Privacy-Preserving Payment Splitting

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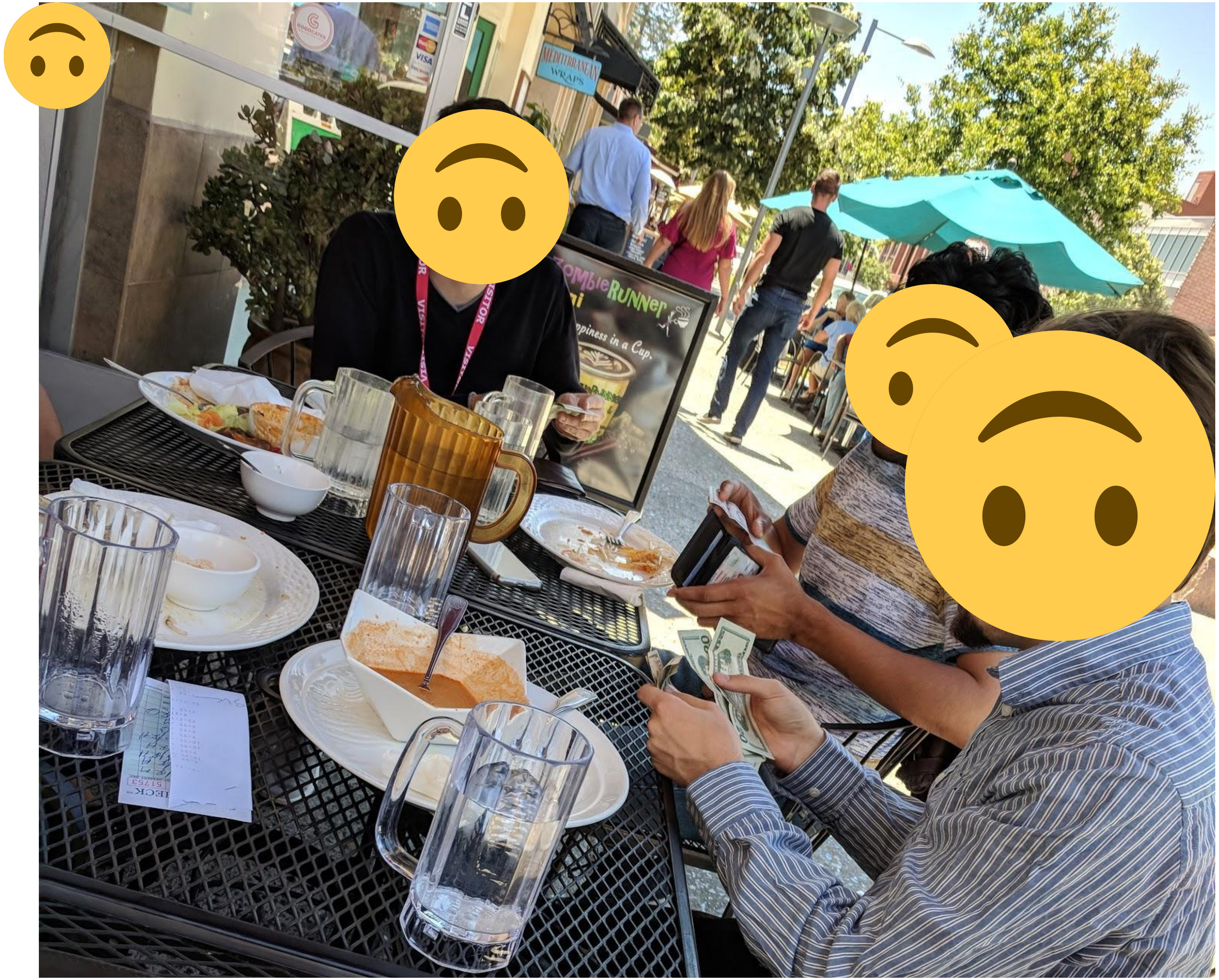
Stanford University

Mihai Christodorescu
Visa Research

Payman Mohassel
Facebook


MEDITERRANEAN WRAPS
ZombieRunner
...ppiness in a Cup
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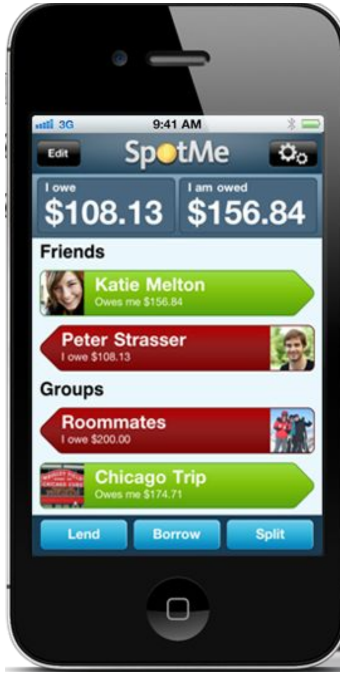
VISA

Payment Splitting Apps

Splitwise, Receipt Ninja, Billpin, SpotMe, Conmigo, Settle Up, …

Convenient way to keep track of costs and debts between groups of friends or colleagues



I owe $108.13

I am owed $156.84

Friends

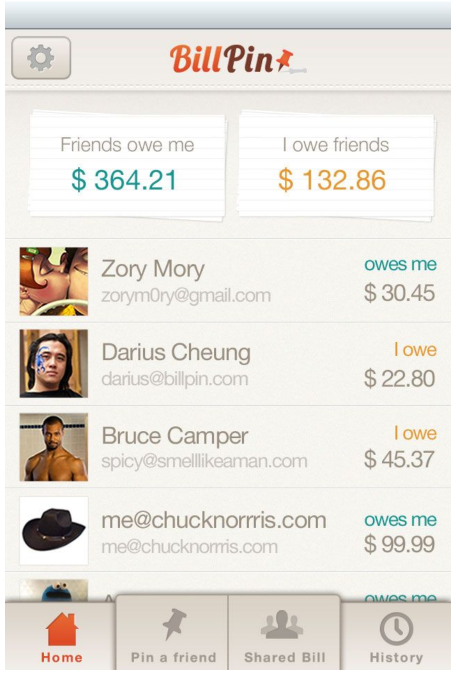
Katie Melton
Owes me $156.84

Peter Strasser
I owe $108.13

Groups

Roommates
I owe $200.00

Chicago Trip
Owes me $174.71



Friends owe me $ 364.21

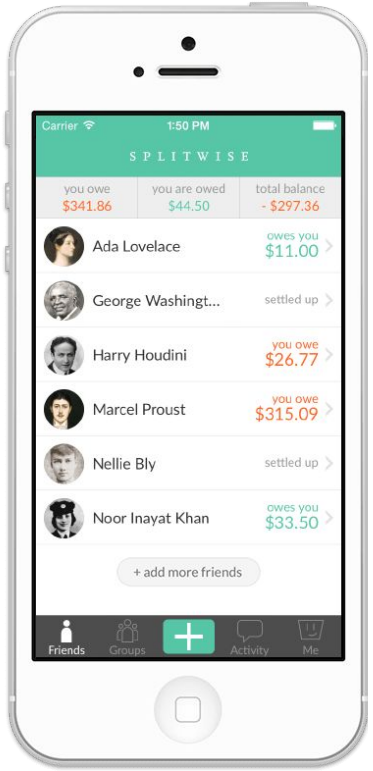
I owe friends $ 132.86

Zory Mory
zorym0ry@gmail.com
owes me $ 30.45

Darius Cheung
darius@billpin.com
I owe $ 22.80

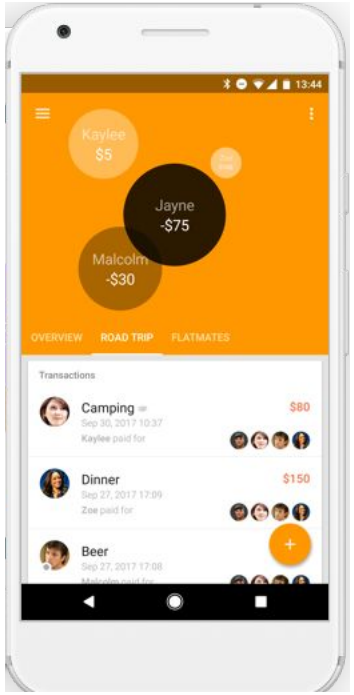
Bruce Camper
spicy@smelllikeaman.com
I owe $ 45.37

me@chucknorrris.com
me@chucknorris.com
owes me $ 99.99



you owe	you are owed	total balance
$341.86	$44.50	- $297.36

Ada Lovelace	owes you $11.00
George Washingt...	settled up
Harry Houdini	you owe $26.77
Marcel Proust	you owe $315.09
Nellie Bly	settled up
Noor Inayat Khan	owes you $33.50

