A Formal Taxonomy of Privacy in Voting Protocols

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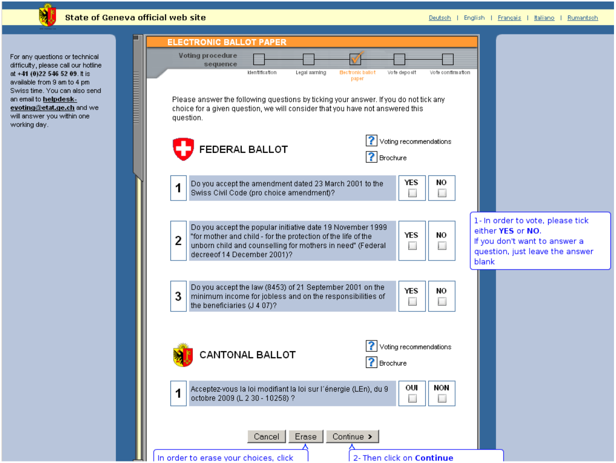
Electronic voting machines. . .

. . . are used all over the world

Internet voting

Available in

- Estonia
- France
- Switzerland
- ...



Security Requirements

Fairness

Individual Verifiability

Eligibility

Universal Verifiability

Security Requirements

Privacy

Vote-Independence

Receipt-Freeness

Robustness

Coercion-Resistance

Security Requirements

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How to secure electronic voting?

Idea: Use formal methods to find bugs and increase confidence

- Need for formal definitions
- Lots of related work: [?, ?, ?, ?, ?, ?, ?]...

Ideally we need definitions that

- can be applied on any protocol
- are comparable
- include known threats: coercion, vote-buying, vote-copying, forced abstention
- are suitable for automation

Plan

1. Introduction
2. Definitions: Four Dimensions
   - Communication
   - Vote-Independence
   - Forced Abstention
   - Knowledge about honest voters
3. Analysis and Case Studies
4. Conclusion

Plan

Four Dimensions

- Communication: Vote-Privacy (VP), Receipt-Freeness (RF), Coercion-Resistance (CR)
- Vote-Independence: Outsider (O), Insider (I)
- Forced Abstention Attacks: Participation Only (PO), Security against Forced-Abstention-Attacks (FA)
- Knowledge about honest voters: Exists Behavior (EB), Any Behavior (AB)

Plan

Vote-Privacy (VP)

Main idea: Observational equivalence between two situations.

	Alice	Bob
Vote	$\boxed{A}$	$\boxed{B}$
	$\approx_l$	
Vote	$\boxed{B}$	$\boxed{A}$

The Applied Pi Calculus [?]

Syntax

$P, Q, R :=$	processes
0	null process
$P \mid Q$	parallel composition
$!P$	replication
$\nu n.P$	restriction (“new”)
$\texttt{if } M = N \texttt{ then } P \texttt{ else } Q$	conditional
$\texttt{in}(u, x).P$	message input
$\texttt{out}(u, x).P$	message output
$\{^{M}/_{x}\}$	active substitution

Vote-Privacy: The formal definition

Definition (Vote-Privacy)

A voting process respects *Vote-Privacy (VP)* if for all votes σ_{v_A} and σ_{v_B} we have

$$VP'\left[V\sigma_{id_A}\sigma_{f_A}\sigma_{v_A}\middle|V\sigma_{id_B}\sigma_{f_B}\sigma_{v_B}\right] \approx_l VP'\left[\sigma_{id_A}\sigma_{f_A}\sigma_{v_B}\middle|V\sigma_{id_B}\sigma_{f_B}\sigma_{v_A}\right]$$

Receipt-Freeness (RF)

Again: Observational equivalence between two situations, but Alice tries to create a receipt or a fake.

Mallory	Alice	Bob
	$\boxed{\text{A}}$	$\boxed{\text{B}}$
	$\approx_l$	
	$\boxed{\text{B}}$	$\boxed{\text{A}}$

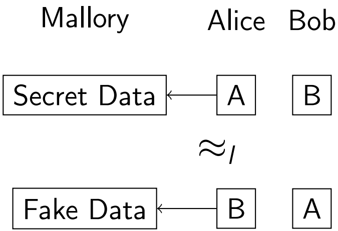
Receipt-Freeness (RF)

Again: Observational equivalence between two situations, but Alice tries to create a receipt or a fake.

$$
\begin{array}{ccc}
\text{Mallory} & \text{Alice} & \text{Bob} \\
\boxed{\text{Secret Data}} \leftarrow & \boxed{A} & \boxed{B} \\
 & \approx_l & \\
\boxed{\text{Fake Data}} \leftarrow & \boxed{B} & \boxed{A}
\end{array}
$$

Coercion-Resistance (CR)

Observational equivalence between two situations, but Alice is under control by Mallory or only pretends to be so.



