
COMPUTER SECURITY LAB
RICE UNIVERSITY

STAR-Vote: A Secure, Transparent, Auditable, and Reliable Voting System

(or, an exercise in secure systems design)

Josh Benaloh (Microsoft Research)
Mike Byrne (Rice University)
Bryce Eakin (independent consultant)
Philip Kortum (Rice University)
Neal McBurnett (ElectionAudits)
Olivier Pereira (Université catholique de Louvain)
Philip B. Stark (University of California Berkeley)
Dan S. Wallach (Rice University)
and the Travis County Elections Office Staff

A rare opportunity

Dana DeBeauvoir (Travis County Clerk),
Keynote speech, EVT/WOTE 2011

We're going to design a new voting system from scratch and we need your help.

Engineering starts with constraints

You can’t just build anything you want

The customer has other ideas...

Travis County (Austin, Texas)

Population: ~1 million

~392k votes cast November 2012

Two weeks of early voting

23 locations

Election-day vote centers

Every local precinct now lets you vote any ballot style in the county

Ballots can have as many as 100 contests (typical for Texas)

Travis County voting technology

Pre-2001: centrally tabulated optical scan ballots

Huge logistical challenges

2001: Hart InterCivic eSlate system

No ambiguity of voter intent

Good accessibility features

Fast results

Unhappy activists

2011: Time for something new

eSlate systems reaching end of life

Nothing attractive on the market

Crazy idea: call in the academics!

First meeting: April 2012

Long weekend in Austin

Olivier flew in on his own money

Josh took vacation time from Microsoft

Travis County elections staff + academics

Constraint #1: DRE-style UI

Consistent UI for all voters

Accessibility features (headphones, buttonbox, etc.)

Voter-intent disambiguated before they leave

Off-the-shelf hardware

Commercial DRE equipment is

$3000+ per machine

E.g., Sony Vaio Tap 20, ~$1000

Cheaper support contracts as well

Printer attached to the DRE

Machine-printed ballot goes into a ballot box

Constraint #2: Paper ballots

Tangible, hand-countable records of voter intent

Machine-printed to avoid ambiguous marks

Only show selected candidates, save lots of space

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

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

Constraint #3: Vote centers

Any voter can go to any precinct and vote

Online voter registration database

Offline voting machines

Carefully limited data flows across the boundary

Thousands of distinct ballot styles

Pre-printed traditional ballots are untenable

Constraint #4: All day battery

Power failures should not close the polls!

12+ hours on battery is a requirement

Printers must be thermal

Laser consumers too much power

Inkjet too unreliable

Touch screen computers with long-life batteries?

Laptops vs. small tablets vs. big tablets

Sony Vaio Tap 20 (20”)	4 hours
Microsoft Surface Pro 3 (13”)	9 hours
Apple iPad Air 2 (10”)	“up to 10 hours”

Sophisticated new features

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In-precinct network

Local wired network (no Internet, no wireless)

Hash chaining, massive data replication

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E2E cryptography

Homomorphic, verifiable tallies

Public bulletin board, full-election ciphertexts

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Verify the paper corresponds to the electronic records

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Verify the paper corresponds to the electronic records

Usability

Help voters and poll workers

Ensure security features don’t damage usability

Workflow: Registration

Registration

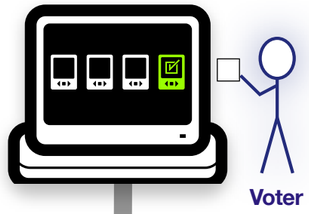
Workflow: Registration

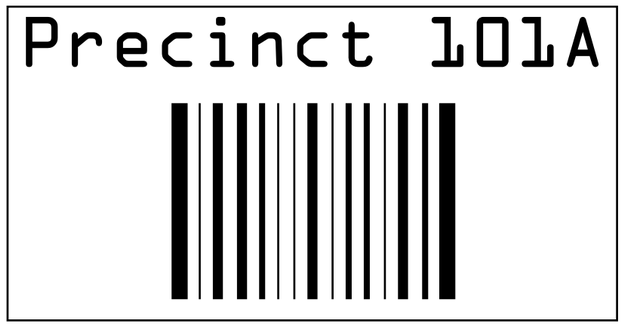
Registration

Voter

Workflow: Registration

Registration



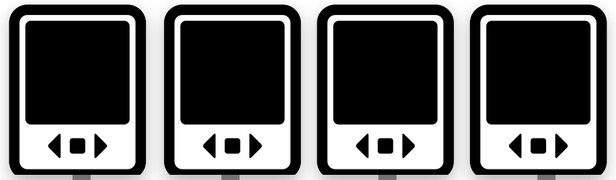


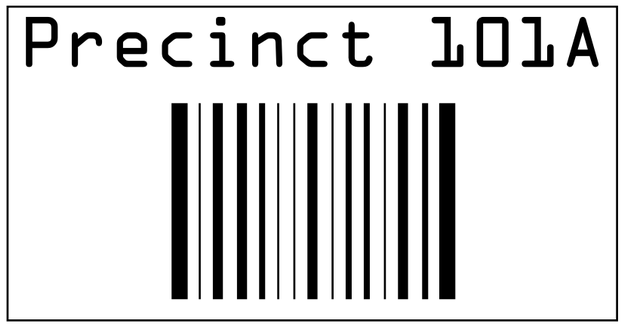
Workflow: Authorization

Registration

Controller

Voting terminals





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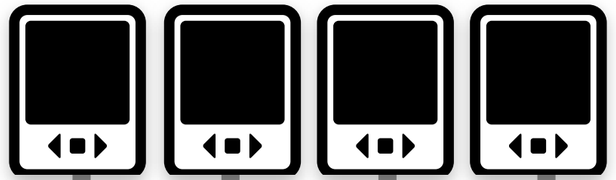

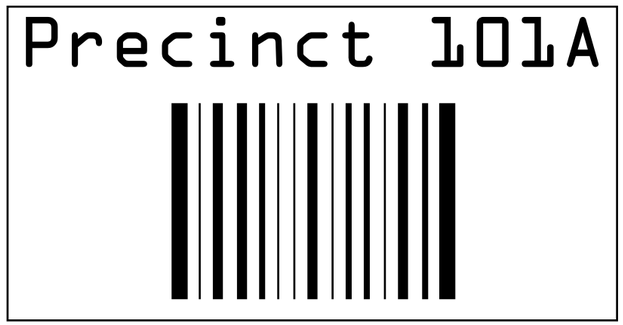

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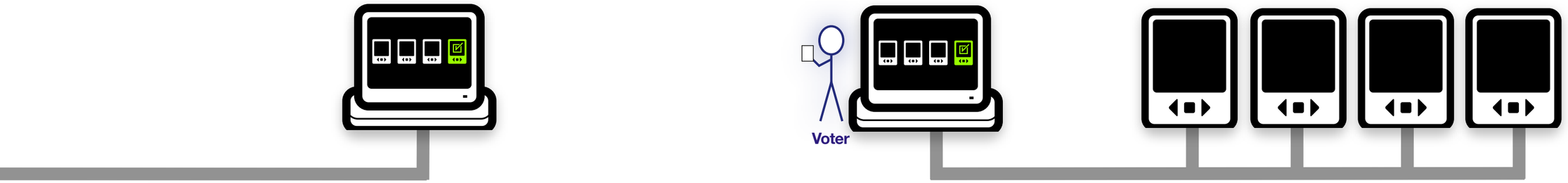
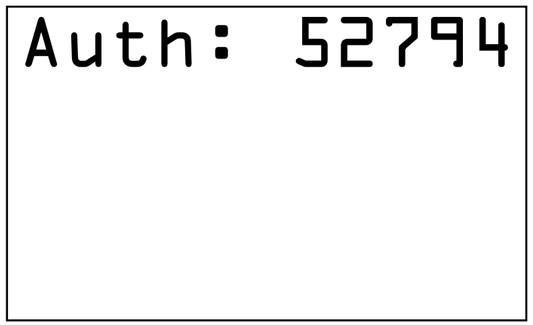




