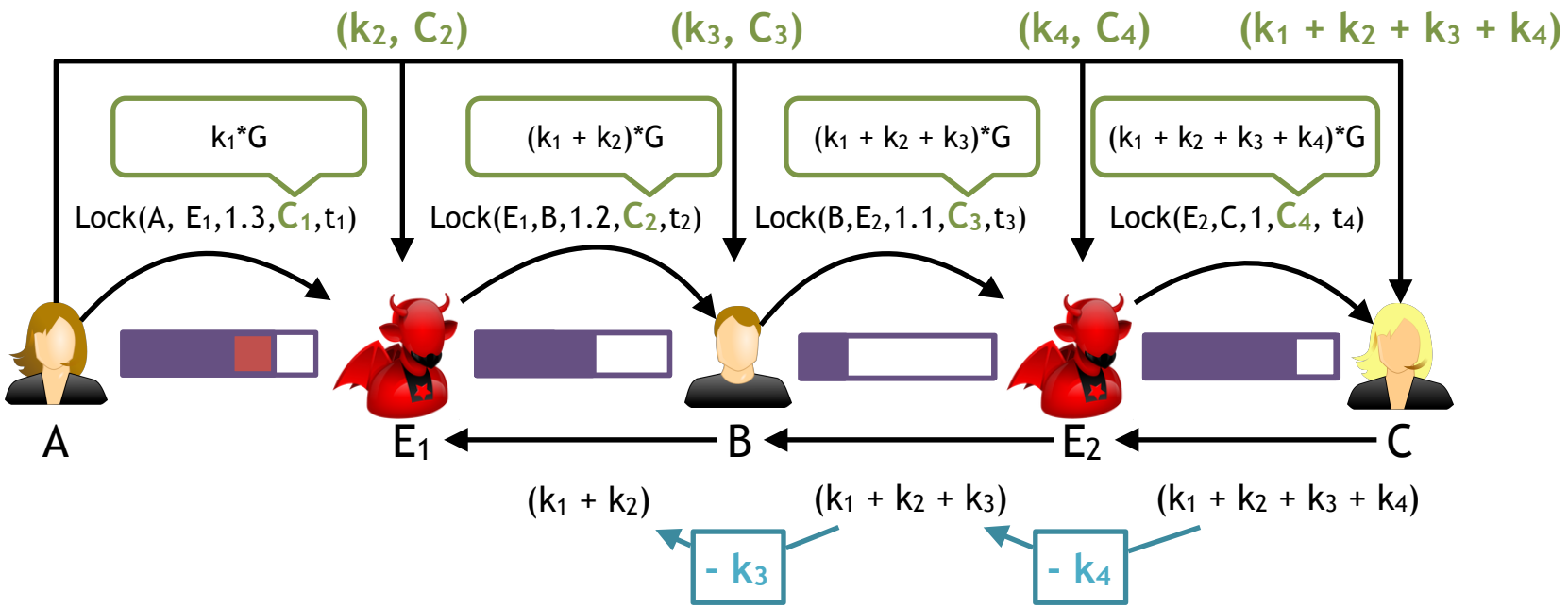


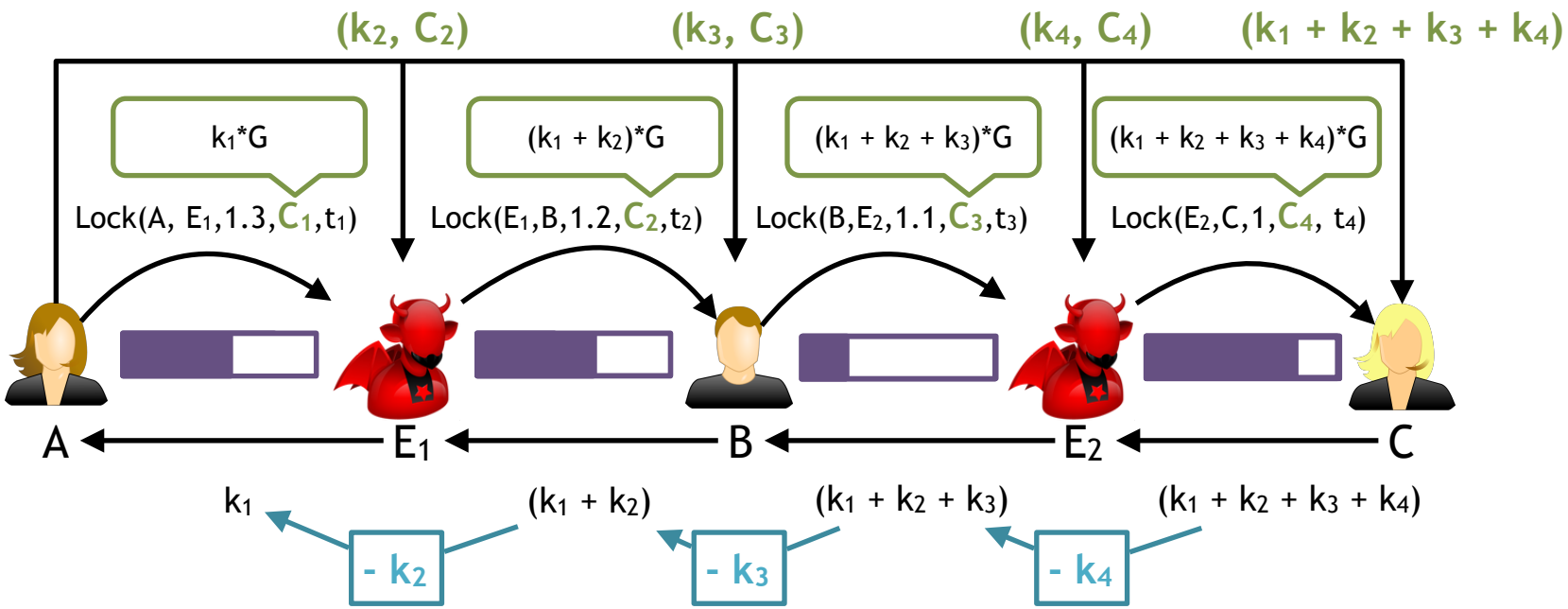
Extension to Multi-hop Locks



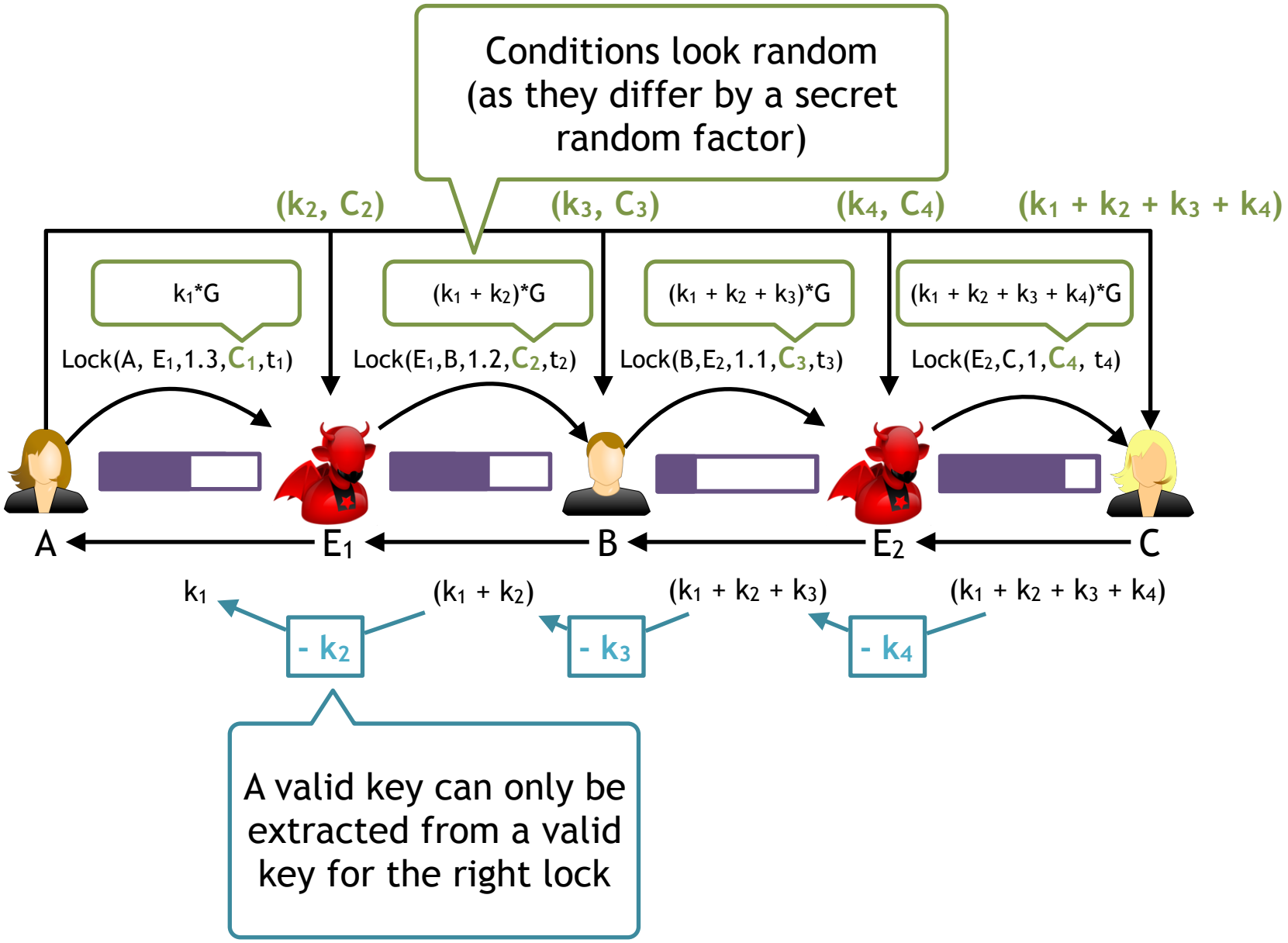
Extension to Multi-hop Locks



Extension to Multi-hop Locks



Extension to Multi-hop Locks



ECDSA-based Scriptless Lock

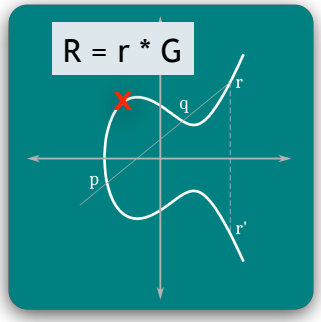
Signature w.r.t. a (public) random elliptic curve point R

secret randomness

secret key

message

