Fast Privacy-Preserving Punch Cards
Hello Saba,

Thank you for your email and checking in. We appreciate it tremendously.

We are currently still closed and don’t have a tentative date to open yet. At the moment, we are waiting to hear back from Stanford as to when we will be able to get the green light. From what we understand, research is slowly ramping back up in phases. We were told that we may be able to open back up once research does, but there are still a lot of details that need to be ironed out before we can do so.

We are currently servicing hospital on Wednesdays and Thursdays via a pop-up location at their old cafe. This has allowed us to at least employ some of our staff.

Please don’t hesitate to reach out if you have any additional questions. We look forward to being able to open back up and once again serving the University community. We miss you guys!

Cheers,

Jeeryn and Marc
BUY 9 BOWLS, GET THE 10TH ONE FREE!

*(CARD WILL BE PUNCHED FOR BUILD-A-BOWLS ONLY. COMPLETED PUNCH CARD CAN BE REDEEMED FOR A FREE BOWL WITH A SINGLE PROTEIN CHOICE AND FRIED EGG. ANY EXTRAS WILL BE AN ADDITIONAL COST)*

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Why go digital?

Customer convenience
No lost cards
Better bookkeeping
Hard to Counterfeit
Contactless
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Why NOT go digital?

Digital loyalty programs can be data-stealing monsters*
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Why NOT go digital?
Digital loyalty programs can be data-stealing monsters*

Can we get the benefits of digital loyalty programs without sacrificing privacy?
Existing Approaches

Anonymous credentials, eCash, uCentive

- Give customers an unlinkable token for each purchase
- Customer redeems by presenting a bunch of tokens
- Work scales linearly in the number of hole punches
Existing Approaches

Recent line of work: BBA [JR16], BBA+ [HHNR17], UACS [BBDE19], Bobolz et al. [BEKS20]

- “Black-box accumulation”/“Updatable anonymous credentials”
- Punch card storage and performance independent of number of punches
- Support for broader functionalities
  - e.g., Offline double spending, negative points, partial redemption
- Performance could be improved -- reliance on pairings, involved proofs
- Mismatch between scheme and punch card deployment scenario
Our Work

Focus on real requirements for punch cards:

- No long-term user identity tied to a public key
- No server work to issue cards (avoids DoS)
- Minimizes round complexity
Our Work

Focus on real requirements for punch cards:
- No long-term user identity tied to a public key
- No server work to issue cards (avoids DoS)
- Minimizes round complexity

Improves performance:
- Removes reliance on pairings
- 14x faster card punch, 25x less communication
- 394x faster card redemption, 62x less communication
Punch Card Functionality

Server setup: initialize server secrets, database of redeemed cards

Card issuance: issue a fresh punch card

Card punch: add a punch to an existing punch card

Card redemption/validation: submit a completed punch card for a reward
Punch Card Security

**Privacy:** Server can’t link any issuances, punches, or redemptions to each other
Server can simulate everything it sees when issuing/punching/redeeming a card.

**Soundness:** Client can’t redeem more punches than it has received
Challenger allows adversary to punch and redeem cards. Adversary wins if more punches redeemed than given.
First Attempt

Idea: server raises group element to secret power for each punch
First Attempt

Client

\[ p_0 \leftarrow_R G \]

Server

\[ \text{Setup} \]

\[ sk \leftarrow_R Z_q \]
First Attempt

Client

Issue

\( p_0 \leftarrow_R G \)

Punch

Server

Setup

\( sk \leftarrow_R Z_q \)

Punch

\[ p_i \]

\[ p_{i+1} \]

\[ p_{i+1} \leftarrow p_i^{sk} \]
First Attempt

Client

Issue
\[ p_0 \leftarrow_R G \]

Punch

\[ p_i \]

Redeem

\[ p_0, p_n \]

Server

Setup
\[ sk \leftarrow_R Z_q \]

