Traceable Encryption for Verifiable Receipt-free Online Voting

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in collaboration with
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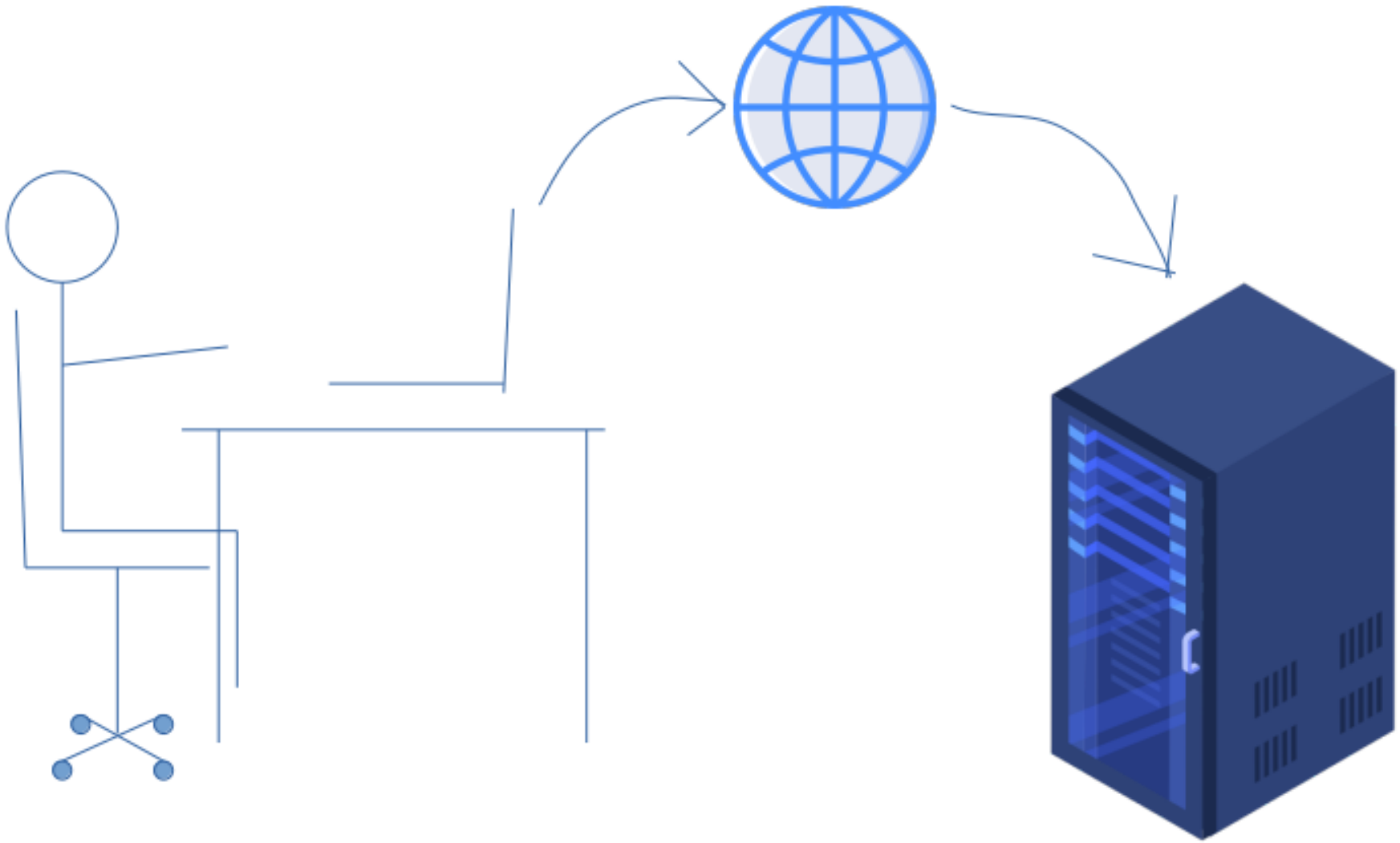
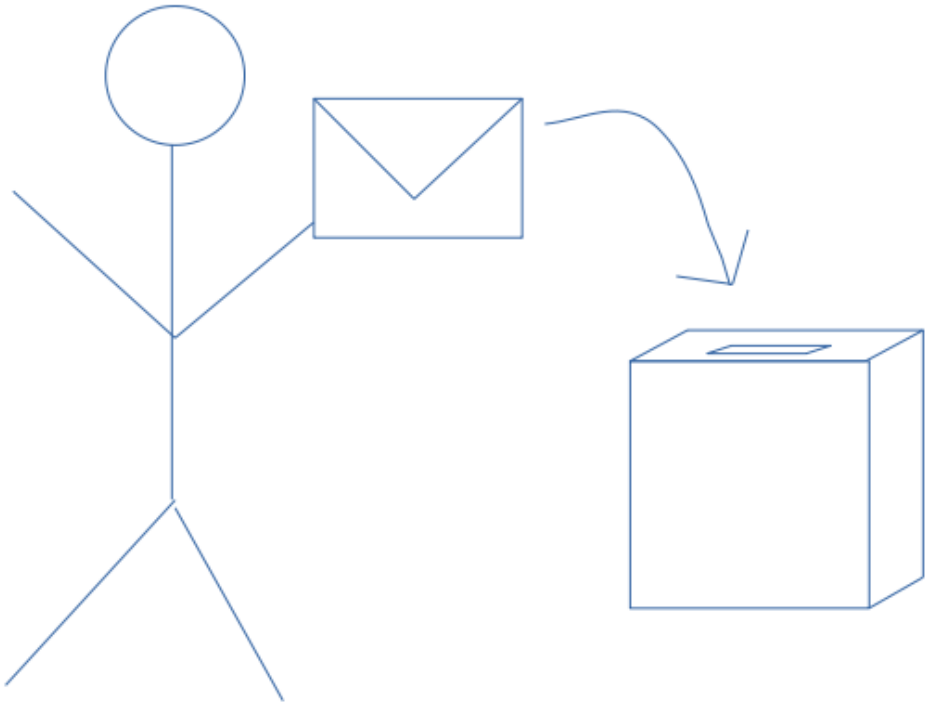
What is electronic voting?