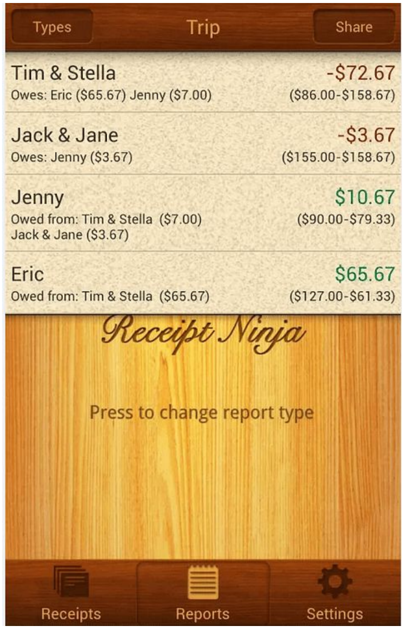


Transactions

Camping
Sep 30, 2017 10:37
Kaylee paid for
$80

Dinner
Sep 27, 2017 17:09
Zoe paid for
$150

Beer
Sep 27, 2017 17:08
Malcolm paid for



Tim & Stella -$72.67
Owes: Eric ($65.67) Jenny ($7.00) ($86.00-$158.67)

Jack & Jane -$3.67
Owes: Jenny ($3.67) ($155.00-$158.67)

Jenny $10.67
Owed from: Tim & Stella ($7.00) ($90.00-$79.33)
Jack & Jane ($3.67)

Eric $65.67
Owed from: Tim & Stella ($65.67) ($127.00-$61.33)

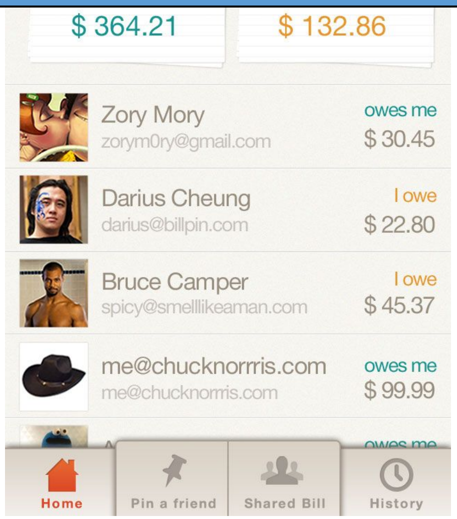
Payment Splitting Apps

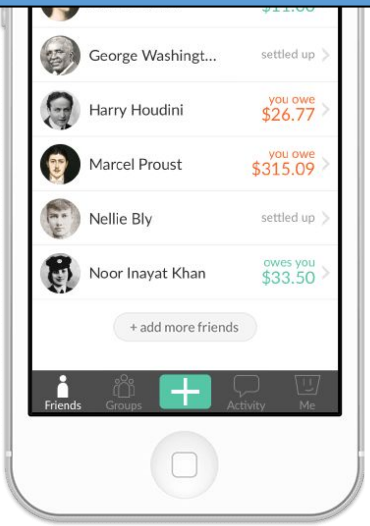
Privacy Policy – Data We Collect:

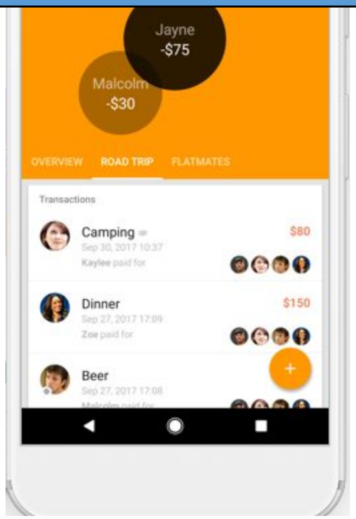
"This data includes, for example, group names, expense descriptions and amounts, payments and their confirmation numbers, comments and reminders, receipt images, notes, and memos, in addition to any other information that you attach or share while using …"

"… the types of expenses you add, the features you use, the actions you take, and the time, frequency and duration of your activities"

nds or colleagues







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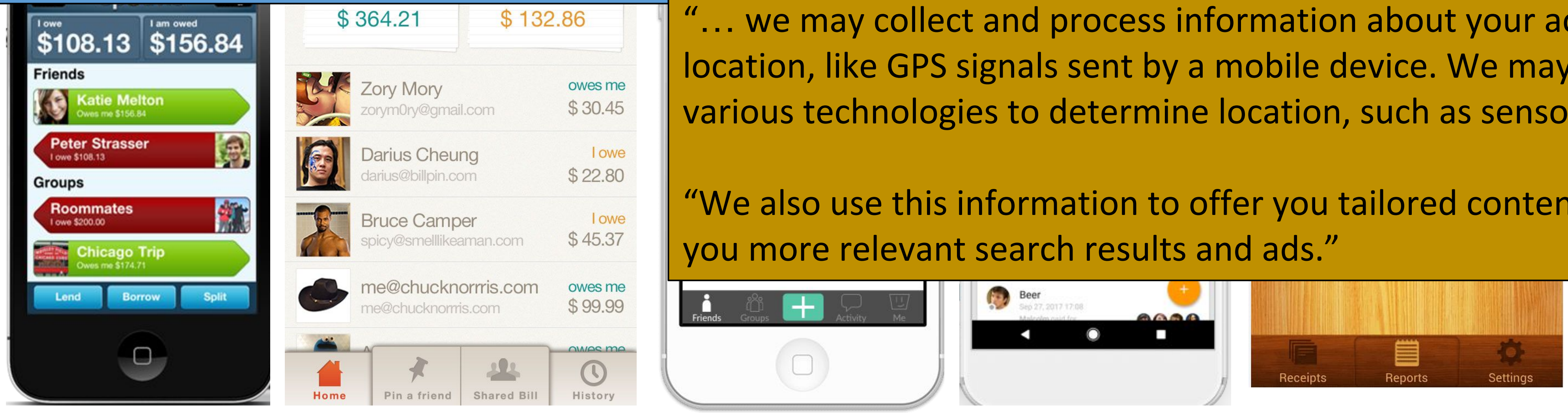
“Personal Information collected may include your name, age, gender, zip code, e-mail address, cell phone number, occupation, hometown, college, personal interests, nickname, friend's list and information about personal finances”

“… we may collect and process information about your actual location, like GPS signals sent by a mobile device. We may also use various technologies to determine location, such as sensor data …”

“We also use this information to offer you tailored content – like giving you more relevant search results and ads.”



