Encryption to the Future

A Paradigm for Sending Secret Messages to Future (Anonymous) Committees

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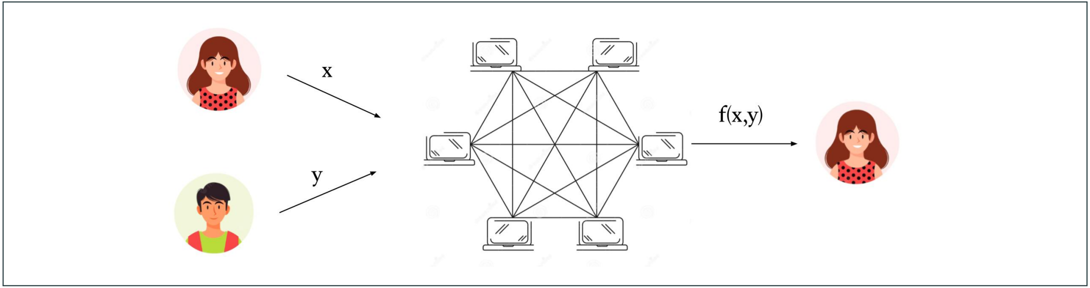
Application: Large-Scale MPC on Public Blockchains



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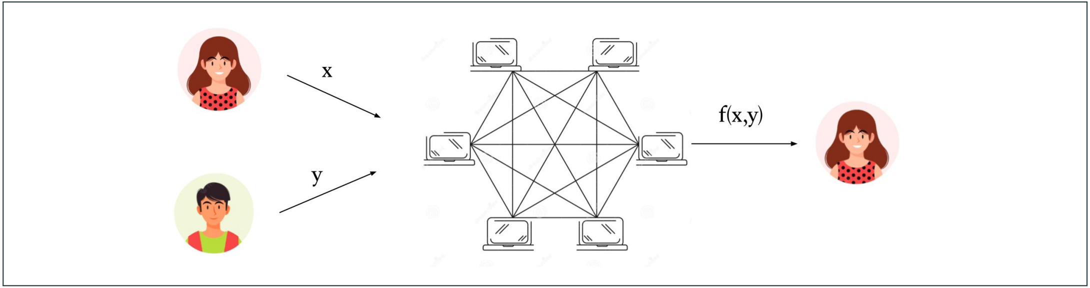

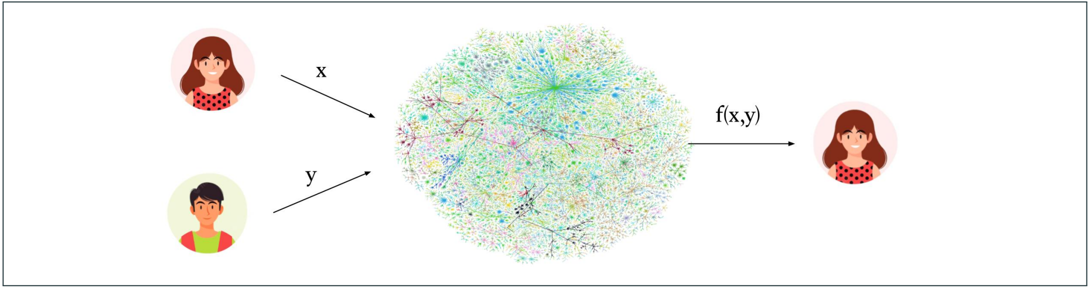

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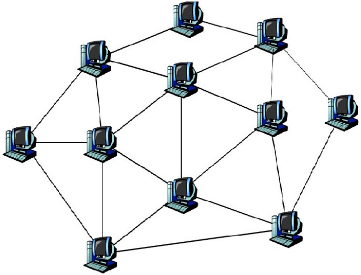
- High-level: (incentivized) coordination platform for miners/stakeholders.
- Blockchains are large public, dynamic P2P networks.
- Built-in consensus layer



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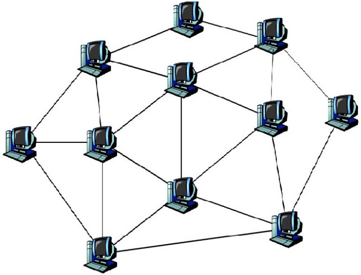

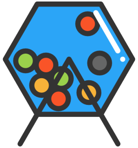

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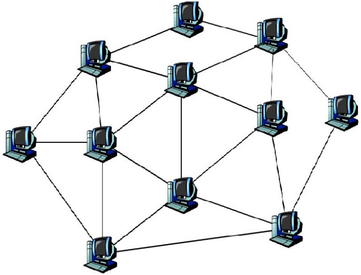

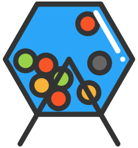

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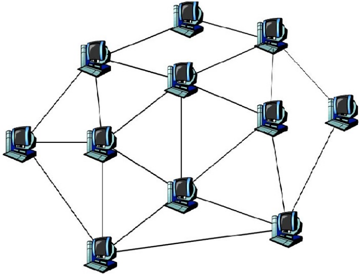

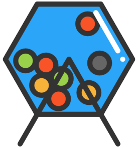

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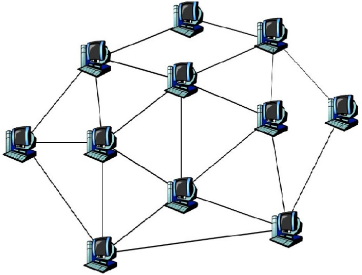

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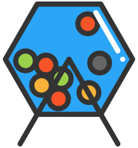
- YES! [BGG$^+$20, GHK$^+$21, CGG$^+$21]



Application: Large-Scale MPC on Public Blockchains

YOSO MPC [GHK$^+$21]

- Mobile Adversary - imposes requirements on the protocol
  - Limited Interaction Pattern (Only Speak Once)
  - Protocol parties are selected at random and are anonymous until they speak

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- Mobile Adversary - imposes requirements on the protocol
  - Limited Interaction Pattern (Only Speak Once)
  - Protocol parties are selected at random and are anonymous until they speak
- Attractive Side-effects
  - Support dynamic network (tolerate node churn)
  - Scalability:
    - Large networks allows for sampling small committees with the right distribution (whp.)
    - Sub-linear size committees can carry out the computation on behalf of the network