Similar to Hart InterCivic eSlate

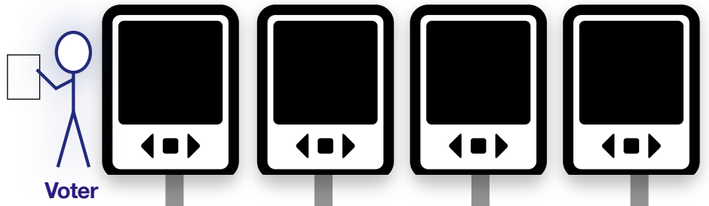
Workflow: Voting

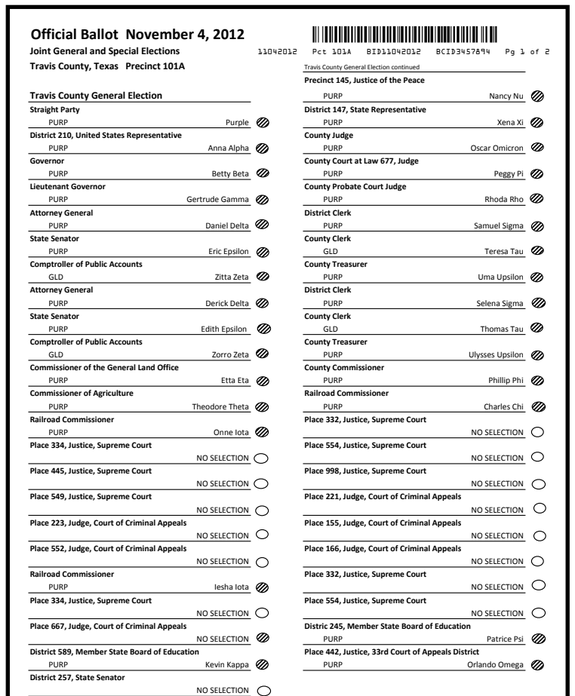
Workflow: Casting

Registration

Controller

Voting terminals





Official Ballot November 4, 2012
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11042012 Pct 101A BID11042012 BCID3457894 Pg 1 of 2

Travis County General Election

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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
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Place 549, Justice, Supreme Court
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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
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PURP Rhoda Rho
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GLD Teresa Tau
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PURP Ulysses Upsilon
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Distric 245, Member State Board of Education
PURP Patrice Psi
Place 442, Justice, 33rd Court of Appeals District
PURP Orlando Omega

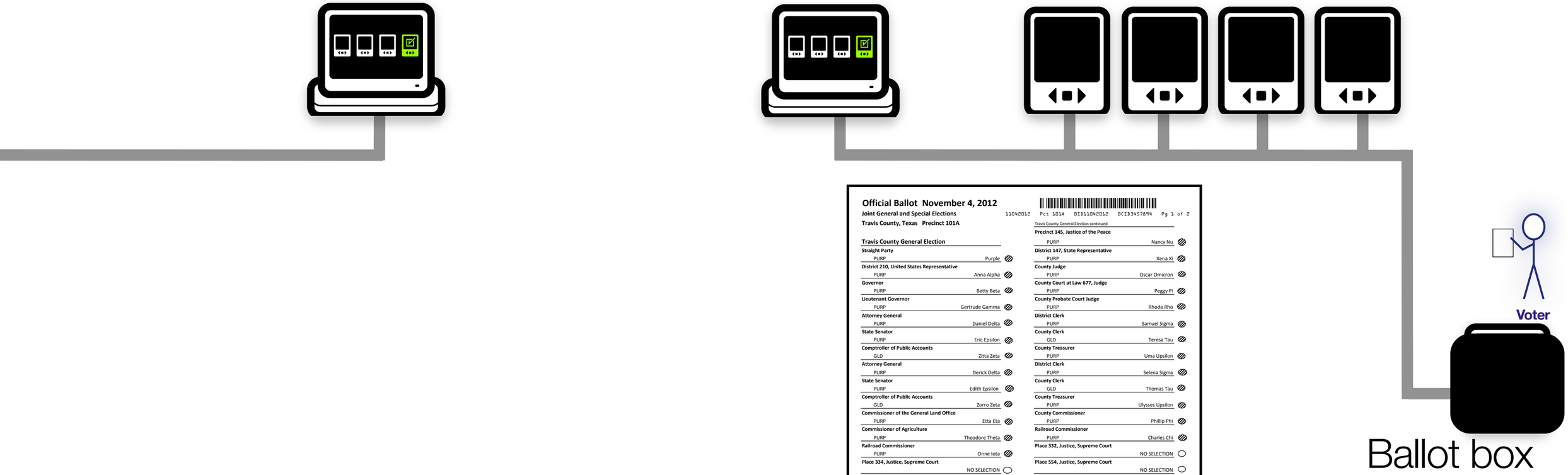
Ballot box

Workflow: Casting

Registration

Controller

Voting terminals



Ballot box

Networked ballot box

Notifies other machines that ballot was deposited

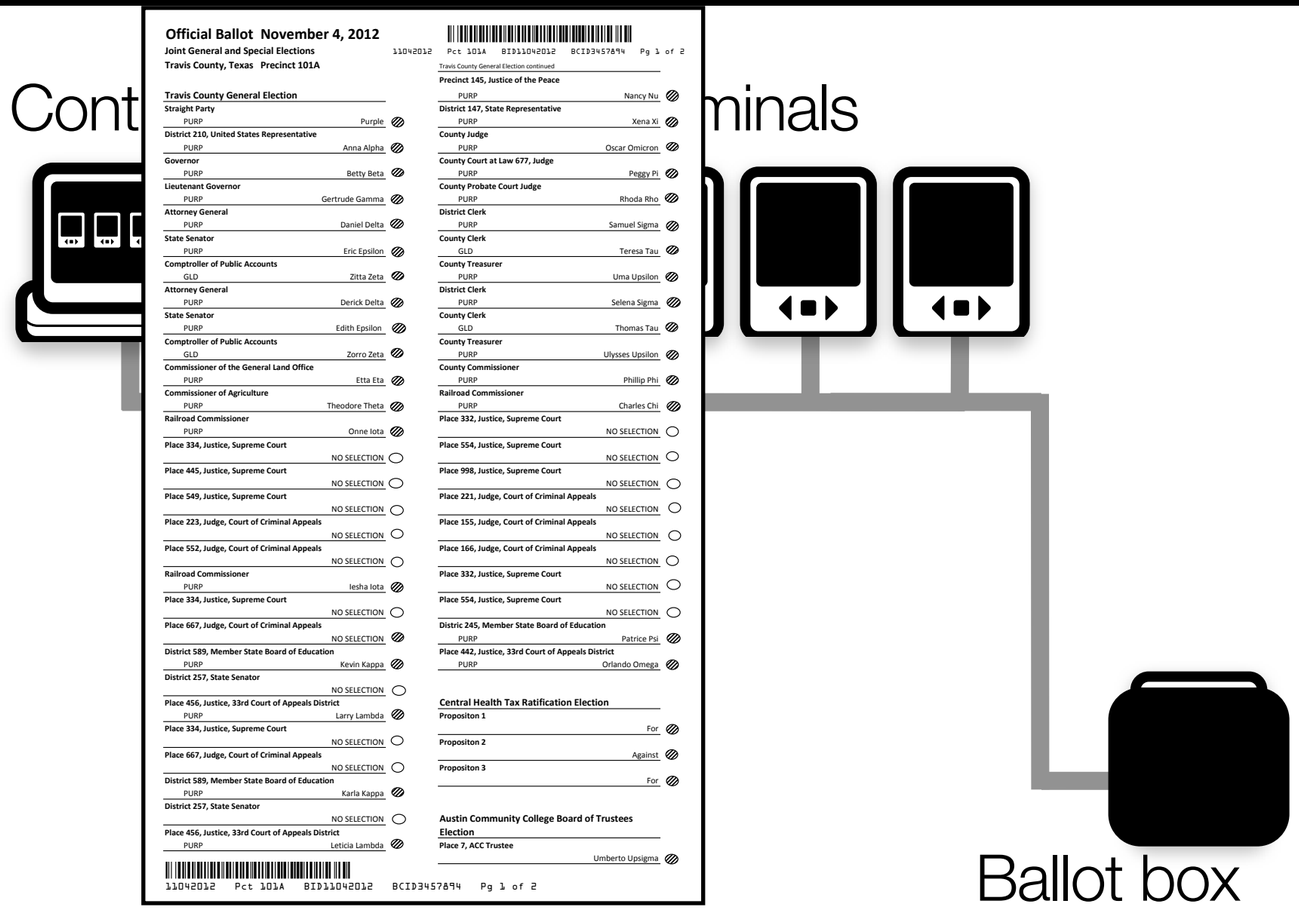
Ballot has random ID

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)



