# Formalising Linked-Data based Verifiable Credentials for Selective Disclosure

Dan Yamamoto (Internet Initiative Japan Inc.)

Yuji Suga (Internet Initiative Japan Inc.)

Kazue Sako (Waseda University)

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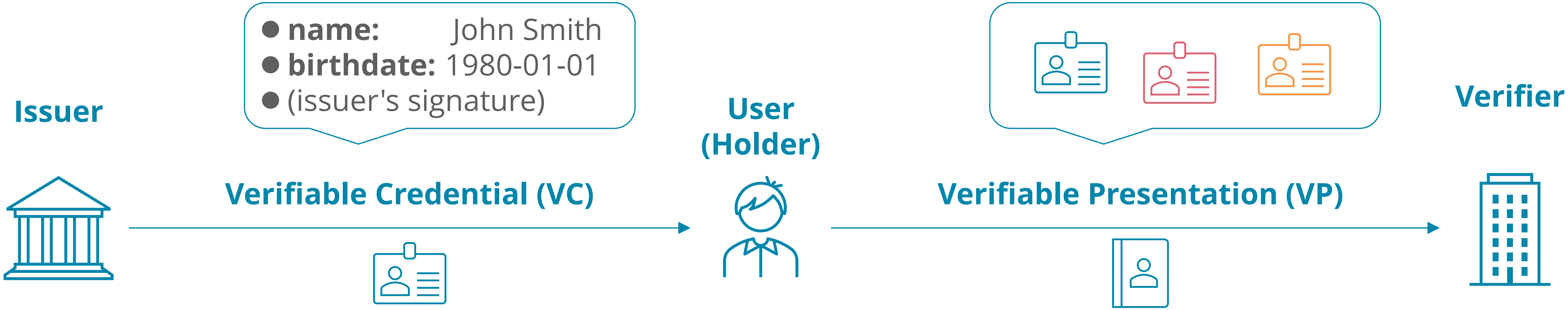
# Verifiable Credentials

- **W3C Recommendation**: Verifiable Credentials Data Model (v1.1, March 2022)
- provides a mechanism to express digital credentials in a way that is **cryptographically secure**, **privacy respecting**, and **machine-verifiable**



- **name:** John Smith
- **birthdate:** 1980-01-01
- (issuer's signature)

Issuer

Verifiable Credential (VC)

User (Holder)

Verifiable Presentation (VP)

Verifier

- Examples: **SMART Health Cards** / IATA Travel Pass / Azure Active Directory Verifiable Credentials (in public preview)

# SMART Health Cards

- Paper or digital versions of clinical information
- developed and standardized by VCI (Vaccination Credential Initiative)
- used in 15 nations: US, UK, Canada, Japan, ...