Application: Large-Scale MPC on Public Blockchains

YOSO MPC [GHK^{+}21]

- Role Execution
  - Execute the steps according to the protocol specification
  - Send messages to future roles (Only Speak Once)
- Role Assignment
  - Associates a machine in the network with a role in the protocol
  - Establishes a receiver-anonymous channel to the machine
  - Cannot rely on "full" WE or Time-Lock puzzles

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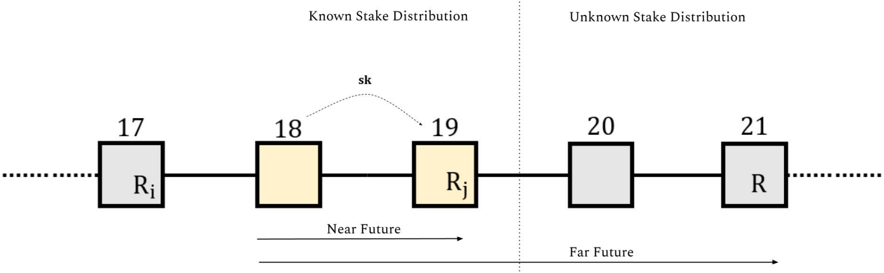
Motivation: Transferring secret state to future committees

- Consider anonymous vs. transparent committee selection.
- Consider secret state to the "near" vs. "far" future.
- Investigate the need for auxiliary committees for carrying state into the future.

Main Contributions

Encryption to the near Future.

1. Instantiate YOSO using EtF with an anonymous lottery.
2. Introduce a relaxed version of WE called "WE over Commitments" (cWE).
3. Construction using cWE based on standard assumptions (OT + GC).



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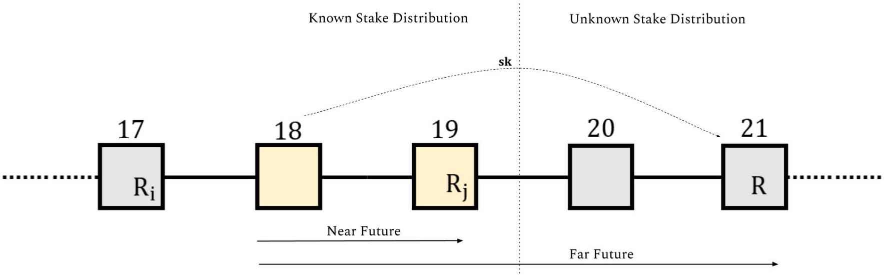
1. No auxiliary committees $\Longrightarrow$ BWE (Blockchain Witness Encryption).



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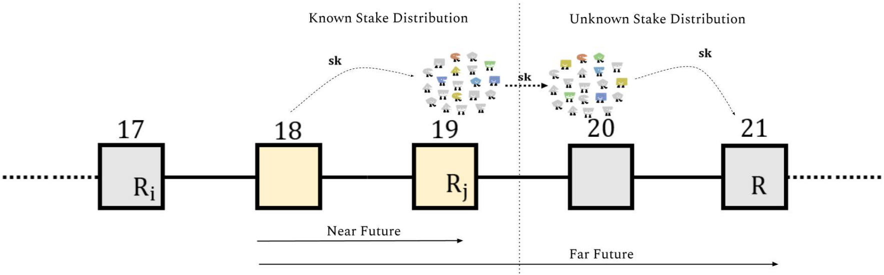

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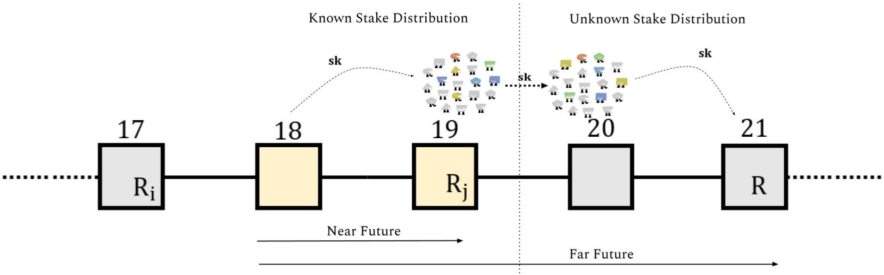
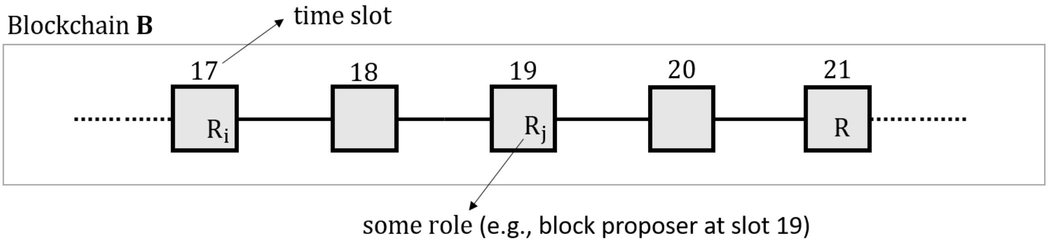


Blockchain Lotteries



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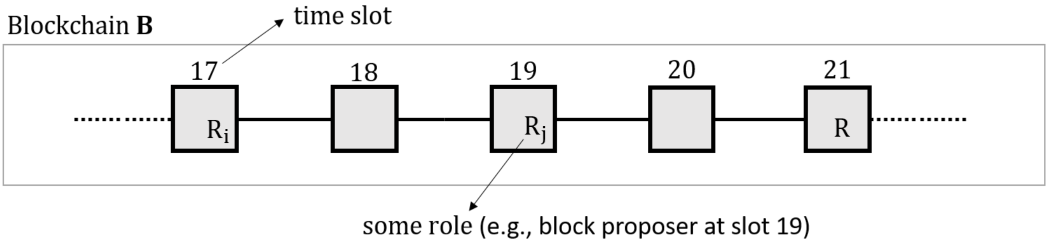
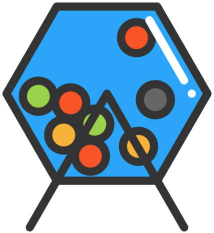


Blockchain Lotteries. A **self-selection** mechanism that gives the winner the right to **play a role** R, e.g.,