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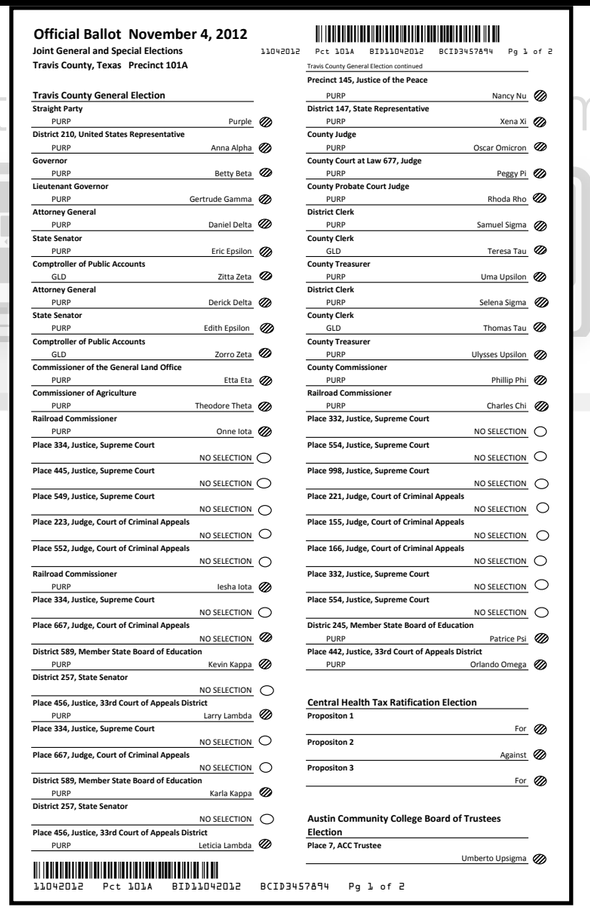

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Central Health Tax Ratification Election

Propositon 1
For
Propositon 2
Against
Propositon 3
For

Austin Community College Board of Trustees Election

Place 7, ACC Trustee
Umberto Upsigma

Ballot box

Catch the machine if it cheats!

Benaloh challenges [2006]

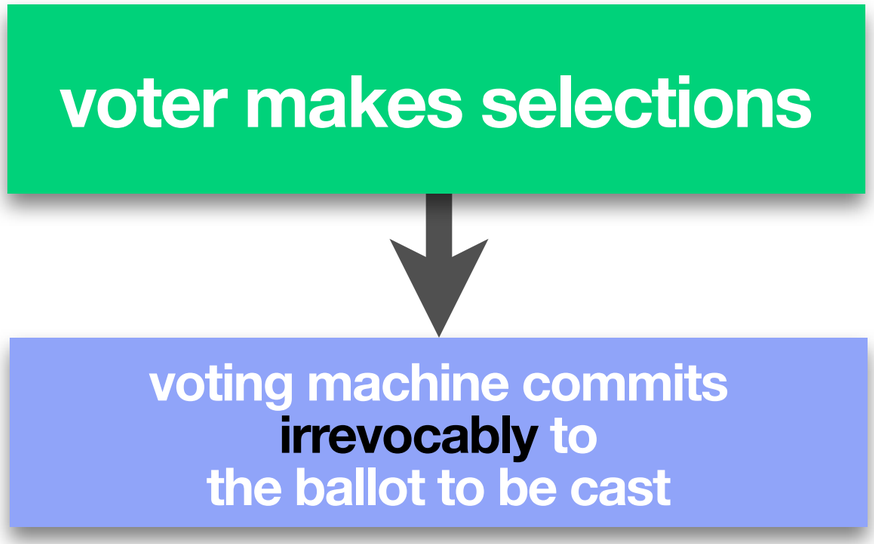
Catch the machine if it cheats!

Benaloh challenges [2006]

voter makes selections

Catch the machine if it cheats!

Benaloh challenges [2006]



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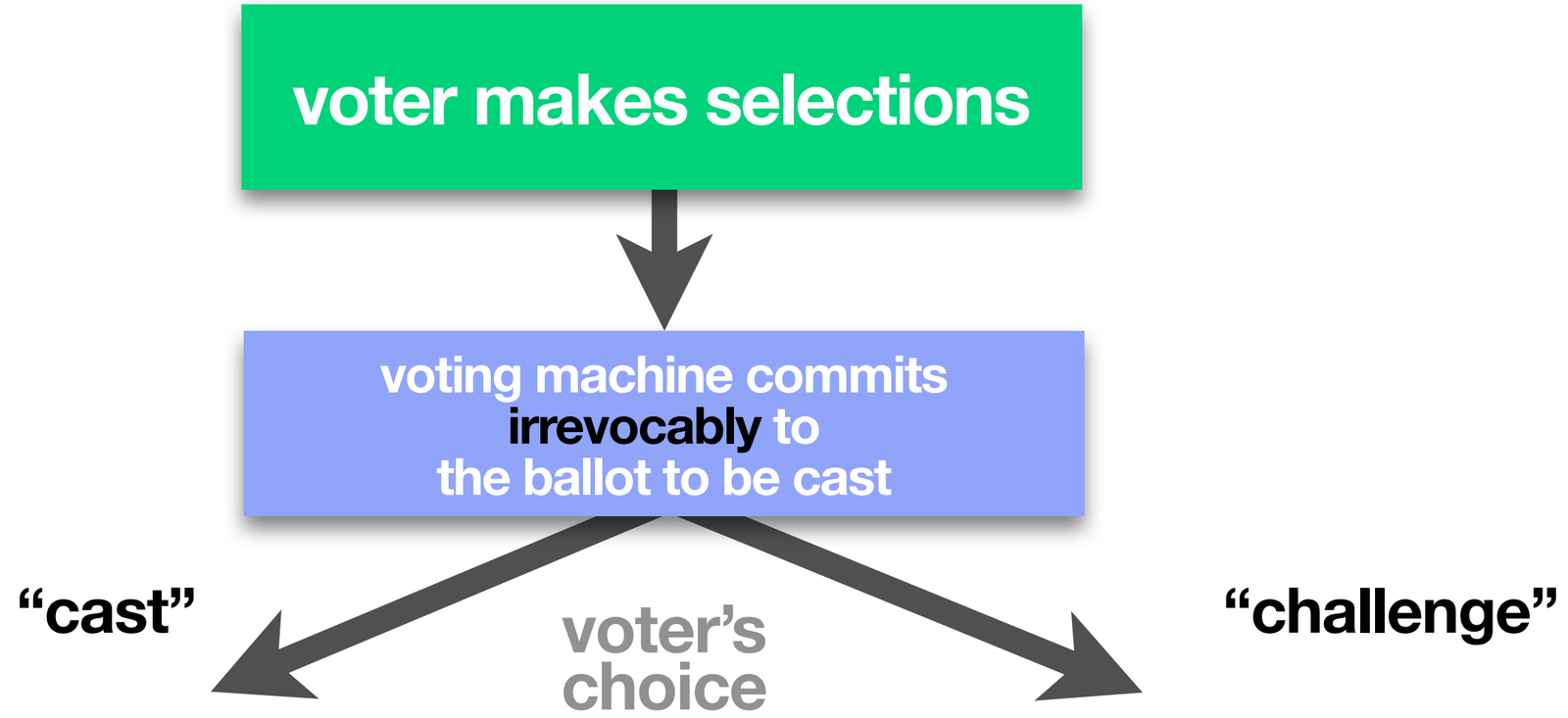

