Design, Implementation, and Assessment of an Improved Revocation Mechanism for Verifiable Credentials

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Agenda

Understanding the Background

- Core Concepts
  - Verifiable Credentials (VCs)
  - Decentralized Identifiers (DIDs)
  - Status List 2021
- Gaps in the Status Quo

Defining the Problem

Solving the Problem

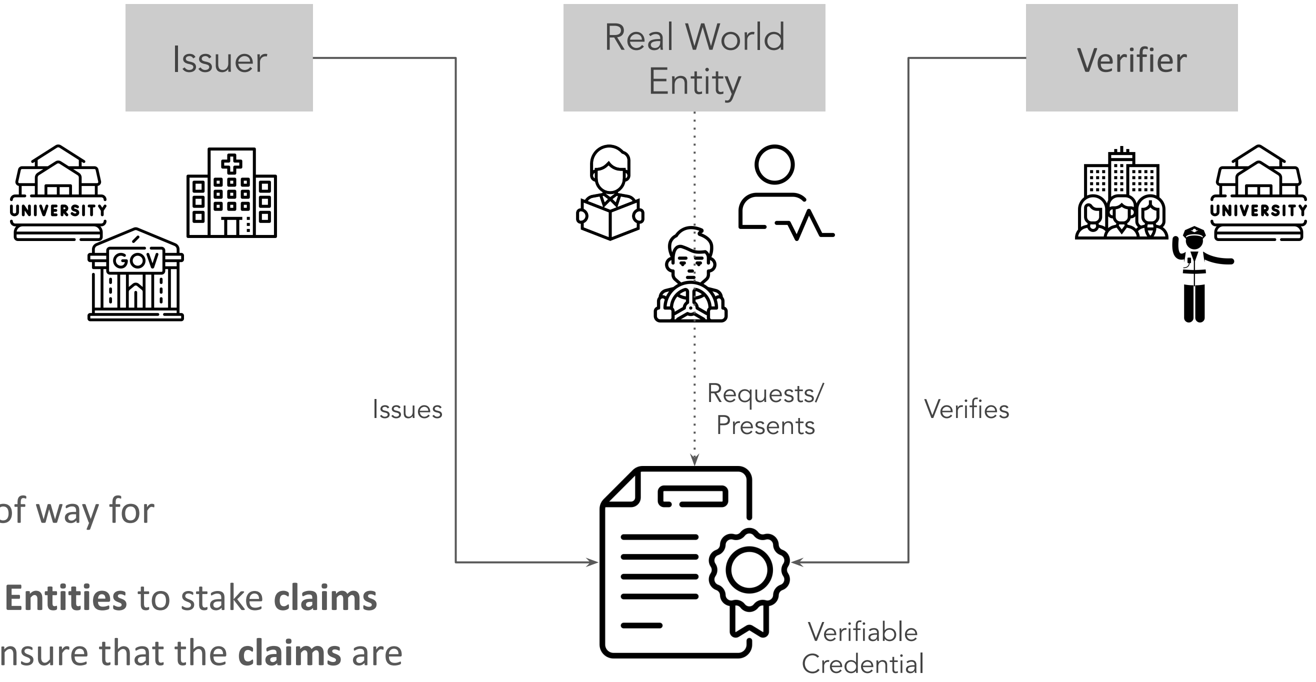
- Finding a Suitable Data Structure
  - The AMQFilter Interface
  - AMQ Filters- Bloom Filters, Cuckoo Filters
  - Experiments with AMQ Filters
- Research Roadmap

Understanding the Background

Design, Implementation, and Assessment of an Improved Revocation Mechanism for Verifiable Credentials

Overview of Verifiable Credentials (VCs)

- Real World Entities to make claims about themselves
- Two categories of information:
  - **Claims** e.g., names, titles of bachelor’s theses, medical records, etc.
  - **Signatures** - proof that the claims are true e.g., holograms, bar codes
- A digital (and decentralised) alternative to a physical document



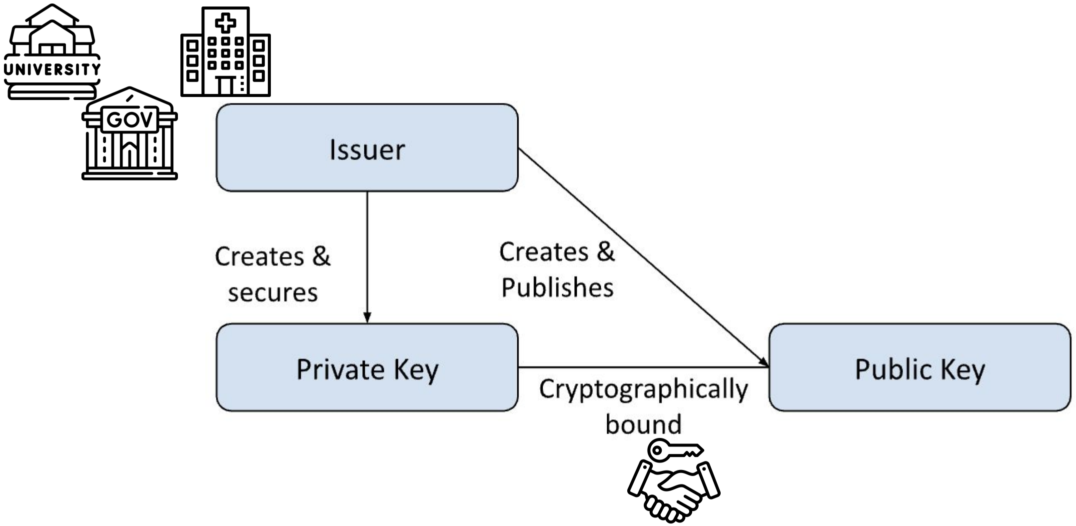
VCs are a foolproof way for

- **Real World Entities** to stake **claims**
- **Issuers** to ensure that the **claims** are **tamper-proof**
- **Verifiers** to ensure that the **claims** are **not falsehoods**

