

State		State	
Governor		Governor	
	Vote for One		Vote for One
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Howard Hughes	<input checked="" type="radio"/>	Howard Hughes	<input type="radio"/>
Charles Lindbergh	<input type="radio"/>	Charles Lindbergh	<input type="radio"/>
Write In	<input type="radio"/>	Write In	<input type="radio"/>

UNCLEARBALLOT: AUTOMATED BALLOT IMAGE MANIPULATION

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Joint work with Matthew Bernhard
and Professor J. Alex Halderman

Post-Election Audits

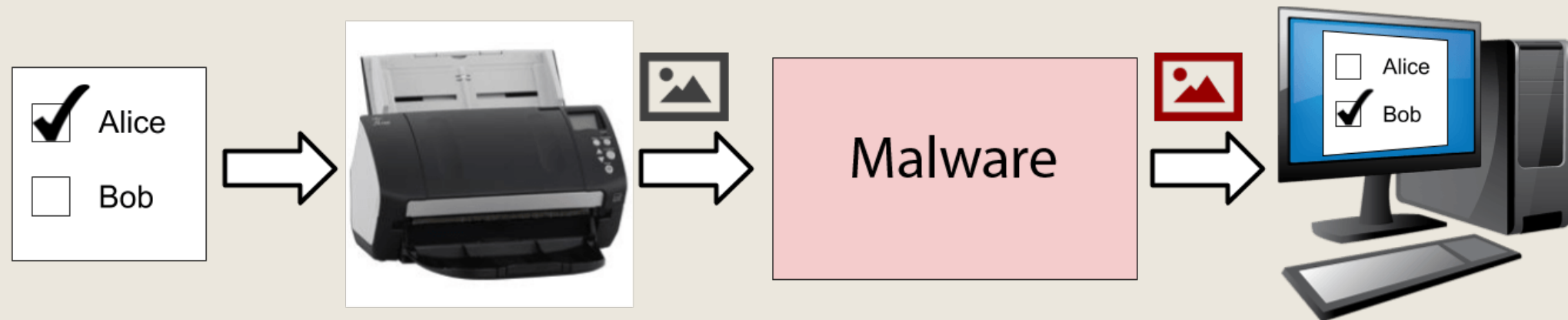
- Audits are one of the most important layers of defense for election security
- Risk-limiting audits: manually inspect large enough random sample of physical paper ballots – considered gold standard
- Other types of post-election audits are gaining popularity in the marketplace
- 37 states along with DC require post-election audits of ballots

Image Audits

- Audit of digital scan rather than physical paper
- Image audit software pioneered by Clear Ballot
- Maryland relies on image audits to provide assurances of election results
 - codified into election code
- Images are disconnected from source of truth—physical paper ballots
 - Not reliable under adversarial conditions

Attack Scenarios

- We investigate how an attacker could automatically alter ballot images to change apparent votes
- Numerous vulnerabilities documented to allow attacker to infect voting equipment and change tabulation results
- Our attack targets a tabulation machine and manipulates each ballot as it is scanned



Attack Strategy

- Our approach: automatically and selectively doctor ballot scans
 - altered marks consistent with voter's marks
 - undetectable to human eye
 - not necessary to alter large proportion

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Template Matching: Identify Race

Clear Ballot

CBG Demonstration Election
November 7, 2017

Precinct 001

To vote: completely darken the oval (●) to the left of your choice.

Note the permitted number of choices directly below the title of each candidate office. Do not mark the ballot for more choices than allowed.

If you mark the ballot for more choices than permitted that contest or question will not be counted.

To vote for a write-in candidate: completely darken the oval (●) to the left of the blank line and write in the candidate's name. Only votes cast for candidates who filed as write-in candidates can be counted.

If you make a mistake or want to change your vote: return your ballot to an election official and get a new ballot. You may ask for a new ballot up to two times.