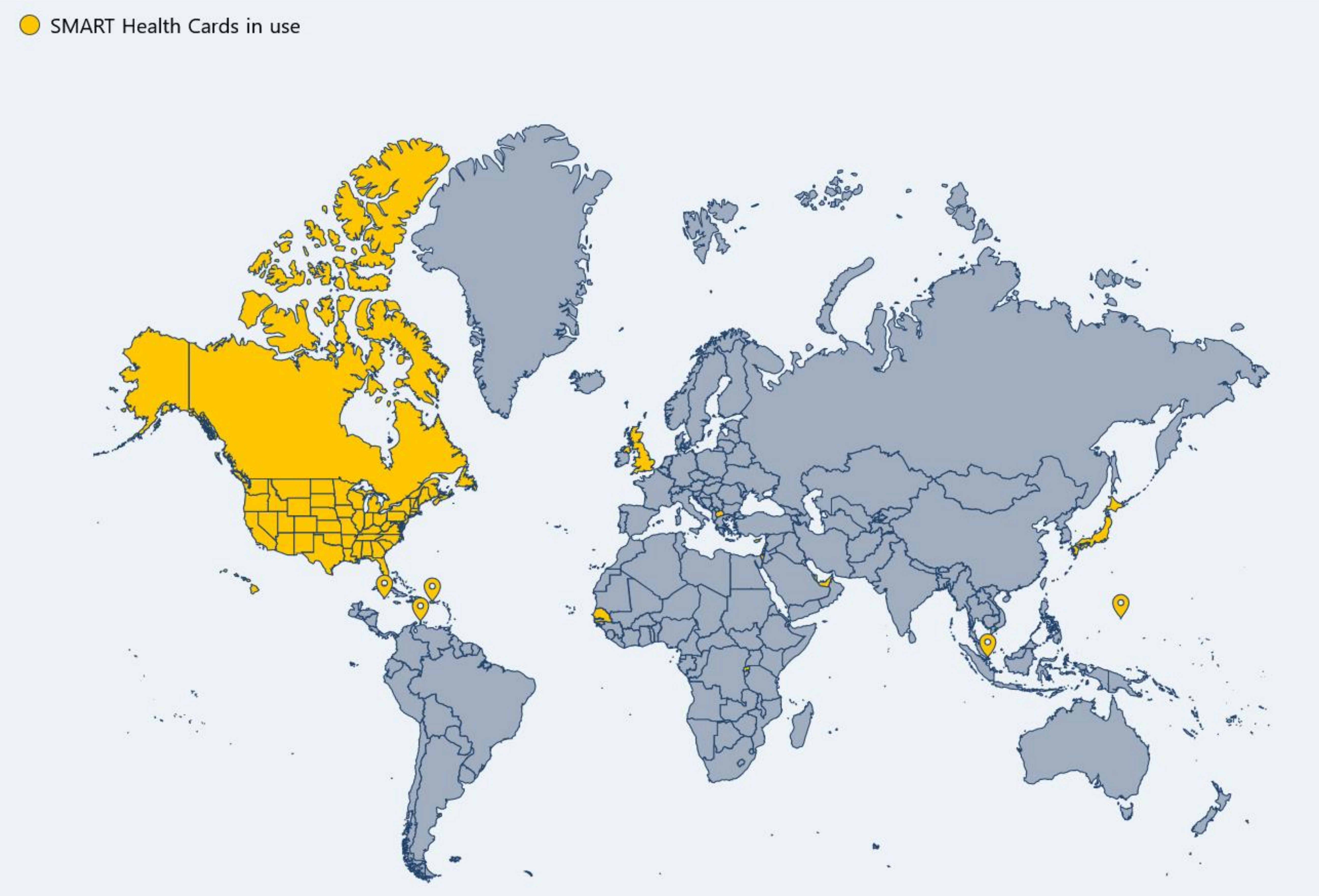
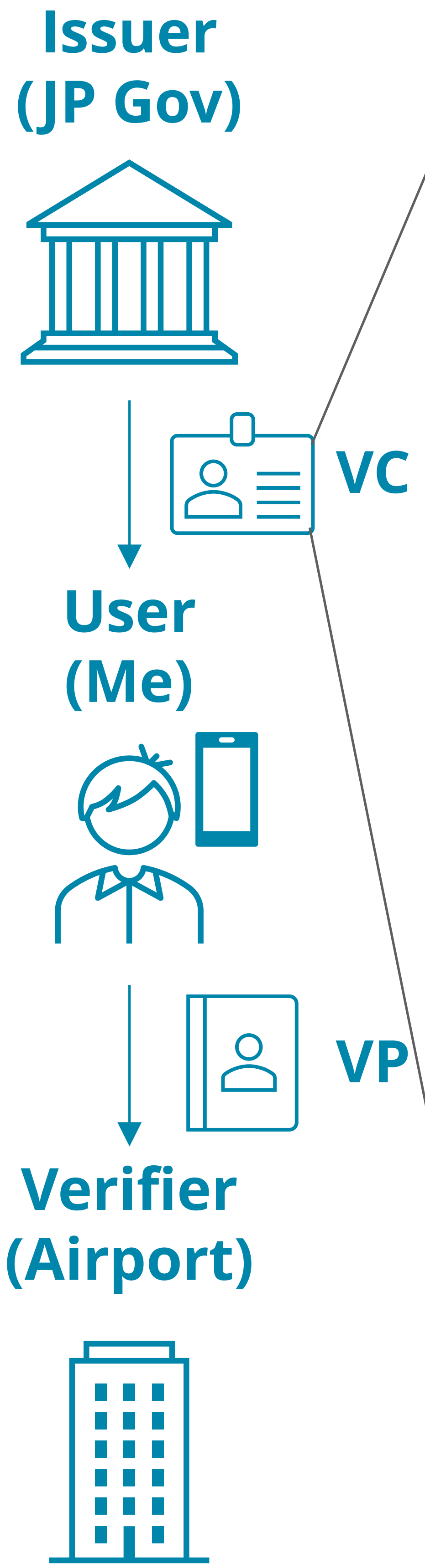