σ_R = sign(r, sk, transaction)



ECDSA-based Scriptless Lock

Signature w.r.t. a (public) random elliptic curve point R

secret randomness

secret key

message

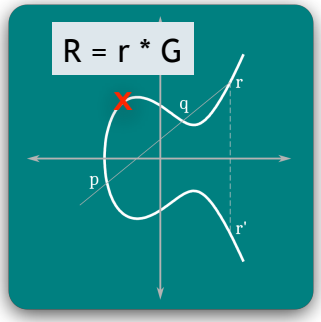
σ_R = sign(r, sk, transaction)

✔AB

$r_A * r_B * G$

$r_A * r_B$

$sk_A * sk_B$



shared signature using a shared key and randomness

ECDSA-based Scriptless Lock

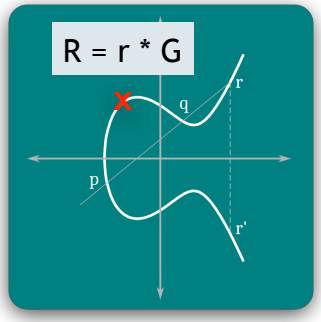
Signature w.r.t. a (public) random elliptic curve point R

secret randomness

secret key

message

σ_R = sign(r, sk, transaction)



✔AB

$r_A * r_B * G$

$r_A * r_B$

$sk_A * sk_B$

shared signature using a shared key and randomness

✔AB

$r_A * r_B * k * G$

$r_A * r_B * k$

$sk_A * sk_B$

embedding of random share (condition) **k**

ECDSA-based Scriptless Lock

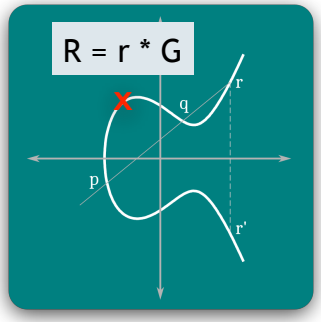
Signature w.r.t. a (public) random elliptic curve point R