For US Senator
(Vote for not more than 1)

Jonathan Hart
Democratic

Adam Martin
Republican

George Smith
Green

Write-In

For Representative to Congress (15th District)
(Vote for not more than 1)

Mary Jo Kilroy
Democrat

Mark Michael Noble
Libertarian

Steve Stivers
Republican

Write-In

For Member of Council
(Vote for not more than 2)

Trudy Ages

Stan Bach

Adam Baum

Hugh Canduit

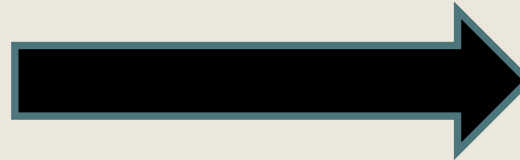
Bill Ding

Cora Napple

Mary Smith

Check both sides of ballot
Page 1 of 2

Precinct 001 [01] Standby (CS 1)



For US Senator
(Vote for not more than 1)

Jonathan Hart
Democratic

Adam Martin
Republican

George Smith
Green

Write-In

Hough Line Transforms: Separate candidates

For US Senator
(Vote for not more than 1)

Jonathan Hart
Democratic

Adam Martin
Republican

George Smith
Green

Write-In _____



For US Senator
(Vote for not more than 1)

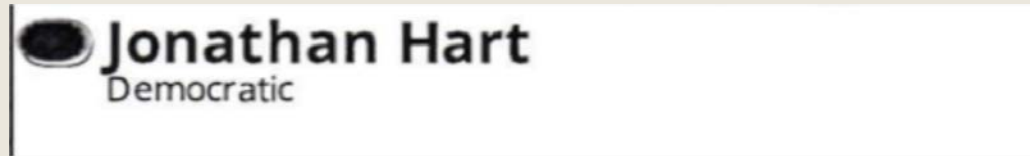
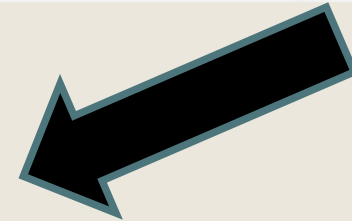
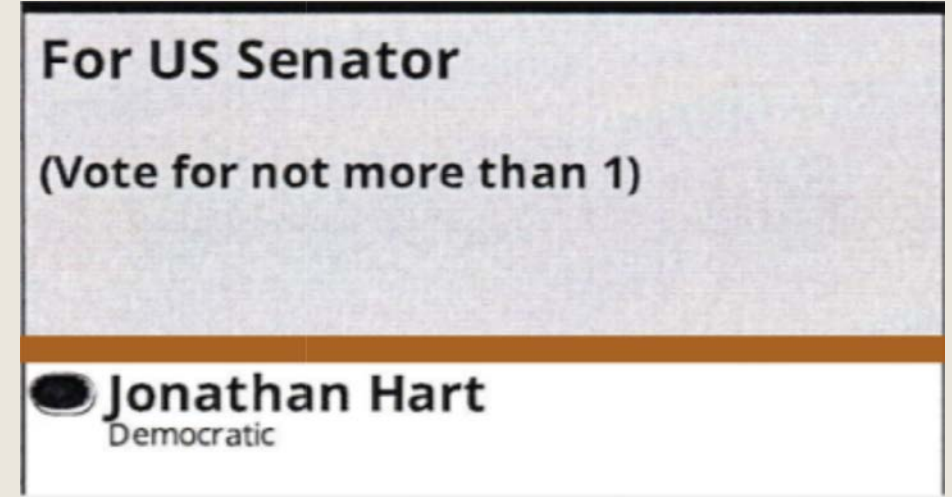
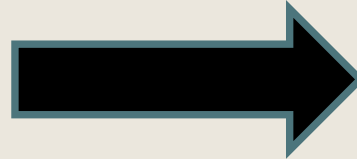
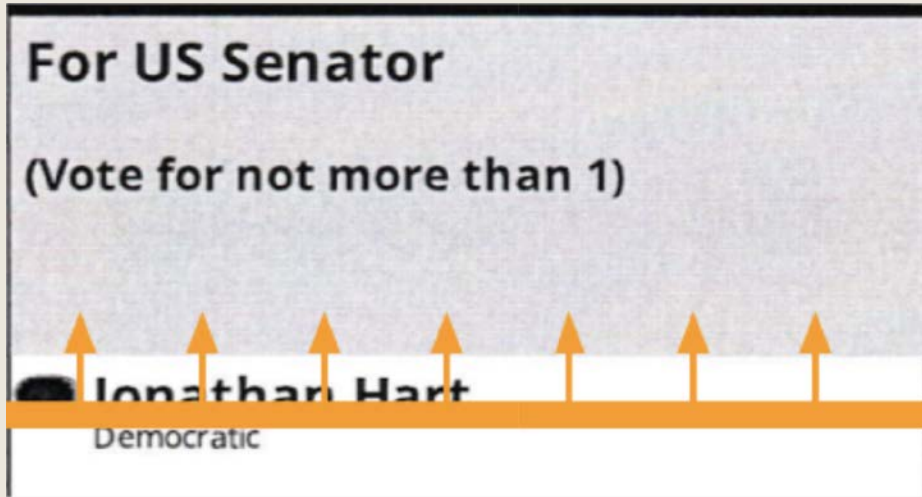
Jonathan Hart
Democratic

