
COMPUTER SECURITY LAB
RICE UNIVERSITY

Crypto and e-Voting: Homomorphisms, Zero-Knowledge Proofs

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Administrivia

Project 1: Going online tomorrow

Some coding, some written bits — get started early

Proper use of Piazza

Please don’t post partial solutions (code, hash values, etc.) without marking those posts as “private” to the instructors.

Our last crypto lecture!

On your own: go read up on how RSA works

Modern cryptographers seem to have concluded that DH-style is the way to go

Instead, this lecture is a whirlwind through several modern crypto topics

Zero-knowledge proofs

Mixnets

Homomorphic cryptography

Application to electronic voting

All of these things are deep topics

Your mission: understand some of the clever things that crypto can do

Reminder: Diffie-Hellman & ElGamal Crypto

Modular arithmetic 101

We're working in $\mathbb{Z}_p^*$, the integers in [1, *p*)

$$
\begin{aligned}
2+3 &= 5 \pmod 7 \\
2+4 &= 6 \pmod 7 \\
2+5 &= 0 \pmod 7 \longleftarrow \textbf{Forbidden!} \\
2*3 &= 6 \pmod 7 \\
2*4 &= 1 \pmod 7 \\
6*6 &= 1 \pmod 7
\end{aligned}
$$

Note: $\mathbb{Z}_p^*$ is closed under multiplication but not addition.

Modular arithmetic 101

In $\mathbb{Z}_p^*$, we want to find *generators* such that $g^1, g^2, g^3, \ldots, g^{p-1}$ cover all the elements in the group.

Example, for *p*=7:

g=2 is not a generator, but *g*=3 is.

Discrete logarithms

Back to the regular integers, say I give you $q = 5^{8437591243259543}$

and ask you to take $\log_5 q$

Logarithms, over integers, are tractable. But what about in $\mathbb{Z}_p^*$**?**

No known efficient solution to DLog problem.

Diffie-Hellman (1976)

$$
\begin{aligned}
\text{Alice} &: \quad \textit{random } a \in \mathbb{Z}_p^* \\
\text{Bob} &: \quad \textit{random } b \in \mathbb{Z}_p^* \\
\text{Public} &: \quad \textit{generator } g \in \mathbb{Z}_p^* \\
A \to B &: \quad g^a \\
B \to A &: \quad g^b \\
\text{Alice} &: \quad \text{computes } (g^b)^a = g^{ab} \\
\text{Bob} &: \quad \text{computes } (g^a)^b = g^{ab} \\
\text{Eve} &: \quad \text{knows } g^a, g^b, \text{cannot compute } g^{ab}
\end{aligned}
$$

ElGamal encryption (1984)

Non-deterministic cryptosystem (different r every time)

$$
\begin{aligned}
E(g^a, r, M) &= \langle g^r, (g^a)^r M \rangle \\
D(g^r, g^{ar} M, a) &= \frac{g^{ar} M}{(g^r)^a} \\
&= M
\end{aligned}
$$

g	group generator
M	plaintext (message)
r	random (chosen at encryption time)
a	(private) decryption key
g^a	(public) encryption key

Digital signature algorithm (1991)

Similar idea to ElGamal encryption, just a bit more involved

$$
\begin{aligned}
k &= \text{random} \in [1, q) \\
r &= (g^k \bmod p) \bmod q \\
s &= k^{-1}\,(H(M) + xr) \bmod q \\
Sign(x, k, M) &= \langle r, s \rangle \\
Verify(y, r, s):& \\
w &= s^{-1} \bmod q \\
u_1 &= H(M) \cdot w \bmod q \\
u_2 &= r \cdot w \bmod q \\
v &= ((g^{u_1} y^{u_2}) \bmod p) \bmod q \\
\text{valid if } v &= r
\end{aligned}
$$

g	group generator
p	large prime (1000+ bits)
q	large-ish prime (~160 bits) divisible by p-1
M	plaintext (message)
k	random (chosen at encryption time)
x	(private) decryption key (chosen randomly < q)
$y=g^x$	(public) encryption key (mod p)

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Fun: if *k* isn't random and unique, attacker can recover *x*. (*PS3 attack, Dec. 2010*). Solution: derive *k* from *x* and *H*(*M*) deterministically. [*RFC 6979*]

Homomorphic property

Anybody can combine two ciphertexts to get a new one.

$$
\begin{aligned}
E(M_1) \oplus E(M_2) &= < g^{r_1}, (g^a)^{r_1} M_1 > \oplus < g^{r_2}, (g^a)^{r_2} M_2 > \\
&= < g^{r_1} g^{r_2}, (g^a)^{r_1} M_1 (g^a)^{r_2} M_2 > \\
&= g^{r_1 + r_2}, g^{a(r_1 + r_2)} M_1 M_2 \\
&= E(M_1 M_2)
\end{aligned}
$$

g	group generator
M	plaintext (message)
r	random (chosen at encryption time)
a	(private) decryption key
g^a	(public) encryption key

Homomorphic vote tallying

Change messages to counters, additive in exponent of *g*.
"Exponential ElGamal"

$$
\begin{aligned}
E(v_1) \oplus E(v_2) &= < g^{r_1}, (g^a)^{r_1} g^{v_1} > \oplus < g^{r_2}, (g^a)^{r_2} g^{v_2} > \\
&= < g^{r_1 + r_2}, g^{a(r_1 + r_2)} g^{v_1 + v_2} > \\
&= E(v_1 + v_2)
\end{aligned}
$$

g	group generator
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Violation of encryption semantics?

If I know M_1 and M_2 and $E(M_1) \oplus E(M_2) = E(M_1 M_2)$
then I can find other messages where
I know their encryption!

Solution: Padding

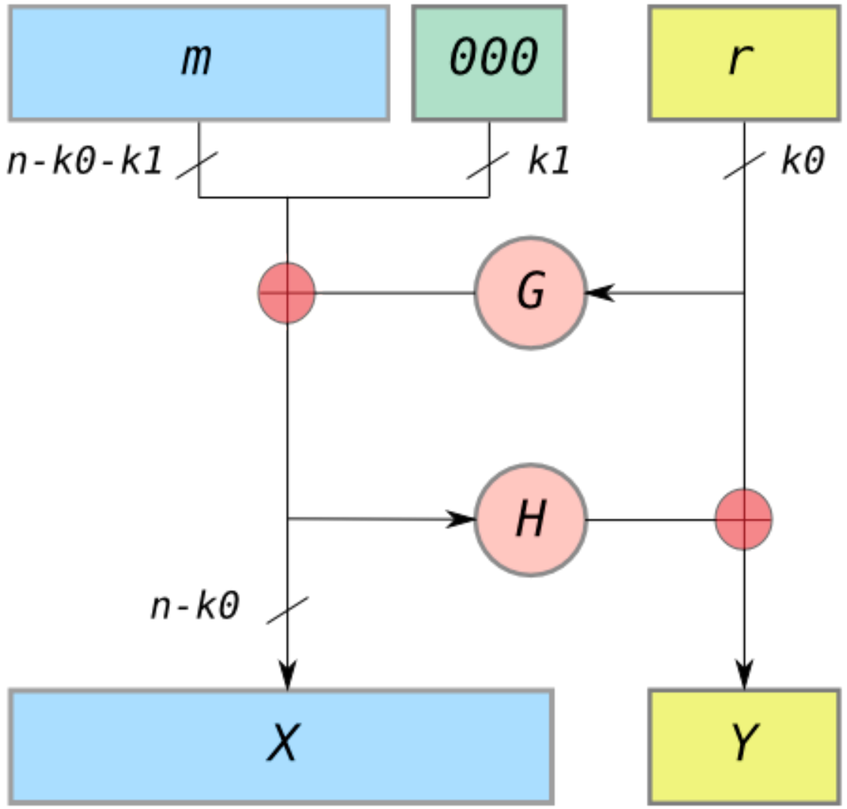
Optimal Asymmetric Encryption Padding (OAEP) - *Belare and Rogaway (1995)*

m - message (plaintext)

r - random number

G, H - cryptographic hash functions

X, Y - the message that gets encrypted



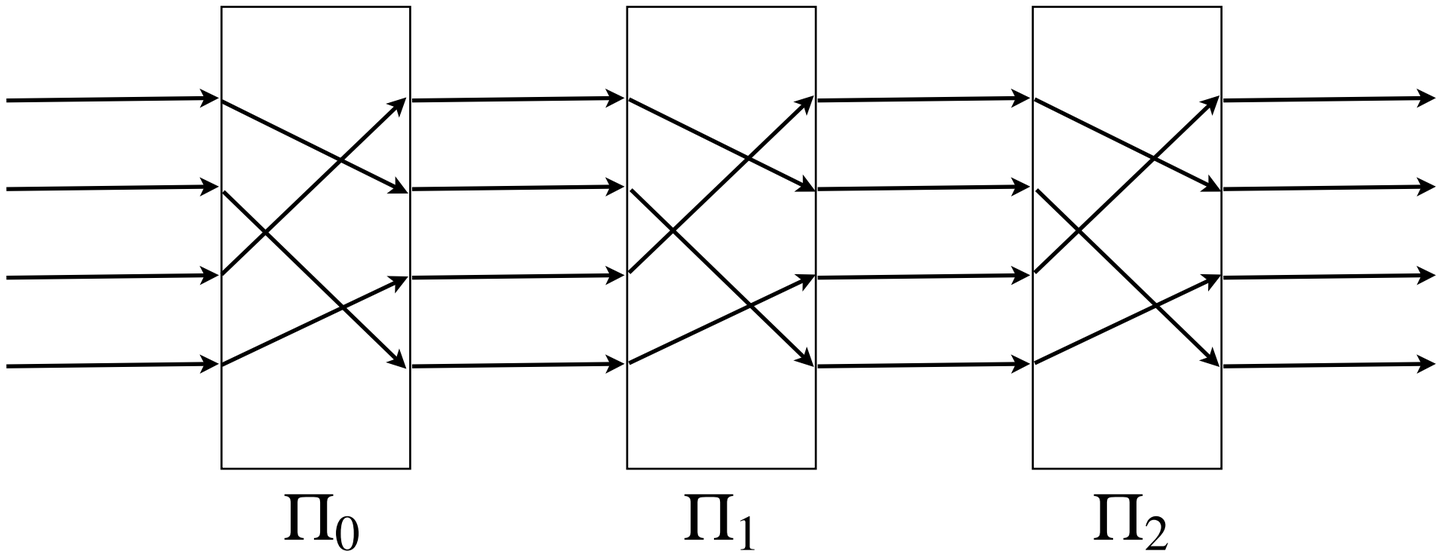
Cool trick: reencryption

$$E(M) \oplus E(0) = E(M)^*$$

Anybody can “reencrypt” a message.
(New random number introduced from $E(0)$.)

Reencryption mixnets

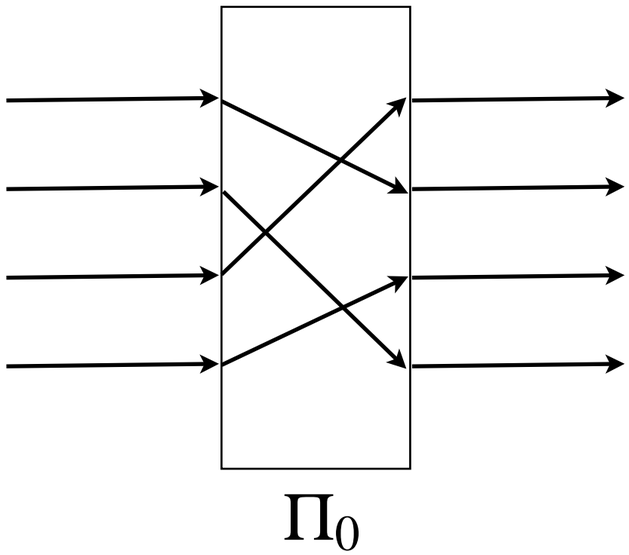
Permutations Π_i, where output is reencrypted.



Each mix permutes/reencrypts.
Must prove output corresponds to input.

Non-solution: reveal the mix

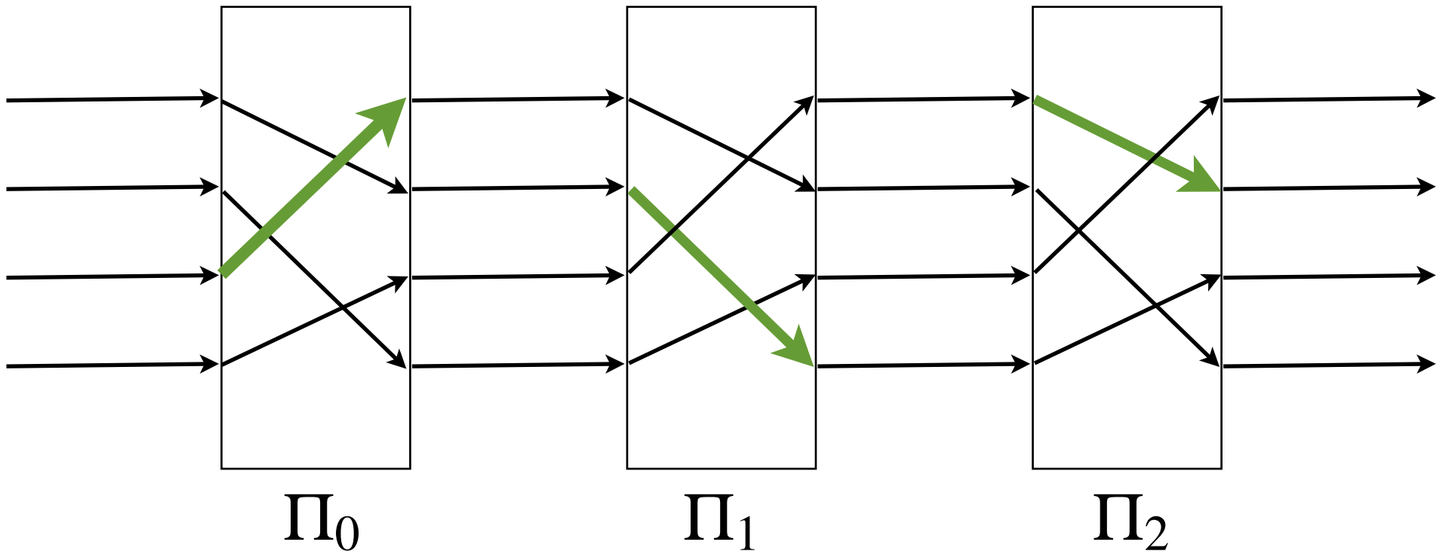
Publish the random numbers and the permutation.