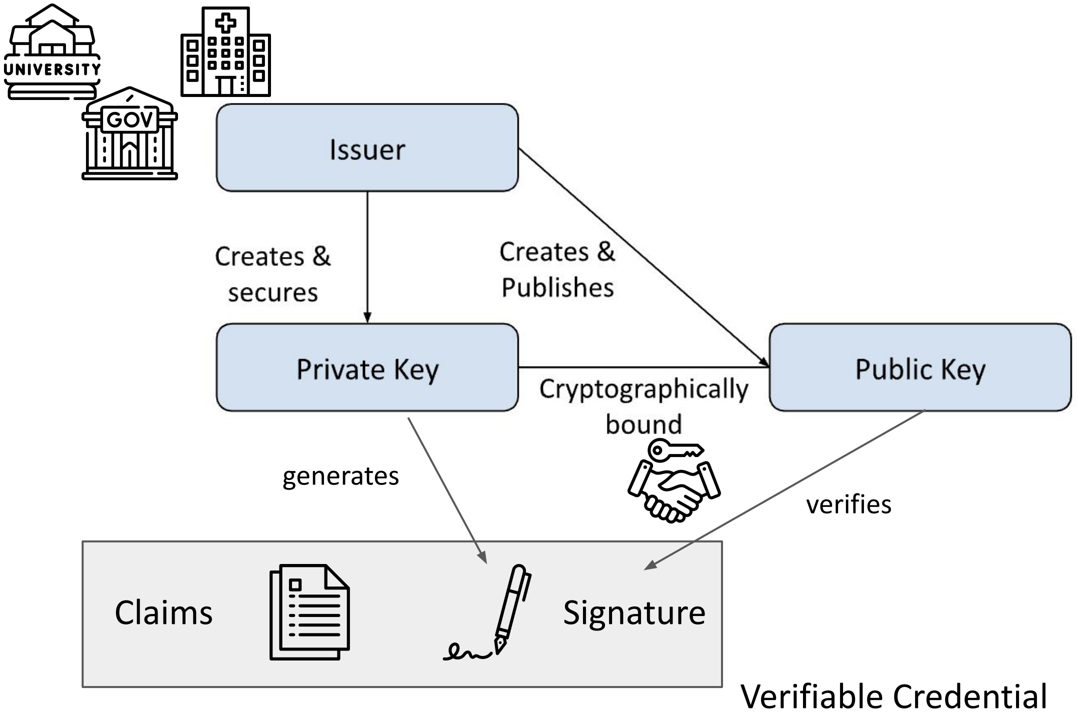
DIDs, VCs, and Asymmetric Encryption - a seamless certification system

Quick show of hands:
How many of us are familiar with Public Key Infrastructure (PKI), or asymmetric encryption, or JSON Web Tokens (JWTs)?

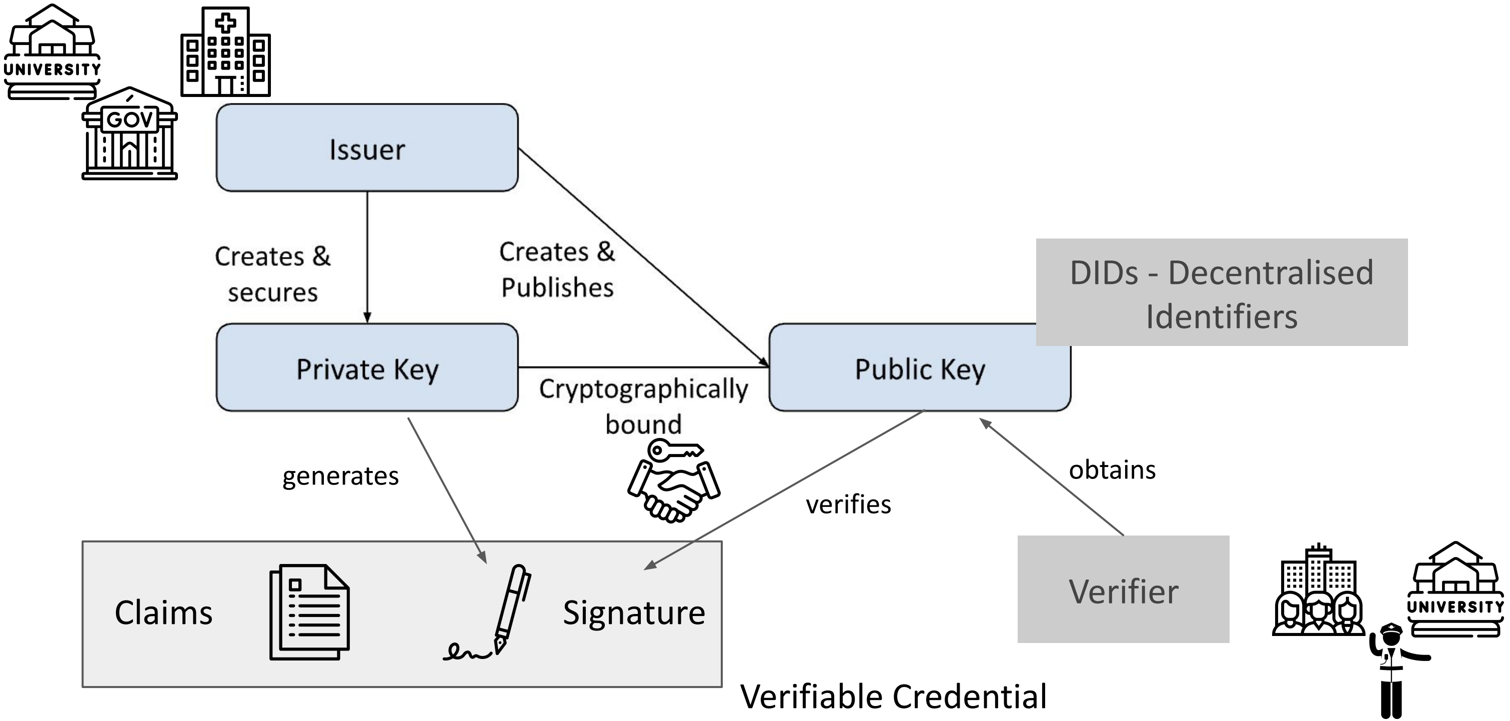
DIDs, VCs, and Asymmetric Encryption - a seamless certification system