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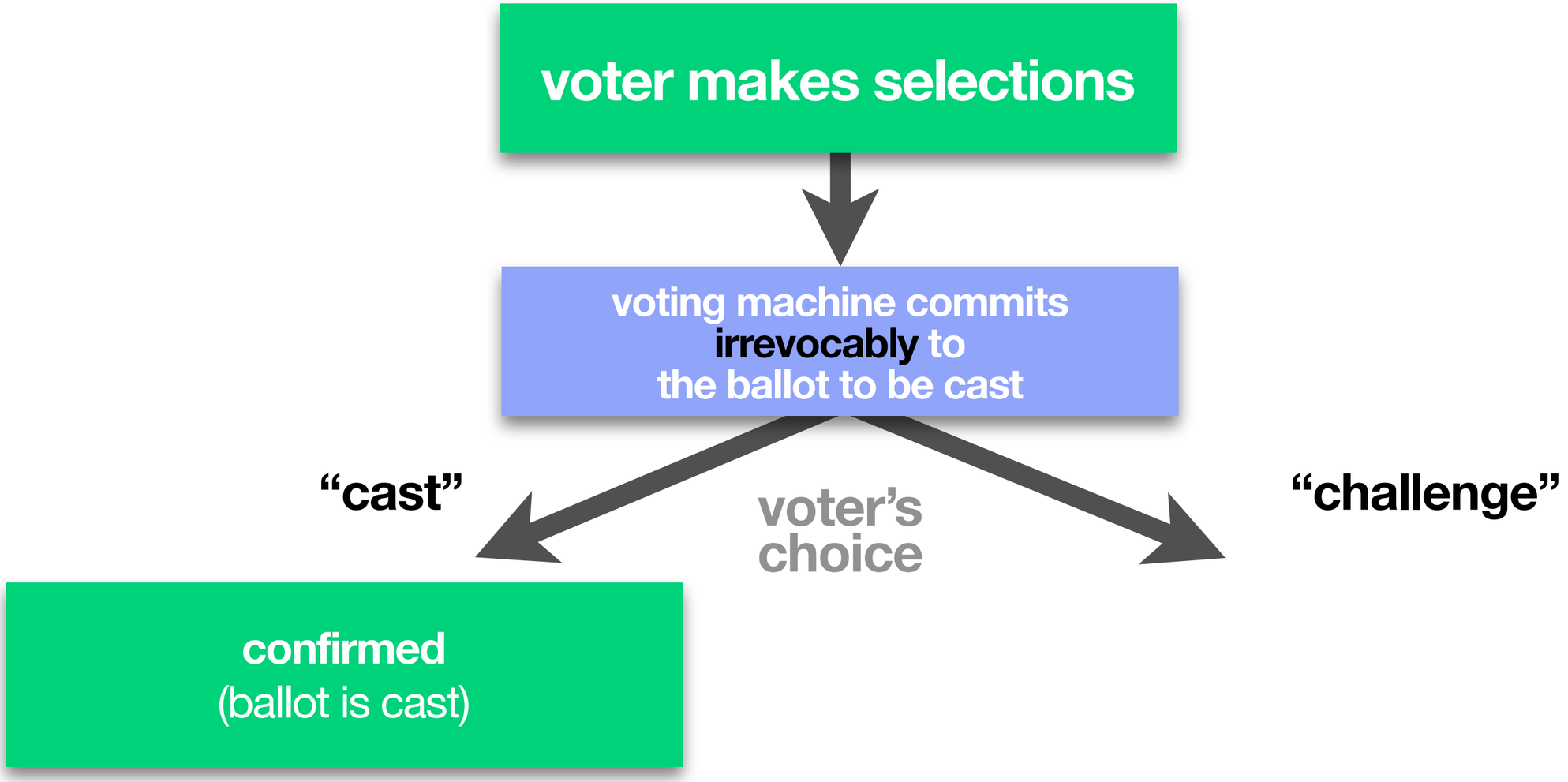

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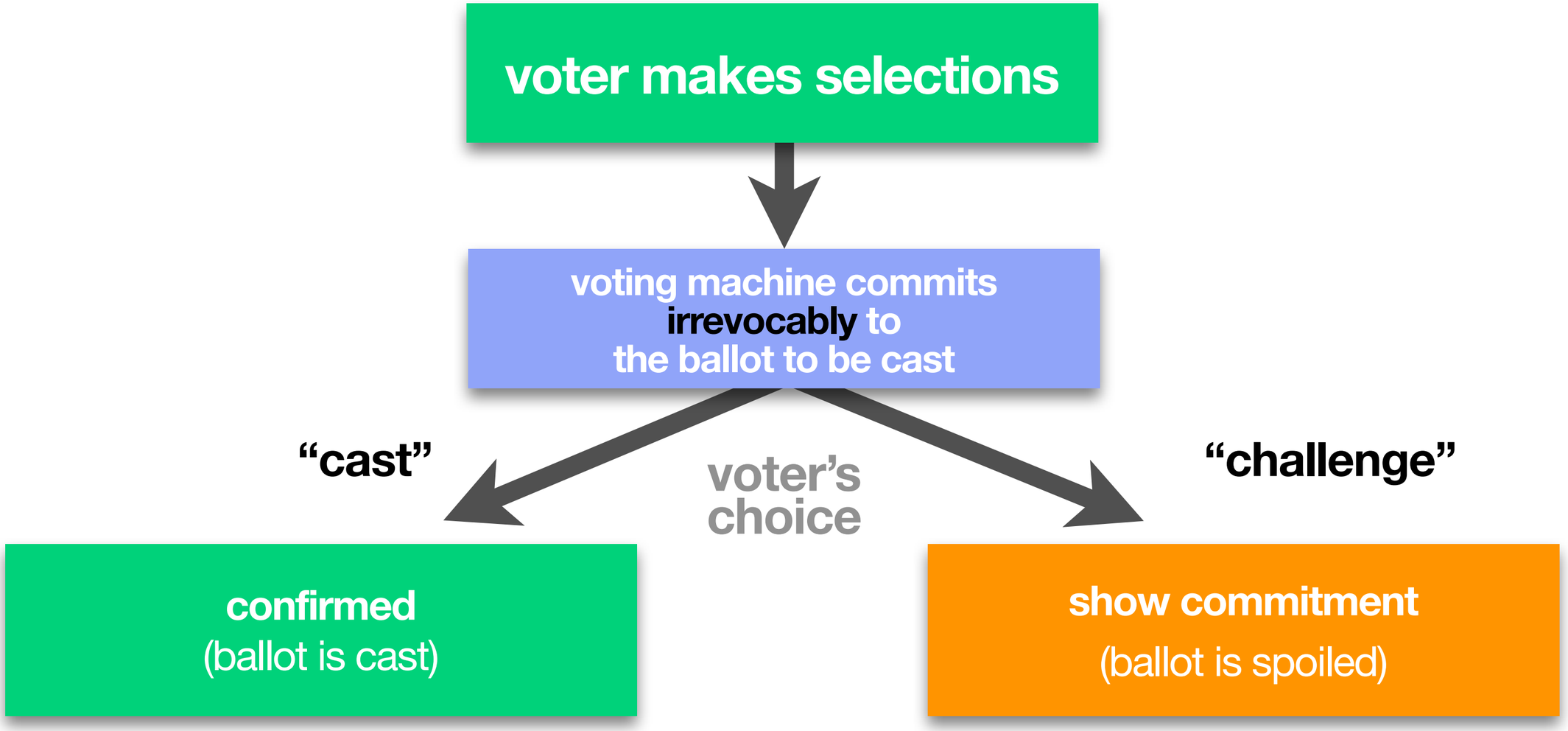

Benaloh challenges in practice

Original idea: print ciphertext behind opaque plate

Helios: hash sent to voter

VoteBox: ciphertext published on LAN

All require asking the voter to *cast* or *challenge*

Significant usability problem

STAR challenges

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

Ballots that aren't deposited are decrypted, posted

Procedurally: same as a spoiled ballot

Big usability win

No need to ask the voter a challenge question

Simple "live parallel testing"

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**

YOUR VOTE COUNTS

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

How does e2e crypto work?