- propose a new block for the chain
- introduce new randomness
- become a member of a committee



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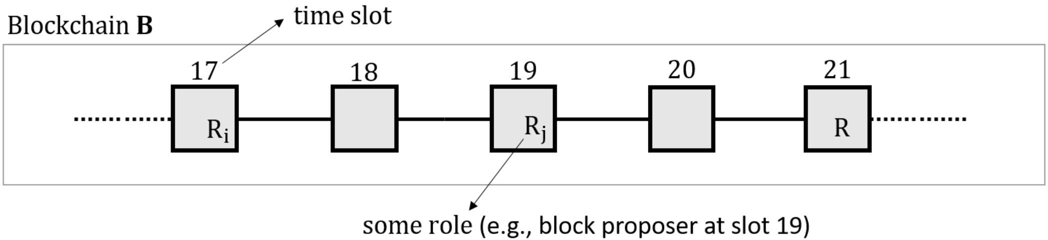
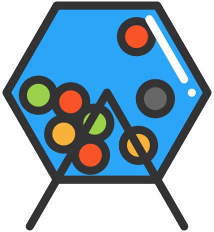
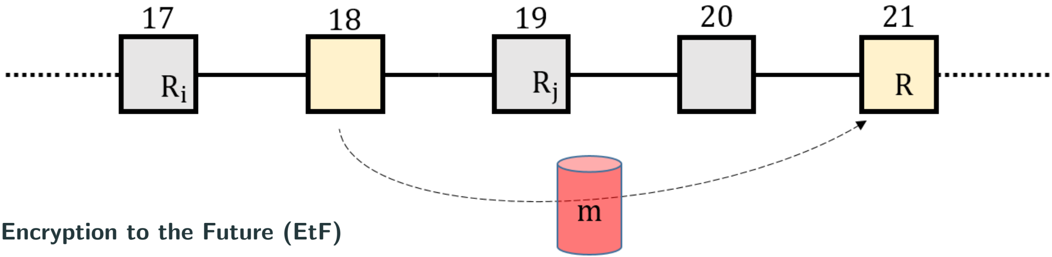


Lottery Predicate. $\text{lottery}(\mathbf{B}, \text{slot}, \text{R}, \text{sk}_i) \in \{0, 1\}$

- Anonymous Lotteries (e.g. Cryptographic Sortition, Nakamoto PoW)
- Transparent Lotteries (e.g. "Follow-the-Satoshi")



Encryption to the Future



Encryption to the Future (EtF)

- Encryption w.r.t. $\mathsf{lottery}(\mathbf{B}, \mathsf{slot}, \mathsf{R}, \mathsf{sk})$.

Encryption. $\mathsf{ct} \leftarrow \mathsf{Enc}(\hat{\mathbf{B}}, \mathsf{slot}, \mathsf{R}, m)$

Decryption. $m/\perp \leftarrow \mathsf{Dec}(\tilde{\mathbf{B}}, \mathsf{ct}, \mathsf{sk})$

Outputs m iff $\mathsf{lottery}(\tilde{\mathbf{B}}, \mathsf{slot}, \mathsf{R}, \mathsf{sk}) = 1$

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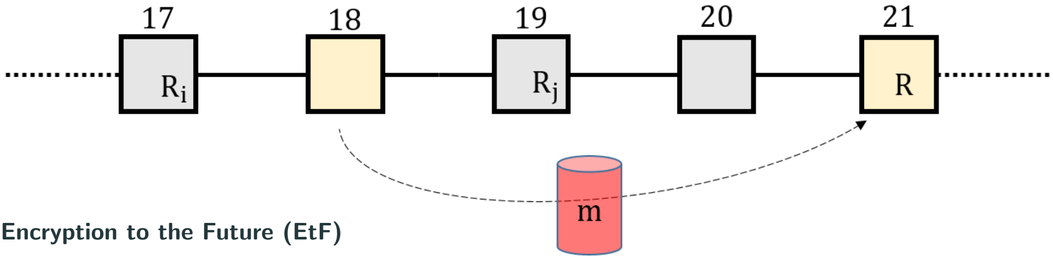

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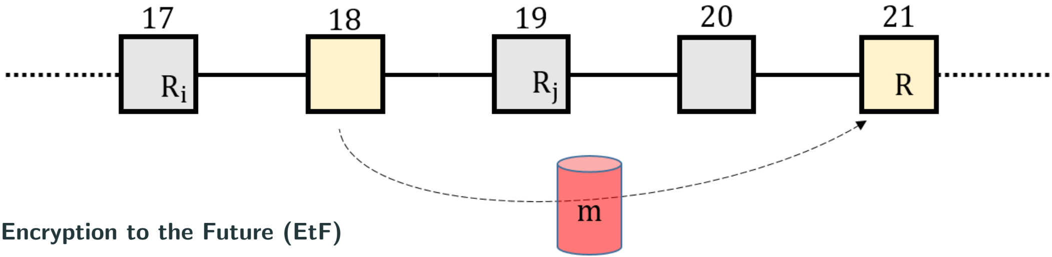

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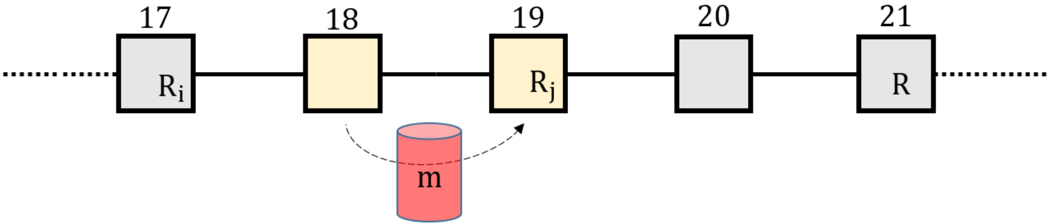
- $\hat{\mathbf{B}} \neq \tilde{\mathbf{B}}$ (but $\hat{\mathbf{B}}^{\lceil\kappa} \preceq \tilde{\mathbf{B}}$) (far future) stake distribution is unknown at encryption time. Harder to realize (implies Blockchain WE, similar to [GKM⁺20])