Coercion-Resistance (CR)

Observational equivalence between two situations, but Alice is under control by Mallory or only pretends to be so.

$$\text{Mallory} \xrightarrow{\text{Orders}} \text{Alice} \quad \text{Bob}$$

$$\boxed{\text{Secret Data}} \longleftarrow \boxed{A} \quad \boxed{B}$$

$$\approx_l$$

$$\boxed{\text{Fake Data}} \longleftarrow \boxed{B} \quad \boxed{A}$$

Plan

Insider (I) vs. Outsider (O)

Main idea: Privacy, but with a voter under control of the attacker. If he can relate his vote to e.g. Alice's vote, Mallory can distinguish both sides.

Mallory		Alice	Bob
	Vote	A	B
			$\approx_I$
	Vote	B	A

Insider (I) vs. Outsider (O)

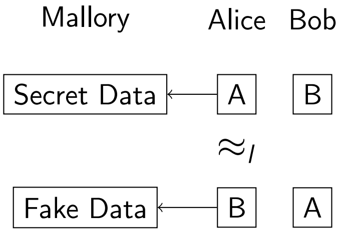
Main idea: Privacy, but with a voter under control of the attacker. If he can relate his vote to e.g. Alice's vote, Mallory can distinguish both sides.

Orders

Mallory	Alice	Bob	Chuck
Vote	$\boxed{A}$	$\boxed{B}$	$\boxed{?}$
		$\approx_I$	
Vote	$\boxed{B}$	$\boxed{A}$	$\boxed{?}$

Can we combine Vote-Independence with Receipt-Freeness?

"Receipt-Freeness with Chuck":



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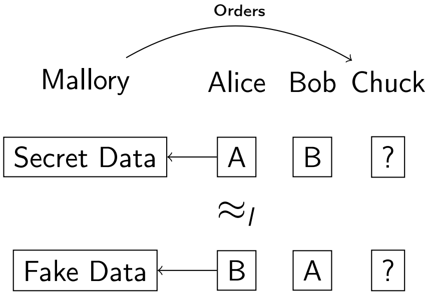

And with Coercion-Resistance?

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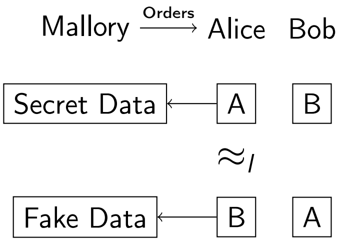

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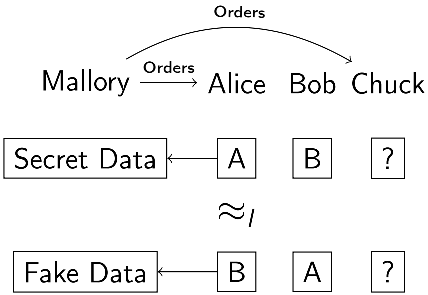

Plan

Security against Forced Abstention Attacks (FA) vs. Participation Only (PO)

Alice abstains or votes in turn with Bob:

	Alice	Bob
Vote	$\boxed{A}$	$\boxed{B}$
	$\approx_l$	
Vote	$\boxed{B}$	$\boxed{A}$

Security against Forced Abstention Attacks (FA) vs. Participation Only (PO)

Alice abstains or votes in turn with Bob:

	Alice	Bob
Vote		$\boxed{\text{B}}$

$$\approx_l$$

	Alice	Bob
Vote	$\boxed{\text{B}}$	

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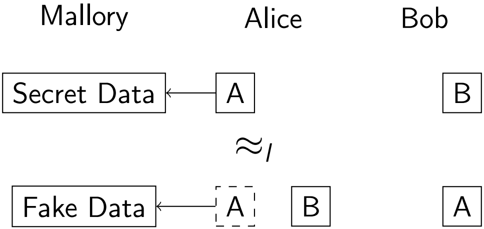
Introducing Fakes: Exists Behavior (EB) vs. Any Behavior (AB)

Some protocols use fake votes [?] to achieve Receipt-Freeness and Coercion-Restistance.