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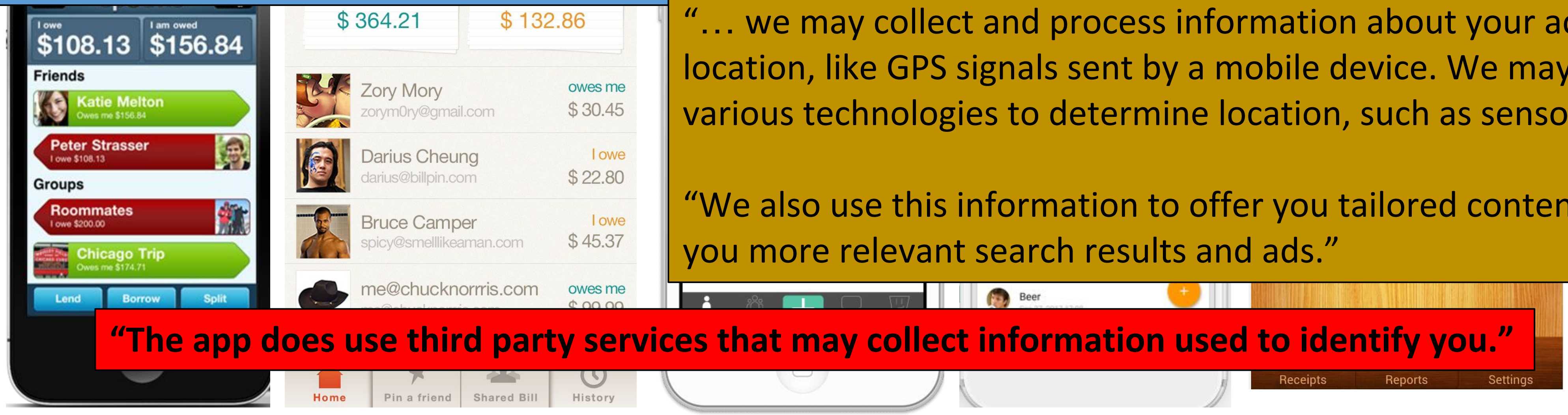

“The app does use third party services that may collect information used to identify you.”

Goal: cash-like privacy for payment splitting

Generic Solutions

Homomorphic encryption based solutions

[e.g. Gen09, BGV11, GSW13]

Server-aided MPC solutions

[e.g. FKN94, KMR11/12, HLP11]

Zero-Knowledge Log Server

[e.g. zkLedger (NVV'18)]

Metadata-hiding anonymous group messaging?

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Goal 2: Strong performance and scalability

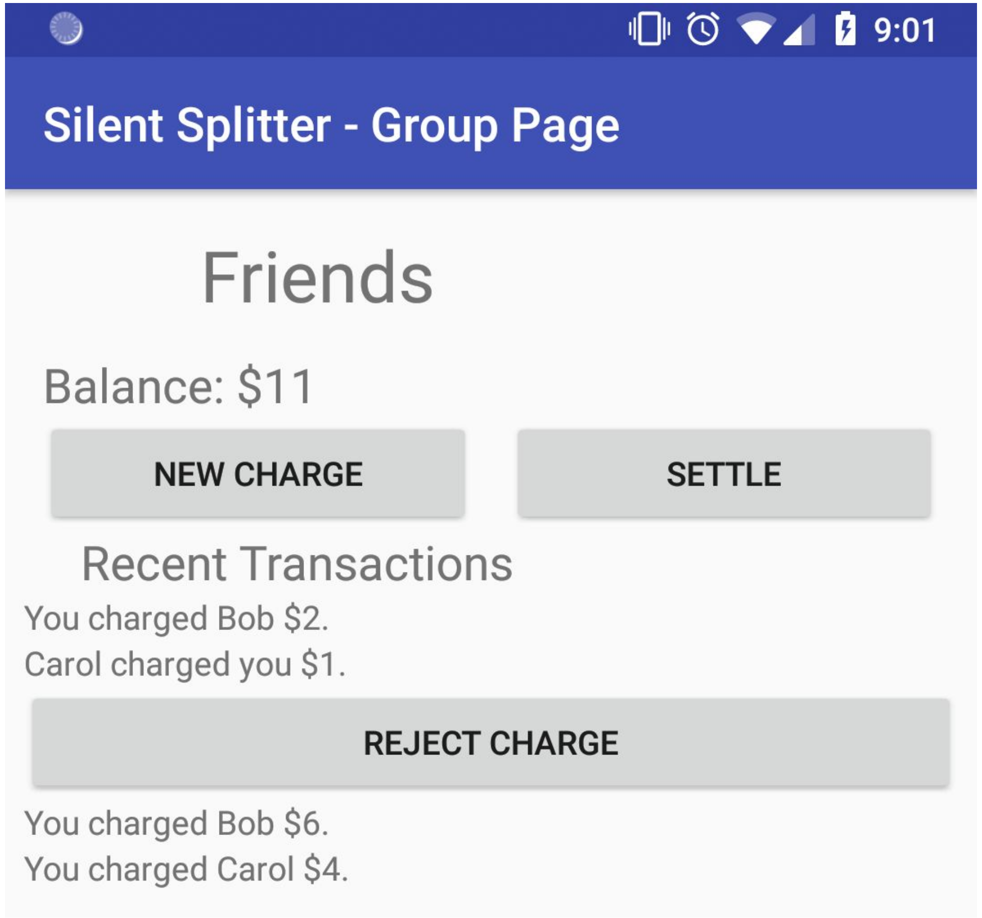
Our Solution

Same functionality as today's payment splitting apps

Hides user data from provider

Runs very fast:
<50ms/round on phone
<300μs/round on server
(for realistic group sizes)

Consists mainly of AES and addition



Balance: $11

You charged Bob $2.
Carol charged you $1.

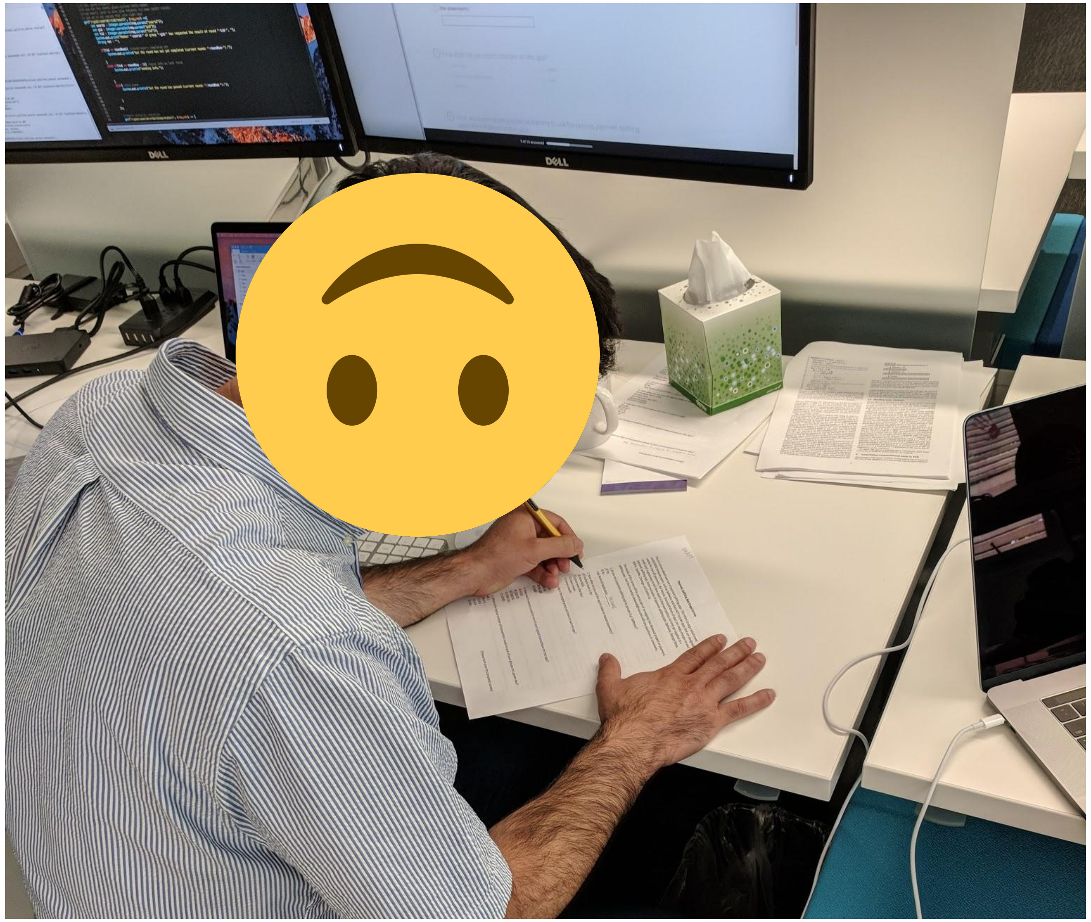
You charged Bob $6.
You charged Carol $4.