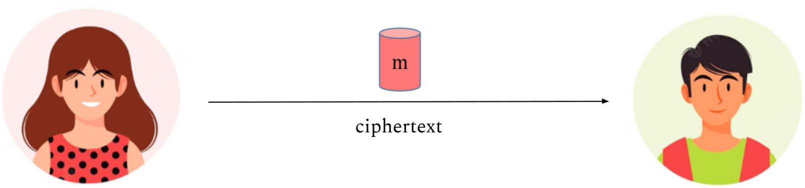
Encryption to the Future



Weaker Notion: Encryption to the Near Future

- Encryption w.r.t. lottery($\tilde{\mathbf{B}}$, slot, R_j, sk)
- The state of blockchain when the lottery winner is decided is known at the time of encryption: $\hat{\mathbf{B}} = \tilde{\mathbf{B}}$
- Can be constructed from "Witness Encryption over Commitments"

Witness Encryption [GGSW13]



m: plaintext

Encryption under NP statement x

Decrypts ciphertext

Using witness w s.t. $(x, w) \in R$

Witness Encryption [GGSW13]

A Witness Encryption scheme for **NP** language $\mathcal{L}$ (and witness relation $\mathbf{R}_{\mathcal{L}}$).

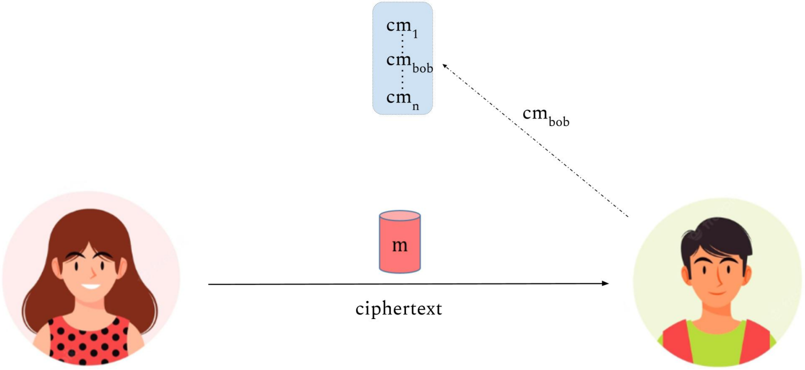
- Encrypt: $\mathsf{ct} \leftarrow \mathsf{Enc}(\mathsf{x}, m)$,
- Decrypt: $m/\perp \leftarrow \mathsf{Dec}(\mathsf{ct}, \mathsf{w})$
- Correctness: For any $\mathsf{x} \in \mathcal{L}$ such that $(\mathsf{x}, \mathsf{w}) \in \mathbf{R}_{\mathcal{L}}$

$$\Pr\left[\mathsf{Dec}(\mathsf{Enc}(x, m), \mathsf{w}) = m\right] = 1$$

- Security: For any PPT A, if $x \notin \mathcal{L}$ then

$$\Pr\left[\mathsf{A}(Enc(x, 0)) = 1\right] - \Pr\left[\mathsf{A}(Enc(x, 1)) = 1\right] \leq \mathsf{negl}(\lambda)$$

Witness Encryption over Commitments (cWE)



m: plaintext

Encryption under statement $x = (\mathrm{cm}_{bob}, C, y)$

Decrypts ciphertext

Using witness $w = (s, \varrho)$ s.t. $\mathrm{C}(s) = y$ AND $\mathrm{cm}_{bob} = \mathrm{Commit}(s, \varrho)$

Witness Encryption over Commitments (cWE)

Setup Phase. Bob publishes a re-usable commitment $\mathsf{cm}_{bob} \leftarrow \mathsf{Commit}(\mathsf{ck}, \mathsf{s}; \rho)$

Encrypt Phase. Define a language of statements $\mathsf{x} = (\mathsf{cm}, C, y)$ and witnesses $\mathsf{w} = (\mathsf{s}, \rho)$.

Let $(\mathsf{x}, \mathsf{w}) \in \mathbf{R}$ iff "cm commits to s using randomness ρ such that $C(\mathsf{s}) = y$"

- Correctness: For any $\mathsf{x} \in \mathcal{L}$ such that $(\mathsf{x}, \mathsf{w}) \in \mathbf{R}$

$$\Pr\left[\mathsf{Dec}(\mathsf{Enc}(x, m), \mathsf{w}) = m\right] = 1$$

- Strong Semantic Security:
  - Adversary receives $\mathsf{ct} \leftarrow \mathsf{Enc}(\mathsf{ck}, (\mathsf{cm}, C, y), m)$ but does not know satisfying witness
  - Adversary sees other $\mathsf{ct}_i \leftarrow \mathsf{Enc}(\mathsf{ck}, (\mathsf{cm}_i, C, y), m)$ but without knowing the opening to cm_i
  - Adversary should still not have an advantage in guessing m.

Encryption to the (near) Future

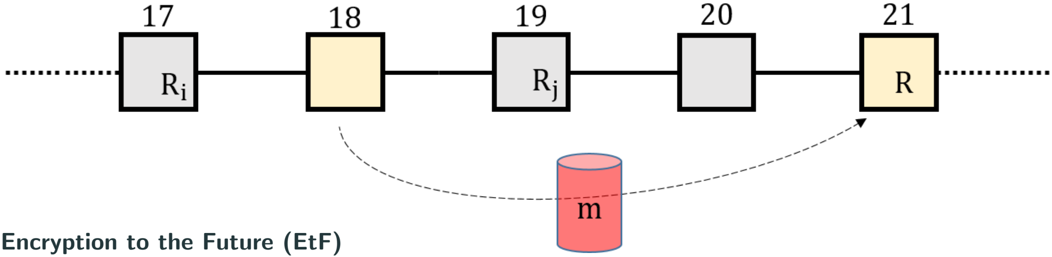
Obtain Encryption to the (near) Future from Witness Encryption over Commitments

- Setup: Let each party publish a commitment $\mathsf{cm}_i \leftarrow \mathsf{Commit}(\mathsf{sk}_i; \rho)$ of the their lottery key
- Encrypt: Let the circuit C encode the predicate $\mathsf{lottery}(\mathbf{B}, \mathsf{slot}, \mathsf{R}, \cdot)$.
  Use the statement $\mathsf{x}_i = (\mathsf{cm}_i, C, 1)$ for encryption.
- Decrypt: The lottery-winning party with sk_i successfully decrypts since $C(\mathsf{sk}_i) = 1$.