DIDs, VCs, and Asymmetric Encryption - a seamless certification system



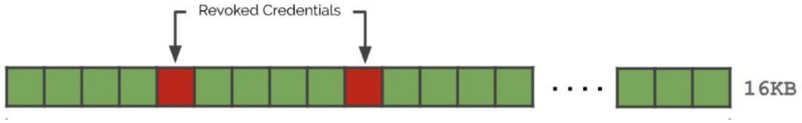
DIDs, VCs, and Asymmetric Encryption - a seamless certification system



Design, Implementation, and Assessment of an Improved Revocation Mechanism for Verifiable Credentials

Status List 2021

- DIDs + VCs = **Indefinite** ownership over claims
- An appendage to enable revocation / temporary suspension of VCs
- Bitstring with 1s indicating revoked VCs
- Design Goals
    - Privacy
    - Scalability
    - Minimum Propagation Delay



Status List with 2 revocations;
16 KB = 131,072 VCs

Gaps in Status Quo

- Status List 2021 falls short on the design goals
  - Privacy
  - Scalability v/s Minimum Propagation Delay

```
{
  "@context": [
    "https://www.w3.org/2018/credentials/v1",
    "https://w3id.org/vc/status-list/2021/v1"
  ],
  "id": "https://example.com/credentials/status/3",
  "type": ["VerifiableCredential", "StatusList2021Credential"],
  "issuer": "did:example:12345",
  "issued": "2021-04-05T14:27:40Z",
  "credentialSubject": {
    "id": "https://example.com/status/3#list",
    "type": "StatusList2021",
    "statusPurpose": "revocation",
    "encodedList":
"H4sIAAAAAAAAA-3BMQEAAADCoPVPbQwfoAAAAAAAAAAAAAAAAAAAAIC3AYbSVKsAQAAA"
  },
  "proof": { ... }
}
```

An instance of Status List 2021

```
{
  "@context": [
    "https://www.w3.org/2018/credentials/v1",
    "https://w3id.org/vc/status-list/2021/v1"
  ],
  "id": "https://example.com/credentials/23894672394",
  "type": ["VerifiableCredential"],
  "issuer": "did:example:12345",
  "issued": "2021-04-05T14:27:42Z",
  "credentialStatus": {
    "id": "https://example.com/credentials/status/3#94567"
    "type": "StatusList2021Entry",
    "statusPurpose": "revocation",
    "statusListIndex": "94567",
    "statusListCredential": "https://example.com/credentials/status/3"
  },
  "credentialSubject": {
    "id": "did:example:6789",
    "type": "Person"
  },
  "proof": { ... }
}
```

Verifier

1. reads the **whole** Status List

2. finds the value at

A Verifiable Credential with a credentialStatus field

- 250M drivers' license holders in the US
- 1 / 10.000 has their license suspended every year
- 25.000 drivers' license suspended every year
- 70 drivers' license suspended (and reinstated) every day
- 150 blockchain transactions per day!

Defining the Problem

Design, Implementation, and Assessment of an Improved Revocation Mechanism for Verifiable Credentials

Three Design Considerations for any Revocation Mechanism - Privacy, Scalability, Minimum Propagation Delay

Privacy: (a) Only the issuer, the holder, and the verifier should know that the VC has been revoked, (b) The issuer should not know who the verifier is

Scalability: Designed for planet-scale - universities issuing degrees over the course of a century, the American DMV

Minimal Propagation Delay: minimal delay to minimize the misuse of an effectively invalid VCs; use case dependent - the traffic police can download a fresh copy for every case, the passport control can use some caching.