Cryptography outline

Every machine: public key for signing messages

Election authority is a CA

Every message: signed, broadcast, logged

Plus a hash of the sender's log head

Tamper-evident, resilient history of what happened

Every ballot: exponential Elgamal counters

Encrypted with public key of election authority

Homomorphic tallying, standard kludge for write-ins

Every counter includes "zero or one" NIZK proof

Threshold crypto for decryption key

Trustees decrypt election totals, challenge ballots

Back to basics: Diffie-Hellman & Elgamal Crypto

Modular arithmetic 101

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

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

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

$$g^1, g^2, \ldots, g^{p-1}$$

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 a very big number $q = 5^{84375912432595 43}$

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

Elgamal decryption

***Two* ways to decrypt:**

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

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

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

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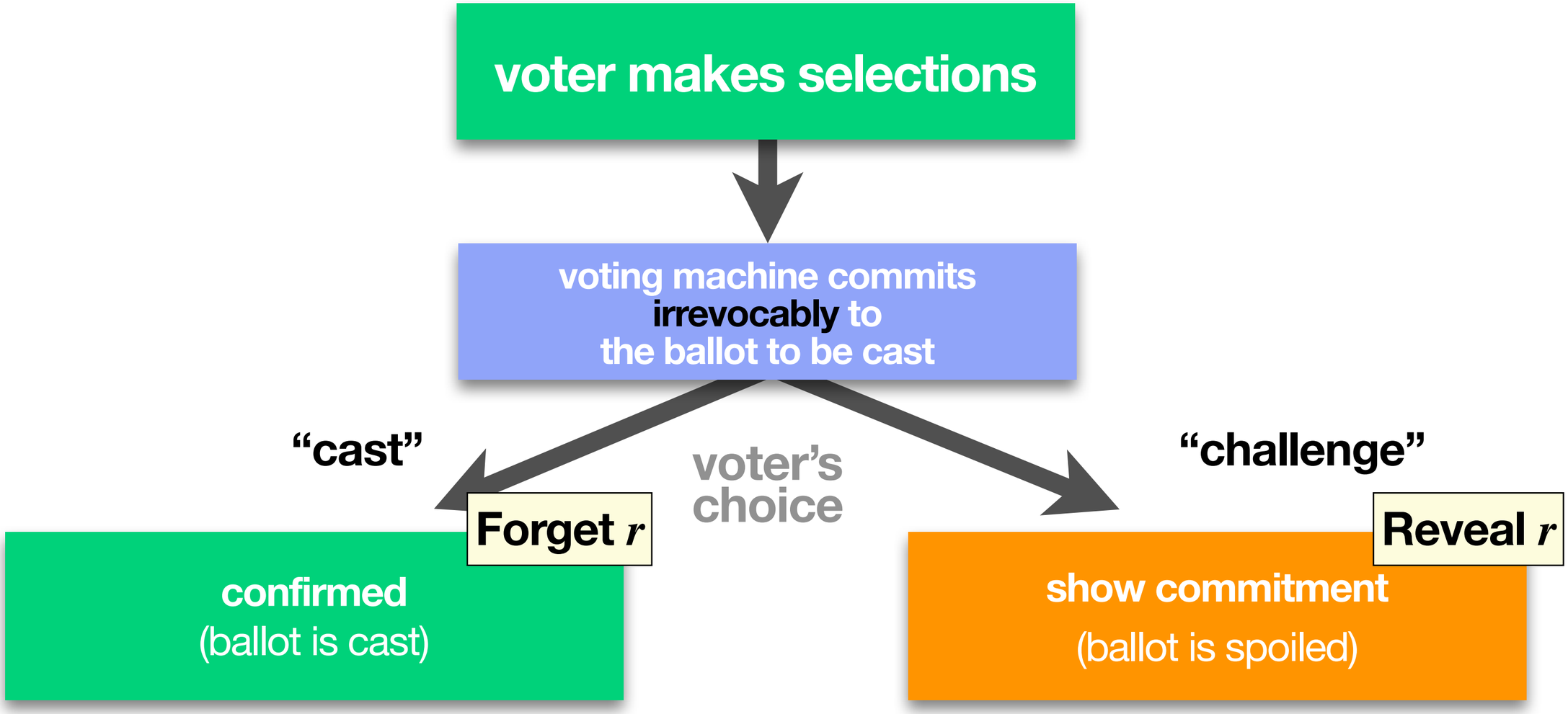


Homomorphic property

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
v	plaintext (counters)
r	random (chosen at encryption time)
a	(private) decryption key
g^a	(public) encryption key

Crypto coolness 1: NIZK proofs

Every encrypted counter has a proof that it's either zero or one

No way for "ballot stuffing" with huge ballots

"Overvote validation" on *every* encrypted ballot, without revealing the vote

Election officials also produce a "decryption proof" after the election

Any observer can recompute *encrypted* election totals (thanks to homomorphism)

Only the election official (or group of trustees) can decrypt the total

Crypto coolness 2: threshold crypto

We can replace “the election official” with “a group of trustees”

Important cryptographic operations can be split across *n* trustees, where *k* of them must cooperate to perform the operation

External observers don’t have to change how they operate

Trustees produce a proof (NIZK) that their result is correct

Crypto coolness 3: hash chaining

Every ballot receipt includes a hash of the encrypted ballot

Voter can validate integrity of their (encrypted) ballot, but can’t prove plaintext

Every ballot receipt hash also covers prior ballots (same precinct)

Mass ballot loss or deletion will be easily detected

E2E verification process

***Easy*: voter visits URL, server does computation**

***Better*: voter runs open-source tool (provided)**

***Alternative*: voter gives receipt to political party, civic organization, newspaper, etc.**

Each organization's smartphone app could scan the QRcode

But what if something goes wrong?

Risk limiting audits (SOBA)