Informal User Survey

Sent to ~250 employees in Visa Palo Alto office, got 51 responses

Some takeaways:

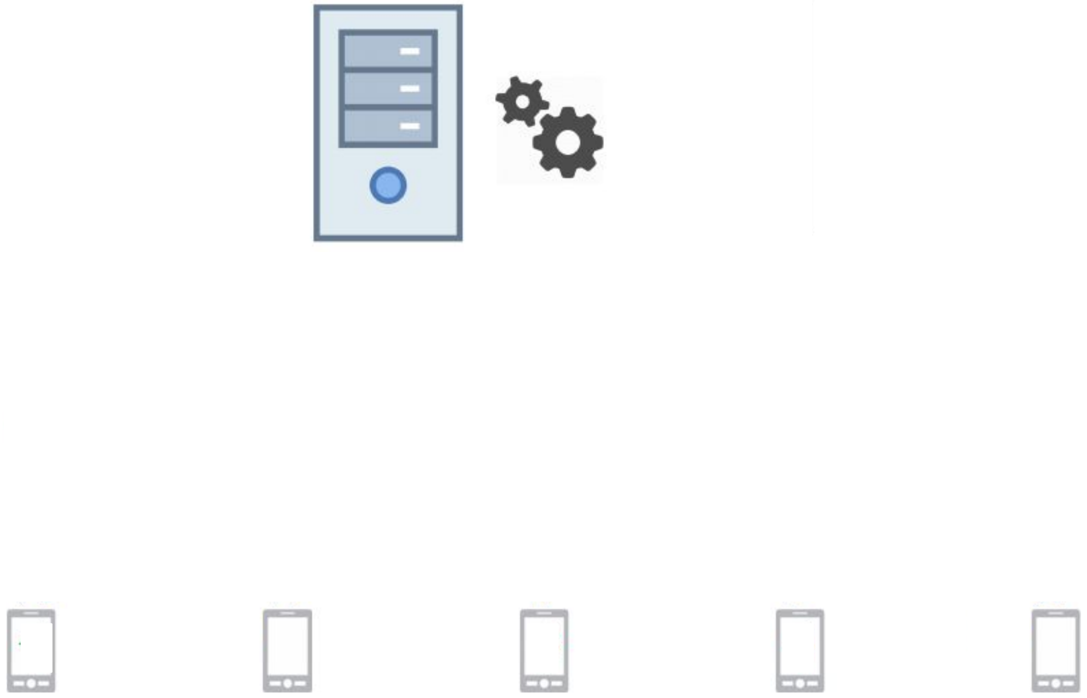
- Groups tend to be small
- Groups have only a few transactions a day
- Transaction amounts are usually fairly small amounts of money



(Dramatization, it was an online survey)

Architecture Overview

Group members connect to server via app



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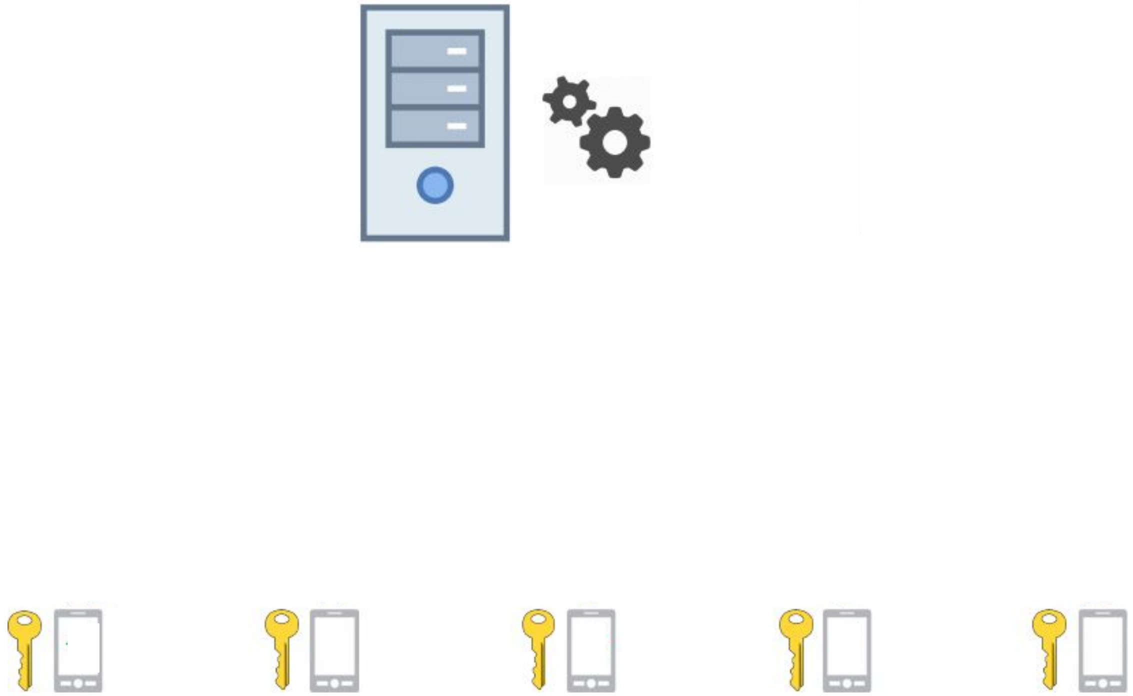

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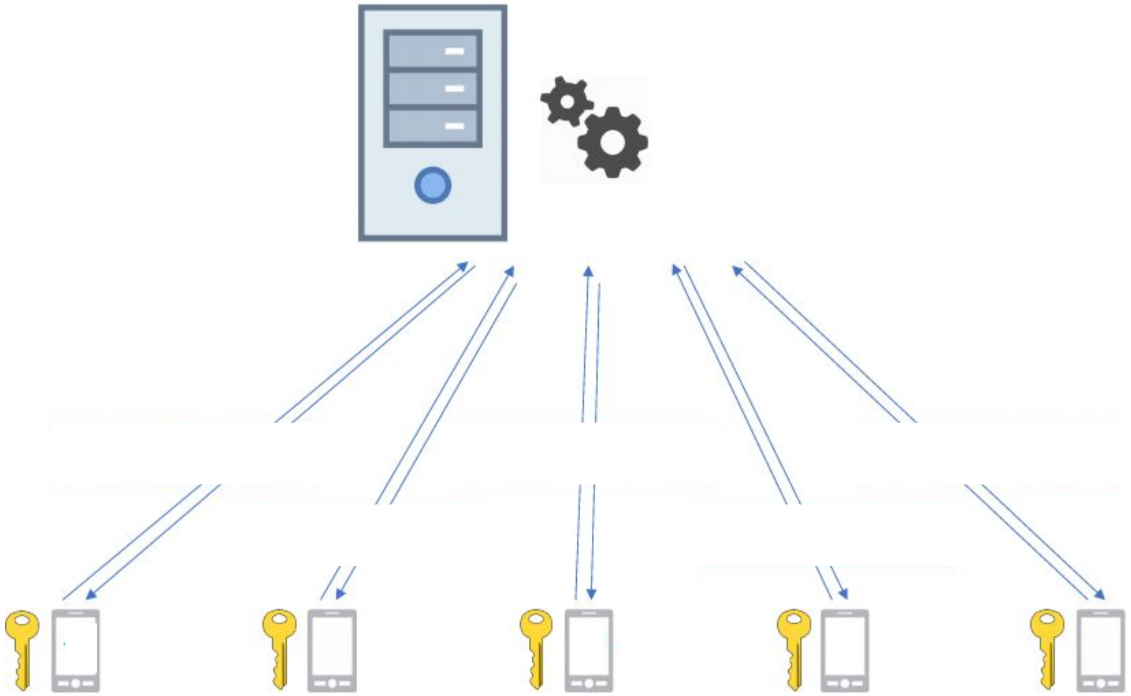