Solving the Problem

Design, Implementation, and Assessment of an Improved Revocation Mechanism for Verifiable Credentials

Solving the Problem

Design, Implementation, and Assessment of an Improved Revocation Mechanism for Verifiable Credentials

→ Data Structure

Solving the Problem

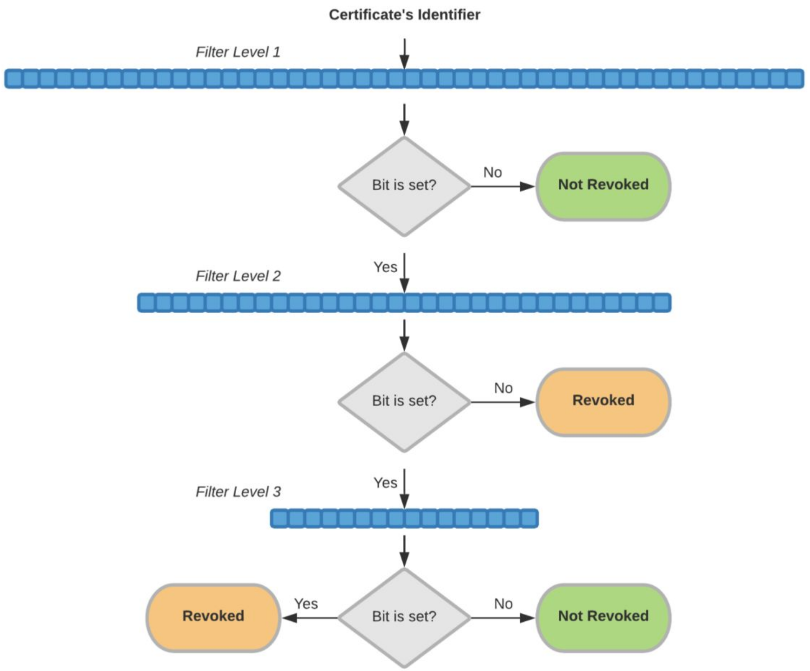
Design, Implementation, and Assessment of an Improved Revocation Mechanism for Verifiable Credentials

→ Data Structure

Essentially a collection!
Which data structure do you usually use for storing arbitrary elements?

Drawing Inspiration from TLS Certificates: CRLite and the concept of Cascading Filters

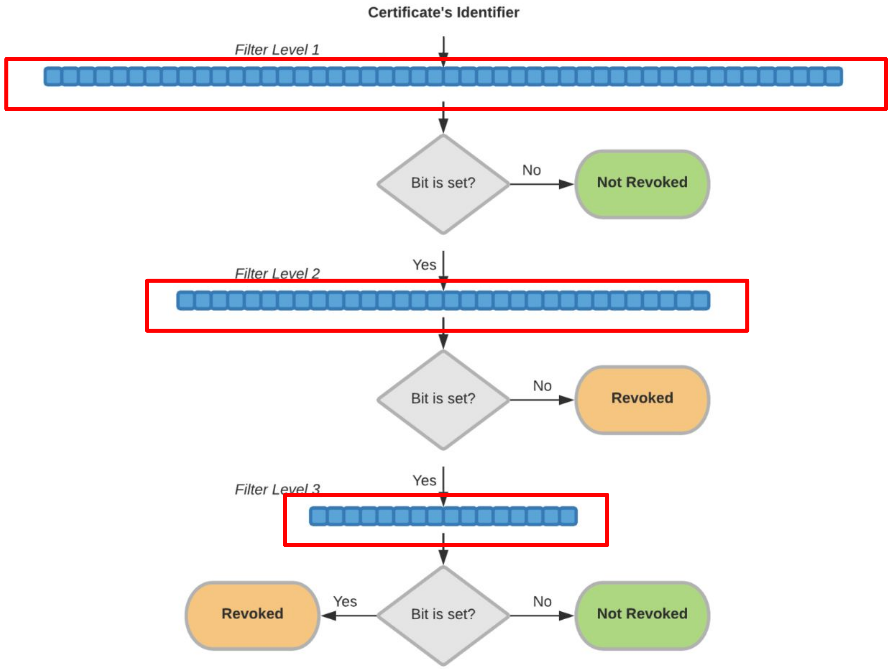
- Research from 2020 by **Mozilla's Security Group**
- Introduced as a mechanism for **revoking SSL/TLS certificates**
- The underlying data structure is a **Bloom Filter**
- A Bloom Filter is an **AMQ - Approximate Membership Query** data structure
  - (potentially) returns **False positives**
  - No means No | Yes means maybe Yes



Drawing Inspiration from TLS Certificates: CRLite and the concept of Cascading Filters

Insertion algorithm:

1. Add all **revoked VCs** to the **filter level 1**
2. Iterate over all **valid VCs** to find **level 1’s FP set**
3. Add all the **VCs in the FP set** to **filter level 2**
4. Iterate over all **revoked VCs** to find **level 2’s FP set**
5. Repeat until **FP set is empty** for a level (Termination criteria)