The security goals in electronic voting



Security properties
✓Eligibility
✓Cast-as-intended
✓Vote secrecy
✓Confidence in the result

Receipt-freeness

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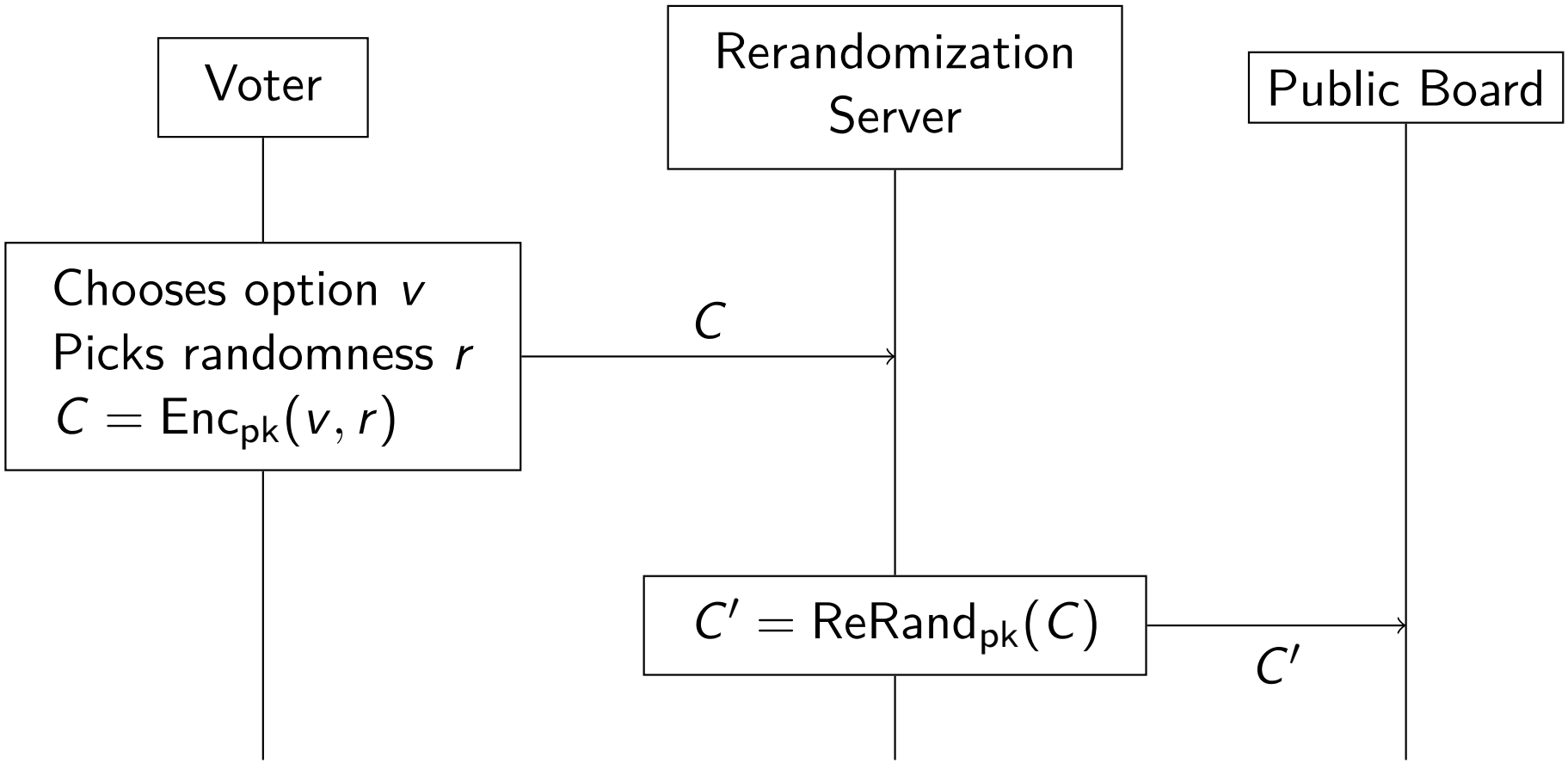
Receipt-freeness: a voter cannot prove how they voted.

The rerandomization paradigm



An example: **BeleniosRF**, Chaidos, Cortier, Fuchsbauer and Galindo (CCS'16)

Outline

Traceable encryption

Definition

A traceable encryption (TREnc) is a public key encryption scheme $(\mathsf{Gen}, \mathsf{Enc}, \mathsf{Dec})$, augmented with:

- $\mathsf{LGen}(\mathsf{pk})$: Generates a (random) link key lk;
- $\mathsf{LEnc}_{\mathsf{pk}}(\mathsf{lk}, m, r)$: Encrypts a message m using the link key lk and the randomness r. We have that $\mathsf{Enc}_{pk}(m, r) = \mathsf{LEnc}(\mathsf{pk}, \mathsf{LGen}(\mathsf{pk}), m, r)$;
- $\mathsf{Trace}_{\mathsf{pk}}(C)$: Outputs a trace from a ciphertext;
- $\mathbf{ReRand}_{\mathsf{pk}}(C, r)$: Rerandomizes a ciphertext C. We require that $Dec_{\mathsf{sk}}(C) = Dec_{\mathsf{sk}}(\mathsf{ReRand}_{\mathsf{pk}}(C))$;
- $\mathsf{Ver}_{\mathsf{pk}}(C)$: Verifies the validity of a ciphertext.

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$\vdots$

Definition (Link traceability)

A TREnc has link traceability if, for all $(\mathsf{pk}, \mathsf{lk}, m, m', r, r')$, we have

$$\mathsf{Trace}_{\mathsf{pk}}(\mathsf{LEnc}_{\mathsf{pk}}(\mathsf{lk}, m, r)) = \mathsf{Trace}_{\mathsf{pk}}(\mathsf{LEnc}_{\mathsf{pk}}(\mathsf{lk}, m', r')).$$

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$$\vdots$$

- $\mathbf{Ver}_{\mathsf{pk}}(C)$: Verifies the validity of a ciphertext.