Random sampling of individual paper ballots

Each should exactly match up with electronic records

Successful in a number of op-scan elections in California

STAR + SOBA: Requires decrypting ballots

Post-election audit process

Only decrypt ballots as needed for the audit

Requires touching tens of ballots, maybe hundreds, unlikely more

Threat Mitigation

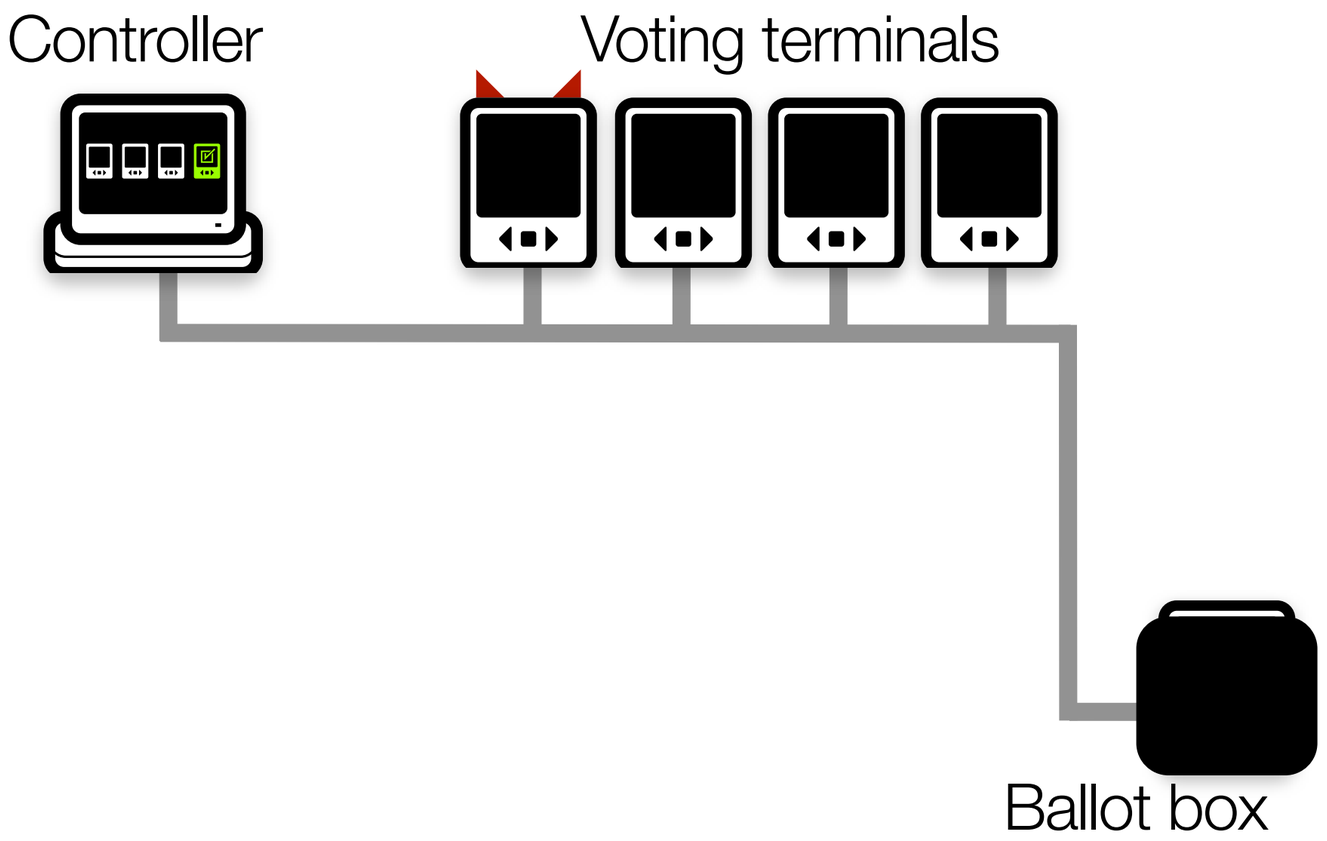
Forged votes on one device?

Trivially detectable

No matching authorizations

Voting terminal can’t forge because it doesn’t have controller’s public key

No matching paper ballots



Conspiracy with controller?

Votes recorded everywhere?

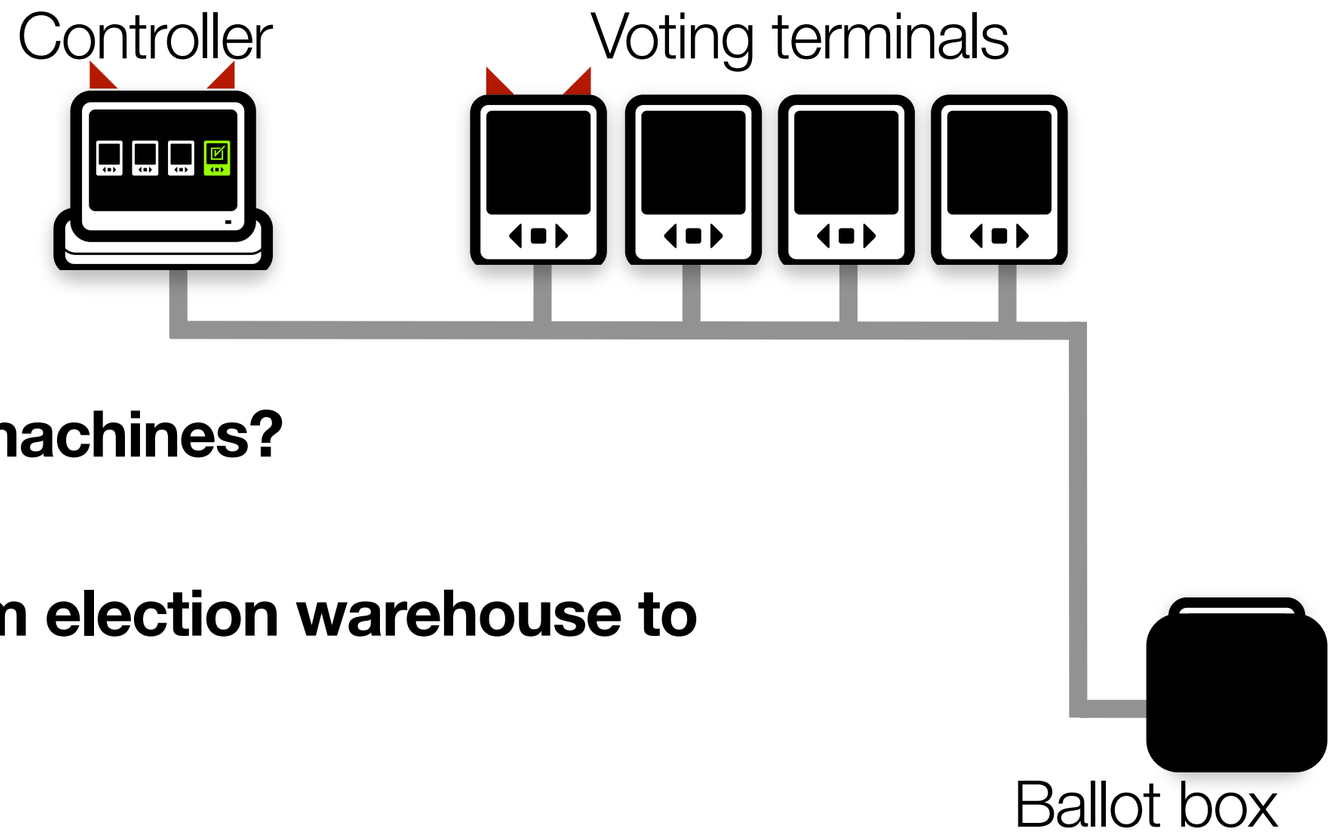
Inconsistent with paper

Inconsistent with registration data

Recorded only on conspiring machines?