Eliminates benefit of randomization.

Randomized partial checking

Effective across larger mixes.
(Jakobsson, Jules, Rivest ’02)



Say we’re mixing 1 million ballots, each mix reveals 1%. After five mixes, 99.99% chance that all ballots reencrypted at least once.

Zero-knowledge proofs (ZKP)

want to prove you know something

while revealing nothing

generalized format

prover: commit to something (e.g., reencryption mix output)

verifier: *challenge* the prover

prover: respond to the challenge

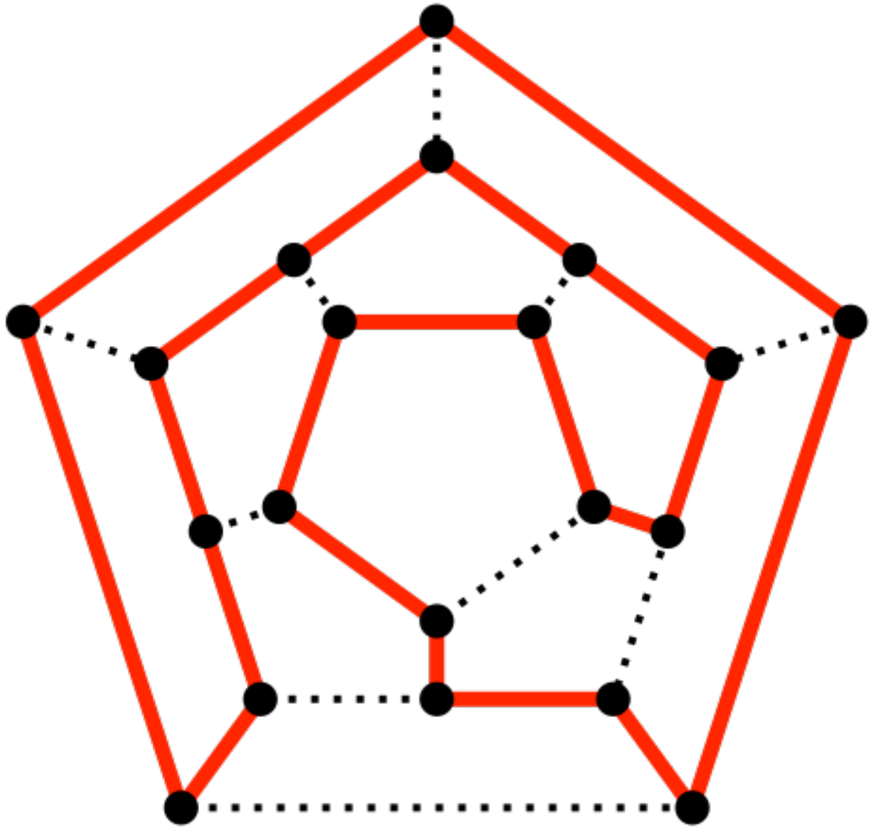
Example: Hamiltonian paths

Prover: “I know a HP over graph *G*.” Compute graph isomorphism *H*. Publish *G, H.*

Verifier: Coin toss.
Heads: tell HP over *H*.
Tails: tell isomorphism *G* to *H*.

(Repeat *N* times.)

If prover doesn’t know HP, verifier catches with high probability.

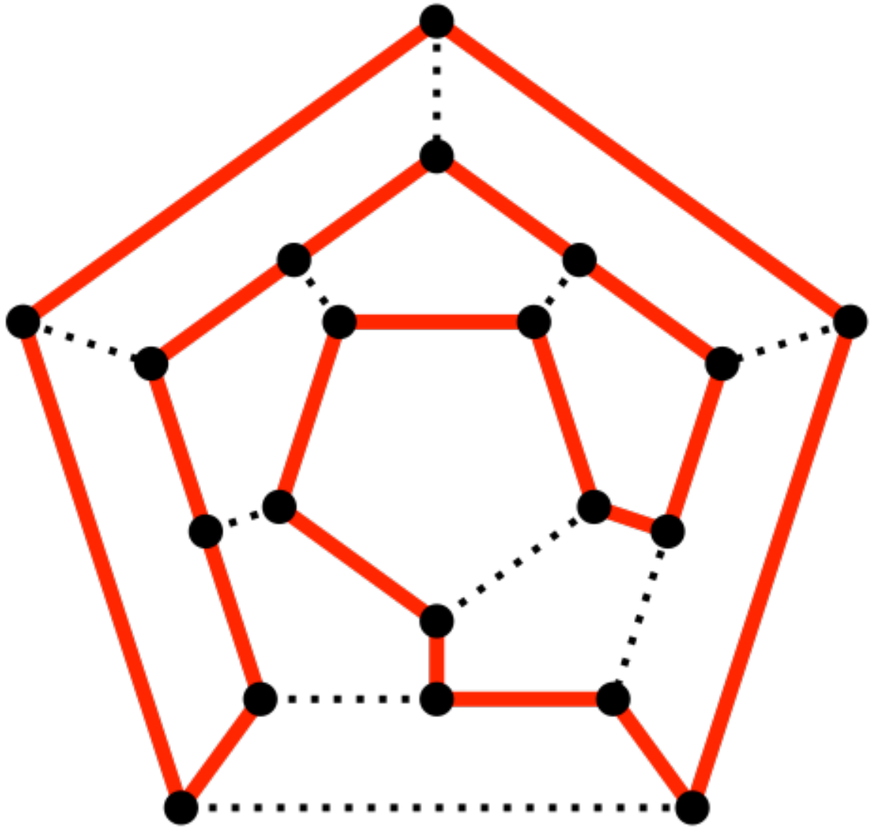


Non-interactive ZK proofs

Prover: Precompute *N* isomorphisms (H_1 to H_N) and hash them. Hash function yields coin tosses for virtual challenger. Then output the results.

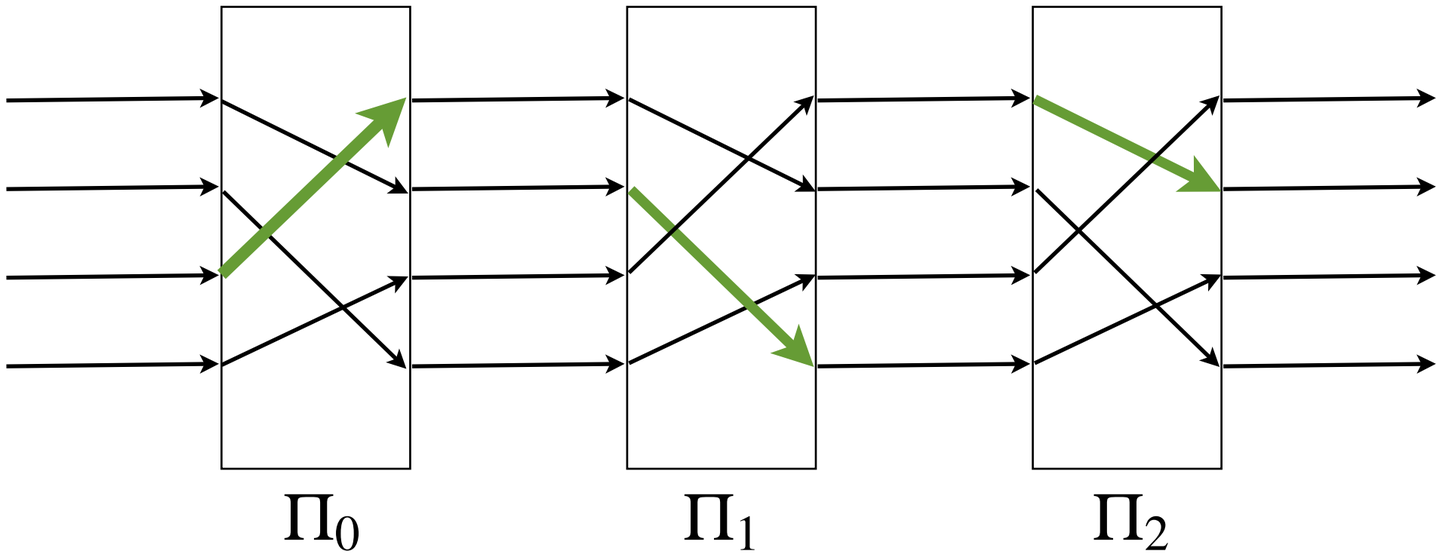
(Assumes good hash functions.)

This is an example of the *Fiat-Shamir heuristic* (1986).



NIZK variant for mixes

Hash the output of the permutation/reencryption. Use those bits to select which edges get revealed.



Say we're mixing 1 million ballots, each mix reveals 1%. After five mixes, 99.99% chance that all ballots reencrypted at least once.

Evil machine: E(bignum)?

Must prove ciphertext corresponds to well-formed plaintext. (Example, prove counters are zero or one.)

We need another ZK tool: Chaum-Pedersen proofs.

Prover knows: $(g, g^x), (h, h^x)$

Wants to prove that these two tuples share x

But x is a secret!

Chaum-Pedersen proofs (1992)

Goal: demonstrate $(g, g^x), (h, h^x)$

P: choose random $w \in \mathbb{Z}_p^*$, compute $(A = g^w, B = h^w)$

Send (A,B) to V

V: pick a random number c (challenge), send to P

P: compute $R = w + xc$

send R to V

V: Compute

$$\begin{aligned} A(g^x)^c &= g^w g^{xc} \\ &= g^{w+xc} \\ &= g^R \end{aligned}$$

$$\begin{aligned} B(h^x)^c &= h^w h^{xc} \\ &= h^{w+xc} \\ &= h^R \end{aligned}$$

Fake C-P proofs?

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Observer can compute $A(g^x)^c$...

V*:* Compute

$$A(g^x)^c = g^w g^{xc} = g^{w+xc} = g^R$$

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ZK protocols only work when "live" (or use Fiat-Shamir heuristic for non-interactive)

C-P for vote testing

Can I prove a vote is zero or one? First, how about "proving" it's zero using C-P.

Want to verify $\langle g^r, g^{ar} g^v \rangle$ for a specific value of v?

"Prove we know r" (or we could symmetrically prove we know a)

Do C-P protocol where $(g, g^x), (h, h^x)$ becomes $(g, g^r), \left(g^a, \frac{g^{ar} g^v}{g^v} \right)$

We could do this for any value of v

Cramer-Damgård-Schoenmakers (1996)

Can run two Chaum-Pedersen (or any two ZK proofs like this) simultaneously, one “real” and one “simulated”.

First, fake a proof (e.g., for $v = 1$) in advance.

Then, announce the first message for both protocols. Challenger sends c, prover announced a split c_0, c_1 where $c_0 + c_1 = c$, then executes both ZK protocols.

Verifier cannot tell which one was real vs. simulated, but knows that **one** of them was real.

Crypto summary

At the end of the day, **any** election observer can now:

- verify every single ballot for being “well-formed”
  (valid ElGamal tuple, encrypted zero-or-one, etc.)
- add together all the ballots (homomorphically)
- verify a proof of the tally (Chaum-Pedersen again)
  (only the election authority can generate this)

But we have no idea if the original ciphertext corresponded to the **intent of the voter** (versus evil machine flipping votes).

One newer, useful trick:

ballot challenge

Catch a machine if it cheats!

Benaloh challenges [2006]

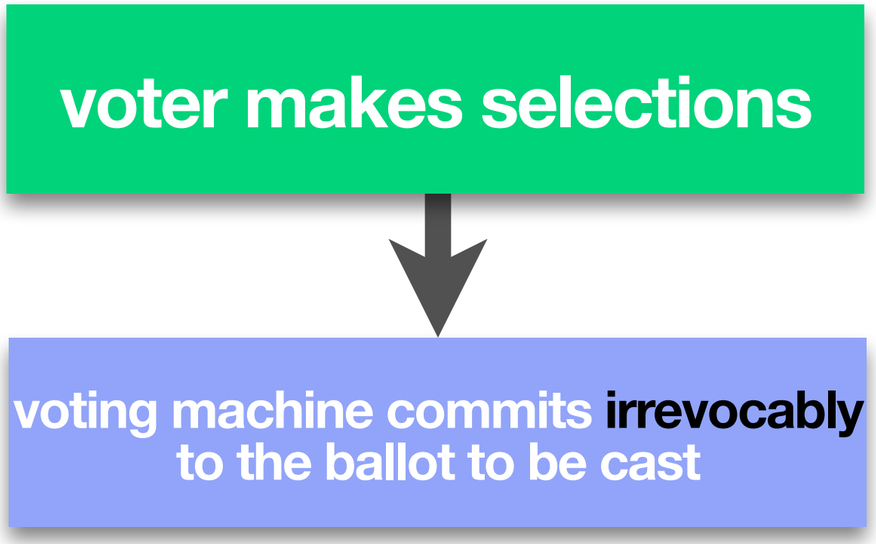
Catch a machine if it cheats!