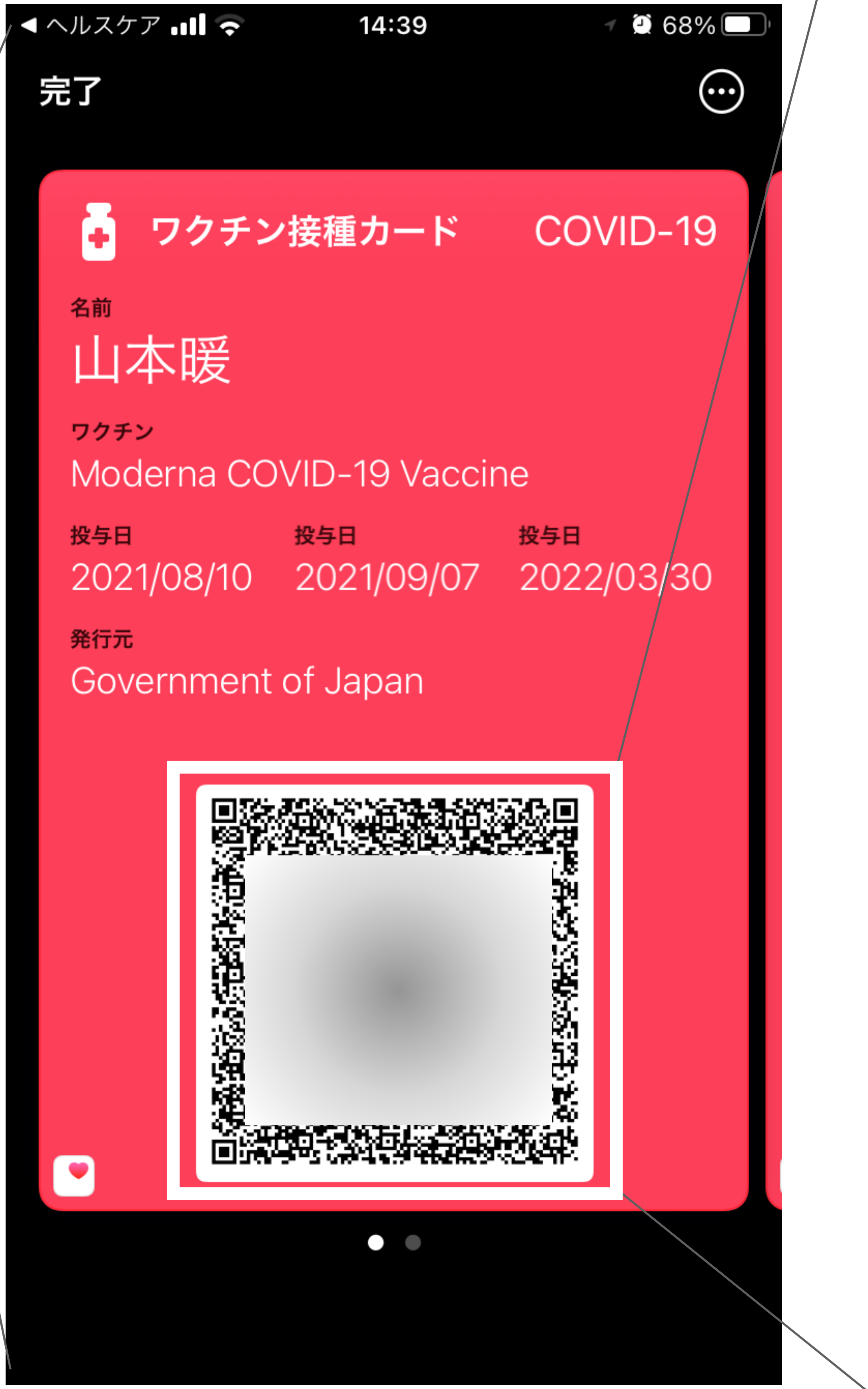