Inconsistent with good machines

Mitigation: Separate paths from election warehouse to the polling place



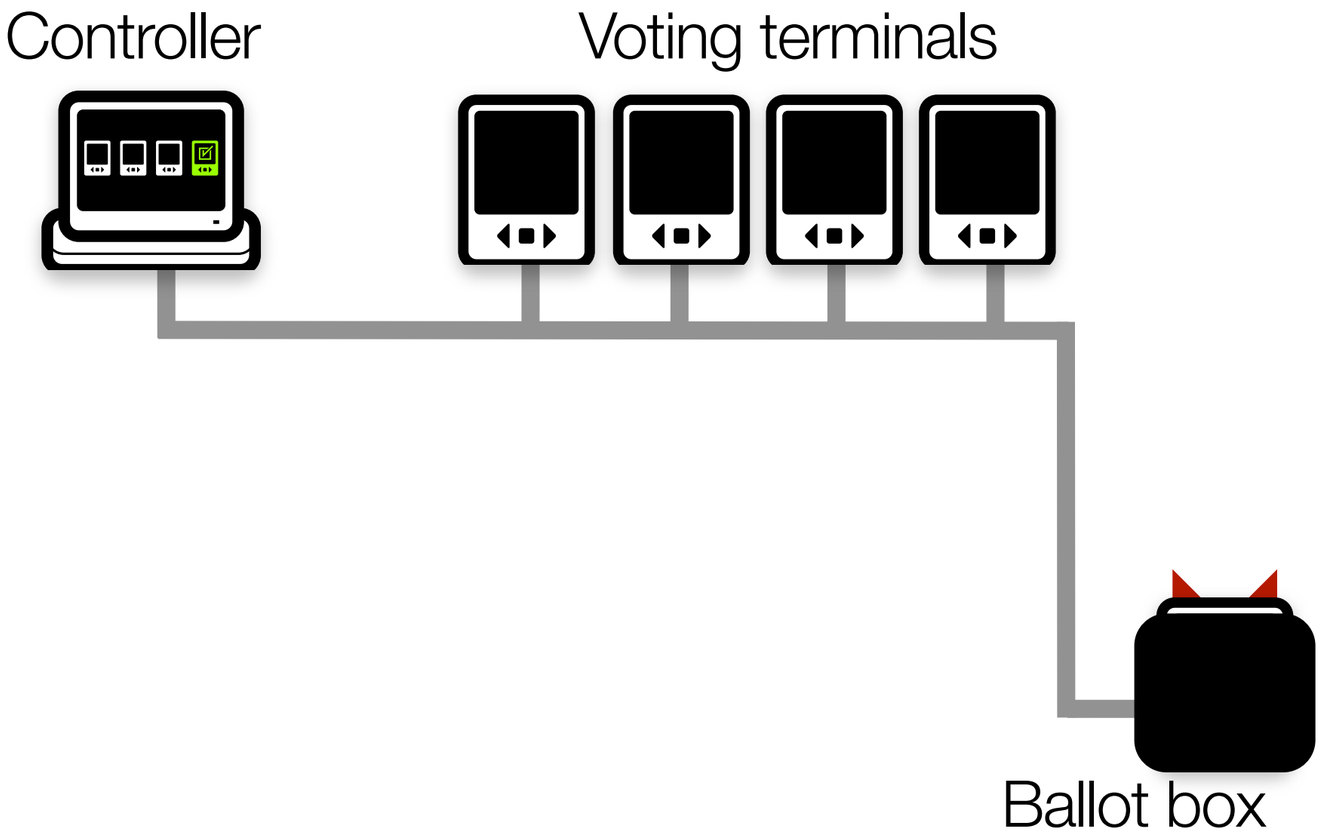
Paper ballot stuffing?

Primary tallies use electronic ballots

Paper without corresponding ciphertext is suspicious

Chain voting

Detect/reject based on timestamps



Malicious machine? (integrity)

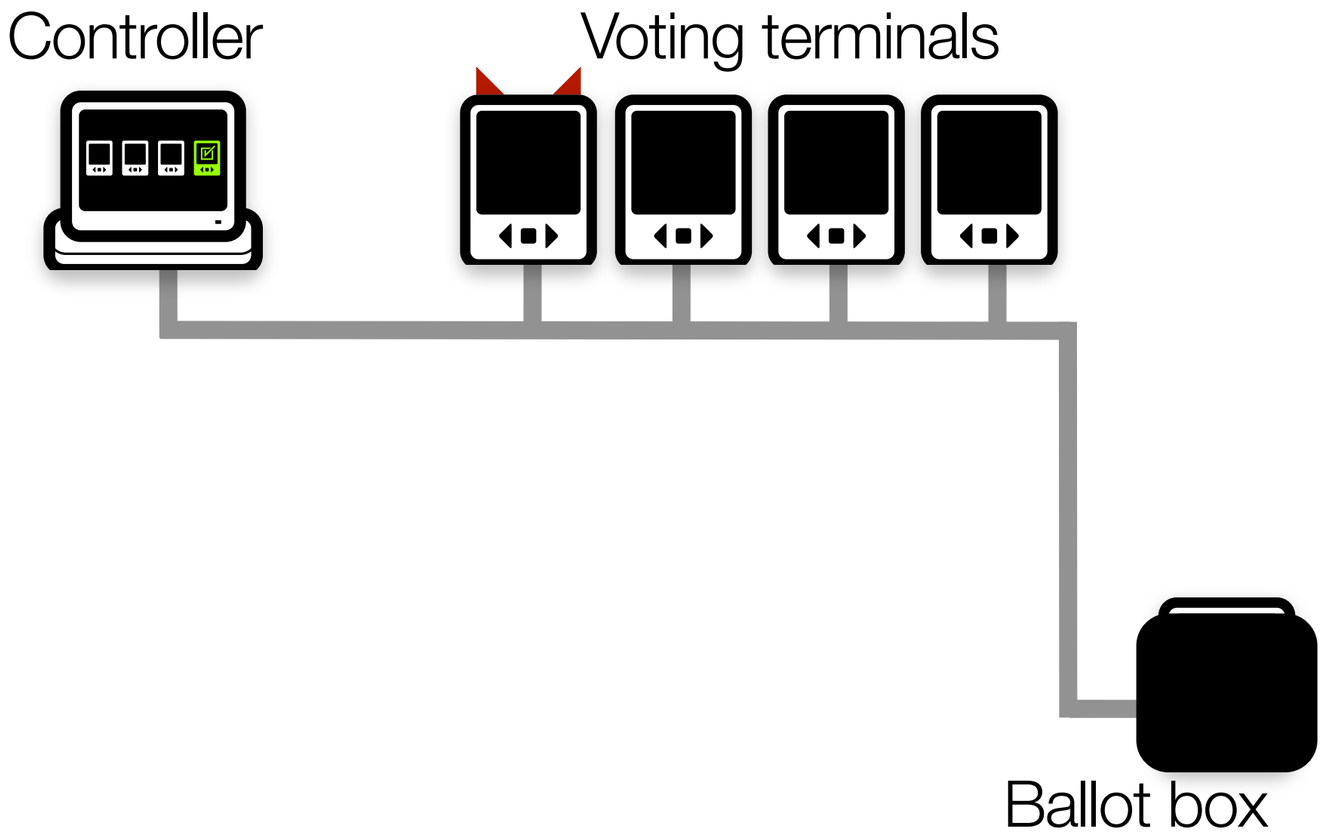
Show A, record B

Paper ballot inconsistent with ciphertext ballot

Two ways to detect

Post-election audit (compare paper to decrypted ciphertexts)