Benaloh challenges [2006]

voter makes selections

Catch a machine if it cheats!

Benaloh challenges [2006]



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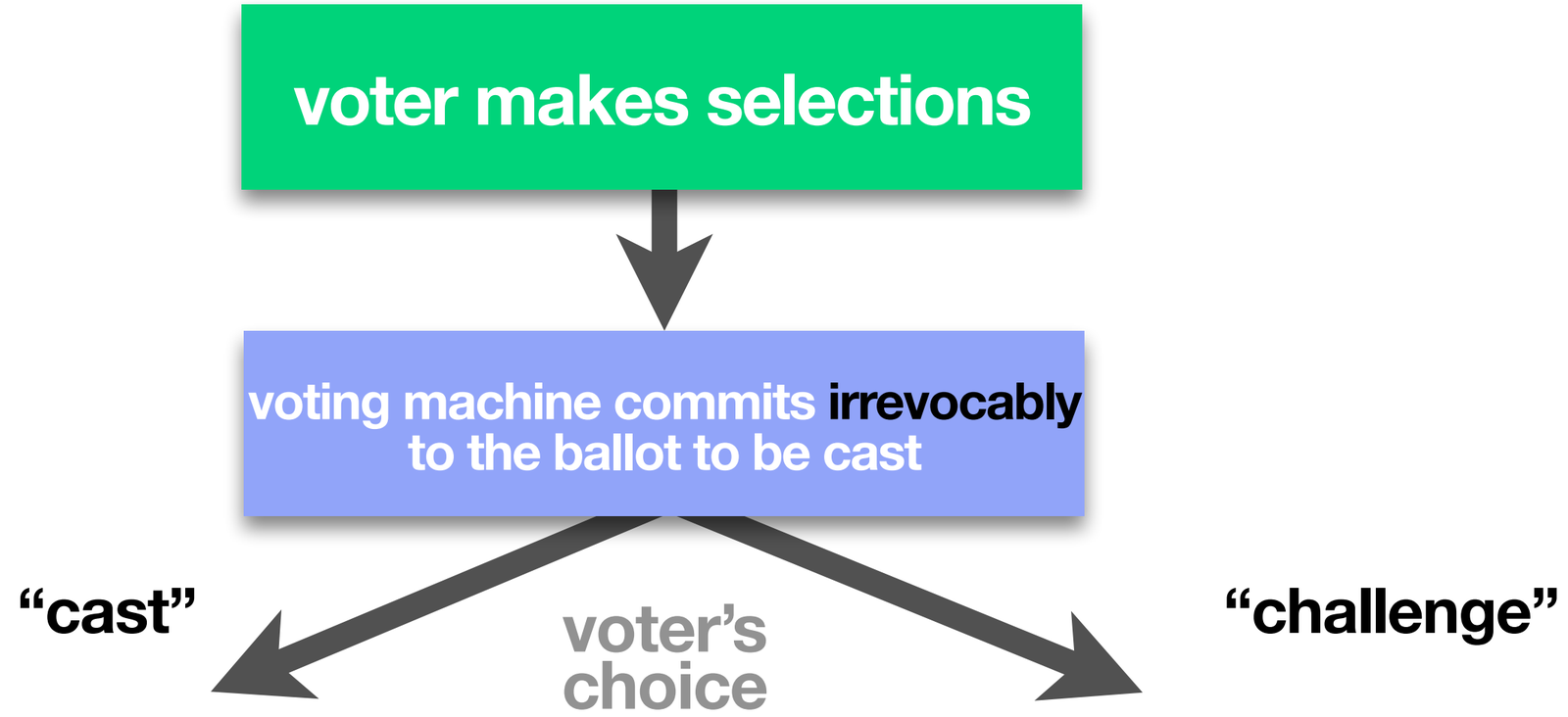

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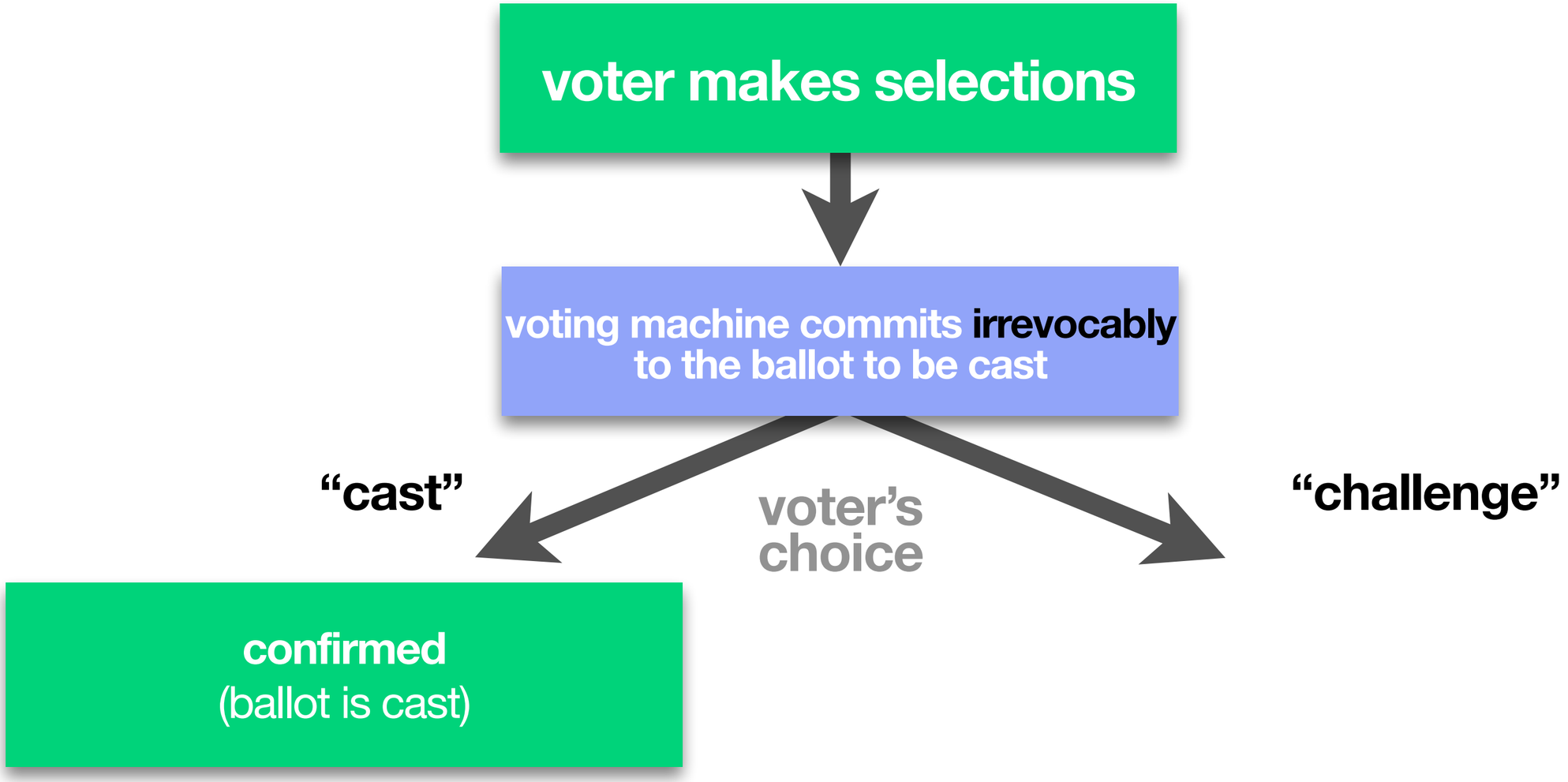

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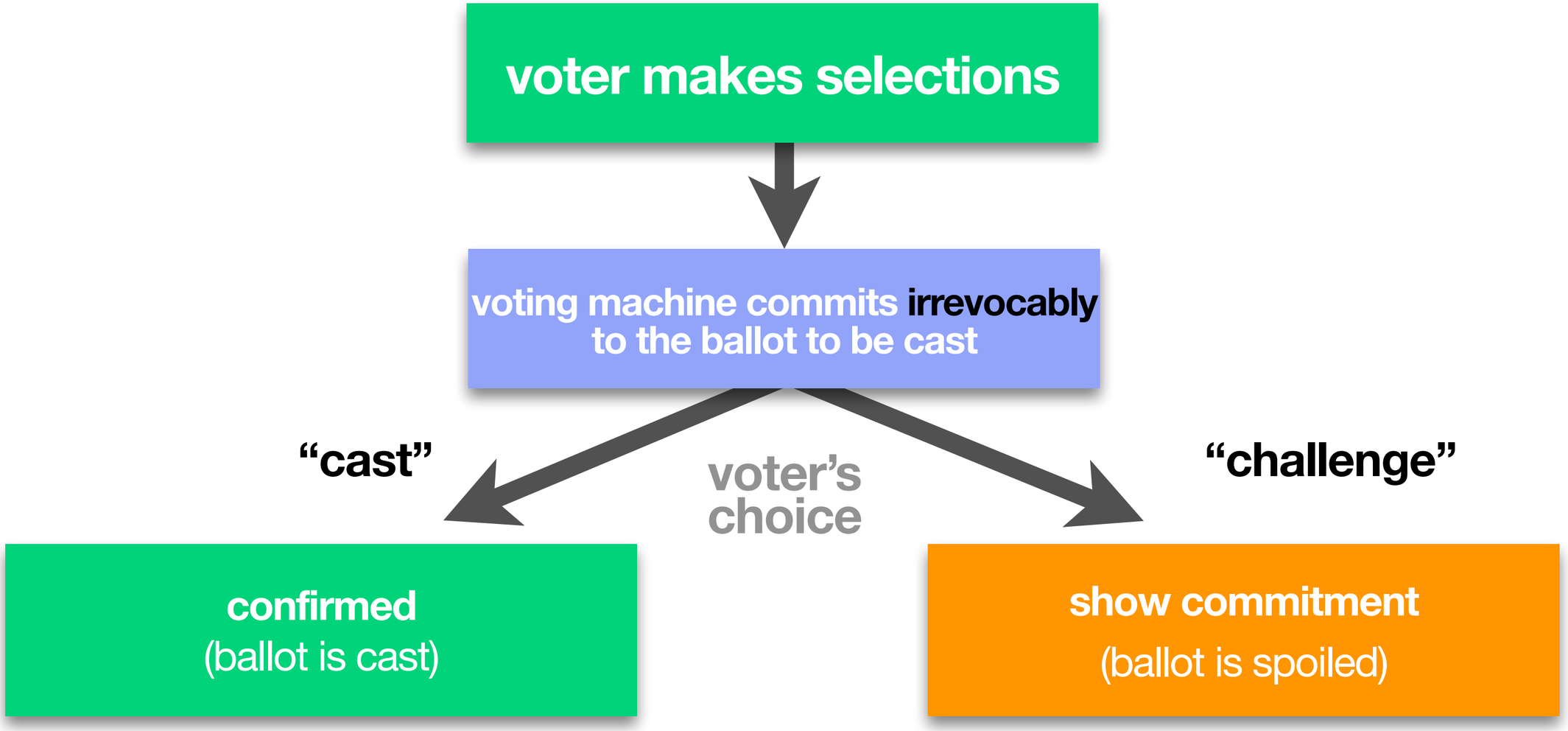

ElGamal extra goodies

Two ways to decrypt:

$$E(g^a, r, M) = \langle g^r, (g^a)^r M \rangle$$

$$D(g^r, g^{ar}M, a) = \frac{g^{ar}M}{(g^r)^a}$$

$$D(g^r, g^{ar}M, r) = \frac{g^{ar}M}{(g^a)^r}$$

g	group generator
M	plaintext (message)
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Only election officials (or trustees) have a (or shares of a) to decrypt totals.

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When challenged, machine reveals random nonces (r), observer can decrypt.

Challenging the machine

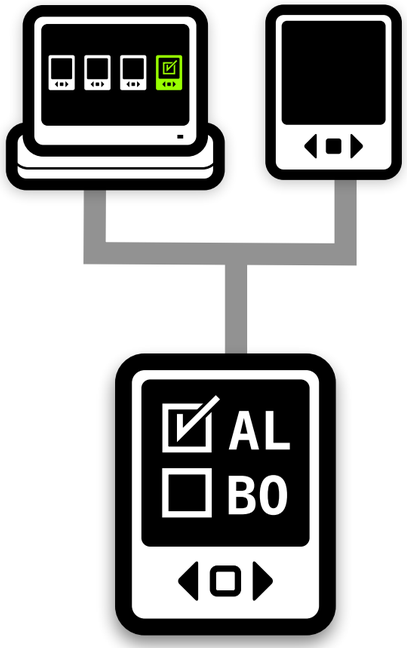
When challenged, the machine must reveal r
We can then decrypt this ballot (only) and see if it's what we expected to see

In Benaloh, the encrypted ballot is on paper
An **irrevocable** output medium
decrypting requires additional equipment

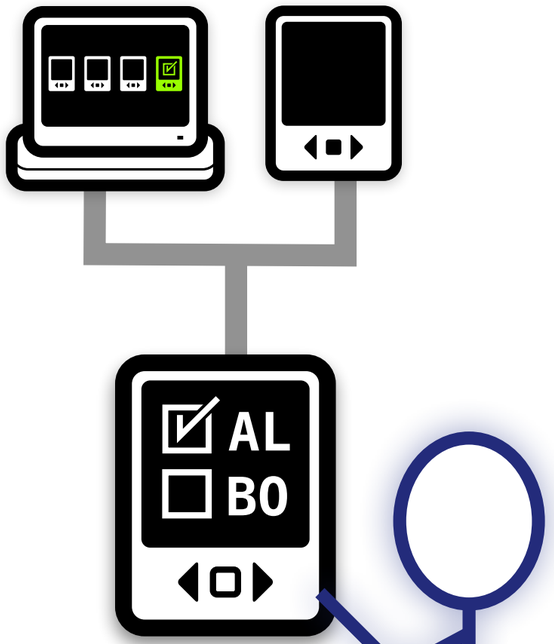
VoteBox (2008) has an irrevocable publishing system
In-precinct LAN, where all machines replicate the history, plus hash entanglement.