Result:

- The first non-interactive (using no auxiliary committees) Role Assignment protocol.
- Downside: The ciphertext size grows linearly with the number of participants in the network (potential lottery winners)
- For additional candidate constructions - read the paper.

Encryption to the Future



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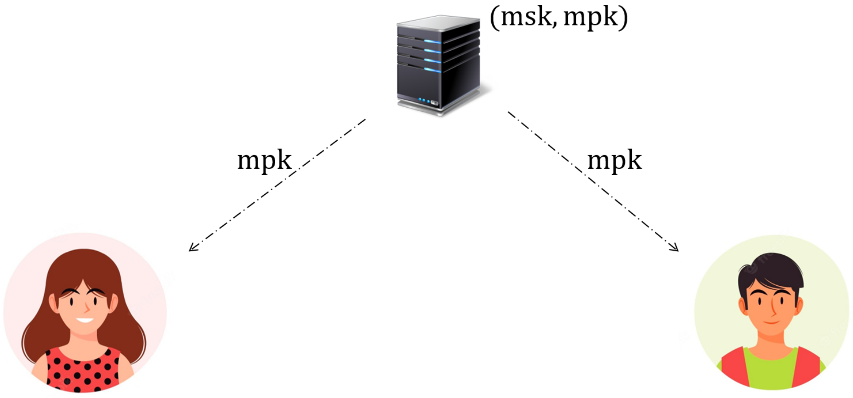
- $\hat{\mathbf{B}} \neq \tilde{\mathbf{B}}$ (but $\hat{\mathbf{B}}^{\lceil \kappa} \preceq \tilde{\mathbf{B}}$) (far future) stake distribution is unknown at encryption time.
  ~~Hard~~ **Easy** to realize using EtF (near future) + TIBE scheme and **use of auxiliary committees**

Identity Based Encryption (IBE)



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$(\mathrm{msk}, \mathrm{mpk})$

m: plaintext

Encryption under $\mathrm{mpk} + \mathrm{ID}_{\mathrm{Bob}}$

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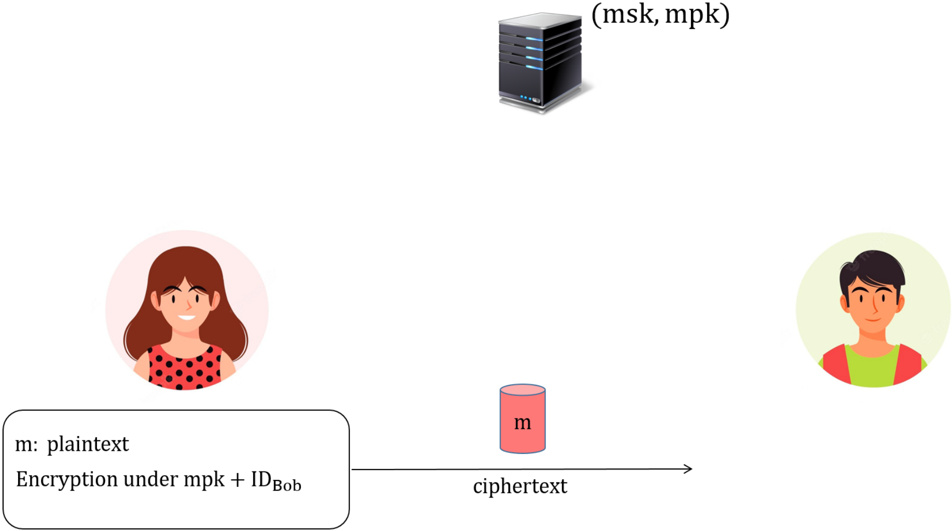

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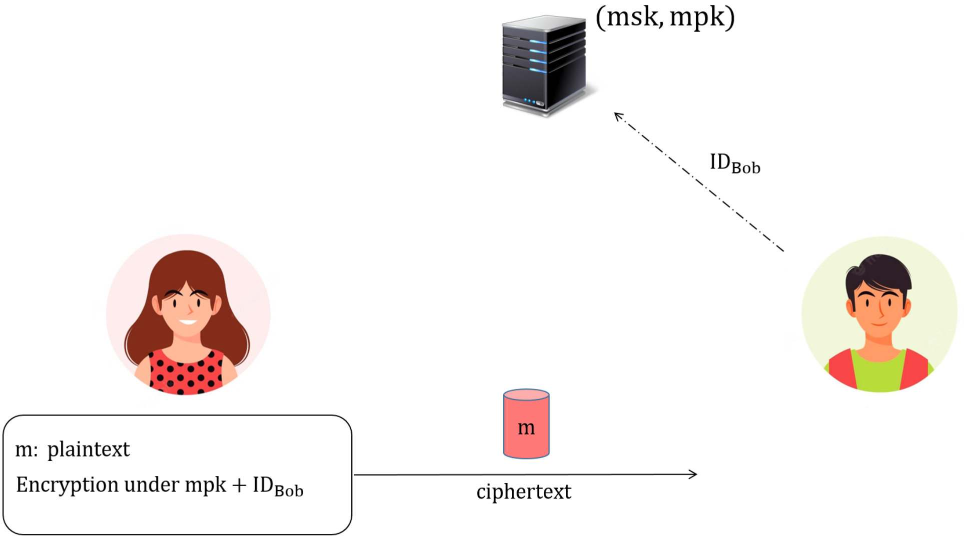