secret randomness

secret key

message

$\sigma_R = \text{sign}(r, sk, \text{transaction})$



✔AB	r_A*r_B*G	r_A*r_B	sk_A*sk_B
✔AB	r_A*r_B*k*G	r_A*r_B*k	sk_A*sk_B
✔AB	r_A*r_B*k*G	r_A*r_B	sk_A*sk_B

shared signature using a shared key and randomness

embedding of random share (condition) k

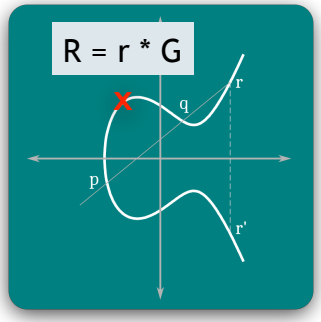
“half signature” without k but still with respect to r_A*r_B*k*G

ECDSA-based Scriptless Lock

Signature w.r.t. a (public) random elliptic curve point R

secret randomness | secret key | message

$\sigma_R = sign(r, sk, transaction)$



✓AB	r_A*r_B*G	r_A*r_B	sk_A*sk_B
✓AB	r_A*r_B*k*G	r_A*r_B*k	sk_A*sk_B
✓AB	r_A*r_B*k*G	r_A*r_B	sk_A*sk_B

shared signature using a shared key and randomness

embedding of random share (condition) k

“half signature” without k but still with respect to r_A*r_B*k*G

Lock Protocol

(sk_A, r_A)

$C=k*G$, transaction

…

“1/3” signature $\sigma_{R,B}$

“1/3” signature $\sigma_{R,A}$

(sk_B, r_B)

✓AB

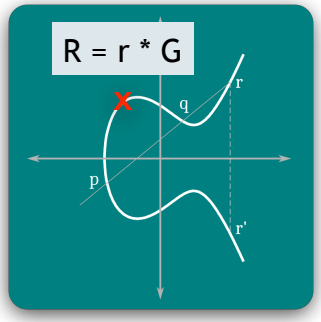
✓AB

ECDSA-based Scriptless Lock

Signature w.r.t. a (public) random elliptic curve point R

secret randomness | secret key | message

σ_R = sign(r, sk, transaction)



✓AB	r_A*r_B*G	r_A*r_B	sk_A*sk_B
✓AB	r_A*r_B*k*G	r_A*r_B*k	sk_A*sk_B
✓AB	r_A*r_B*k*G	r_A*r_B	sk_A*sk_B

shared signature using a shared key and randomness

embedding of random share (condition) k

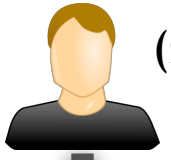
“half signature” without k but still with respect to r_A*r_B*k*G

Lock Protocol

(sk_A, r_A)

C=k*G, transaction

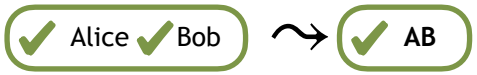
Hard for ECDSA as σ_R has a non-linear structure



(sk_B, r_B)