Helios (also 2008) just showed it to you on the web

polling place

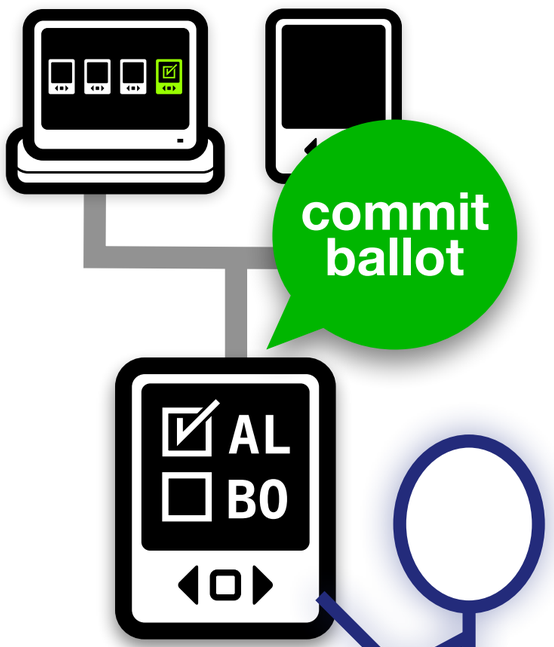


polling place



voter

polling place



voter

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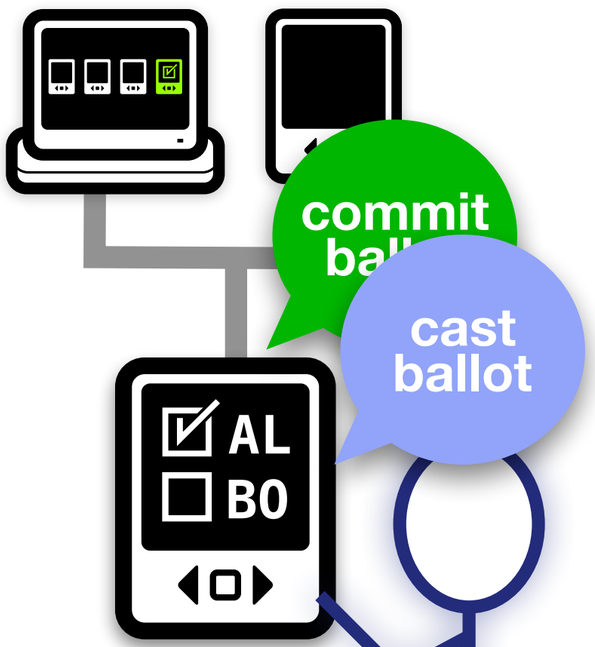

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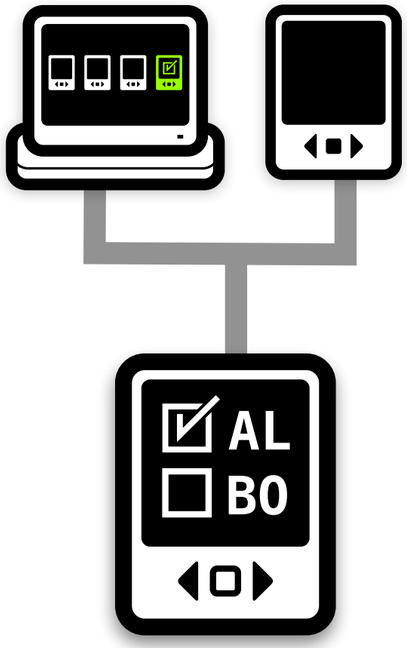

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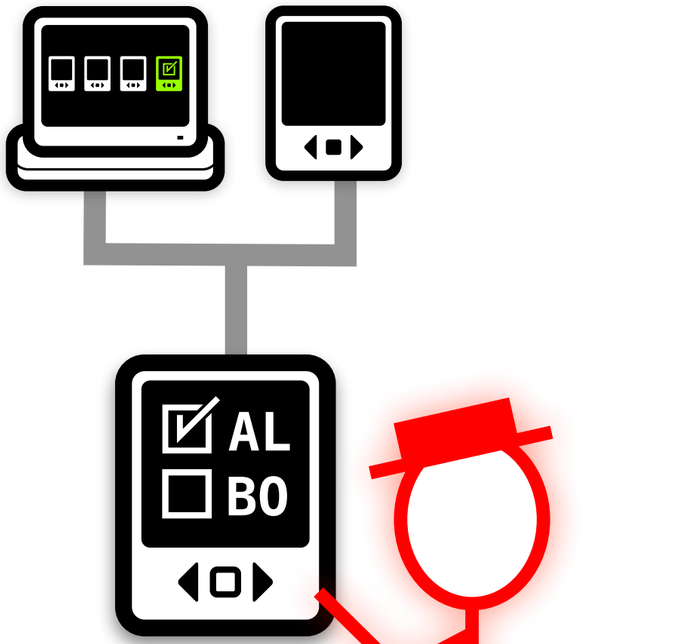
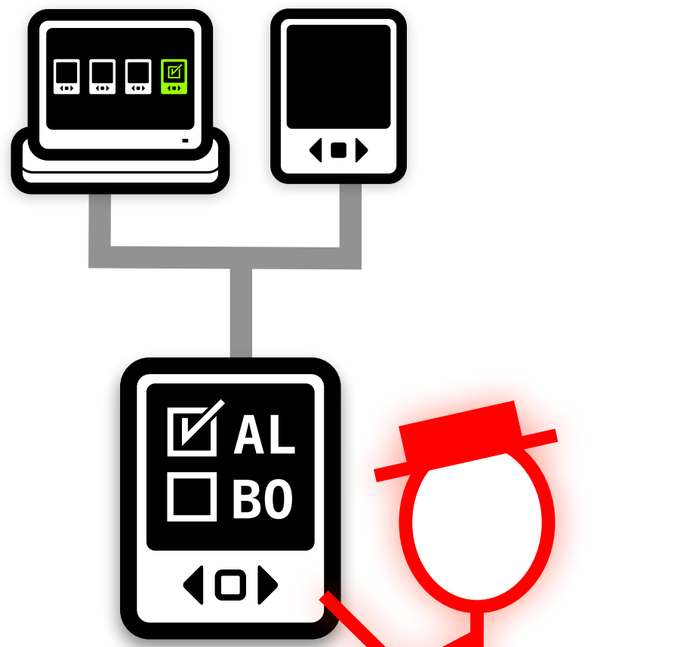