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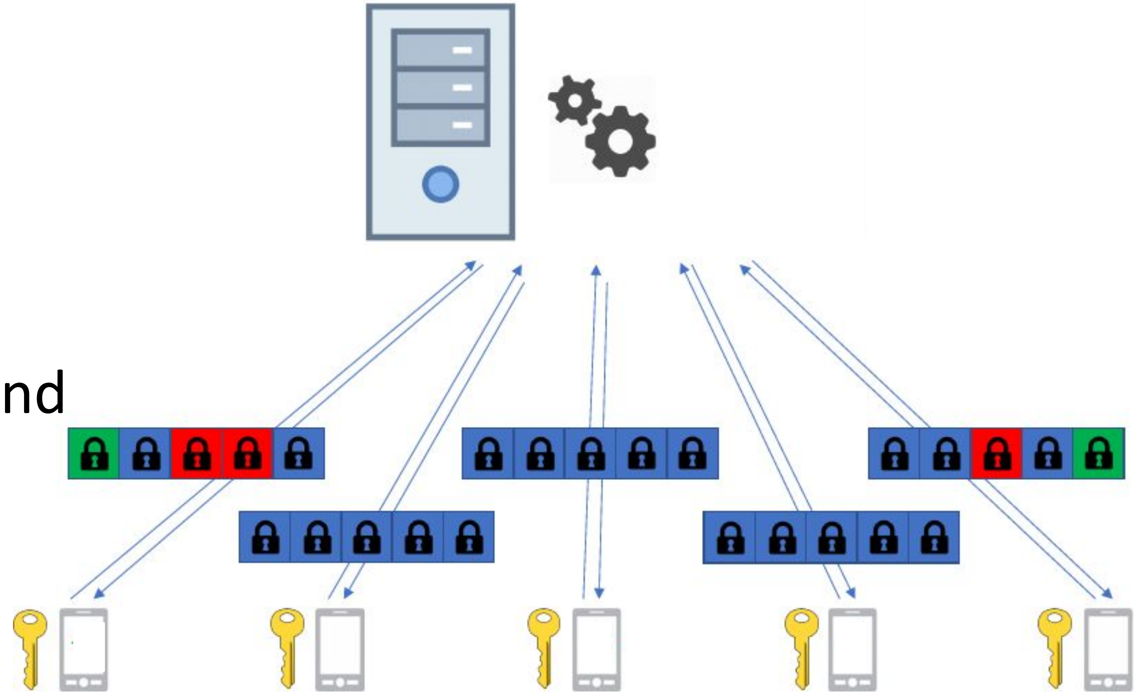

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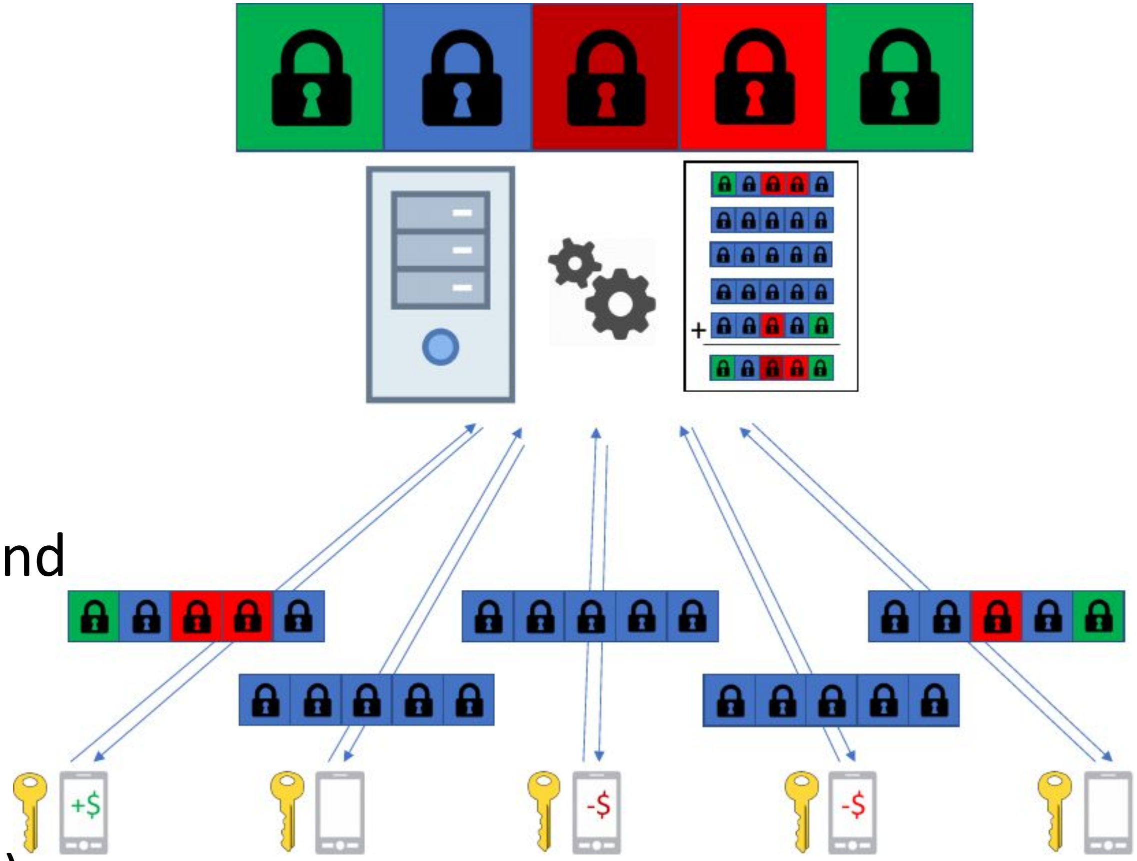
Server *blindly* sums values and sends results (New balance, charger identity, integrity check)



Security Properties

Server Privacy: any two sets of transactions indistinguishable to server

Debtor Privacy: transaction hides who it puts into debt to others

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User Integrity:

1) No user can create or destroy money (assume >0 honest users)
2) No user can undetectably frame an honest user for making a charge

Server Integrity: Malicious server can only cause denial of service

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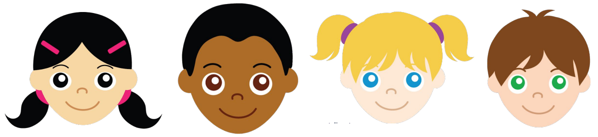
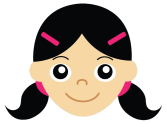
Limitations:

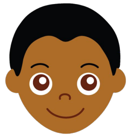
We do not hide group membership from the server

We do not protect against collusion between a malicious user and server

Making a Request

Example: Alice requests $1 from Bob in their friend group 





Faces from sweetclipart.com

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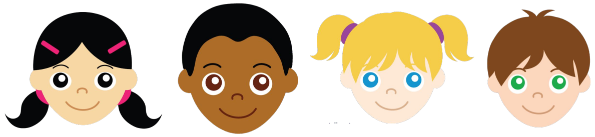
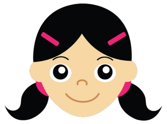
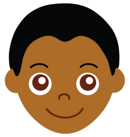
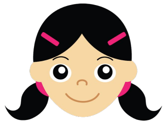
Example: Alice requests $1 from Bob in their friend group 