Properties/Evaluation

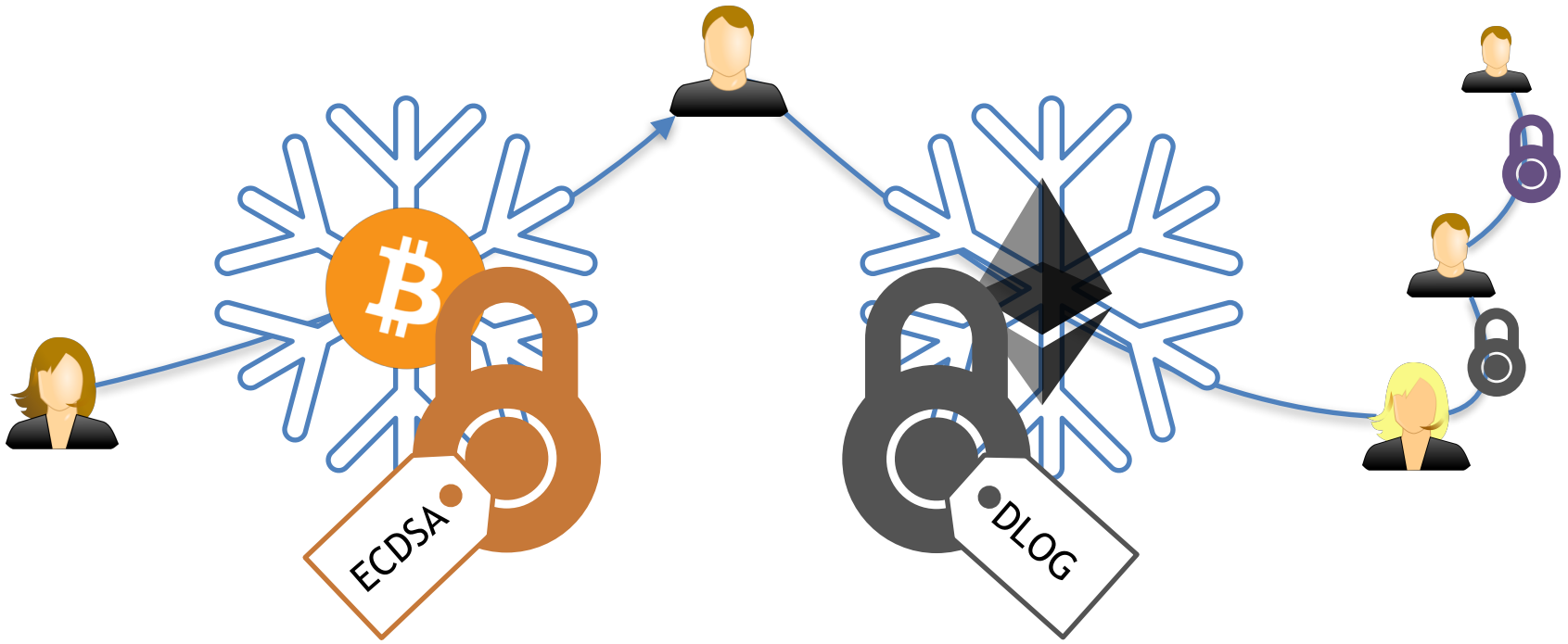
- Security and Privacy proven in the UC Framework
- Compatible with Bitcoin and current PCNs
  - ✓ Implemented in the Lightning Network (https://github.com/cfromknecht/tpec)
- Reduces transaction size for conditional payments
  - ✓ Encoding of condition within signature 

- Makes settlement transactions indistinguishable from regular ones (Fungibility) 

- Little overhead:
  - ✓ < 500 bytes communication
  - ✓ few ms computation

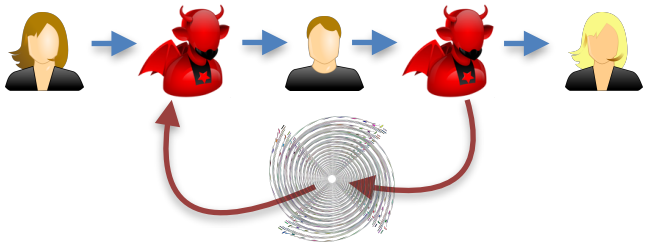
Interoperability

- AMHLs are suitable for cross-currency usage
  - even with different primitive instantiations
  - ✓ Inter-currency payment channels
  - ✓ Atomic swaps