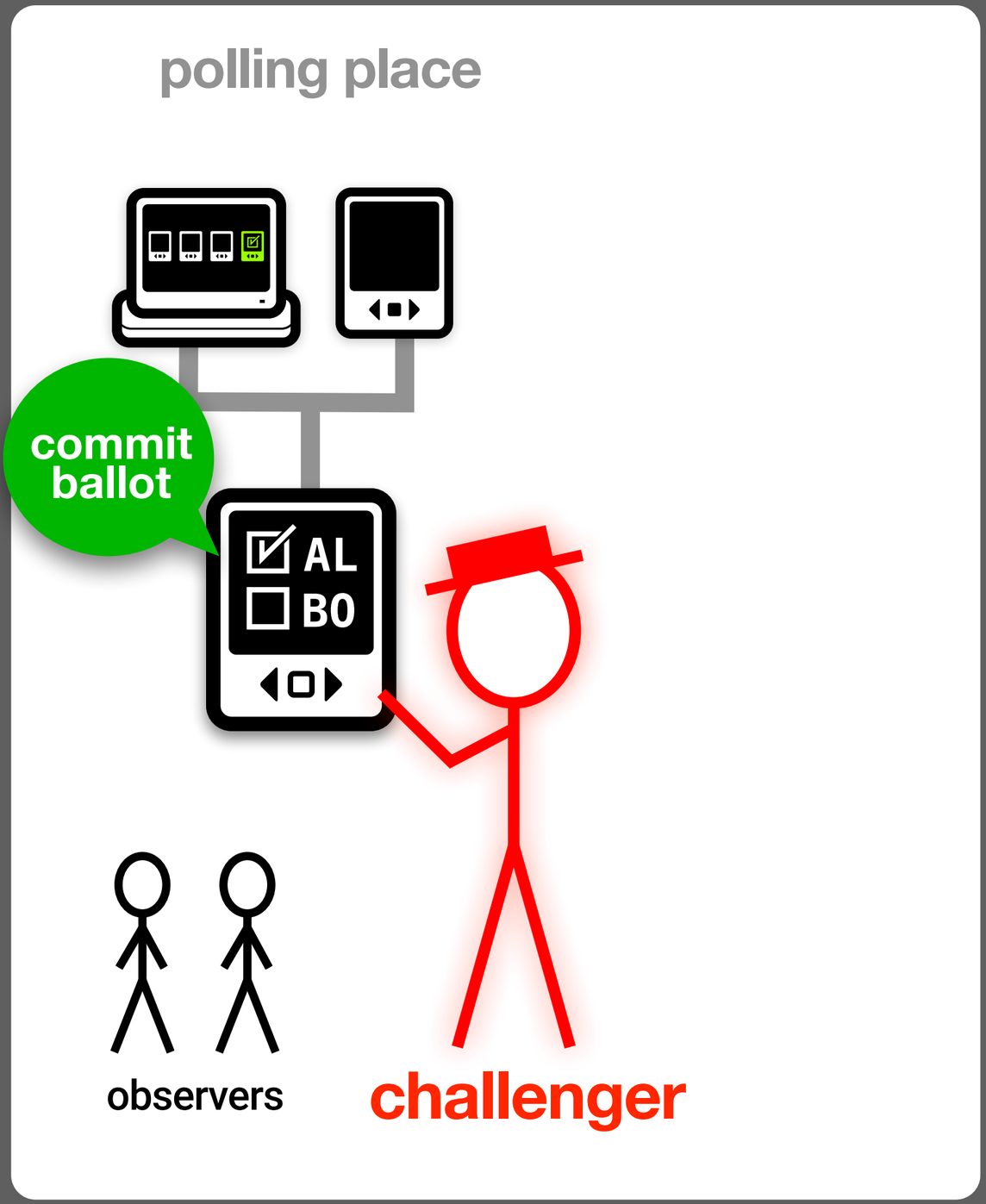
challenger

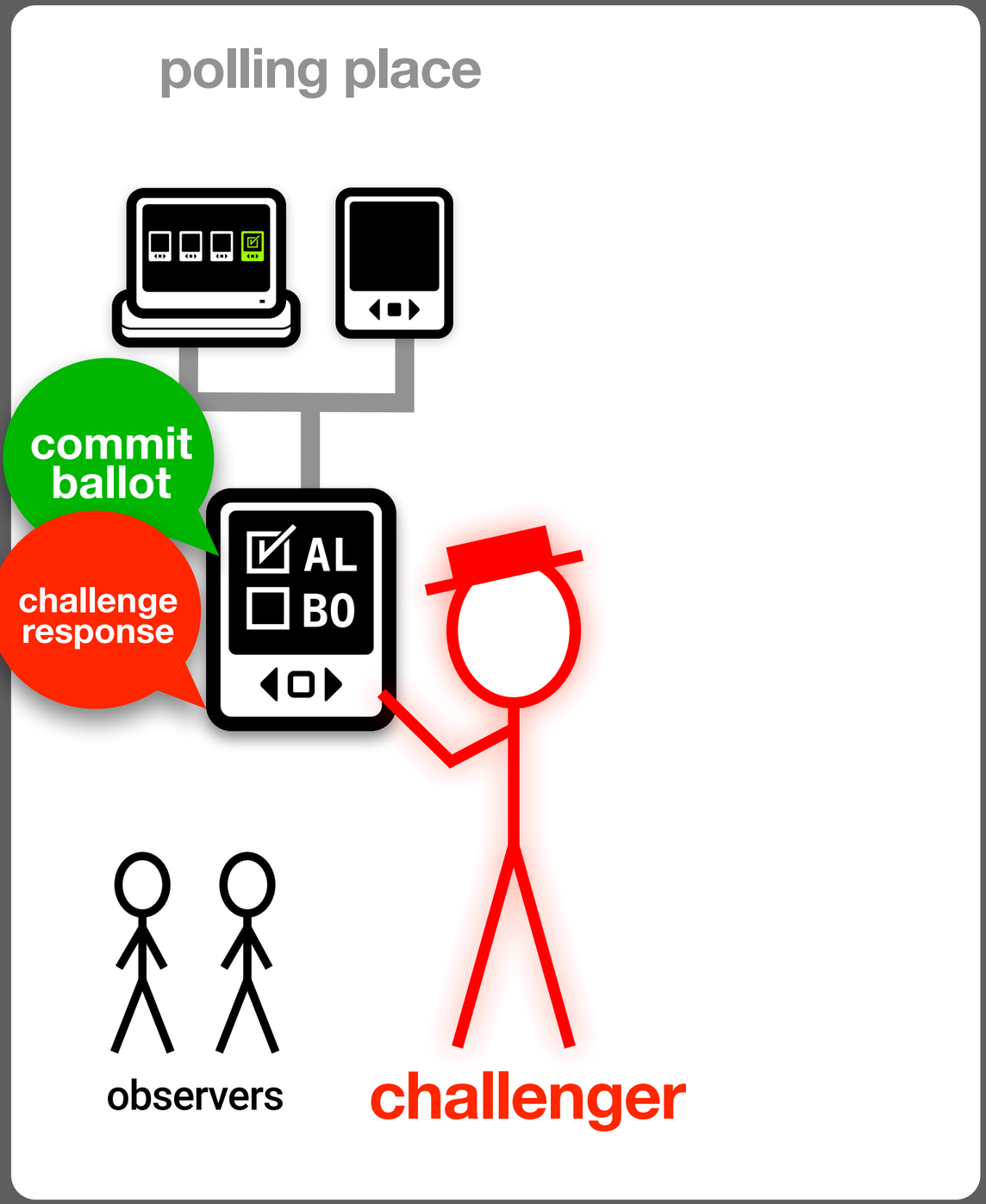
polling place



observers

challenger


polling place
commit ballot
AL
BO
observers
challenger


polling place
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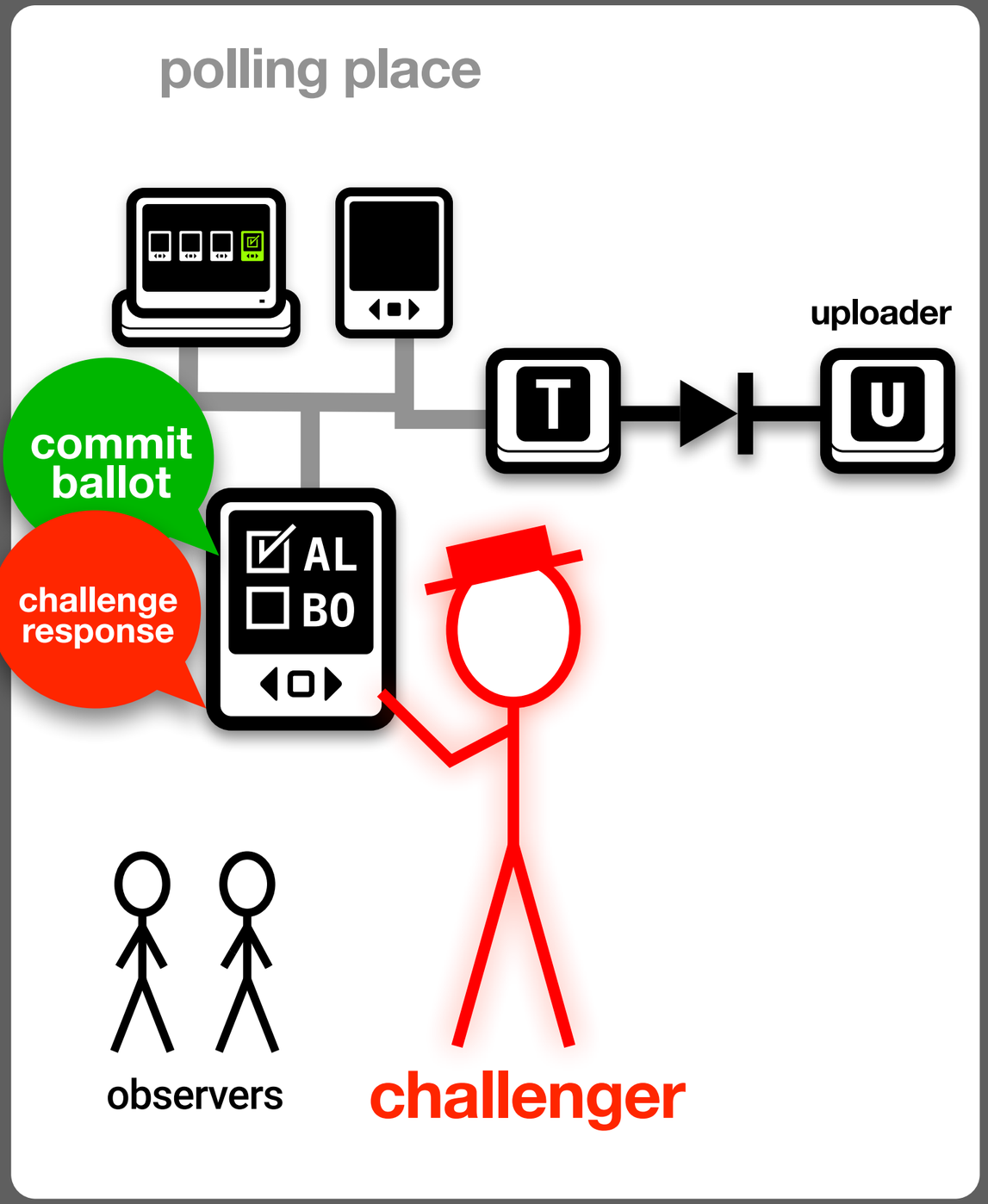
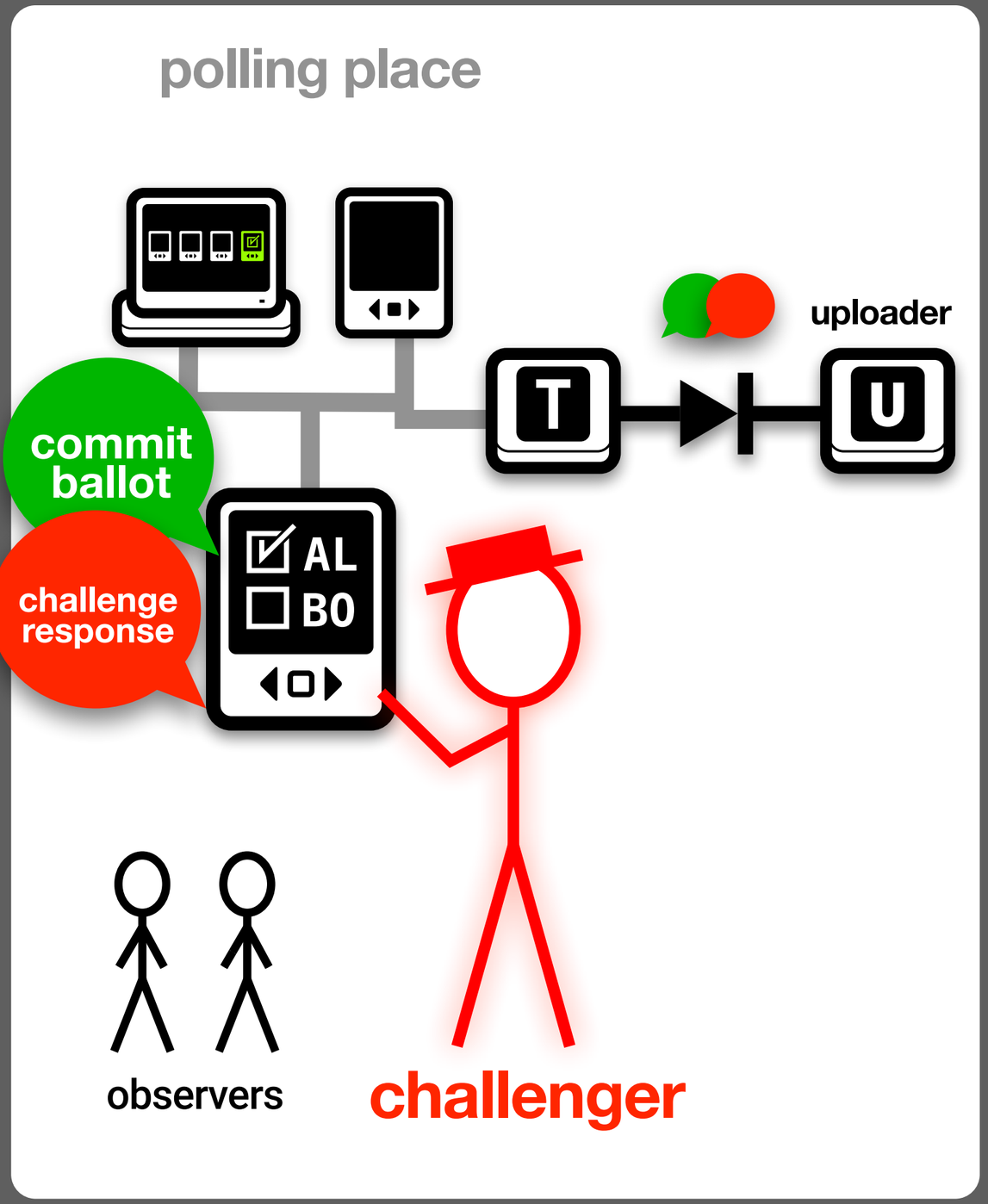
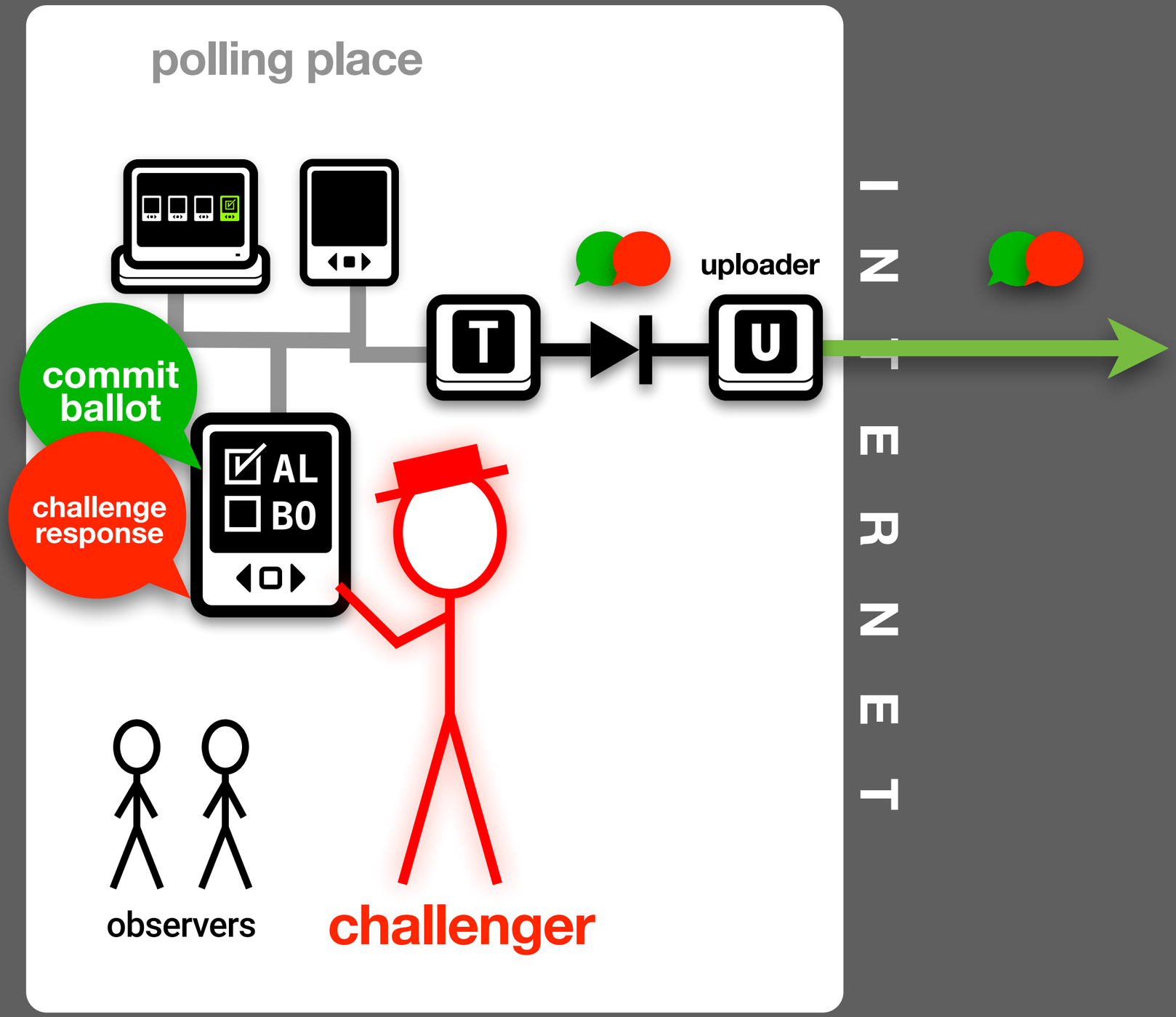
observers
challenger


polling place
uploader
T
U
commit ballot
challenge response
AL
BO
observers
challenger


polling place
uploader
T
U
commit ballot
challenge response
AL
BO
observers
challenger