Definition (Verifiability)

A TREnc is verifiable is no PPT adversary can produce some C such that $\mathsf{Ver}_{\mathsf{pk}}(C) = 1$ while C is not in the range of Enc.

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We also require the link traceability and verifiability properties.

Traceable encryption

Definition (Traceability)

A TREnc is traceable if, for every PPT adversary $\mathbb{A}$, the following experiment returns 1 with negligible probability.

$\mathsf{Exp}^{\mathrm{trace}}_{\mathbb{A}}(\lambda)$

$(\mathsf{pk}, \mathsf{sk}) \leftarrow\!\!\$\ \mathsf{Gen}(\lambda)$

$m \leftarrow\!\!\$\ \mathbb{A}(\mathsf{pk}, \mathsf{sk})$

$C \leftarrow\!\!\$\ \mathsf{Enc}_{\mathsf{pk}}(m)$

$C^\star \leftarrow\!\!\$\ \mathbb{A}(C)$

if $\mathsf{Trace}_{\mathsf{pk}}(C) = \mathsf{Trace}_{\mathsf{pk}}(C^\star)$ and $\mathsf{Ver}_{\mathsf{pk}}(C^\star) = 1$ and $\mathsf{Dec}_{\mathsf{sk}}(C^\star) \neq m$

then return 1

else return 0

Traceable encryption

Definition (IND-TCCA)

A TREnc is IND-TCCA secure if for every PPT adversary $\mathbb{A}$, the following experiment returns 1 with a probability negligibly close to $1/2$.

$\mathsf{Exp}^{\mathrm{tcca}}_{\mathbb{A}}(\lambda)$

$(\mathsf{pk}, \mathsf{sk}) \leftarrow\!\!\$\ \mathsf{Gen}(\lambda)$
$(C_0, C_1) \leftarrow\!\!- \ \mathbb{A}^{\mathsf{Dec}(\cdot)}(\mathsf{pk})$
$b \leftarrow\!\!\$\ \{0,1\}$
if $\mathsf{Trace}_{\mathsf{pk}}(C_0) \neq \mathsf{Trace}_{\mathsf{pk}}(C_1)$ or
$\mathsf{Ver}_{\mathsf{pk}}(C_0) = 0$ or $\mathsf{Ver}_{\mathsf{pk}}(C_1) = 0$
then return b
$C^\star \leftarrow\!\!\$\ \mathsf{ReRand}_{\mathsf{pk}}(C_b)$
$b' \leftarrow\!\!\$\ \mathbb{A}^{\mathsf{Dec}^\star(\cdot)}(C^\star)$
return $b' == b$

Outline

Application to BeleniosRF

BeleniosRF uses an encryption which is:

- ✓ Rerandomizable: ElGamal encryption.
- ✓ Verifiable: Groth-Sahai proofs.
- ✓ Traceable: Asymmetric Waters Signature.

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BeleniosRF uses an encryption which is:

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- ✓ Traceable: Asymmetric Waters Signature.

However, it comes with a few limitations:

- Restricted to small bitstrings.
- Low modularity.

Asymmetric Waters Signatures

Setting:

- Bilinear groups $(\mathbb{G}, \hat{\mathbb{G}}, \mathbb{G}_T)$ of prime order p with generators $g \in \mathbb{G}$ and $\hat{g} \in \hat{\mathbb{G}}$ and a pairing e.
- Random elements $z, u_0, \cdots, u_k \in \mathbb{G}$.
- A function $\mathcal{F} : \{0,1\}^k \longrightarrow \mathbb{G}$ such that $\mathcal{F}(m) = u_0 \prod_{i=1}^{k} u_i^{m_i}$.

Secret key: $\alpha \in \mathbb{Z}_p$ and $y = z^\alpha$.
Public key: $x = g^\alpha$ and $\hat{x} = \hat{g}^\alpha$.