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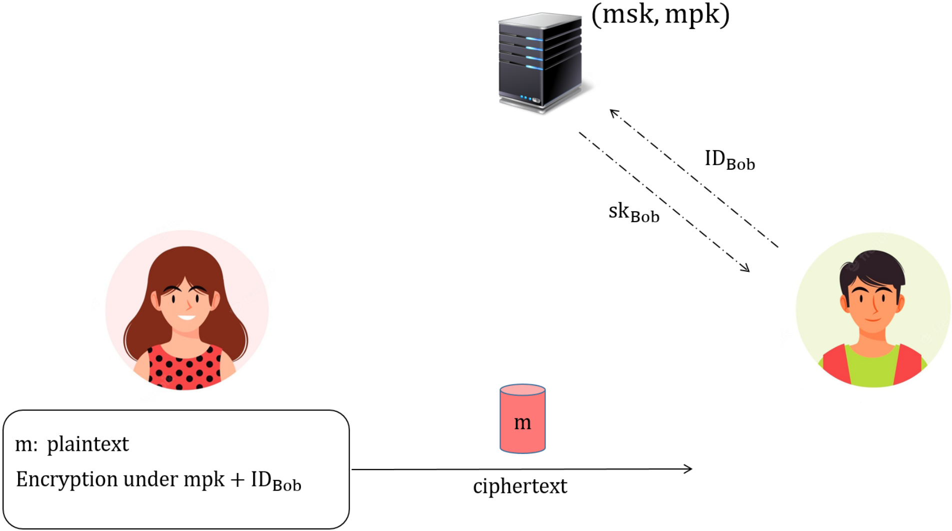

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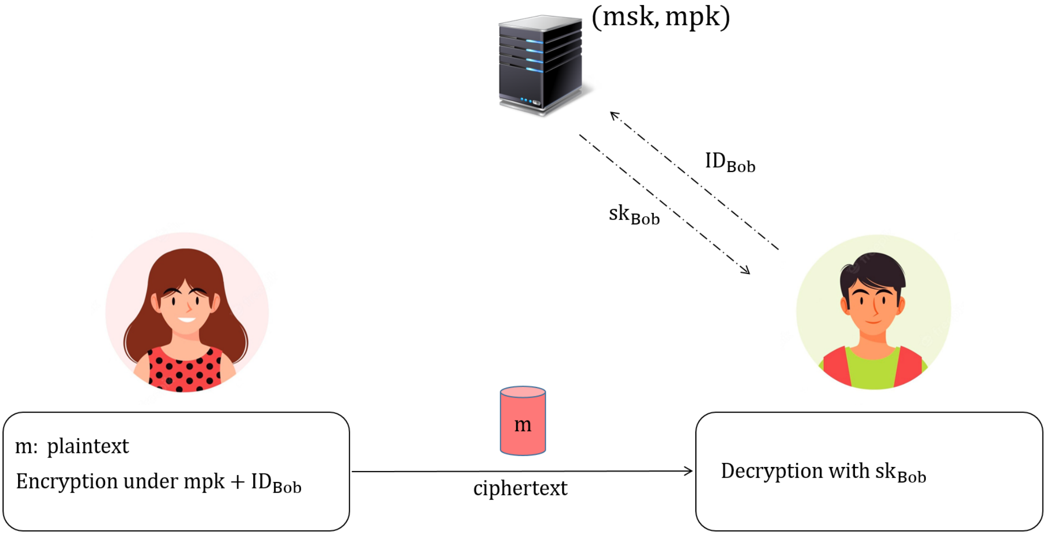

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Encryption under mpk + $\mathrm{ID}_{\mathrm{Bob}}$

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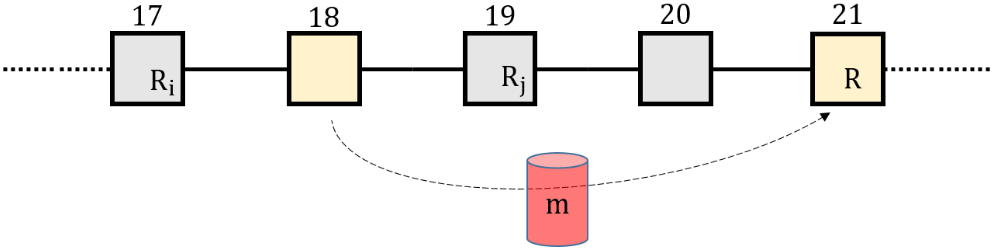
ciphertext

Decryption with $\mathrm{sk}_{\mathrm{Bob}}$

Encryption to the Future with Committee



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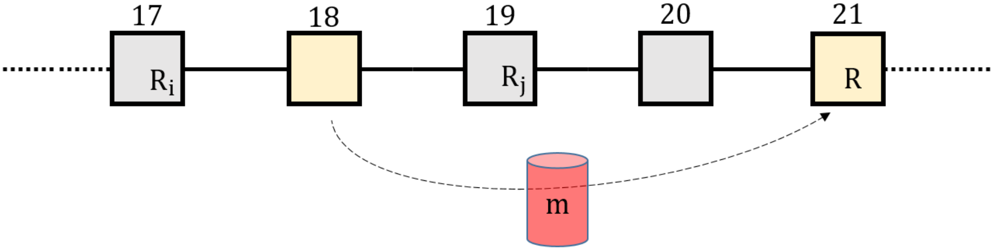

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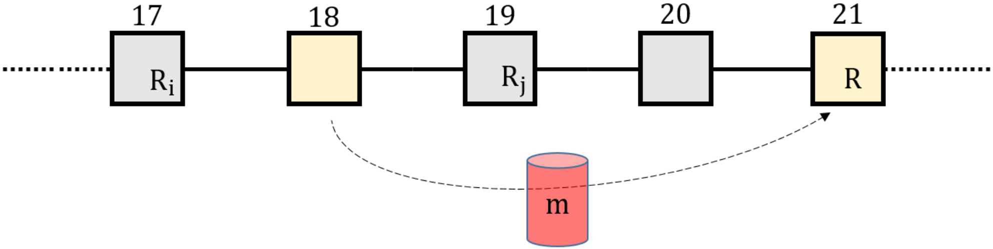

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  2. Check if any EtF ciphertexts have a receiving $(\mathsf{slot}, \mathsf{R})$ that has been decided. If true, then:
     - Sample share of the IBE key for $(\mathsf{slot}, \mathsf{R})$ $\mathsf{sk}^i_{(\mathsf{slot},\mathsf{R})} \leftarrow \Pi_{\mathsf{TIBE}}.\mathsf{IDKeygen}(\mathsf{msk}_i, (\mathsf{slot}, \mathsf{R}))$
     - Send shares of ID-key by EtF (near) $\mathsf{ct}^{\mathsf{sk},i}_{(\mathsf{slot},\mathsf{R})} \leftarrow \Pi_{\mathsf{EtF}}.\mathsf{Enc}(\mathbf{B}, \mathsf{slot}, \mathsf{R}, \mathsf{sk}^i_{(\mathsf{slot},\mathsf{R})})$