polling place
uploader
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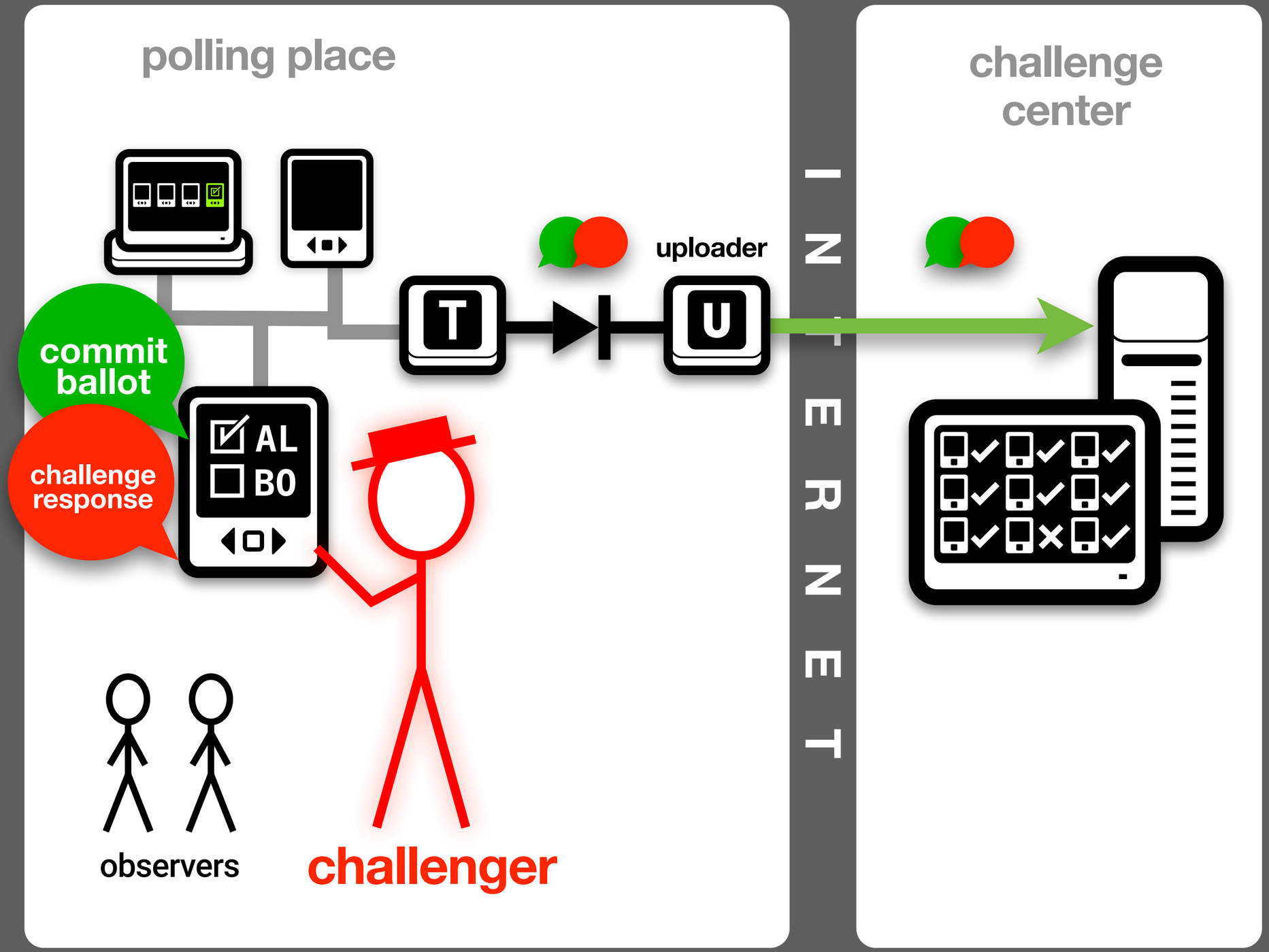
INTERNET
commit ballot
challenge response
AL
BO
observers
challenger


polling place
challenge center
INTERNET
uploader
T
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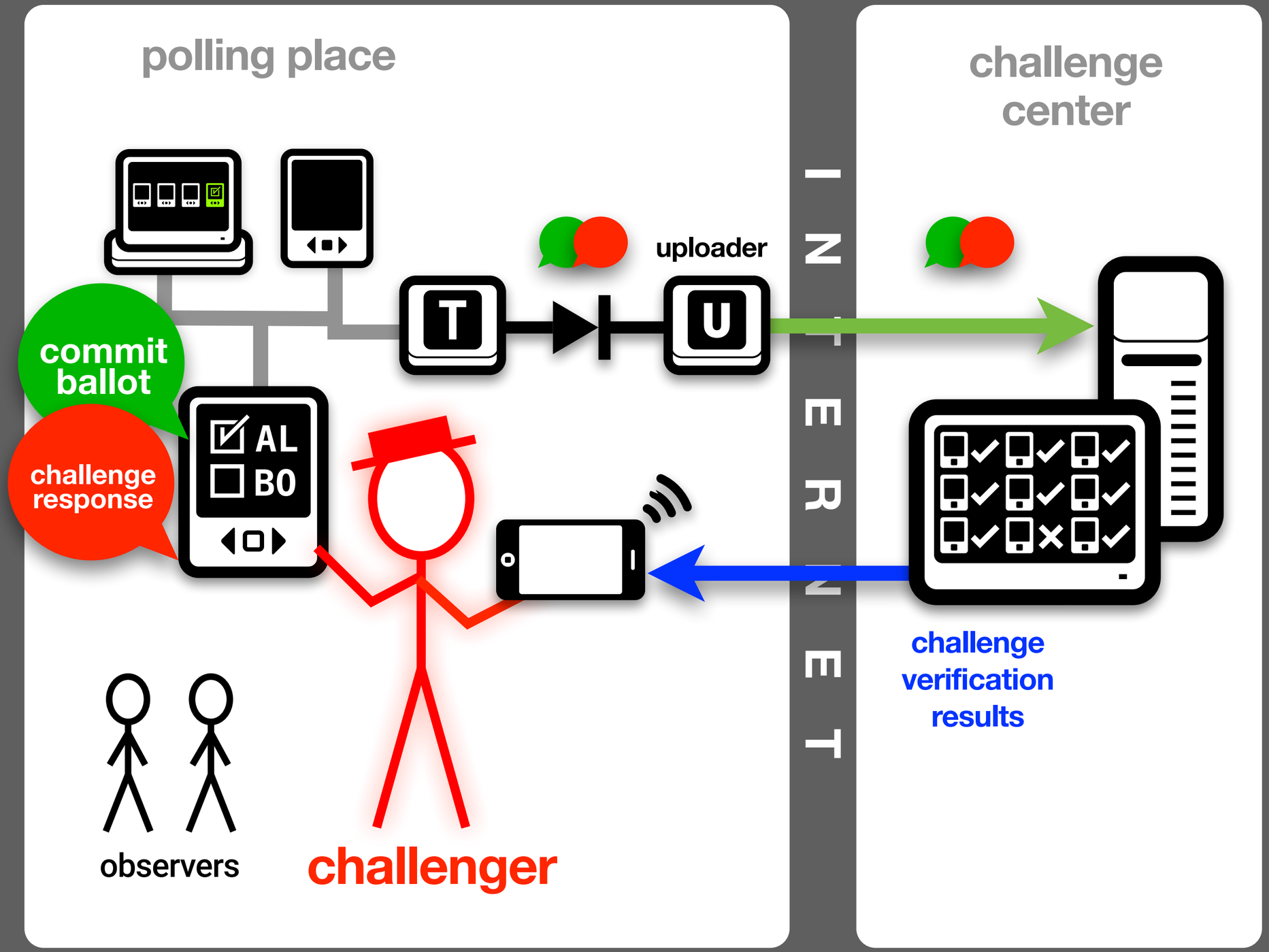
commit ballot
challenge response
AL
BO
observers
challenger


polling place
challenge center
INTERNET
uploader
T
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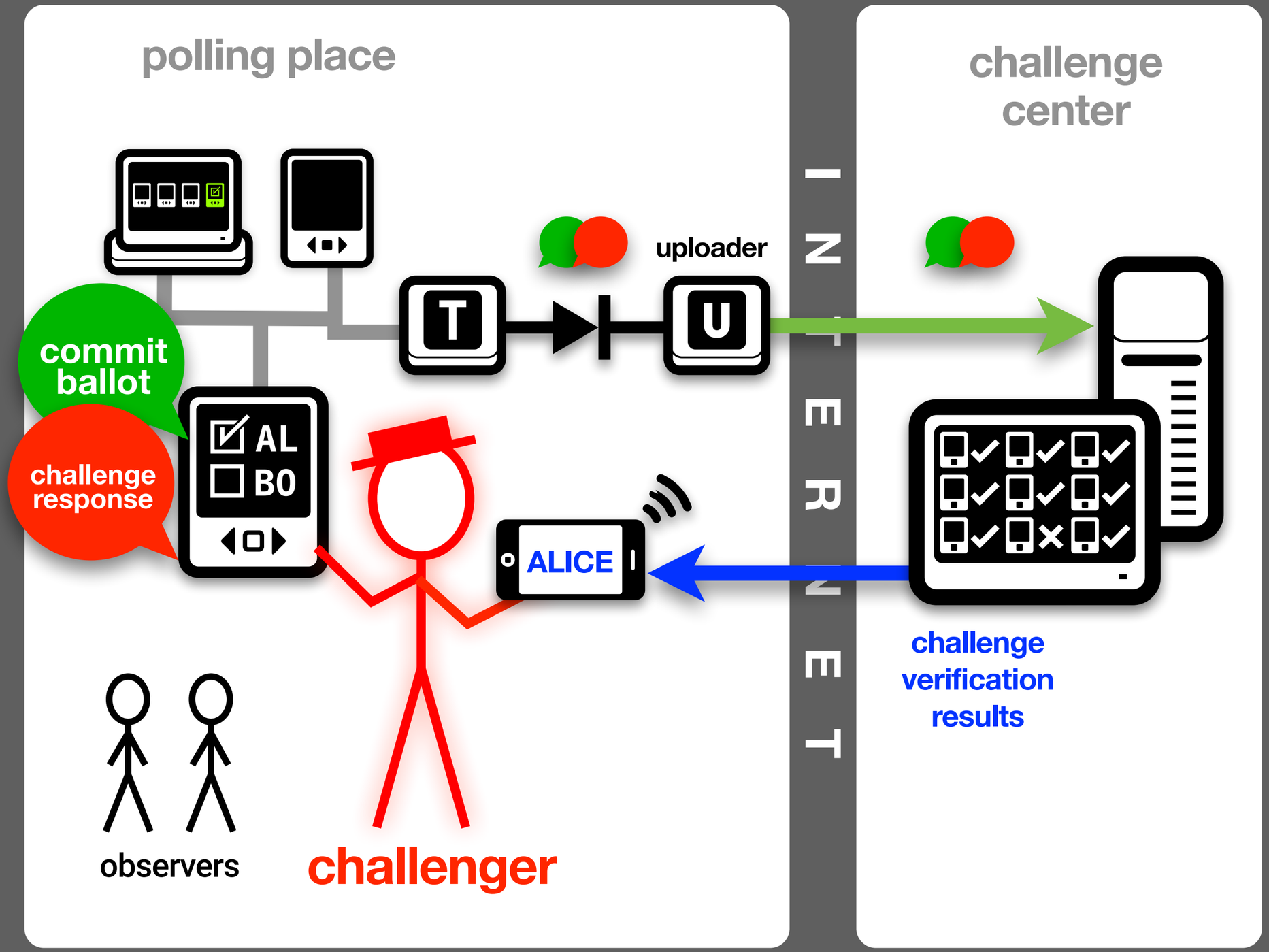
commit ballot
challenge response
AL
BO
challenge verification results
observers
challenger


polling place
challenge center
INTERNET
uploader
T
U
commit ballot
challenge response
AL
BO
ALICE
challenge verification results
observers
challenger

STAR challenges (2013)

Commitment: ciphertext broadcast to terminals

Happens when the ballot is printed, just like VoteBox

Challenge: voter deposits or keeps ballot

Challenger takes home printed ballot

Ballot randomness posted, anyone can decrypt (ballots not counted!)

Procedurally: same as a spoiled ballot

Big usability win

No need to ask the voter a challenge question

Simple “live parallel testing”