Alice sets her vector to all 0s except a 1 in Bob's position



0	1	0	0

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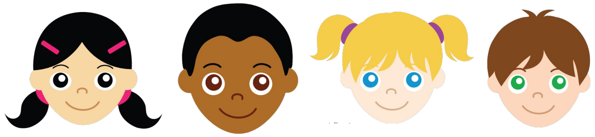

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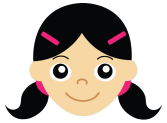

0	1	0	0

Anyone not making a charge puts a 1 in their own position

0	1	0	0

0	0	1	0

0	0	0	1

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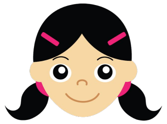

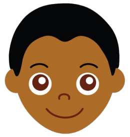

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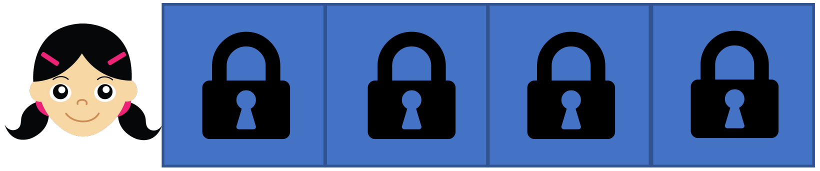
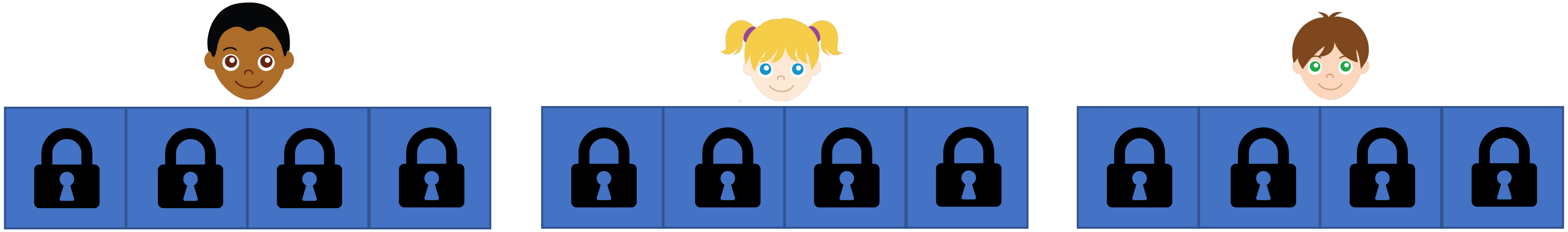


Each user encrypts his/her vector and sends the result to the server

Anyone not making a charge puts a 1 in their own position



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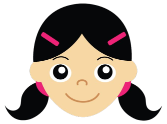

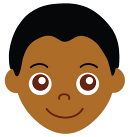

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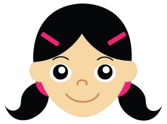

0	1	0	0

We'll start by showing the protocol without encryption

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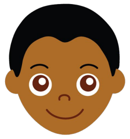
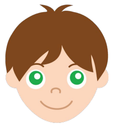


0	1	0	0

0	0	1	0



0	0	0	1

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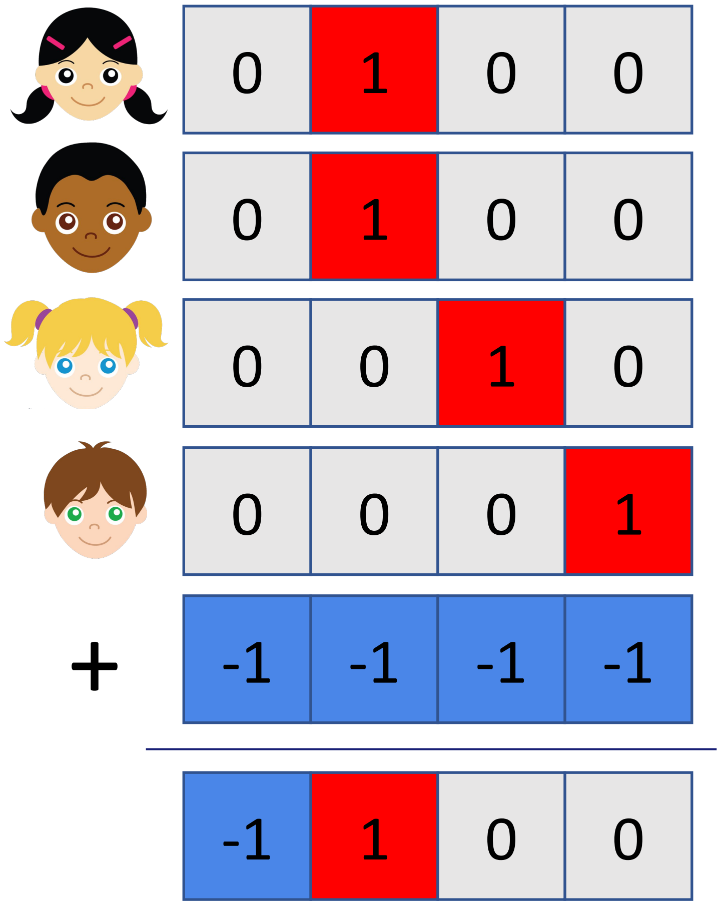
Making a Request

The server adds up everyone’s values and subtracts 1



	0	1	0	0
	0	1	0	0
	0	0	1	0
	0	0	0	1
+	-1	-1	-1	-1
	-1	1	0	0

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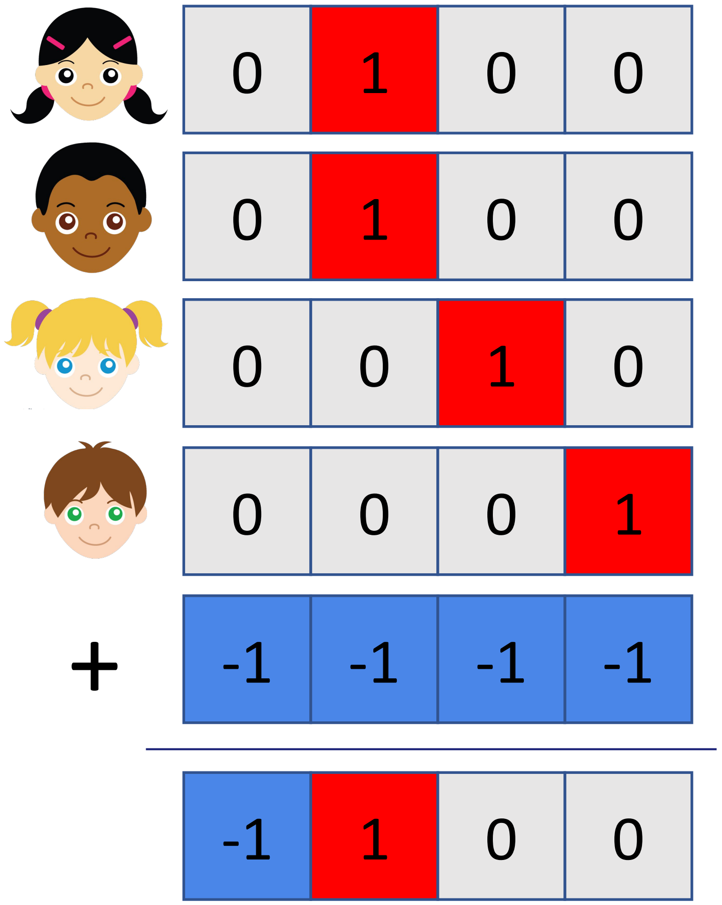

	0	1	0	0
	0	1	0	0
	0	0	1	0
	0	0	0	1
+	-1	-1	-1	-1
	-1	1	0	0

The result is added to users’ existing balances

Note: server tracks *debt*, so negative is less debt

Tracing Charges

How does Bob know it was Alice who charged him?