Sign$(\mathbf{m}, \mathbf{s})$: $\sigma_1 = y\mathcal{F}(m)^s$, $\sigma_2 = g^s$ and $\hat{\sigma} = \hat{g}^s$.
Verify$(\mathbf{m}, \sigma)$: Check that

$$e(\sigma_1, \hat{g}) = e(z, \hat{x})e(\mathcal{F}(m), \hat{\sigma}) \text{ and } e(\sigma_2, \hat{g}) = e(\sigma_1, \hat{\sigma}).$$

BeleniosRF's limitations

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Groth-Sahai proofs

Setting:

- Bilinear groups $\mathbb{G}, \hat{\mathbb{G}}, \mathbb{G}_T$ of prime order p with a pairing e.
- We rely on the SXDH assumption.

Groth-Sahai proofs are Non-Interactive Witness Indistinguishable proofs for bilinear equations, such as

$$\prod_{i=1}^{n} e(A_i, Y_i) \prod_{j=1}^{n} e(X_j, B_i) \prod_{i=1}^{n} \prod_{j=1}^{n} e(X_j, Y_i)^{\alpha_{i,j}} = t_T,$$

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Linearly Homomorphic Structure-Preserving Signature

Setting: Bilinear groups $(\mathbb{G}, \hat{\mathbb{G}}, \mathbb{G}_T)$ of prime order p with independent generators $\hat{g}, \hat{h} \in \hat{\mathbb{G}}$ and a pairing e.
Secret key: $(\alpha_i, \beta_i)_{i=1}^n \in \mathbb{Z}_p$
Public key: $\hat{k}_i = \hat{g}^{\alpha_i} \hat{h}^{\beta_i}$ for $i = 1$ to n.

$$\textbf{Sign}(\mathbf{M_1}, \cdots, \mathbf{M_n}) : \left(Z = \prod_{i=1}^{n} M_i^{\alpha_i}, R = \prod_{i=1}^{n} M_i^{\beta_i} \right)$$

$$\textbf{Verify}(\mathbf{Z}, \mathbf{R}) : \text{Check that } e(Z, \hat{g}) e(R, \hat{h}) = \prod_{i=1}^{n} e(M_i, \hat{k}_i)$$

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Security proofs

Things I have proven:

- ✓ Verifiability
- ✓ Traceability
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The adversary is given:

- $\hat{g}, \hat{h}, \hat{k}_1, \cdots, \hat{k}_n$ such that $\hat{k}_i = \hat{g}^{\alpha_i} \hat{h}^{\beta_i}$.
- Some valid signatures on messages $\overrightarrow{M}_1, \cdots, \overrightarrow{M}_k$: (Z_i, R_i) such that $Z_i = \prod_{j=1}^{n} M_{i,j}^{\alpha_j}$ and $R_i = \prod_{j=1}^{n} M_{i,j}^{\beta_j}$.
- A message $\overrightarrow{M} \notin < \overrightarrow{M}_1, \cdots, \overrightarrow{M}_k >$ to sign.

The adversary outputs Z', R' such that $e(Z', \hat{g})e(R', \hat{h}) = \prod_{i=1}^{n} e(M_i, \hat{k}_i)$.

By computing $Z = \prod_{i=1}^{n} M_i^{\alpha_i}$ and $R = \prod_{i=1}^{n} M_i^{\beta_i}$, we have

$$e(Z/Z', \hat{g})e(R/R', \hat{h}) = 1.$$

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First step: Rule out $(Z/Z', R/R') \neq (1, 1)$.

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DDH tuple: there exists α such that

$$\begin{aligned}(\hat{g}_3, \hat{g}_4) &= (\hat{g}_1, \hat{g}_2)^{\alpha} \\ e(Z/Z', \hat{g}_3)e(R/R', \hat{g}_4) &= (e(Z/Z', \hat{g}_1)e(R/R', \hat{g}_2))^{\alpha} \\ &= 1.\end{aligned}$$

Random tuple: the pairing product is random.

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First step: Rule out $(Z/Z', R/R') \neq (1, 1)$.

Second step: Conclude.

The adversary is given:

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- ✓ IND-TCCA + Verifiable + "nice" tally $\Longrightarrow$ receipt-freeness

The definition of Receipt-freeness

The control flow in receipt-freeness

1. The voter votes.
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The adverary could instruct to use a specific trace!