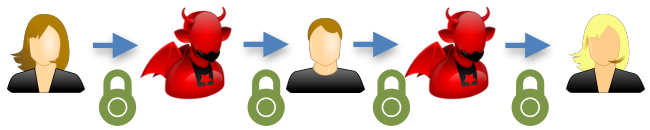


Summary

The **Wormhole Attack**:
A novel attack on Payment Channel Network Security



AMHLs: A **new primitive** for secure + anonymous Payment Channel Networks

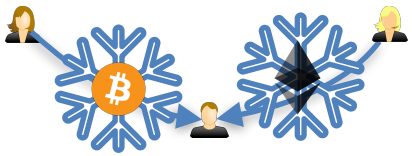


Concrete **constructions** of AMHLs that

… are efficient

… got implemented in Bitcoin's Lightning Network

… enable inter-blockchain Payment Channels

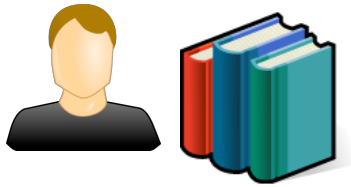


Additional Material

HTLC in practice

Alice

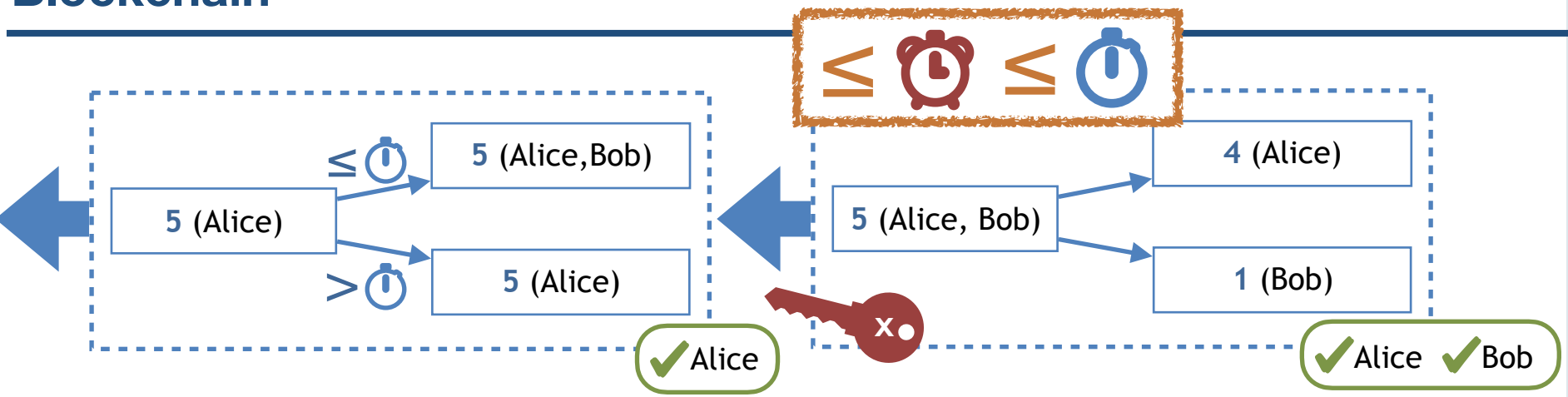
HTLC (Alice, Bob, 1, y, ⏰):
Alice pays Bob 1 BTC iff Bob shows some x such that H(x) = y before ⏰



Bob

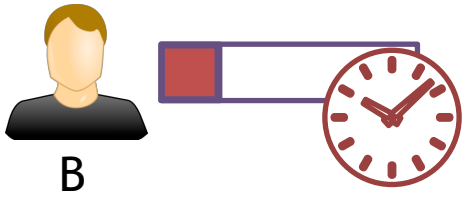
Transaction can only be added
1) Before the expiration of the payment channel
2) Before the expiration of the HTLC
3) when providing the pre-image x

Blockchain



Implications of the Wormhole Attack

- Collateral cost: Honest intermediaries' coins are locked (cannot be used in a successful payment)



- Attacked intermediaries cannot distinguish between an attack and a failed payment

➡ Destroys the incentive for intermediaries to participate in multi-hop payments at all

Properties of Multi-hop-lock-based PCN

Atomicity

Balance Security

Consistency

Prevents Wormhole Attacks

Relationship Anonymity

(limited) Privacy

Minimal requirements

which (cryptographic) constructs are needed for implementing the Locks

Compatibility + Interoperability

Communication

Which amount of communication is required for building payment paths from locks

Performance

Blockchain Effects

How do the locks influence the transactions visible on the Blockchain

Fungibility + Blockchain growth

Properties of the Different Constructions

	Current PCN	OWH-based PCN	Schnorr-based PCN	ECDSA-based PCN
Atomicity	✔	✔	✔	✔
Consistency	✘	✔	✔	✔
Privacy	✘	✔	✔	✔
Compatibility/ Interoperability	✘	partly	partly	✔
Fungibility + reduced transaction size	✘	✘	✔	✔

Scriptless Locks

signature with respect to message m and (random) point (R_x,R_y) on a elliptic curve