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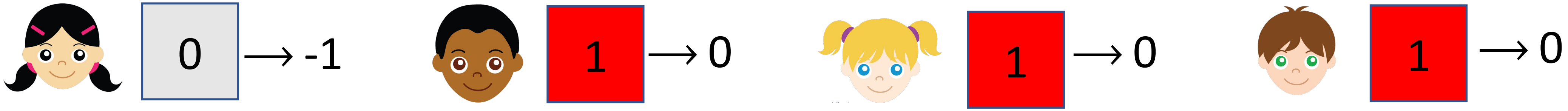
For each user, server takes “(input in user’s own position) – 1”



0 ⟶ -1

1 ⟶ 0

1 ⟶ 0

1 ⟶ 0

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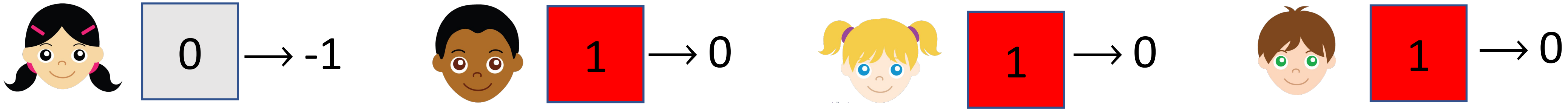

0 → -1   1 → 0   1 → 0   1 → 0

Multiplies by a power of 2 assigned to that user

x1 = -1 + x2 = 0 + x4 = 0 + x8 = 0

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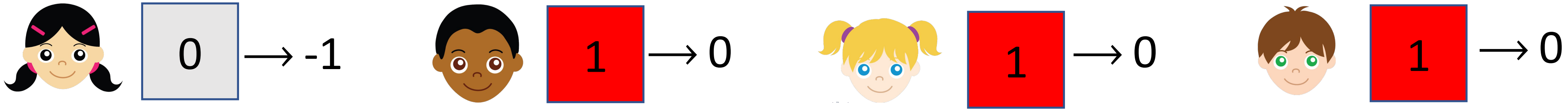

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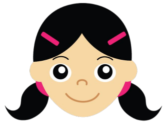
And sums up the results to identify the charger(s)

= -1 ⟶



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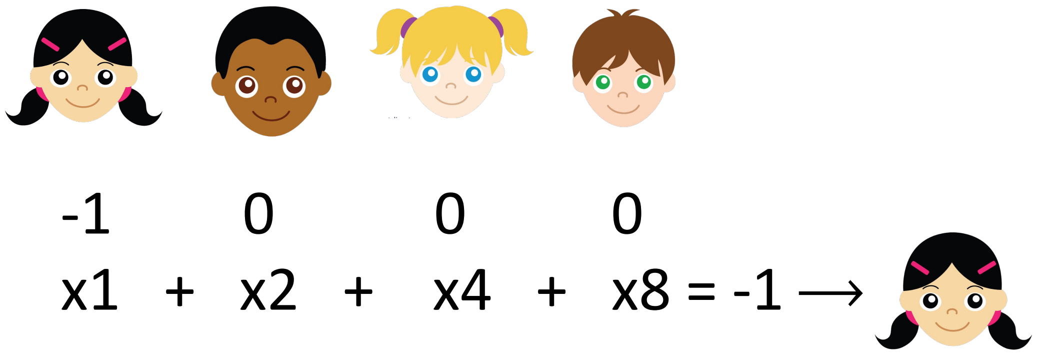
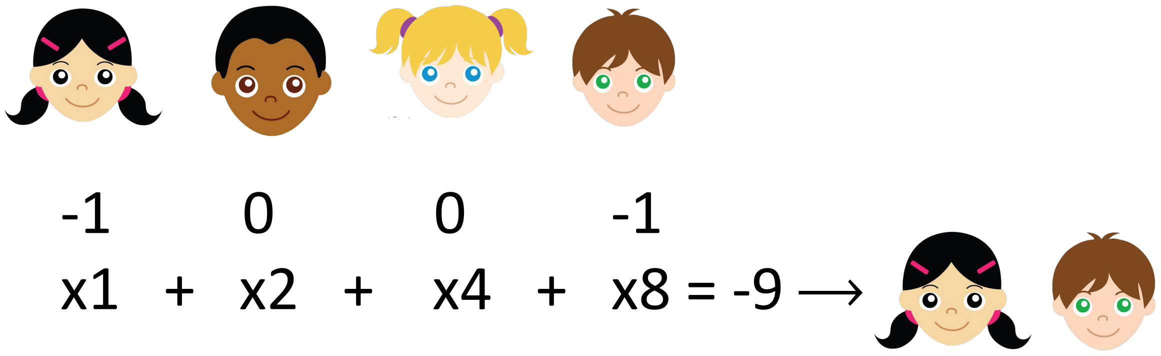


-1 0 0 0

x1 + x2 + x4 + x8 = -1 ⟶



-1 0 0 -1

x1 + x2 + x4 + x8 = -9 ⟶

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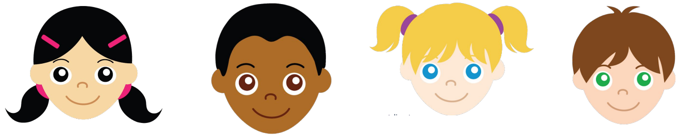

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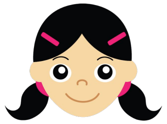
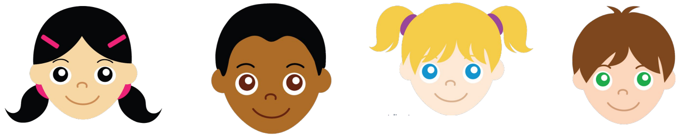
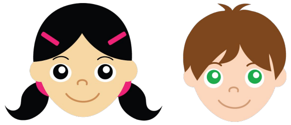
x1 + x2 + x4 + x8 = -1 ⟶ 



-1 0 0 -1

x1 + x2 + x4 + x8 = -9 ⟶ 

What to do for collisions? Roll back and repeat one by one (server is oblivious)

Adding Server Privacy

Observation 1: server does the same *fixed* set of additions every round.

No data-dependent operations

Adding Server Privacy

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No data-dependent operations

Observation 2: all the clients share a secret key *k*.

They can independently generate the same PRF outputs

Adding Server Privacy

Solution:

Instead of actually encrypting, users mask values with a PRF output

They send $v_i + r_i$, where $r_i = PRF(k$, group, user, round, $i)$

Users calculate sum of masks and remove them from server responses

Calculating/removing masks fast because it's just AES and addition

Extensions

- Integrity
- Larger transactions
- Multiple charges per Round
- Identifying misbehaving users
- Handling framing
- Handling users going offline
- Improving usability for charge requests
- Integration with payment systems
- Payment splitting with collateral

See paper for details!