The definition of Receipt-freeness

$\mathsf{Exp}^{\beta}_{\mathcal{A},\mathcal{V},\mathcal{D}}(\lambda)$

$\mathsf{pk} \leftarrow \mathcal{O}\mathsf{init}(\lambda); \mathcal{A}^{\mathcal{O}\mathsf{cast},\mathcal{O}\mathsf{board},\mathcal{O}\mathsf{voteLR},\mathcal{O}\mathsf{receiptLR}}(\mathsf{pk}); (\mathsf{r},\Pi) \leftarrow \mathcal{O}\mathsf{tally}();$
$\mathsf{g} \leftarrow \mathcal{A}(\mathsf{r},\Pi);$ **return** $(\mathsf{g} == \beta)$

$\mathcal{O}\mathsf{init}(\lambda)$

if $\beta = 0$
  then $(\mathsf{pk},\mathsf{sk}) \leftarrow \mathsf{Setup}(\lambda)$
else $(\mathsf{pk},\mathsf{sk},\tau) \leftarrow \mathsf{SimSetup}(1^{\lambda})$
$\mathsf{PB}_0 \leftarrow \varnothing; \mathsf{PB}_1 \leftarrow \varnothing$
return pk

$\mathcal{O}\mathsf{cast}(\mathsf{b})$

if $\mathsf{Valid}(\mathsf{PB}_0,\mathsf{b}) = 0$
  or $\mathsf{Valid}(\mathsf{PB}_1,\mathsf{b}) = 0$
  then return $\perp$
else $\mathsf{Append}(\mathsf{PB}_0,\mathsf{b});$
  $\mathsf{Append}(\mathsf{PB}_1,\mathsf{b})$

$\mathcal{O}\mathsf{board}()$

return PB_{β}

$\mathcal{O}\mathsf{receiptLR}(\mathsf{I},\mathsf{v})$

$\mathsf{s}_0,\mathsf{b}_0 \leftarrow \mathsf{Vote}(\mathsf{I},\mathsf{RS},\mathsf{PB}_0)$
$\mathsf{s}_1,\mathsf{b}_1 \leftarrow \mathsf{Vote}(\mathcal{D}_{\mathsf{I}}(\mathsf{v}),\mathsf{RS},\mathsf{PB}_1)$
if $\mathsf{Valid}(\mathsf{PB}_0,\mathsf{b}_0) = 0$ **or** $v \notin \mathcal{C}$
 or $\mathsf{Valid}(\mathsf{PB}_1,\mathsf{b}_0) = 0$ **then return** $\perp$
else $\mathsf{Append}(\mathsf{PB}_0,\mathsf{b}_0); \mathsf{Append}(\mathsf{PB}_1,\mathsf{b}_1)$
return s_{β}

$\mathcal{O}\mathsf{voteLR}(\mathsf{v}_0,\mathsf{v}_1)$

if $\mathsf{v}_0 \notin \mathcal{C}$ **or** $\mathsf{v}_1 \notin \mathcal{C}$ **then return** $\perp$
$\mathsf{b}_0 \leftarrow \mathsf{Vote}(\mathsf{v}_0,\mathsf{RS},\mathsf{PB}_0)$
$\mathsf{b}_1 \leftarrow \mathsf{Vote}(\mathsf{v}_1,\mathsf{RS},\mathsf{PB}_1)$
$\mathsf{Append}(\mathsf{PB}_0,\mathsf{b}_0); \mathsf{Append}(\mathsf{PB}_1,\mathsf{b}_1)$

$\mathcal{O}\mathsf{tally}()$

$(\mathsf{r},\Pi) \leftarrow \mathsf{Tally}(\mathsf{PB}_0,\mathsf{sk})$
if $\beta = 1$ **then** $\Pi \leftarrow \mathsf{SimProof}(\mathsf{PB}_1,\mathsf{r},\tau)$
return (r,Π)

Conclusion

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- Took the notion of receipt-freeness to the next step
- Constructed a voting scheme and proved its security
- Adapted the scheme for cast-as-intended verification

Our work was submited at S&P in August.

Bonus: the voting protocol