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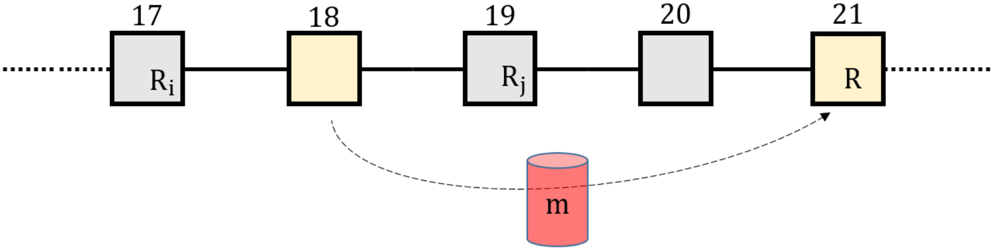

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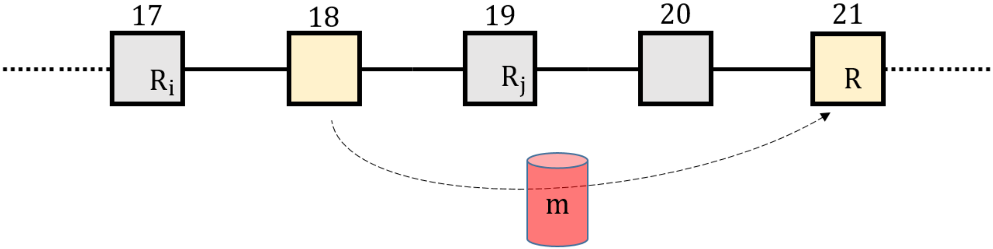
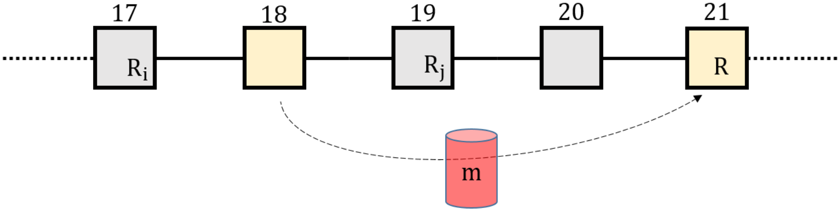
  1. $\vec{\mathsf{msk}} = (\mathsf{msk}_1, \ldots, \mathsf{msk}_n)$ is proactively reshared through the slots in blockchain execution.
  2. Check if any EtF ciphertexts have a receiving $(\mathsf{slot}, \mathsf{R})$ that has been decided. If true, then:
     - Sample share of the IBE key for $(\mathsf{slot}, \mathsf{R})$ $\mathsf{sk}^i_{(\mathsf{slot},\mathsf{R})} \leftarrow \Pi_{\mathsf{TIBE}}.\mathsf{IDKeygen}(\mathsf{msk}_i, (\mathsf{slot}, \mathsf{R}))$
     - Send shares of ID-key by EtF (near) $\mathsf{ct}^{\mathsf{sk},i}_{(\mathsf{slot},\mathsf{R})} \leftarrow \Pi_{\mathsf{EtF}}.\mathsf{Enc}(\mathbf{B}, \mathsf{slot}, \mathsf{R}, \mathsf{sk}^i_{(\mathsf{slot},\mathsf{R})})$
- Encrypt: Party publishes $\mathsf{ct} \leftarrow \Pi_{\mathsf{TIBE}}.\mathsf{Enc}(\mathsf{mpk}, \mathsf{ID} = (\mathsf{slot}, \mathsf{R}), m)$.

Encryption to the Future with Committee

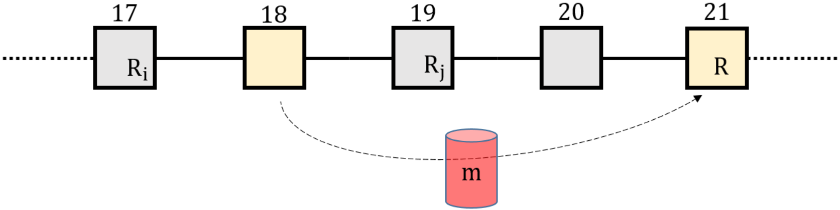


- Setup: (YOSO MPC) constructs the TIBE setup $(\mathsf{mpk}, \vec{\mathsf{msk}} = (\mathsf{msk}_1, \ldots, \mathsf{msk}_n))$.
  1. $\vec{\mathsf{msk}} = (\mathsf{msk}_1, \ldots, \mathsf{msk}_n)$ is proactively reshared through the slots in blockchain execution.
  2. Check if any EtF ciphertexts have a receiving $(\mathsf{slot}, \mathsf{R})$ that has been decided. If true, then:
     - Sample share of the IBE key for $(\mathsf{slot}, \mathsf{R})$ $\mathsf{sk}^i_{(\mathsf{slot},\mathsf{R})} \leftarrow \Pi_{\mathsf{TIBE}}.\mathsf{IDKeygen}(\mathsf{msk}_i, (\mathsf{slot}, \mathsf{R}))$
     - Send shares of ID-key by EtF (near) $\mathsf{ct}^{\mathsf{sk},i}_{(\mathsf{slot},\mathsf{R})} \leftarrow \Pi_{\mathsf{EtF}}.\mathsf{Enc}(\mathbf{B}, \mathsf{slot}, \mathsf{R}, \mathsf{sk}^i_{(\mathsf{slot},\mathsf{R})})$
- Encrypt: Party publishes $\mathsf{ct} \leftarrow \Pi_{\mathsf{TIBE}}.\mathsf{Enc}(\mathsf{mpk}, \mathsf{ID} = (\mathsf{slot}, \mathsf{R}), m)$.
- Decrypt: The lottery-winner for $(\mathsf{slot}, \mathsf{R})$ decrypts EtF (near) ciphertexts and combine shares $\{\mathsf{sk}^i_{(\mathsf{slot},\mathsf{R})}\}$ to obtain $\mathsf{sk}_{(\mathsf{slot},\mathsf{R})}$. Finally outputs $m \leftarrow \Pi_{\mathsf{TIBE}}.\mathsf{Dec}(\mathsf{sk}_{(\mathsf{slot},\mathsf{R})}, \mathsf{ct})$.