Adam Martin
Republican

George Smith
Green

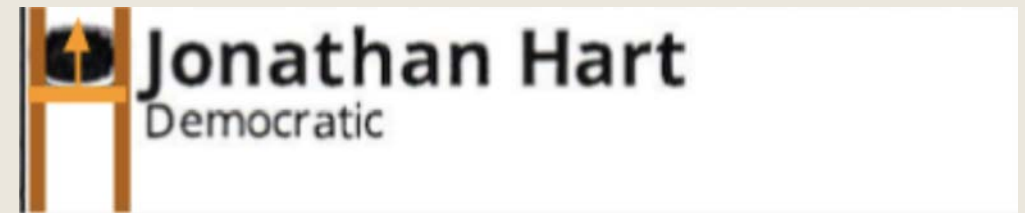
Write-In _____

Vertical Sweep: Remove race title



Linear Sweeps: Create bounding box

- Four linear sweeps
- Taking pixel intensity





Jonathan Hart
Democratic

Identify and move the mark

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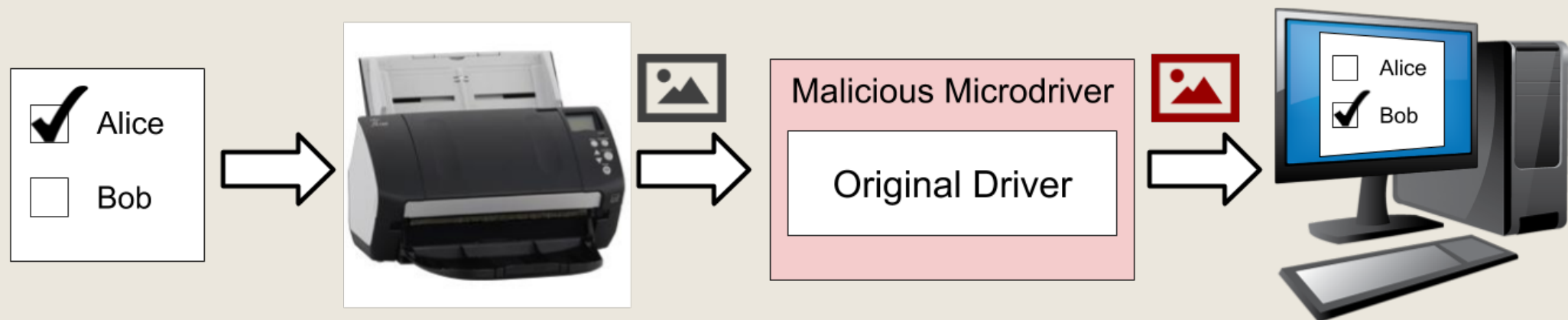
County		County	
Supervisor, District 1		Supervisor, District 1	
	Vote for One		Vote for One
Alfred Hitchcock	<input type="radio"/>	Alfred Hitchcock	<input checked="" type="radio"/>
Vincent Price	<input checked="" type="radio"/>	Vincent Price	<input type="radio"/>
Write In	<input type="radio"/>	Write In	<input type="radio"/>

Example swaps



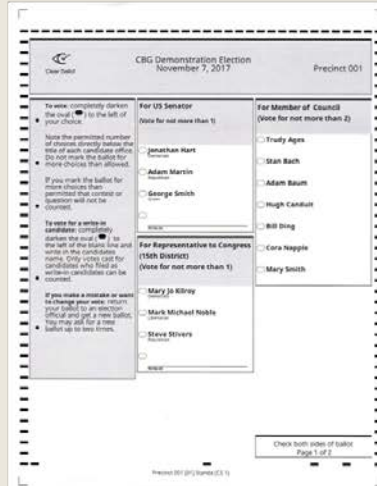
Proof-of-Concept Implementation

- Packaged as malicious Windows scanner driver
- Tested with Fujitsu fi-7180 scanner
 - EAC certified for use in U.S. elections: Clear Ballot's ClearVote system