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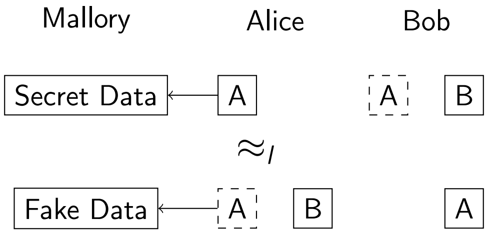

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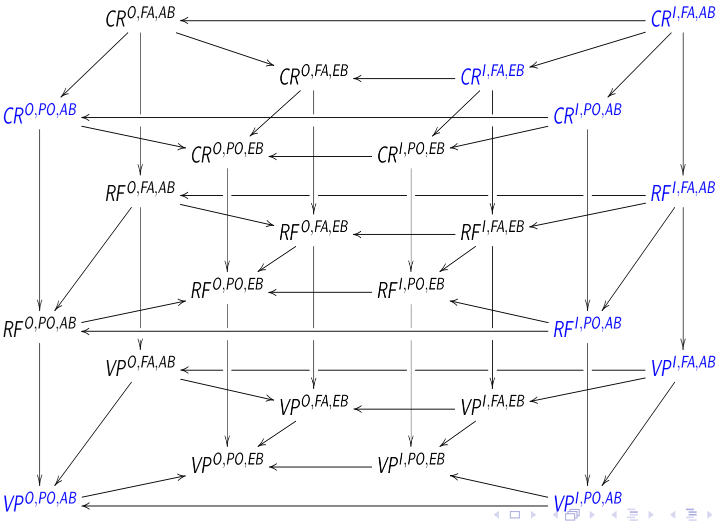
Relations among the notions



Plan

Conclusion

- Generalized model
- New modular definition
- Includes known threats
- Hierarchy of notions
- Allows fine-grained comparison of different types of protocols
- Can be automatically verified using existing tools (within certain complexity limits)

Future Work

- Automate and/or automatically verify more of the proofs
- Computational definition

Thank you for your attention!

Questions?

Existing definitions

- [?, ?]: Tailored to a specific protocol
- [?, ?]: Unsuitable for protocol by Juels/Civitas
- [?, ?]: Vote-Independence based on definitions by [?, ?]
- [?]: Coercion Resistance, very fine-grained $\rightarrow$ difficult to compare
- [?]: Privacy as unlinkability, unsuitable for automated verification
- ...

Case Studies

Protocol	Priv. Notion	Comments
Juels et al. [?]	$CR^{I,FA,EB}$	Requires fakes to achieve CR
Bingo Voting [?]	$CR^{I,PO,AB}$	Trusted voting machine
- variant	$CR^{I,FA,AB}$	Secure against forced abstention
Lee et al. [?]	$CR^{O,PO,AB}$	Vulnerable to vote-copying
Okamoto [?]	$RF^{I,PO,AB}$	Based on trap-door commitments
- variant	$RF^{I,FA,AB}$	Private channel to administrator
Fujioka et al. [?]	$VP^{I,PO,AB}$	Based on blind signatures
- variant	$VP^{I,PO,AB}$	Permits multiple votes
Simp. Voting Prot.	$VP^{O,PO,AB}$	Vulnerable to vote-copying

Modeling a voting protocol

Definition (Voting Protocol)

A voting protocol is a tuple of processes $(V, A_1, \ldots, A_m)$ where V is the process that is executed by the voter, and the A_j's are the processes executed by the election authorities.

Definition (Voting Process)

A voting process of a voting protocol $(V, A_1, \ldots, A_m)$ is a closed plain process

$$VP = \nu\tilde{n}.(V\sigma_{id_1}\sigma_{f_1}\sigma_{v_1}|\ldots|V\sigma_{id_n}\sigma_{f_n}\sigma_{v_n}|A_1|\ldots|A_l)$$

We define an evaluation context VP' which is like VP, but has a hole instead of two $V\sigma_i$.

Definition (Process P^{ch} [?])