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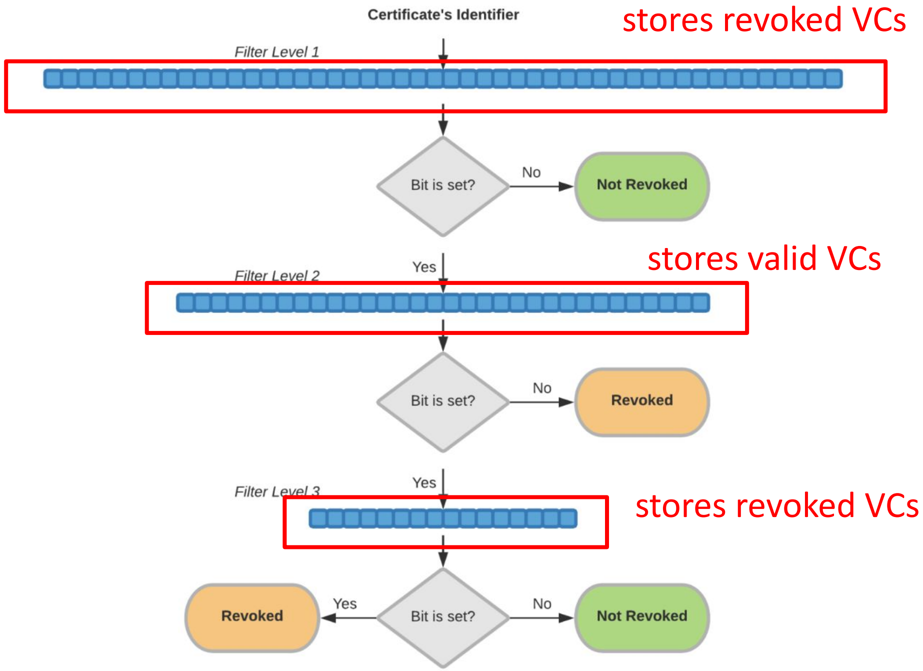
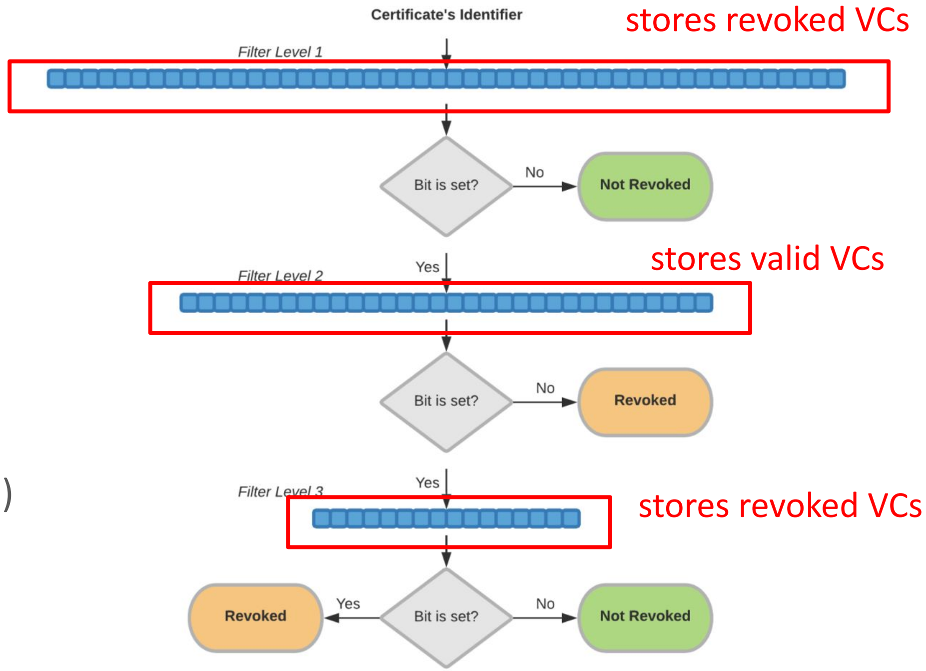


Drawing Inspiration from TLS Certificates: CRLite and the concept of Cascading Filters

isContained algorithm:

- The only **conclusive** answer is **"No"**
  (recall - No means No | Yes means maybe Yes)
- No at an **odd level** => **not revoked**
- No at an **even level** => **revoked**
- The **last level** has **no FPs** (recall: termination criteria)
  => No means No | Yes means ~~maybe~~ Yes



Drawing Inspiration from TLS Certificates: CRLite and the concept of Cascading Filters

The Novel Idea in CRLite

AMQFilter Interface

prone to false positives - **probabilistic** in answers to membership queries

```
void insert(E element)
boolean maybeContains(E element)
```

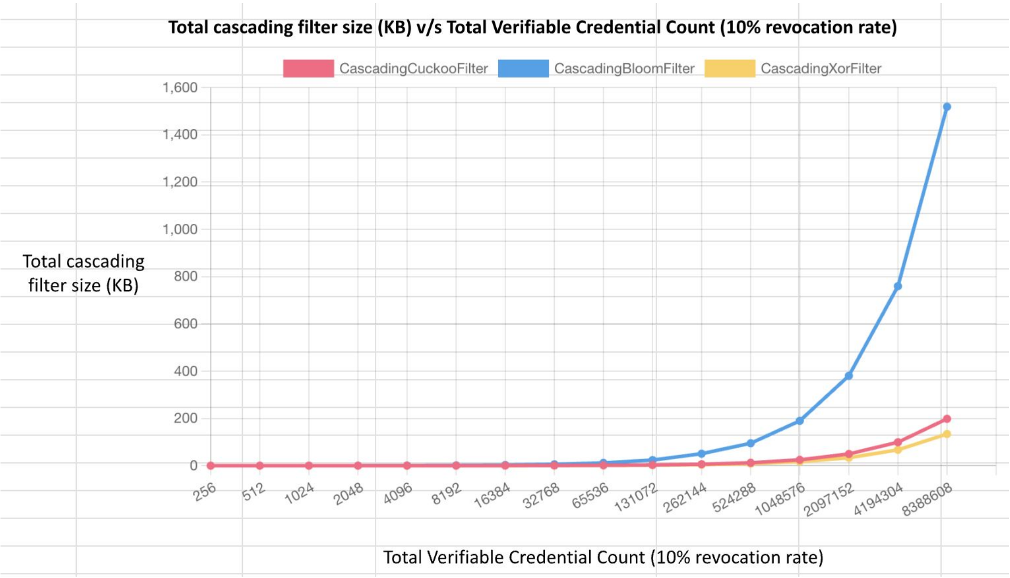
Cascading

Deterministic Set Membership Data Structure

no false positives/negatives - **deterministic** in answers to membership queries