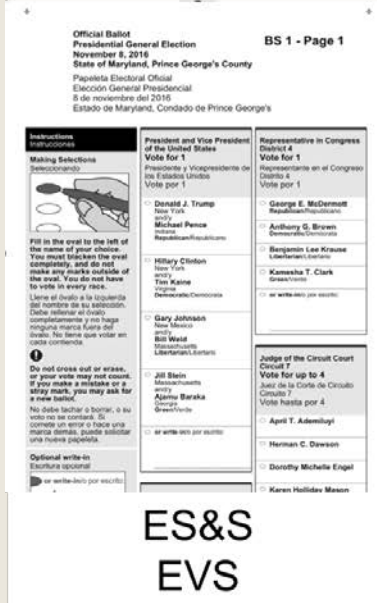


Testing across ballot styles

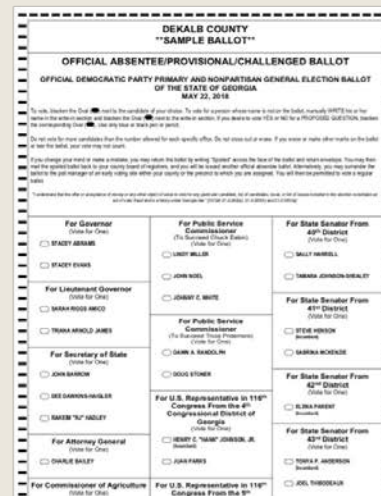
- Four largest U.S. election vendors
 - ES&S, Hart InterCivic, Dominion, Clear Ballot
- Two older styles of ballots
 - Hart InterCivic, Diebold