Schnorr Signature

m

$$(R_x, R_y) = r * G$$

$$r + sk * m$$

ECDSA Signature

$$\frac{R_x * sk + m}{r}$$

simple linear combination of additive key and random shares

Signature of shared key and randomness

complex combination (x-coordinate, multiplicative shares, inverse)

$$= (r_A + r_B) * G$$

$$= (r_A * r_B) * G$$

$$(r_A + r_B) + (sk_A + sk_B) * m$$

$$\frac{R_x * sk_A * sk_B + m}{r_A * r_B}$$

Embedding of arbitrary random shares (conditions)

$$= (r_A + r_B + k) * G$$

$$= (r_A * r_B * k) * G$$

$$(r_A + r_B + k) + (sk_A + sk_B) * m$$

$$\frac{R_x * sk_A * sk_B + m}{r_A * r_B * k}$$

$$\sigma_{sk_A * sk_B}^{(r_A * r_B * k) * G}(m, r_A * r_B * k)$$

ECDSA-based Lock

For condition $C = k*G$ compute signature $\sigma^{/\{k\}}$ s. t. $\frac{\sigma^{/\{k\}}}{k} = \sigma_{sk_{AB}}^{r_A * r_B * C}(m, r_A * r_B * k)$

pk_{AB} m

sk_A

Alice

AB

$(sk_{AB}, pk_{AB}) = (sk_A * sk_B, sk_A * sk_B * G)$

pk_{AB} m

Alice

sk_A

sk_B

Bob

$r_A, R_B = r_B*G$

$R = (R_x, R_y) = r_A*r_B*C$

joint randomness generation

$r_B, R_A = r_A*G$

$R = (R_x, R_y) = r_A*r_B*C$

$= r_A*r_B*k*G$

Alice $\sigma^{/\{k, r_A\}}$

Alice $\sigma^{/\{k, r_A\}}$:= Alice $\sigma_{sk_{AB}}^{R}(m, r_B)$

$\sigma^{/\{k\}} := \frac{\sigma^{/\{k, r_A\}}}{r_A}$

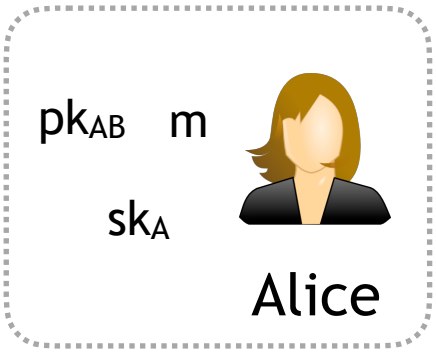
$= \sigma_{sk_{AB}}^{R}(m, r_A * r_B)$

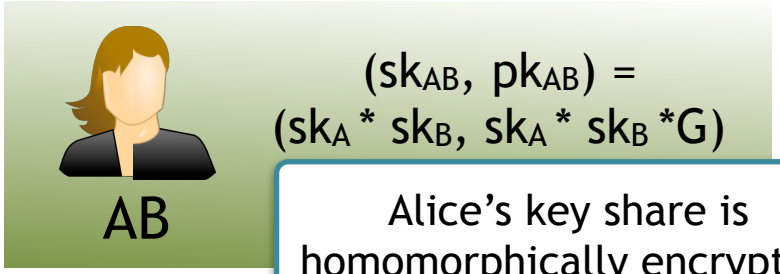
$\sigma^{/\{k\}}$

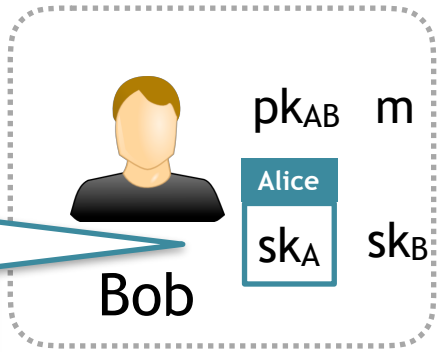
requires sk_A and hence can only be performed under homomorphic encryption for Alice

ECDSA-based Lock

For condition $C = k*G$ compute signature $\sigma^{/\{k\}}$ s. t. $\frac{\sigma^{/\{k\}}}{k} = \sigma_{sk_{AB}}^{r_A * r_B * C}(m, r_A * r_B * k)$







$r_A, R_B = r_B*G$

$R = (R_x, R_y) = r_A*r_B*C$

$= r_A*r_B*k*G$

$r_B, R_A = r_A*G$

$R = (R_x, R_y) = r_A*r_B*C$

Alice $\sigma^{/\{k, r_A\}}$

Alice $\sigma^{/\{k, r_A\}}$:= Alice $\sigma_{sk_{AB}}^{R}(m, r_B)$

$\sigma^{/\{k\}} := \frac{\sigma^{/\{k, r_A\}}}{r_A}$

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$\sigma^{/\{k\}}$

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