Punch

\[ p_{i+1} \]

Verify
Accept iff
1. \[ p_n = p_0^{sk^\wedge n} \]
2. \[ p_0 \] not redeemed before
First Attempt

Client

Issue

\( p_0 \leftarrow_R G \)

Punch

\( p_i \)

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Server

Setup

\( sk \leftarrow_R Z_q \)

Punch

\( p_{i+1} \leftarrow p_i^{sk} \)

Verify

Accept iff

1. \( p_n = p_0^{sk^*n} \)
2. \( p_0 \) not redeemed before

Neither private nor sound!
Adding Privacy

Idea: client masks punch card before sending to server
Adding Privacy

Idea: client masks punch card before sending to server

Client

\[ m \leftarrow_R Z_q \]

\[ p_i' \leftarrow p_i^m \]

\[ p_i' \]

\[ p_{i+1}' \leftarrow (p_i')^{sk} \]

\[ p_{i+1} \leftarrow (p_{i+1}')^{m^{-1}} \]

Server
Adding Privacy

Idea: client masks punch card before sending to server

Client

\[ m \leftarrow_R Z_q \]

\[ p_i' \leftarrow p_i^m \]

\[ p_i' \]

\[ p_{i+1}' \leftarrow (p_i')^{sk} \]

Server

Only semihonest security!
Malicious Privacy

Malicious attack: server raises one punch card to a different power
Malicious Privacy

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Defense: Server provides proof that it raised card to the same power each time
Malicious Privacy

Malicious attack: server raises one punch card to a different power

Defense: Server provides proof that it raised card to the same power each time

Modify server setup to include $pk = g^{sk}$

Use Chaum-Pedersen Proof: Given $g$, $pk$, $p$,
prove knowledge of $sk$ s.t. $pk = g^{sk}$, $p' = p^{sk}$
Adding Soundness

Current redeem process: client sends $p_0, p_n$

Server checks $p_n = (p_0)^{sk^n}, \ p_0$ not redeemed before
Adding Soundness

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Server checks $p_n = (p_0)^{sk^n}$, $p_0$ not redeemed before

Attack:

1. Malicious client sends $p_0, p_n$
2. Server checks $p_n = (p_0)^{sk^n}$, $p_0$ not redeemed before, redeems $n$ points
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4. Malicious client sends $p_1, p_{n+1}$
5. Server checks $p_{n+1} = (p_1)^{sk^{(n+1)}}, p_1$ not redeemed before, redeems $n$ points
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4. Malicious client sends $p_1, p_{n+1}$
5. Server checks $p_{n+1} = (p_1)^{sk^{n+1}}$, $p_1$ not redeemed before, redeems $n$ points

Client gets $n+1$ punches, redeems $2n$ points, breaks soundness
Adding Soundness

Idea: client can’t redeem a punch card $p_0$ unless it knows the preimage of a hash function (modeled as RO) that outputs $p_0$
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Client

Issue

$id \leftarrow_R \{0, 1\}^\lambda$

$p_0 \leftarrow H(id)$

Server

Setup

$sk \leftarrow_R Z_q$

$pk \leftarrow_R g^{sk}$
Adding Soundness

Idea: client can’t redeem a punch card $p_0$ unless it knows the preimage of a hash function (modeled as RO) that outputs $p_0$

Client

Issue

$id \leftarrow_R \{0,1\}^k$

$p_0 \leftarrow H(id)$

...

Redeem

Server

Setup

$sk \leftarrow_R Z_q$

$pk \leftarrow_R g^{sk}$

...

Verify

Accept iff 1. $p_n = H(id)^{sk^{n}}$

2. $id$ not redeemed before
Proving Soundness

Proof in Algebraic Group Model (most prior work proven in more restrictive GGM)

Adversaries in the AGM must accompany each group element they send with a representation of that group element in terms of previously seen elements

In this model, DDH-style assumptions are equivalent to discrete log
Proving Soundness

Proof in Algebraic Group Model (most prior work proven in more restrictive GGM)

Adversaries in the AGM must accompany each group element they send with a representation of that group element in terms of previously seen elements.