STAR Workflow: Registration

Registration

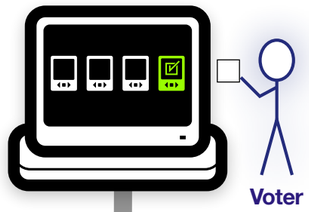
STAR Workflow: Registration

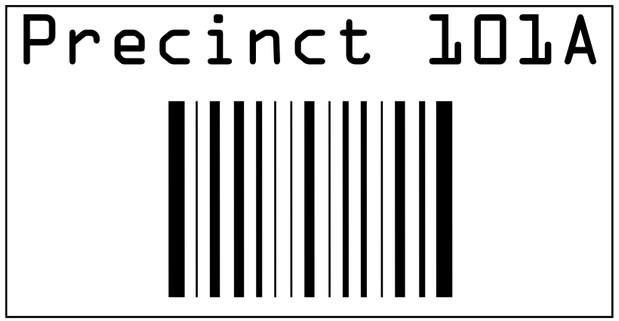
Registration

Voter

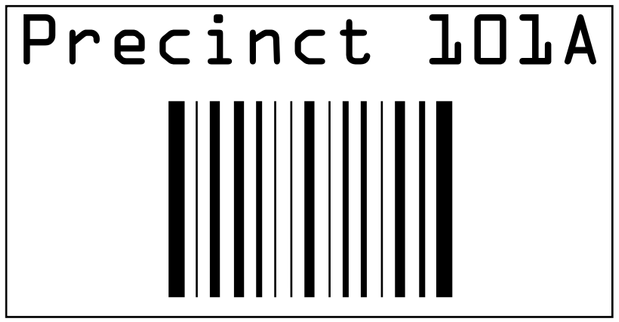
STAR Workflow: Registration

Registration

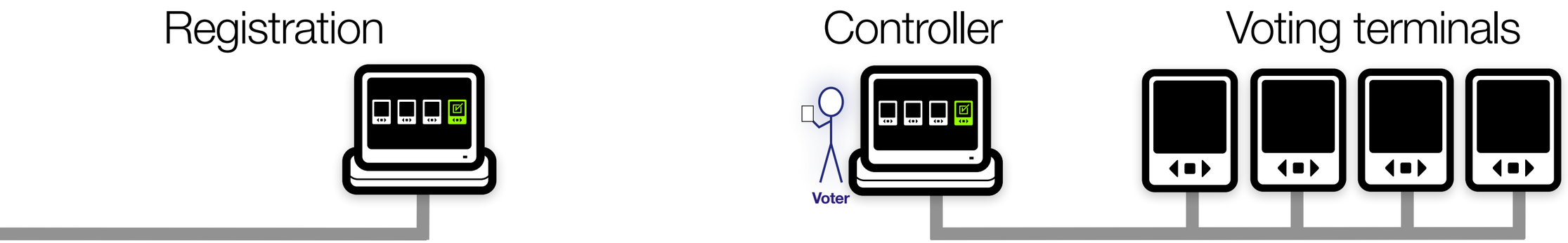


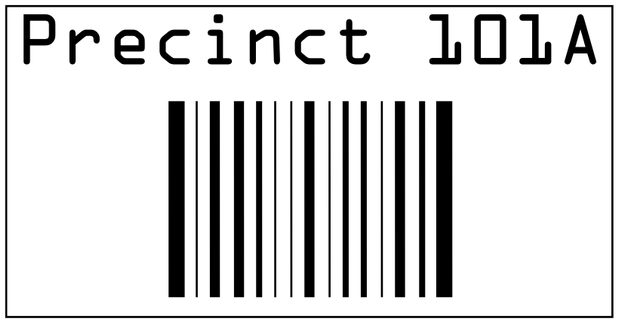


Workflow: Authorization



Workflow: Authorization



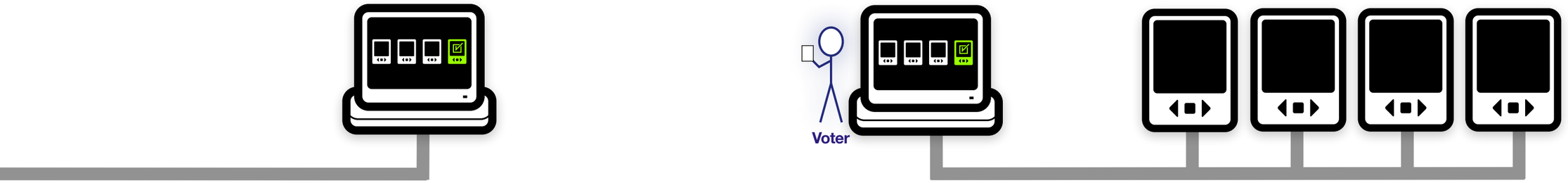


Workflow: Authorization

Registration

Controller

Voting terminals

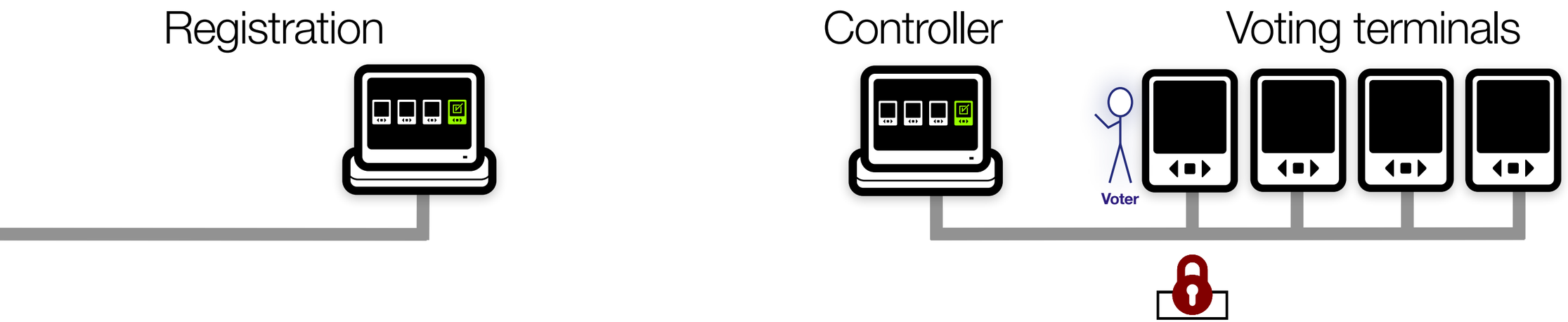



```
Auth: 52794
```

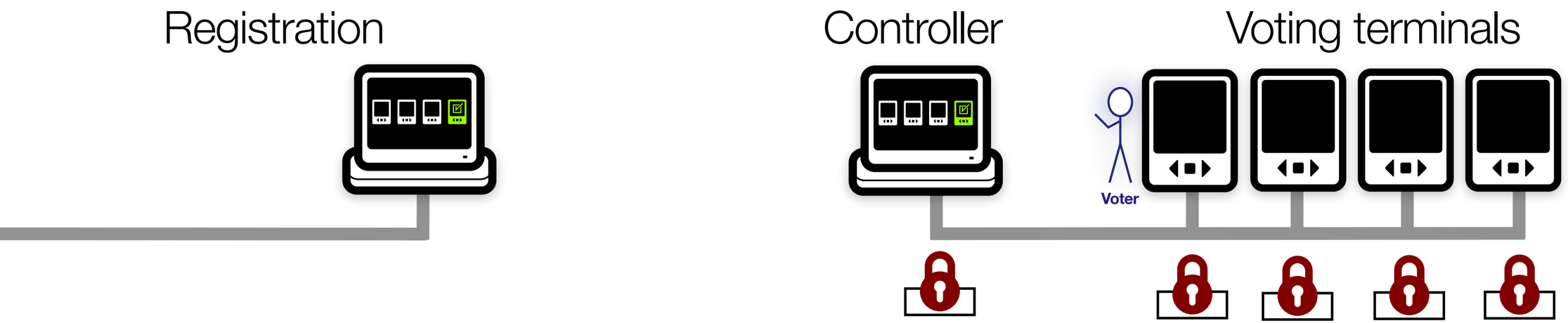
Similar to Hart InterCivic eSlate

Workflow: Voting

Workflow: Ciphertext copies distributed



Workflow: Ciphertext copies distributed

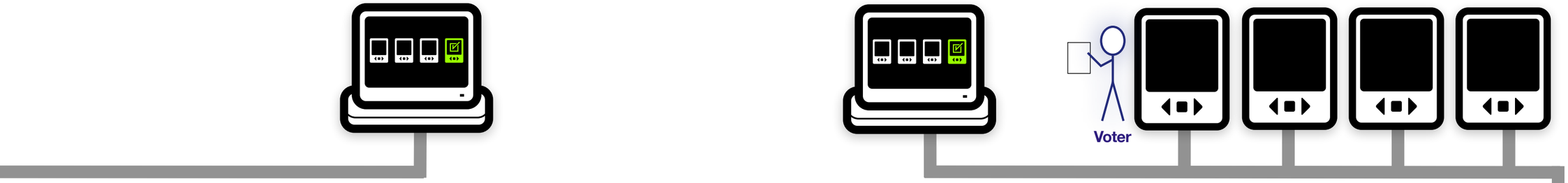


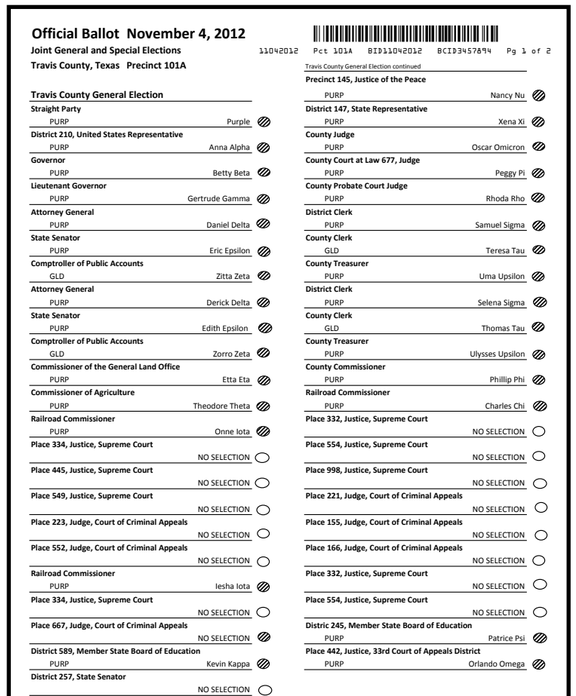
Workflow: Casting

Registration

Controller

Voting terminals





Official Ballot November 4, 2012
Joint General and Special Elections
Travis County, Texas Precinct 101A

11042012 Pct 101A BID11042012 BCID3457894 Pg 1 of 2

Travis County General Election

Straight Party
PURP Purple
District 210, United States Representative
PURP Anna Alpha
Governor
PURP Betty Beta
Lieutenant Governor
PURP Gertrude Gamma
Attorney General
PURP Daniel Delta
State Senator
PURP Eric Epsilon
Comptroller of Public Accounts
GLD Zitta Zeta
Attorney General
PURP Derick Delta
State Senator
PURP Edith Epsilon
Comptroller of Public Accounts
GLD Zorro Zeta
Commissioner of the General Land Office
PURP Etta Eta
Commissioner of Agriculture
PURP Theodore Theta
Railroad Commissioner
PURP Onne Iota
Place 334, Justice, Supreme Court
NO SELECTION
Place 445, Justice, Supreme Court
NO SELECTION
Place 549, Justice, Supreme Court
NO SELECTION
Place 223, Judge, Court of Criminal Appeals
NO SELECTION
Place 552, Judge, Court of Criminal Appeals
NO SELECTION
Railroad Commissioner
PURP Iesha Iota
Place 334, Justice, Supreme Court
NO SELECTION
Place 667, Judge, Court of Criminal Appeals
NO SELECTION
District 589, Member State Board of Education
PURP Kevin Kappa
District 257, State Senator
NO SELECTION

Travis County General Election continued

Precinct 145, Justice of the Peace
PURP Nancy Nu
District 147, State Representative
PURP Xena Xi
County Judge
PURP Oscar Omicron
County Court at Law 677, Judge
PURP Peggy Pi
County Probate Court Judge
PURP Rhoda Rho
District Clerk
PURP Samuel Sigma
County Clerk
GLD Teresa Tau
County Treasurer
PURP Uma Upsilon
District Clerk
PURP Selena Sigma
County Clerk
GLD Thomas Tau
County Treasurer
PURP Ulysses Upsilon
County Commissioner
PURP Phillip Phi
Railroad Commissioner
PURP Charles Chi
Place 332, Justice, Supreme Court
NO SELECTION
Place 554, Justice, Supreme Court
NO SELECTION
Place 998, Justice, Supreme Court
NO SELECTION
Place 221, Judge, Court of Criminal Appeals
NO SELECTION
Place 155, Judge, Court of Criminal Appeals
NO SELECTION
Place 166, Judge, Court of Criminal Appeals
NO SELECTION
Place 332, Justice, Supreme Court
NO SELECTION
Place 554, Justice, Supreme Court
NO SELECTION
Distric 245, Member State Board of Education
PURP Patrice Psi
Place 442, Justice, 33rd Court of Appeals District
PURP Orlando Omega