image: https://vci.org

# SMART Health Cards




◀ ヘルスケア 14:39 68%

完了

ワクチン接種カード COVID-19

名前
山本暖

ワクチン
Moderna COVID-19 Vaccine

| 投与日 | 投与日 | 投与日 |
|---|---|---|
| 2021/08/10 | 2021/09/07 | 2022/03/30 |

発行元
Government of Japan

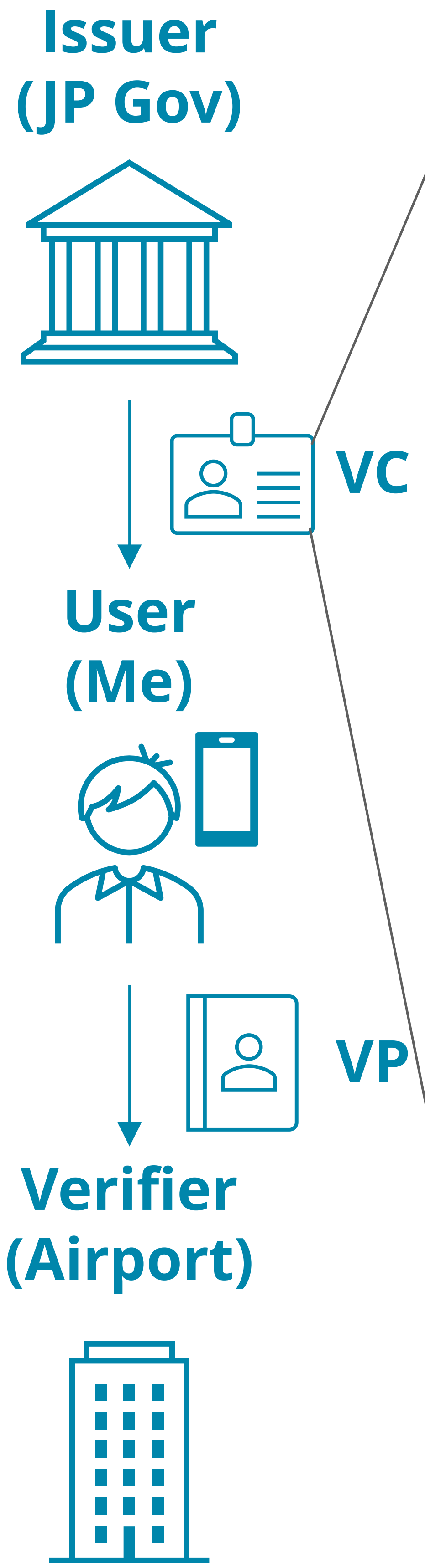
JWT

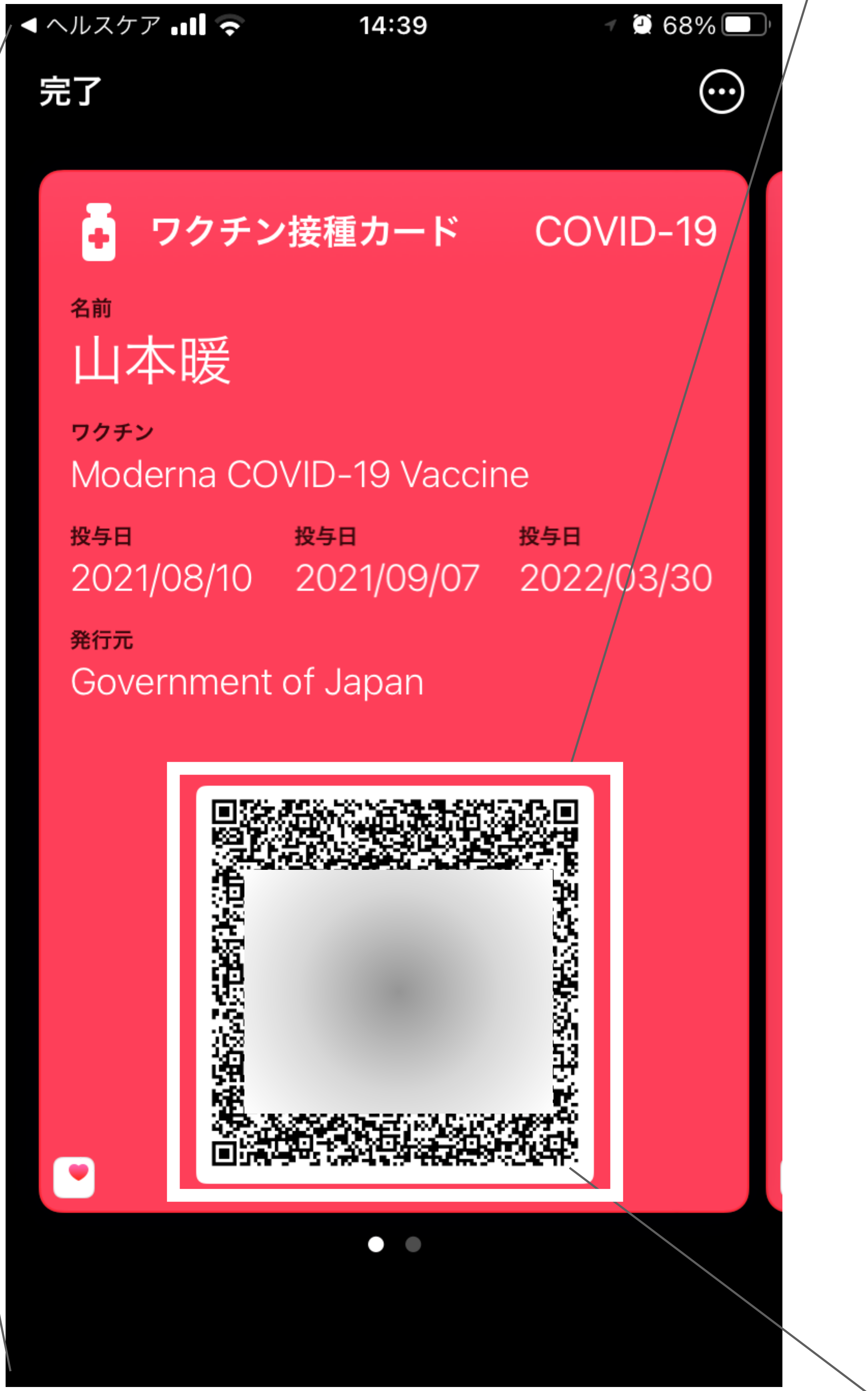
Header

```
{ "iss": "https://vc.vrs.digital.go.jp/issuer",
  "nbf": 1648956149.461584,   // ~= 2022-04-03
  "vc": {
    "type": ["https://smarthealth.cards#health-card",...],
    "credentialSubject": {
      "fhirVersion": "4.0.1",
      "fhirBundle": { ...,
        "entry": [
          { "fullUrl": "resource:0",
            "resource": {
              "resourceType": "Patient",
              "name": [ ... , {
                  "use": "official",
                  "given": [ "DAN" ], "family": "YAMAMOTO",
                }],
              "birthDate": "xxxx-xx-xx"
            } },
          { "fullUrl": "resource:1",
            "resource": {
              "resourceType": "Immunization",
              "status": "completed",
              "occurrenceDateTime": "2021-08-10",
              "vaccineCode": { "coding": [ {
                    "system": "http://hl7.org/fhir/sid/cvx",
                    "code": "207"
                  } ] },
              "patient": { "reference": "resource:0" },
              "lotNumber": "9999999" ...
```

Signature