Let P be a process and ch be a channel. We define P^{ch} as follows:

- $0^{ch} \triangleq 0$,
- $(P|Q)^{ch} \triangleq P^{ch}|Q^{ch}$,
- $(\nu n.P)^{ch} \triangleq \nu n.\mathtt{out}(ch, n).P^{ch}$ when n is a name of base type,
- $(\nu n.P)^{ch} \triangleq \nu n.P^{ch}$ otherwise,
- $(\mathtt{in}(u, x).P)^{ch} \triangleq \mathtt{in}(u, x).\mathtt{out}(ch, x).P^{ch}$ when x is a variable of base type,
- $(\mathtt{in}(u, x).P)^{ch} \triangleq \mathtt{in}(u, x).P^{ch}$ otherwise,
- $(\mathtt{out}(u, M).P)^{ch} \triangleq \mathtt{out}(u, M).P^{ch}$,
- $(!P)^{ch} \triangleq !P^{ch}$,
- $(\mathtt{if}\ M = N\ \mathtt{then}\ P\ \mathtt{else}\ Q)^{ch} \triangleq \mathtt{if}\ M = N\ \mathtt{then}\ P^{ch}\ \mathtt{else}\ Q^{ch}$.

Definition (Process P^{c_1,c_2} [?])

Let P be a process, c_1, c_2 channels. We define P^{c_1,c_2} as follows:

- $0^{c_1,c_2} \triangleq 0$,
- $(P|Q)^{c_1,c_2} \triangleq P^{c_1,c_2}|Q^{c_1,c_2}$,
- $(\nu n.P)^{c_1,c_2} \triangleq \nu n.\mathtt{out}(c_1,n).P^{c_1,c_2}$ if n is a name of base type,
- $(\nu n.P)^{c_1,c_2} \triangleq \nu n.P^{c_1,c_2}$ otherwise,
- $(\mathtt{in}(u,x).P)^{c_1,c_2} \triangleq \mathtt{in}(u,x).\mathtt{out}(c_1,x).P^{c_1,c_2}$ if x is a variable of base type & x is a fresh variable,
- $(\mathtt{in}(u,x).P)^{c_1,c_2} \triangleq \mathtt{in}(u,x).P^{c_1,c_2}$ otherwise,
- $(\mathtt{out}(u,M).P)^{c_1,c_2} \triangleq \mathtt{in}(c_2,x).\mathtt{out}(u,x).P^{c_1,c_2}$,
- $(!P)^{c_1,c_2} \triangleq !P^{c_1,c_2}$,
- $(\mathtt{if}\ M = N\ \mathtt{then}\ P\ \mathtt{else}\ Q)^{c_1,c_2} \triangleq \mathtt{in}(c_2,x).\mathtt{if}\ x = \mathrm{true}$ $\mathtt{then}\ P^{c_1,c_2}\ \mathtt{else}\ Q^{c_1,c_2}$ where x is a fresh variable and true is a constant

Definition (Process $A^{\setminus out(ch,\cdot)}$ [?])

Let A be an extended process. We define the process $A^{\setminus out(ch,\cdot)}$ as $\nu ch.(A|!\mathrm{in}(ch,x))$.

Definition (Equivalence in a Frame)

Two terms M and N are equal in the frame ϕ, written $(M = N)\phi$, if and only if $\phi \equiv \nu \tilde{n}.\sigma$, $M\sigma = N\sigma$, and $\{\tilde{n}\} \cap (fn(M) \cup fn(N)) = \emptyset$ for some names $\tilde{n}$ and some substitution σ.

Definition (Static Equivalence ($\approx_s$))

Two closed frames ϕ and ψ are statically equivalent, written $\phi \approx_s \psi$, when $\mathrm{dom}(\phi) = \mathrm{dom}(\psi)$ and when for all terms M and N $(M = N)\phi$ if and only if $(M = N)\psi$. Two extended processes A and B are statically equivalent ($A \approx_s B$) if their frames are statically equivalent.

Definition (Labelled Bisimilarity ($\approx_l$))

Labelled bisimilarity is the largest symmetric relation $\mathcal{R}$ on closed extended processes, such that $A \ \mathcal{R} \ B$ implies

1. $A \approx_s B$,
2. if $A \rightarrow A'$, then $B \rightarrow B'$ and $A' \ \mathcal{R} \ B'$ for some B',
3. if $A \xrightarrow{\alpha} A'$ and $fv(\alpha) \subseteq \mathrm{dom}(A)$ and $bn(\alpha) \cap fn(B) = \emptyset$, then $B \rightarrow^* \xrightarrow{\alpha} \rightarrow^* B'$ and $A' \ \mathcal{R} \ B'$ for some B'.