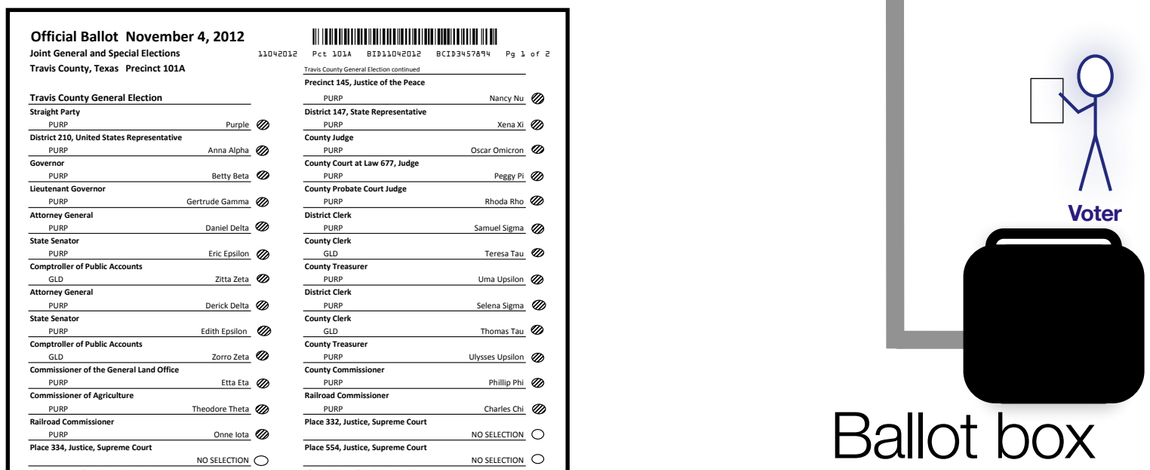
Ballot box

Workflow: Casting

Registration

Controller

Voting terminals



Voter

Ballot box

Networked ballot box

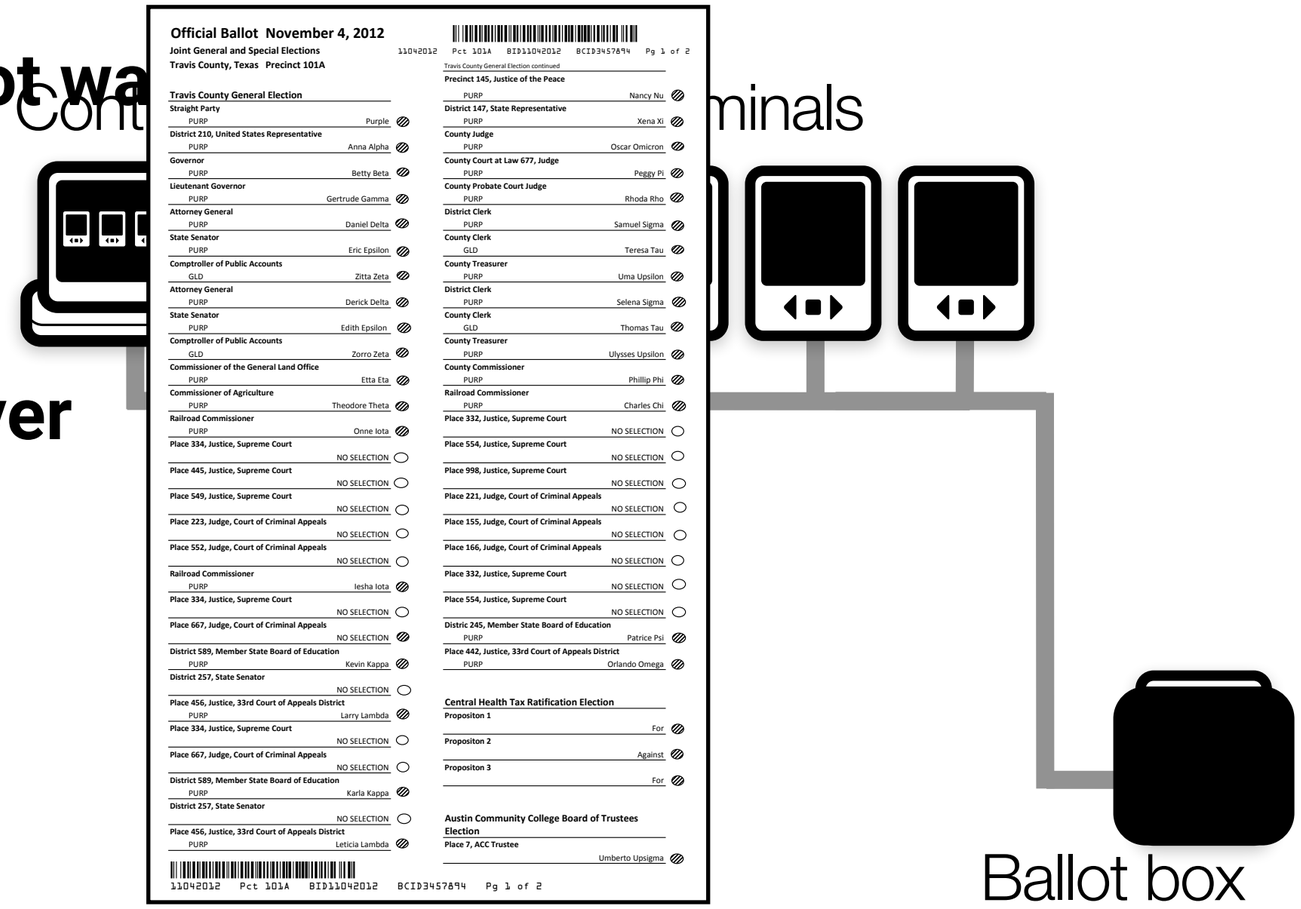
Notifies other machines that ballot wa

Ballot has random ID

Voter can spoil ballot and start over

Usability win!

Ballot box has no UI



Deposit and done (just need a scanner for the ballot ID)

Networked ballot box

Notifies other machines that ballot wa

Ballot has random ID

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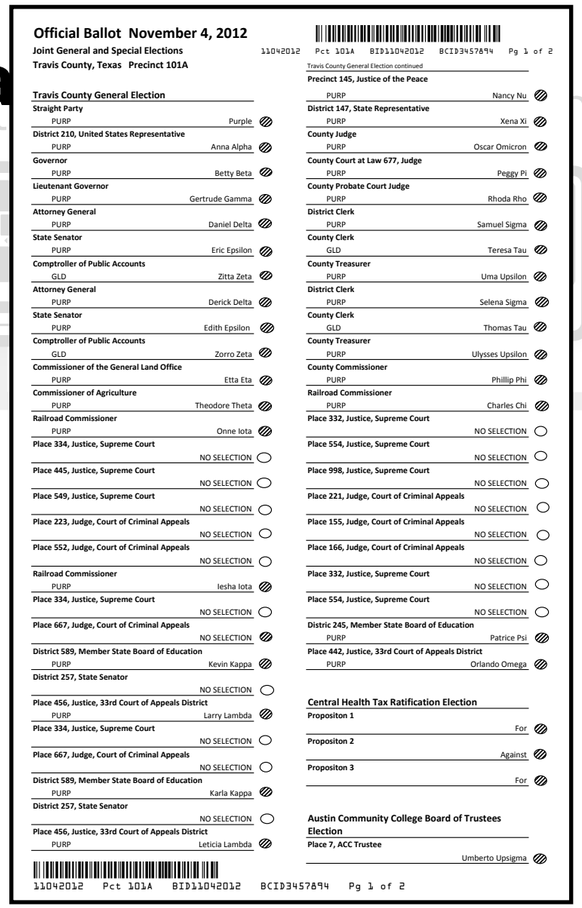

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PURP Eric Epsilon
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GLD Zitta Zeta
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PURP Derick Delta
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NO SELECTION
Railroad Commissioner
PURP Iesha Iota
Place 334, Justice, Supreme Court
NO SELECTION
Place 667, Judge, Court of Criminal Appeals
NO SELECTION
District 589, Member State Board of Education
PURP Kevin Kappa
District 257, State Senator
NO SELECTION
Place 456, Justice, 33rd Court of Appeals District
PURP Larry Lambda
Place 334, Justice, Supreme Court
NO SELECTION
Place 667, Judge, Court of Criminal Appeals
NO SELECTION
District 589, Member State Board of Education
PURP Karla Kappa
District 257, State Senator
NO SELECTION
Place 456, Justice, 33rd Court of Appeals District
PURP Leticia Lambda

11042012 Pct 101A BID11042012 BCID3457894 Pg 1 of 2

Travis County General Election continued

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PURP Nancy Nu
District 147, State Representative
PURP Xena Xi
County Judge
PURP Oscar Omicron
County Court at Law 677, Judge
PURP Peggy Pi
County Probate Court Judge
PURP Rhoda Rho
District Clerk
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GLD Teresa Tau
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PURP Uma Upsilon
District Clerk
PURP Selena Sigma
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Place 332, Justice, Supreme Court
NO SELECTION
Place 554, Justice, Supreme Court
NO SELECTION
Distric 245, Member State Board of Education
PURP Patrice Psi
Place 442, Justice, 33rd Court of Appeals District
PURP Orlando Omega

Central Health Tax Ratification Election
Propositon 1
For
Propositon 2
Against
Propositon 3
For

Austin Community College Board of Trustees Election
Place 7, ACC Trustee
Umberto Upsigma

Ballot box

Deposit and done (just need a scanner for the ballot ID)

Post-election verification

Separate page to take home

Ballot hash for lookup on public bulletin board

Cast ballot: **ciphertext will match**

Challenge ballot: **plaintext also present, verifiable**

Homomorphic tallying**: provably includes all ballots on the bulletin board**

Hash chains**: also publicly verifiable**

YOUR VOTE COUNTS

COUNTY OF TRAVIS
1839
STATE OF TEXAS

Thank you for voting!

Take this confirmation of voting with you

Verify your ballot at:

www.star-vote.org/ballot/HV1235Z7568RK84

Or, scan this code with your phone:

Find your code on the STAR-Vote website to ensure that your vote was recorded correctly.

Look for Election results and other tools for confirming the election at:
www.traviscountyelections.org

Voting Date: October 30, 2012
Voting Terminal: UI12345

Location: Randall's South Mopac
Time: 18:45:56

Risk limiting audits

Random sampling of individual paper ballots

Each should exactly match up with electronic records

Required in many states, growing in popularity

- *Requires touching tens of ballots, rarely hundreds, unlikely more*

Mitigates malicious software in the ballot scanners

Discrepancies require more samples, degenerates to a full manual recount of the ballots

Voting + Cryptography

Microsoft's open 'ElectionGuard' SDK aims to secure democratic elections

ElectionGuard is open source and built to make sure votes are verifiable, secure, and auditable.

DAN THORP-LANCASTER 6 May 2019 14

How *not* to do e2e cryptography

Ceci n'est pas une preuve

The use of trapdoor commitments in Bayer-Groth proofs and the implications for the verifiabilty of the Scytl-SwissPost Internet voting system*

Sarah Jamie Lewis[1], Olivier Pereira[2], and Vanessa Teague[3]

[1]Open Privacy Research Society, sarah@openprivacy.ca
[2]UCLouvain – ICTeam, B-1348 Louvain-la-Neuve, Belgium,
olivier.pereira@uclouvain.be
[3]The University of Melbourne, Parkville, Australia,
vjteague@unimelb.edu.au

March 12, 2019

The implementation of the commitment scheme in the SwissPost-Scytl mixnet uses a trapdoor commitment scheme, which allows an authority who knows the trapdoor values to generate a shuffle proof transcript that passes verification but actually alters votes. We give two examples of details of how this could be used. The first example allows the first mix to use the trapdoors to substitute votes for which it knows the randomness used to generate the encrypted vote. The second example does not even require knowledge of the random factors used to generate the votes, and could be used by the last mix in the sequence.

*Since making this work public, we have learned that the same issue was identified independently by Thomas Haines of NTNU, and also by Rolf Haenni of the Bern University of Applied Sciences, https://e-voting.bfh.ch/publications/2019/

Swiss Post Public Intrusion Test

Undetectable Attack Against Vote Integrity and Secrecy

Rolf Haenni

Bern University of Applied Sciences

1 Theoretical Background

Commitment schemes are usually *perfectly hiding* and *computationally binding*. This means that no information about the message can be derived from the commitment and that the commitment can not be opened to a message other than the original one. The Pedersen commitment scheme achieves these properties by computing $c = G^m H^r$ in a multiplicative cyclic group, for which the discrete logarithm assumption (DL) is believed to hold. This scheme is perfectly binding, because a randomization $r' \neq r$ exists for any other message $m' \neq m$ such that $c = G^{m'} H^{r'}$. This means that c could potentially be opened to all q messages from $\mathbb{Z}_q$, but this requires the computation of the discrete logarithm. The Swiss Post voting protocol works with a subgroup $G_q \subseteq \mathbb{Z}_p^*$ of integers modulo p, where $q = |G_q|$ denotes the prime order of the subgroup, $m \in \mathbb{Z}_q$ the message, and $r \in \mathbb{Z}_q$ the randomization. Both G and H are elements of G_q.

A pre-condition for the scheme to be computationally binding is the *independence* of the two values $G, H \in G_q \backslash \{1\}$ (in a group of prime order q, both values are generators of G_q). Independence means that respective discrete logarithms $h = \log_G H$ and $g = \log_H G$ are unknown to everyone. Otherwise, for example if $h = \log_G H$ is known to the person who created c, then c can be rewritten as

$$c = G^m H^r = G^m (G^h)^r = G^{m+hr \bmod q}.$$

Therefore, to open c to a different message $m' \neq m$, the adversary can easily solve

$$m + hr \equiv m' + hr' \pmod{q}$$

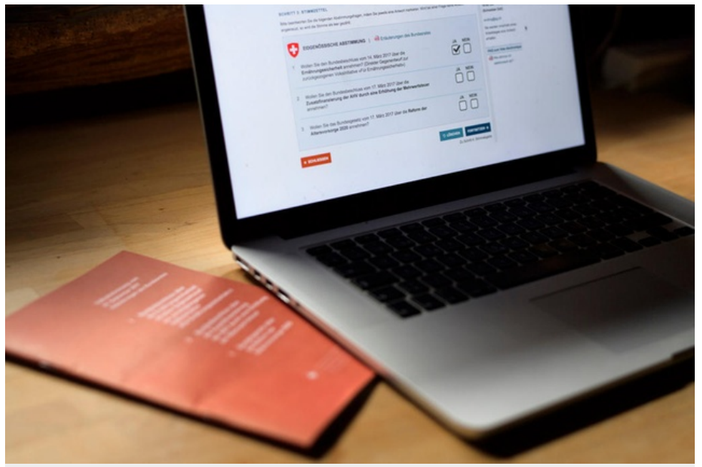
to find the matching randomization $r' = (m - m')h^{-1} + r \bmod q$. As a consequence, the binding property of the commitment scheme is completely broken in that case.

SWI swissinfo.ch

ONLINE DEMOCRACY

Swiss Post's e-voting system pulled for May votes

MAR 29, 2019 - 13:46



Swiss Post's e-voting system had been in use in four cantons: Basel City, Fribourg, Neuchâtel and Thurgau

(Keystone)

The e-voting system operated by Swiss Post will not be available for nationwide votes on May 19. This is the consequence of "critical errors" found during a public intrusion test, the Federal Chancellery and Swiss Post announced on Friday.

The Federal Chancellery said in a statement it would review the licensing and certification procedures for e-voting systems. It added that it had no indication that these flaws had resulted in votes being manipulated in previous ballots.

Swiss Post's e-voting system had been in use in four cantons: Basel City, Fribourg, Neuchâtel and Thurgau.

Will ElectionGuard be better?

Talented researchers from Microsoft Research, others (including Wallach)

Multiple current implementations (open source, on GitHub today)

Your project 1 (going online tomorrow!) is based on ElectionGuard

The ElectionGuard model: plugins for existing voting machines

Targeted outreach to election equipment vendors

Still requires in-precinct voting

Sophisticated cryptography doesn’t solve problems with internet voting