Overview of the Filter Benchmarking Setup and results

- Data generation: A randomly generated set of integer values; size ∈ [2^8, 2^23]; revocation rate 10%
- A interface-based benchmarking code where the underlying AMQFilter can rapidly be changed
  - Bloom Filters
  - Cuckoo Filters
  - **XOR Filters**
- Results (raw data on next slide):
  - Computation time ranging from 60 ms for 100k VCs to 4000 ms for 8M VCs
  - Filter size (see adjacent graph)



Overview of the Filter Benchmarking Setup and results

Total VC Count	Filter Type	Revoked VC count	# layers	Layer-wise size (bits)	Total cascading filter size (bits)	Total cascading filter size (bytes)	Total cascading filter size (KB)	Layer-wise FP count	Computation time (ms)
	CascadingCuckooFilter		3	[12288|384|12|]	12684	1585.5	1.59	[227|6|0|]	39
	CascadingBloomFilter		3	[94232|536|104|]	94872	11859	11.86	[37|7|0|]	34
65536	CascadingXorFilter	6554	4	[8115|351|87|57|]	8610	1076.25	1.08	[242|27|2|0|]	42
	CascadingCuckooFilter		4	[24576|192|48|6|]	24822	3102.75	3.11	[106|25|1|0|]	64
	CascadingBloomFilter		3	[188464|1168|144|]	189776	23722	23.73	[81|10|0|]	63
131072	CascadingXorFilter	13108	4	[16176|621|117|57|]	16971	2121.375	2.13	[461|51|1|0|]	62
	CascadingCuckooFilter		3	[49152|384|96|]	49632	6204	6.21	[172|46|0|]	102
	CascadingBloomFilter		3	[376912|2048|26144|]	405104	50638	50.64	[142|1818|0|]	112
262144	CascadingXorFilter	26215	4	[32298|1206|183|63|]	33750	4218.75	4.22	[936|104|6|0|]	127
	CascadingCuckooFilter		4	[98304|768|96|6|]	99174	12396.75	12.4	[433|56|1|0|]	226
	CascadingBloomFilter		3	[753808|4504|848|]	759160	94895	94.9	[313|59|0|]	294
524288	CascadingXorFilter	52429	5	[64542|2271|318|60|57|]	67248	8406	8.41	[1802|215|4|2|0|]	262
	CascadingCuckooFilter		4	[196608|1536|384|6|]	198534	24816.75	24.82	[713|138|1|0|]	454
	CascadingBloomFilter		3	[1507616|8504|1584|]	1517704	189713	189.72	[591|110|0|]	658
1048576	CascadingXorFilter	104858	5	[129030|4719|576|75|57|]	134457	16807.125	16.81	[3793|424|16|2|0	439
	CascadingCuckooFilter		4	[393216|3072|768|6|]	397062	49632.75	49.64	[1530|476|3|0|]	1089
	CascadingBloomFilter		3	[3015224|24304|3240|]	3042768	380346	380.35	[1690|225|0|]	1048
2097152	CascadingXorFilter	209716	6	[258006|9030|1029|96|57|57|]	268275	33534.375	33.54	[7297|792|34|1|1	1128
	CascadingCuckooFilter		4	[786432|6144|768|12|]	793356	99169.5	99.17	[3039|459|4|0|]	1942
	CascadingBloomFilter		3	[6030432|38192|7104|]	6075728	759466	759.47	[2656|494|0|]	2159
4194304	CascadingXorFilter	419431	7	[515955|18228|2109|117|63|57|57|]	536586	67073.25	67.08	[14774|1671|50|	2328
	CascadingCuckooFilter		5	[1572864|12288|1536|24|6|]	1586718	198339.75	198.34	[6060|983|11|3|0	5390
	CascadingBloomFilter		5	[12060840|75272|12440|88|32|]	12148672	1518584	1518.59	[5235|865|6|2|0|]	4482
8388608	CascadingXorFilter	838861	5	[1031853|36480|4026|201|78|]	1072638	134079.75	134.08	[29615|3230|119	4319

Future Roadmap

Research Question	Timeline
Identifying requirements and design goals for revocation/suspension mechanisms for VCs Identifying key metric dimensions to be considered for these requirements/design goals Identifying use cases and categorising them on these key metric dimensions	W1 - W3
Researching the state of the art for **data structures** that support exclusion operations Identifying parallels between **revocation schemes used by TLS** and the VC ecosystem Identifying the differences in requirements between TLS and the VC ecosystem	W4 - W8
Delineating possible options for an alternative Revocation/Suspension mechanism Categorizing them based on the use cases defined above **Benchmarking/evaluating candidate data structures**	W9 - W14
Building/Designing the E2E revocation infrastructure Experiments with off-chain data storage systems e.g. IPFS Benchmarking with other systems e.g. Status List 2021	W15 - W20
Collating the research into document form, preparing for the thesis defence	W21 - W23

Zooming out to the Research Roadmap

- Identifying use cases and benchmarking them on the basis of their needs to optimise scale v/s minimum propagation delay
- Building/Designing the E2E revocation infrastructure
  - Proposed changes to the VC standard
  - Publishing the revocation list for different use cases to a DLT system
  - Experiments with off-chain data storage systems e.g. IPFS

Q & A

Prof. Dr.