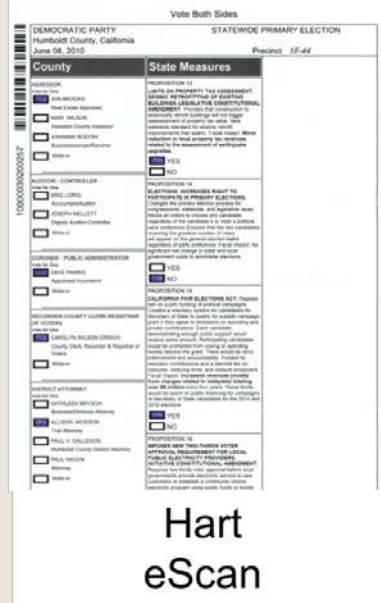
Clear Ballot
ClearVote



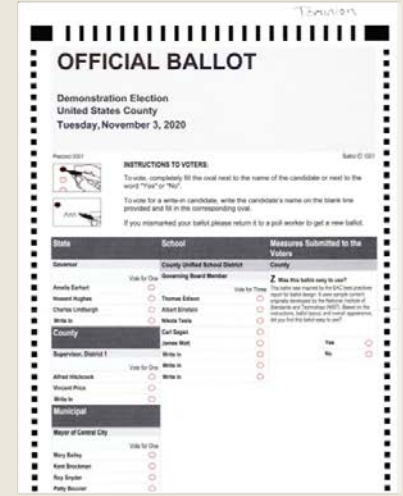
ES&S
EVS



Diebold
AccuVote



Hart
eScan



Dominion
Democracy Suite



Hart
Verity

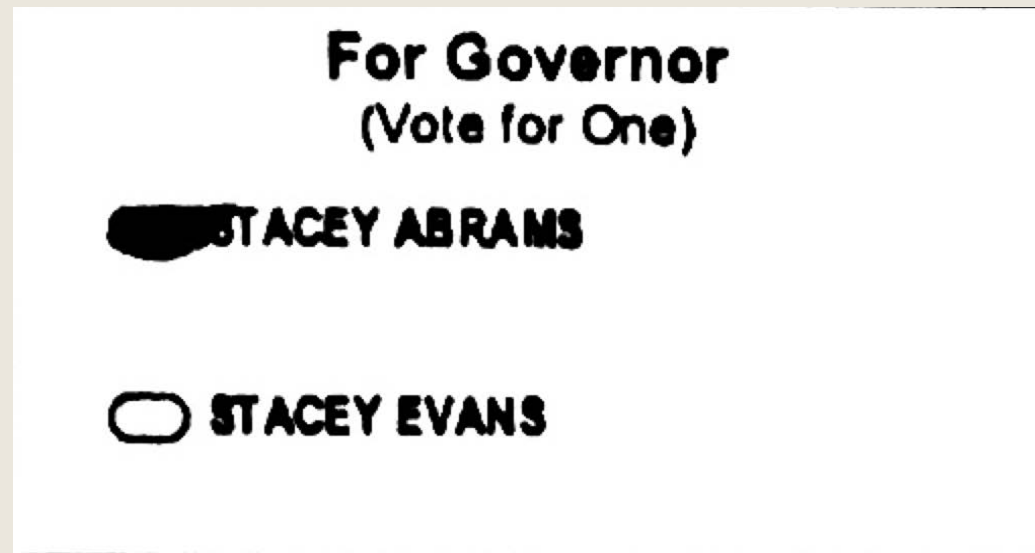
Marking Ballots

- Bajcsy systemization
- Prepared 720 marked contests
 - 120 per ballot style
- For each ballot style:
 - 60 “Filled” marks
 - 10 of each marginal mark and 10 empty



Key insight!

- We only need to move marks we can confidently manipulate without leaving artifacts – ensure not visibly noticeable that marks have been moved
- We only have to move enough marks to change result: realistically only small fraction, people need to believe result



Example ballot we would not manipulate

Performance of UnclearBallot

Ballot Style	Invalid Marks			Valid Marks			Time / Success
	Skipped	Success	Failure	Skipped	Success	Failure	
Clear Ballot	55	5	0	26	34	0	25 ms
Diebold	60	0	0	6	54	0	11 ms
Dominion	38	22	0	7	53	0	30 ms
ES&S	52	8	0	29	31	0	54 ms
Hart (eScan)	60	0	0	38	22	0	46 ms
Hart (Verity)	60	0	0	27	33	0	21 ms

Feasibility in real election

- For every style of ballot, we were able to move at least 18% of ballot marks. Could swap results in 48/51 districts in 2016 election
 - Wyoming and WV are only red districts that could not have been turned blue
 - D.C. is only blue district that could not have been turned red
- Not realistic for Wyoming to vote blue, wouldn't be believed
- Shows that in a close election we could change the results

Testing with Real Voted Ballots

- Corpus of scans of 181,541 real ballots
 - Nov 6, 2018 General Election Clackamas County, Oregon
 - Votes centrally counted with optical scanner
 - Hart Verity-style

Real Ballot Results

- Rejected 20,117 (11%)
 - Scanning glitches
- Conservative parameters
- Altered 62,400 (34%)
- Random sample inspected
 - No visible artifacts
- Alteration time: 279 ms
- Hart scan time: 352 ms

Measure 102

Referred to the People by the Legislative Assembly

Amends Constitution: Allows local bonds for financing affordable housing with nongovernmental entities. Requires voter approval, annual audits

Result of "Yes" Vote: "Yes" vote allows local governments to issue bonds to finance affordable housing with nongovernmental entities. Requires local voters' approval of bonds, annual audits, public reporting.

Result of "No" Vote: "No" vote retains constitutional prohibition on local governments raising money for/loaning credit to nongovernmental entities; no exception for bonds to pay for affordable housing.

Yes

No

Measure 102

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Result of "No" Vote: "No" vote retains constitutional prohibition on local governments raising money for/loaning credit to nongovernmental entities; no exception for bonds to pay for affordable housing.

Yes

No

What good are image audits?

- Useful for catching non-adversarial error
- Identify and document discrepancies
 - 2,000 ballots discovered missing in Maryland in 2016
 - Identified flaw in ES&S DS850 high speed scanner: some ballots were sticking together
- Cannot be relied upon to detect attacks

Detection?

- Detecting image manipulation is an arms race at best
- Likely that attacker could gain access to detection code
 - Could improve manipulation algorithm
 - Could use detector as part of mark-moving algorithm
- To our knowledge, no vendor does even minimum automated detection today...

Securing against image manipulation

- Best solution is to do an RLA where people are looking at physical ballots
- Fully software independent
- High probability of detecting and correcting any outcome altering, error, or fraud even if all election equipment has been infected with malware

Conclusions

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- Image audits involve checking a digital photo of the ballot
- However, an attacker could use computer vision techniques to automatically alter ballot images to show a different result
- We implemented this with an EAC certified scanner
- Attack works across widely used ballot styles from all major vendors
- Best defense: people audit physical ballots - software independence

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