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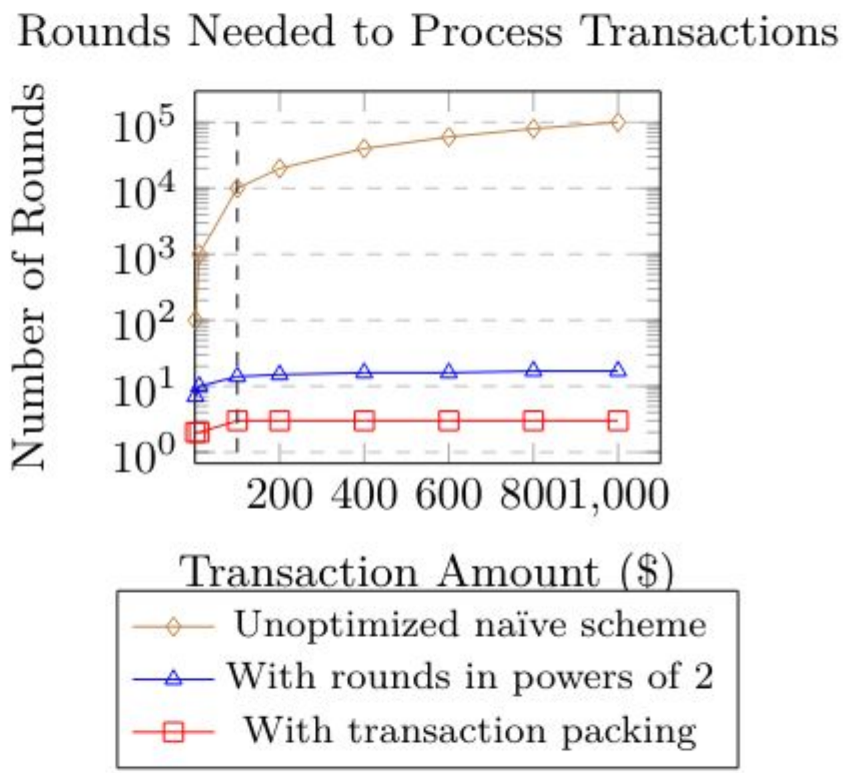

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Performance

Client Performance

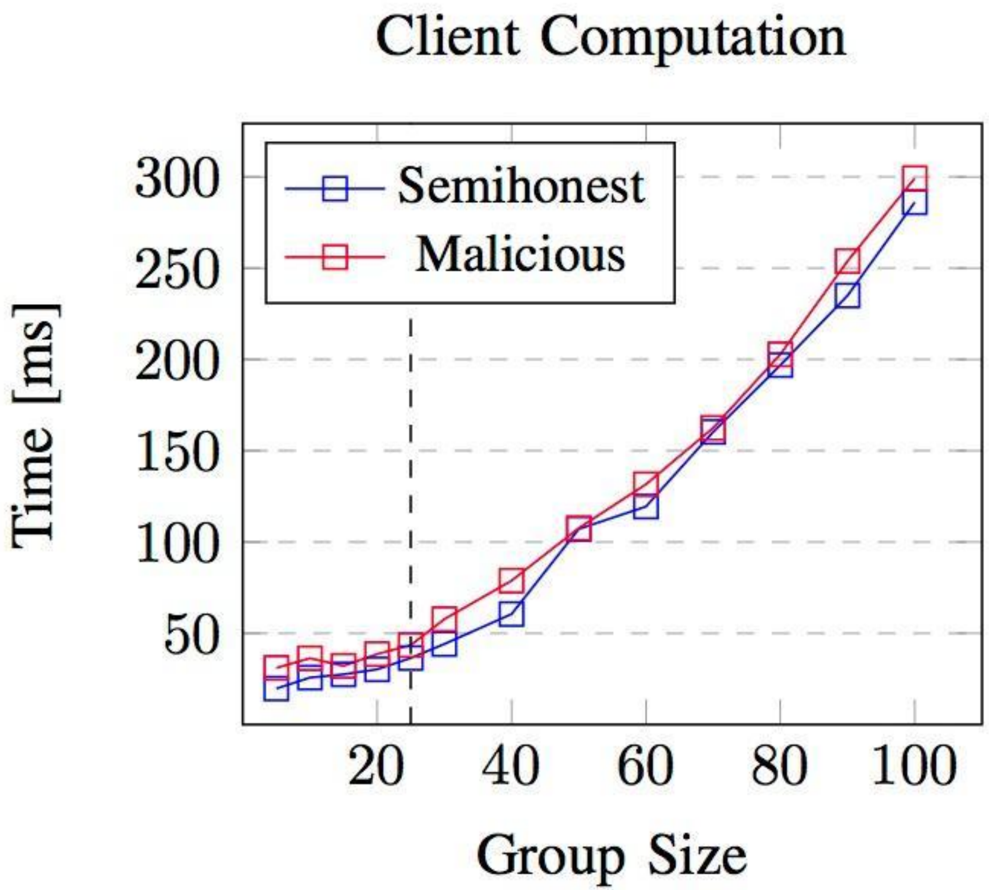
<50ms/round for realistic groups (realistic based on user survey)

Malicious server overhead <20ms

Only computes AES and addition

Client bandwidth for group size:

- 10 (≥69%of groups in survey): 160 Bytes
- 25 (≥92% of groups in survey): 400 Bytes
- 100 (≥100% of groups in survey): 1.6Kb



Server Performance

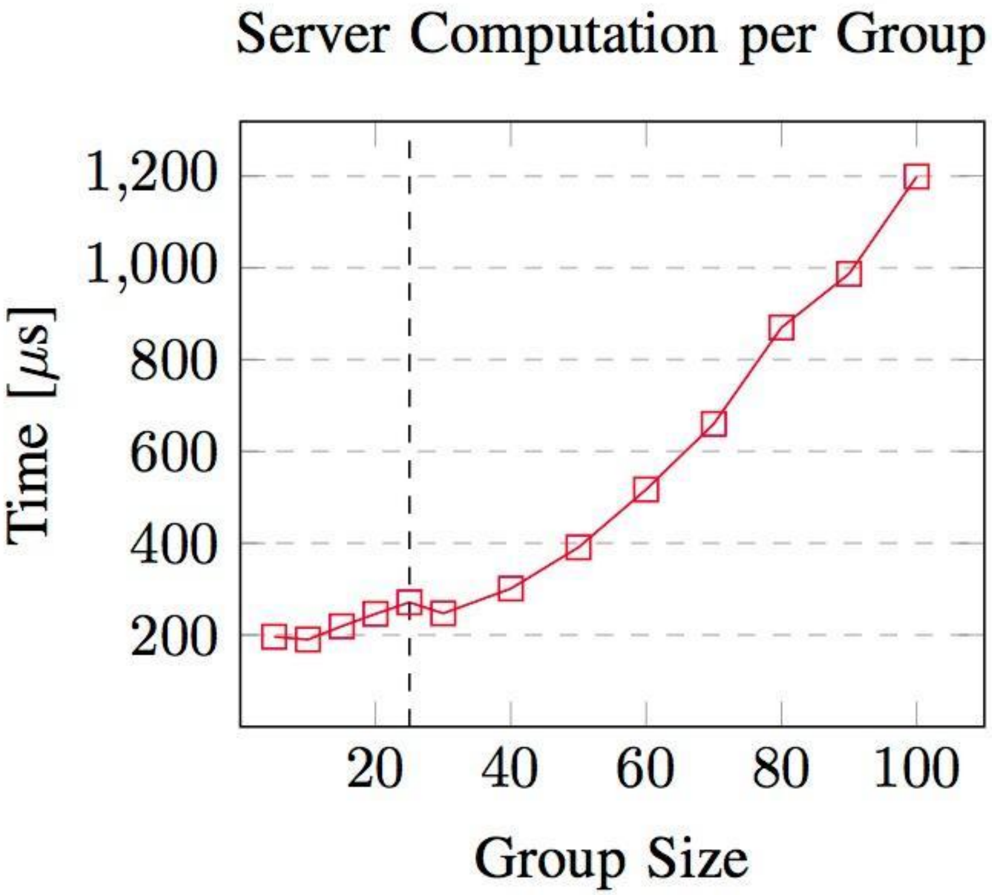
<300 *micro*seconds for realistic groups (realistic based on user survey)

No changes for malicious security

Only computes addition

Server memory requirements small – can handle user inputs as they arrive, no need to keep in memory

See paper for more evaluation details



Summary

Our system allows payment-splitting groups to hide

- Who pays,
- Who is paid,
- How much is spent,
- When transactions are made,
- And more

From a potentially malicious server at minimal performance cost

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