Encryption to the Future with Committee

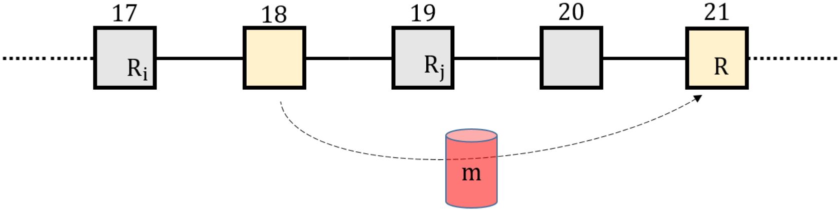


Encryption to the Future with Committee



- 📢 $\mathrm{IBE.\,Enc}_R(m)$

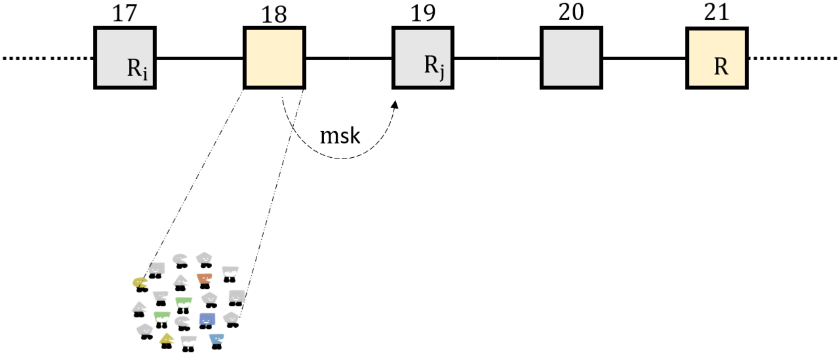
Encryption to the Future with Committee



— 📢 $\text{IBE.}\,\text{Enc}_R(m)$

— Secret share msk to the next comittees

Encryption to the Future with Committee



— 📢 IBE. $\mathrm{Enc}_R(m)$

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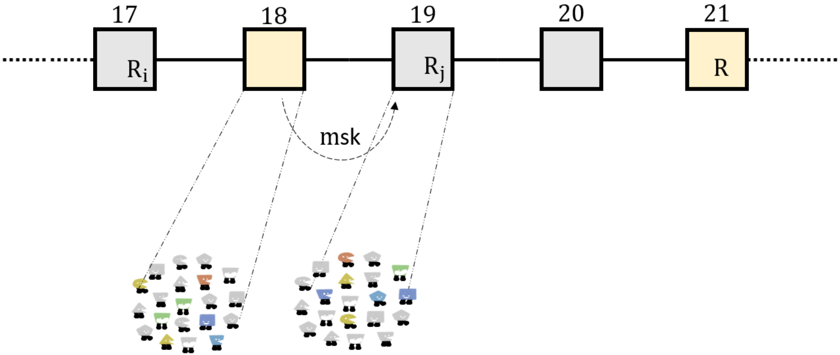
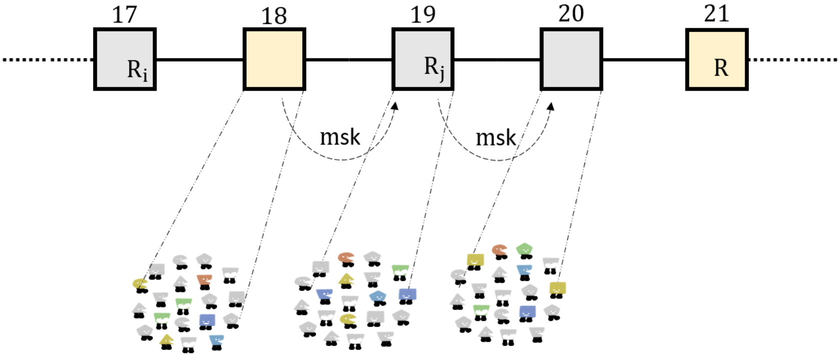
Encryption to the Future with Committee



- 📢 $\mathrm{IBE.Enc}_R(m)$
- Secret share msk to the next comittees

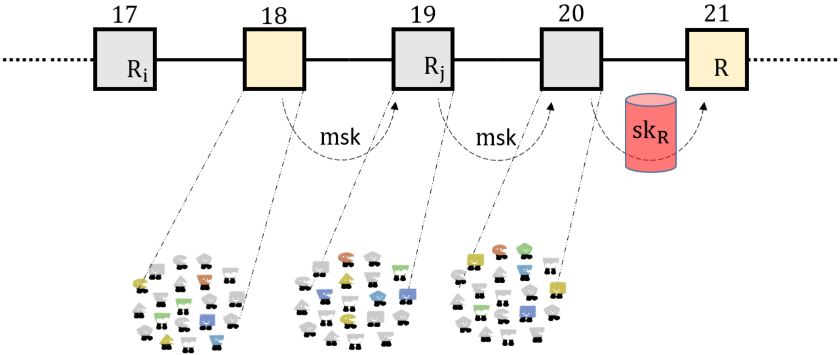
Encryption to the Future with Committee



— 📢 IBE. $\mathrm{Enc}_R(m)$

— Secret share msk to the next comittees

Encryption to the Future with Committee



- 📢 $\mathrm{IBE.Enc}_R(m)$
- Secret share msk to the next comittees
- Committee at slot 20 generates sk_R for R, and encrypt it using encrypion to the near future

Results

Type	Scheme	Communication	Committee?	Interaction?
EtF (near)	CaBKaS [BGG+20]	$O(1)$	yes	yes
	RPIR [GHK+21]	$O(1)$	yes	yes
	cWE(GC+OT) (Sec. 4.2)	$O(N)$	no	no*
EtF (far)	IBE (Sec. 7)	$O(1)$	yes	yes
	WEB [GKM+20]	$O(M)$	yes	yes
	Full-fledged WE	$O(1)$	no	no

- "Committee?" indicates whether a committee is required.
- "Communication" refers to the communication complexity in the number of all parties N, or the number of plaintexts (called deposited secrets in [GKM+20]) M of a given fixed length.
- Asterisk* means non-interactive solutions that require sending a first reusable message

Thank you!

https://eprint.iacr.org/2021/1423

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