In this model, DDH-style assumptions are equivalent to discrete log.

Proof relies on hardness of \textit{d-discrete log assumption}: given $g, g^x, g^{x^2}, g^{x^d}$, find $x$. 
Proving Soundness

1. Let $d$-dlog group elements be $X_0 = g$, $X_1 = g^x$, ..., $X_d = g^{x^d}$
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3. Program RO so that every hash output is of the form $g^r$ where the soundness challenger knows $r \leftarrow_R Z_q$ (but output still looks random to the adversary)
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4. To punch a card, look at algebraic representation of punch card and replace each $X_i$ with $X_{i+1}$.
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1. Let $d$-dlog group elements be $X_0 = g$, $X_1 = g^x$, ..., $X_d = g^{x^d}$
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4. To punch a card, look at algebraic representation of punch card and replace each $X_i$ with $X_{i+1}$.
5. Soundness adversary who wins the soundness game produces a punch card whose representation does not include $X_n^r$, which gives the challenger 2 representations of $X_n$. It can use this to break discrete log.
Implementation

Java (Android) wrapper around Rust implementation

Main construction implemented using curve25519-dalek

Evaluated on Pixel 1 (client) and recent Thinkpad laptop with i5 processor (server)
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<table>
<thead>
<tr>
<th></th>
<th>ServerSetup</th>
<th>Issue</th>
<th>ServerPunch</th>
<th>ClientPunch</th>
<th>ClientRedeem</th>
<th>ServerVerify</th>
</tr>
</thead>
<tbody>
<tr>
<td>Computation Time (ms)</td>
<td>0.019</td>
<td>0.304</td>
<td>0.134</td>
<td>4.314</td>
<td>0.890</td>
<td>0.064</td>
</tr>
<tr>
<td>Data Sent (Bytes)</td>
<td>32</td>
<td>0</td>
<td>128</td>
<td>32</td>
<td>64</td>
<td>0</td>
</tr>
</tbody>
</table>
Computation Comparison

Prior work evaluated on comparable hardware (Pixel/OnePlus 3, i7 processor)

Prior work uses BN curves with slightly lower security (~100 bits)

Each prior work dominated others in one part of protocol, our work improves on the best prior work in each category by order(s) of magnitude

<table>
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<tbody>
<tr>
<td>BBA+ scheme</td>
<td>115.27</td>
<td>385.61</td>
<td><strong>375.73</strong></td>
</tr>
<tr>
<td>UACS scheme</td>
<td><strong>86</strong></td>
<td>127</td>
<td>454</td>
</tr>
<tr>
<td>Bobolz et al. scheme</td>
<td>130</td>
<td><strong>64</strong></td>
<td>1254</td>
</tr>
<tr>
<td>Our main scheme</td>
<td><strong>0.304 (282.99× faster)</strong></td>
<td><strong>4.448 (14.4× faster)</strong></td>
<td><strong>0.954 (393.8× faster)</strong></td>
</tr>
</tbody>
</table>

(All times in ms)
Communication Comparison

Only one prior work reports communication costs

Our scheme requires no server involvement to issue a card

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<td>992</td>
<td>4048</td>
<td>3984</td>
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<td>Our main scheme</td>
<td>0</td>
<td>160 (25.3× reduction)</td>
<td>64 (62.3× reduction)</td>
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(All sizes in bytes)
Fast Privacy-Preserving Punch Cards

Key takeaways:
- 14x faster card punch, 25x less communication than prior work
- 394x faster card redemption, 62x less communication than prior work
- Qualitative improvements to better capture punch card setting

See paper for more details and extensions

Code: https://github.com/SabaEskandarian/PunchCard
Contact: saba@cs.stanford.edu