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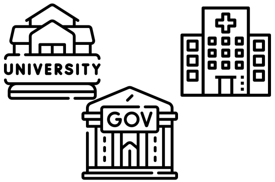
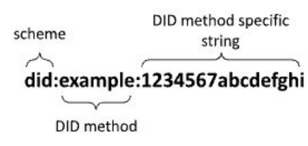
Backup slides after this point

Decentralized Identifiers (DIDs) - route to the Issuer’s Metadata

Issuer




```json
{
  "@context": [
    "https://www.w3.org/2018/credentials/v1",
    "https://w3id.org/vc/status-list/2021/v1"
  ],
  "id": "https://example.com/credentials/23894672394",
  "type": ["VerifiableCredential"],
  "issuer": "did:example:12345",
  "issued": "2021-04-05T14:27:42Z",
  "credentialStatus": {
    "id": "https://example.com/credentials/status/3#94567",
    "type": "StatusList2021Entry",
    "statusPurpose": "revocation",
    "statusListIndex": "94567",
    "statusListCredential": "https://example.com/credentials/status/3"
  },
  "credentialSubject": {
    "id": "did:example:6789",
    "type": "Person"
  },
  "proof": { ... }
}
```



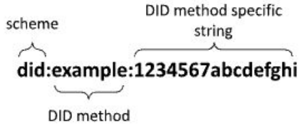
did:**btcr**:xz35-jzv2-qqs2-9wjt

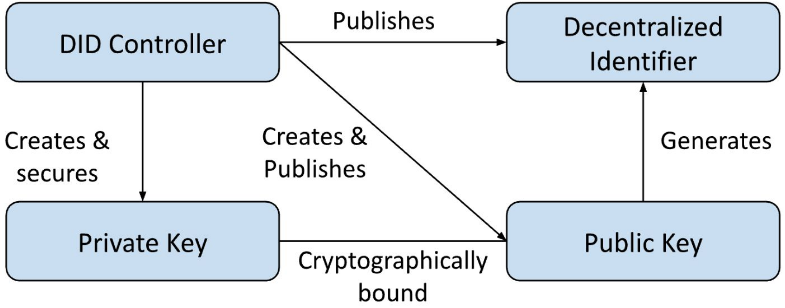
did:**ethr**:0xE6Fe788d8ca214A080b0f6ac7F48480b2AEfa9a6

DIDs, VCs, and Asymmetric Encryption - a seamless certification system

DID are:

- Resolvable to DID document -> used to obtain metadata about the issuing party.
- Cryptographically verifiable - asymmetric cryptography is used to ensure this
- Decentralized - a central authority is not required to allocate DIDs
    - No single point of failure
    - No unilateral revocation by an authoritarian central server





AMQFilter Interface

1. void insert(E element)
2. boolean maybeContains(E element)
3. [optional] void delete(E element)

Algorithm 1: `Insert(x)`

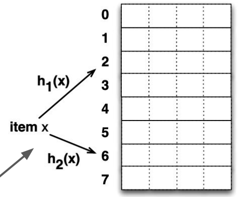
```
f = fingerprint(x);
i1 = hash(x);
i2 = i1 ⊕ hash(f);
if bucket[i1] or bucket[i2] has an empty entry then
    add f to that bucket;
    return Done;
// must relocate existing items;
i = randomly pick i1 or i2;
for n = 0; n < MaxNumKicks; n++ do
    randomly select an entry e from bucket[i];
    swap f and the fingerprint stored in entry e;
    i = i ⊕ hash(f);
    if bucket[i] has an empty entry then
        add f to bucket[i];
        return Done;
// Hashtable is considered full;
return Failure;
```

Any Hash function

“partial-key cuckoo hashing to derive an item’s alternate location based on its fingerprint”

i1 = hash(x)
i2 = i1 ^ hash(f)
i1 = i2 ^ hash(f)
= i1 ^ hash(f) ^ hash(f)
= i1 ^ 0
= i1

8 buckets with 4 entries per bucket



(c) A cuckoo filter, two hash per item and functions and four entries per bucket

AMQFilter Interface

1. void insert(E element)
2. boolean maybeContains(E element)
3. [optional] void delete(E element)

Algorithm 2: `Lookup(x)`

f = fingerprint(x);
i_1 = hash(x);
$i_2 = i_1 \oplus$ hash(f);
if bucket[i_1] or bucket[i_2] has f **then**
    return `True`;
return `False`;

Trivial

Algorithm 3: `Delete(x)`

f = fingerprint(x);
i_1 = hash(x);
$i_2 = i_1 \oplus$ hash(f);
if bucket[i_1] or bucket[i_2] has f **then**
    remove a copy of f from this bucket;
    return `True`;
return `False`;

Trivial

Algorithm 1: `Insert(x)`

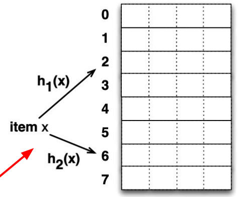
f = fingerprint(x);
i_1 = hash(x);
$i_2 = i_1 \oplus$ hash(f);
if bucket[i_1] or bucket[i_2] has an empty entry **then**
    add f to that bucket;
    return `Done`;
// must relocate existing items;
i = randomly pick i_1 or i_2;
for $n = 0$; $n <$ MaxNumKicks; n++ **do**
    randomly select an entry e from bucket[i];
    swap f and the fingerprint stored in entry e;
    $i = i \oplus$ hash(f);
    if bucket[i] has an empty entry **then**
        add f to bucket[i];
        return `Done`;
// Hashtable is considered full;
return `Failure`;