Benaloh-style challenge

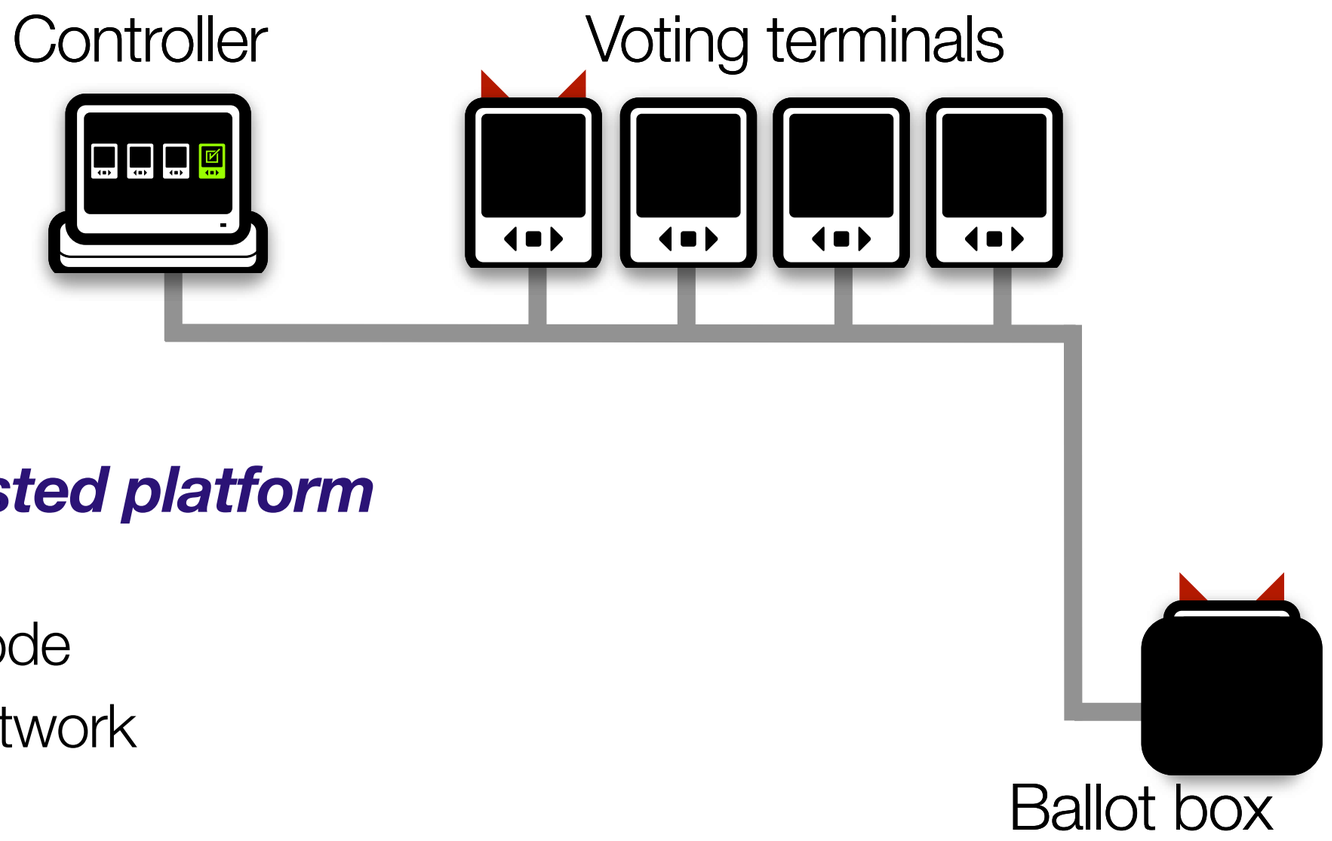


Malicious machine? (privacy)

Record plaintext ballots in order cast

(or *subliminal channels*)

Fundamental problem!



Work-in-progress solution: *trusted platform management* (TPM)

Terminals refuse to boot unsigned code

Integrity attestations broadcast to network

Malicious / offline ballot box

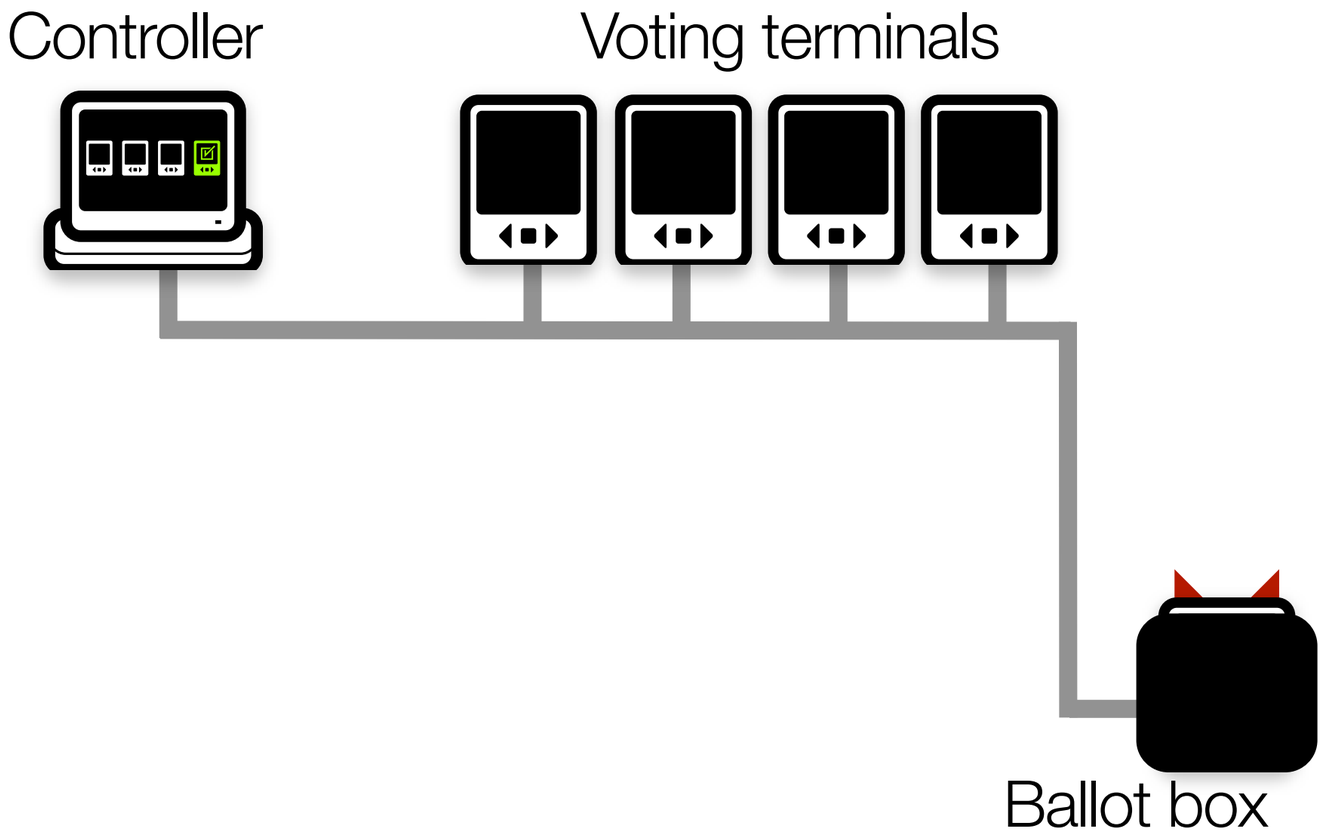
No ballot acknowledgements

Observable by controller

Warn poll workers

Election-night resolution

Rescan deposited ballots



Coerce voter w/ ballot randomness?

E.g., “cast if even, challenge if odd.”

Voter can deliberately spoil and revote many times (“oops!”)

Stronger mitigations possible (e.g., don’t print textual hashes, only barcode)

Bad impact on usability

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

Voter presents “fake” receipt

Falsely impugn the election?

Possible mitigations:

- Watermarking on physical paper
- Digital signature within QRcode

Similar issues with challenge ballots

Ballot spoiling process can include wet signatures of poll workers

YOUR VOTE COUNTS

COUNTY OF TRAVIS
1839
STATE OF TEXAS

Thank you for voting!

Take this confirmation of voting with you

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Voting Terminal: UI12345

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

Status

VoteBox-based proof-of-concept implementation in progress

Production system would want to start from scratch

Human-subject usability studies under way

Browser-based mockup of STAR, running in the lab

Design mostly set

RFP/RFI almost ready to launch

Publication

Bell et al., *USENIX Journal of Election Technology & Systems (JETS)*, vol 1., no. 1, August 2013.

Ballot box prototype as well

Example usability testing: how will users respond to rejected ballots?

STAR-Vote: It's happening

Registration

Controller

Voting terminals

E2E verification

Risk-limiting audits

Tons of redundancy

Usability/accessibility

COTS hardware

Ballot box

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

Acknowledgements

ACCURATE - A Center for Correct, Usable, Reliable, Auditable, and Transparent Elections

Premiere NSF research center on e-voting, 2005-2011

Many ideas in STAR were developed in ACCURATE

NSF SaTC Medium: Voting Systems Architectures for Security and Usability

Research support for STAR effort, 2014-2018

Microsoft SEIF

Investigating integration of Win8 measured boot (2013+)