Any Hash function

"partial-key cuckoo hashing to derive an item's alternate location based on its fingerprint"

i1 = hash(x)
i2 = i1 ^ hash(f)
i1 = i2 ^ hash(f)
= i1 ^ hash(f) ^ hash(f)
= i1 ^ 0
= i1

8 buckets with 4 entries per bucket

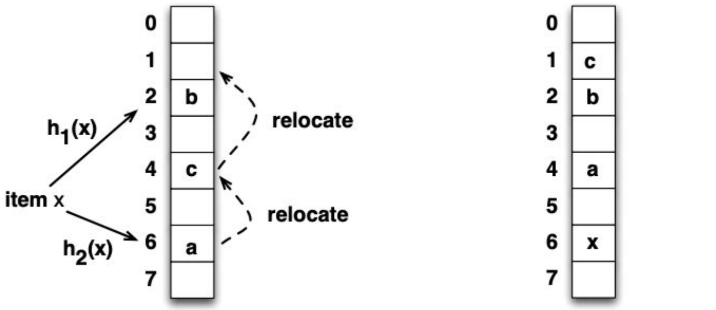


(c) A cuckoo filter, two hash per item and functions and four entries per bucket

Cuckoo Filters

Quick Overview

- AMQ data structures like Bloom filters don’t need to store ‘anything’ related to the original element - only bits
- DSM data structures like Sets, Maps need to store the original element because there is a possibility of rehashing -> when we have more elements than we allocated space for, hash collisions, etc.
- Cuckoo Filters take ideas from both
    - eviction and relocation of elements needs to store ‘something’
    - Fingerprints - unique proxy for the element, upper bound on the size of what is being stored
    - [+ve side effect] privacy - we don’t want raw VCs to be stored in the AMQ data structure



(a) before inserting item x (b) after item x inserted

Research Questions

1. What requirements exist for revocation/suspension mechanisms for VCs?
   a. What general requirements can we identify?
   b. What are key metric dimensions we need to consider?
   c. Can we look at some example use cases and place them on the key metric dimensions to validate?
2. What is the state of the art for data structures that support exclusion operations?
   a. What work exists towards VC revocation/suspension specifically?
   b. What can we learn from other (experimental) revocation schemes for TLS certificates?
      Some examples include Bloom Filters, Mozilla CRLite.
   c. Compared to TLS, what significant differences in requirements/environment can we identify for a VC ecosystem?
3. Choosing or designing the Revocation/Suspension data structure
   a. Delineating possible options
   b. Categorizing options based on use case requirements (see 1c)
   c. Benchmarking/evaluating candidate data structures
4. Building/Designing the E2E revocation infrastructure i.e., in tandem with a DLT
   a. How can we minimize cost?
   b. Do we need to keep data off-chain and if so, what data and where?
   c. What key metrics of the system can we measure and benchmark with other systems?

Core Concepts: Verifiable Credentials (VCs)

- Foolproof way for real-world entities to stake claims - claim + signature
- Issuing Party
- Holder
- Verifying Party

VERIFIABLE CREDENTIALS DATA MODEL V1.1 PUBLICATION HISTORY

See also the history of the other specifications of the series: vc-data-model-2.0

2022-03-03	Verifiable Credentials Data Model v1.1 Recommendation
2021-11-09	Verifiable Credentials Data Model v1.1 Recommendation
2019-11-19	Verifiable Credentials Data Model 1.0 Recommendation
2019-09-05	Proposed Recommendation
2019-07-25	Candidate Recommendation Snapshot
2019-03-28	Candidate Recommendation Snapshot
2019-02-08	Working Draft
2017-08-03	First Public Working Draft

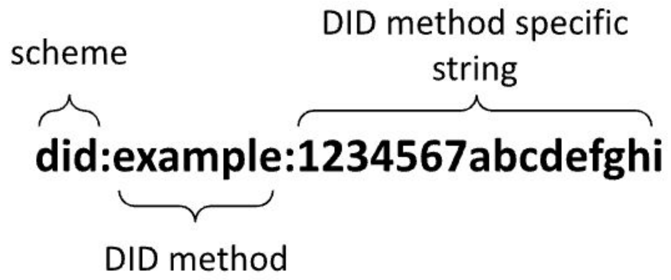
W3C Standard that has seen mature development since 2019; vc-data-model-2.0 is in the works

Core Concepts: Decentralised Identifiers (DIDs)

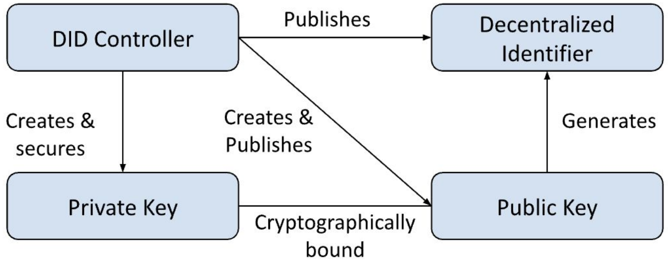
- Uniform Resource Locator (URI) leading to the DID document
- Multiple specifications

```
did:btcr:xz35-jzv2-qqs2-9wjt
did:ethr:0xE6Fe788d8ca214A080b0f6ac7F48480b2AEfa9a6
```

- Design Properties
  - Resolvable
  - Cryptographically Verifiable
  - Decentralised (self-certifying identifiers)
  - Permanent (even with Key Rotation)



Syntax of Decentralized Identifiers (DIDs)



The DID Trust Triangle