# SMART Health Cards





ワクチン接種カード COVID-19

名前
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ワクチン
Moderna COVID-19 Vaccine

| 投与日 | 投与日 | 投与日 |
|---|---|---|
| 2021/08/10 | 2021/09/07 | 2022/03/30 |

発行元
Government of Japan

**JWT**

Header

```
{ "iss": "https://vc.vrs.digital.go.jp/issuer",
  "nbf": 1648956149.461584,  // ~= 2022-04-03
  "vc": {
```

- ✓ issued by: **Japanese Government**
- ✓ issued on: **April 3, 2022**
- ✓ patient name: **Dan Yamamoto**
- ✓ got vaccinated on: **August 10, 2021**
- ✓ vaccine code: **207**
- ✓ lot number: **9999999**

```
                "use": "official",
                "given": [ "DAN" ], "family": "YAMAMOTO",
               }],
             "birthDate": "1980-05-03"
           } },
         { "fullUrl": "resource:1",
           "resource": {
             "resourceType": "Immunization",
             "status": "completed",
             "occurrenceDateTime": "2021-08-10",
             "vaccineCode": { "coding": [ {
                   "system": "http://hl7.org/fhir/sid/cvx",
                   "code": "207"
                 } ] },
             "patient": { "reference": "resource:0" },
             "lotNumber": "9999999" ...
```

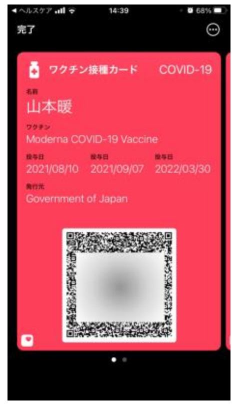
Signature

# VC flavors

## JWT-based VC

**(e.g., SMART Health Cards)**

JWT



◀ ヘルスケア 14:39 68%

完了

ワクチン接種カード COVID-19

名前
山本暖

ワクチン
Moderna COVID-19 Vaccine

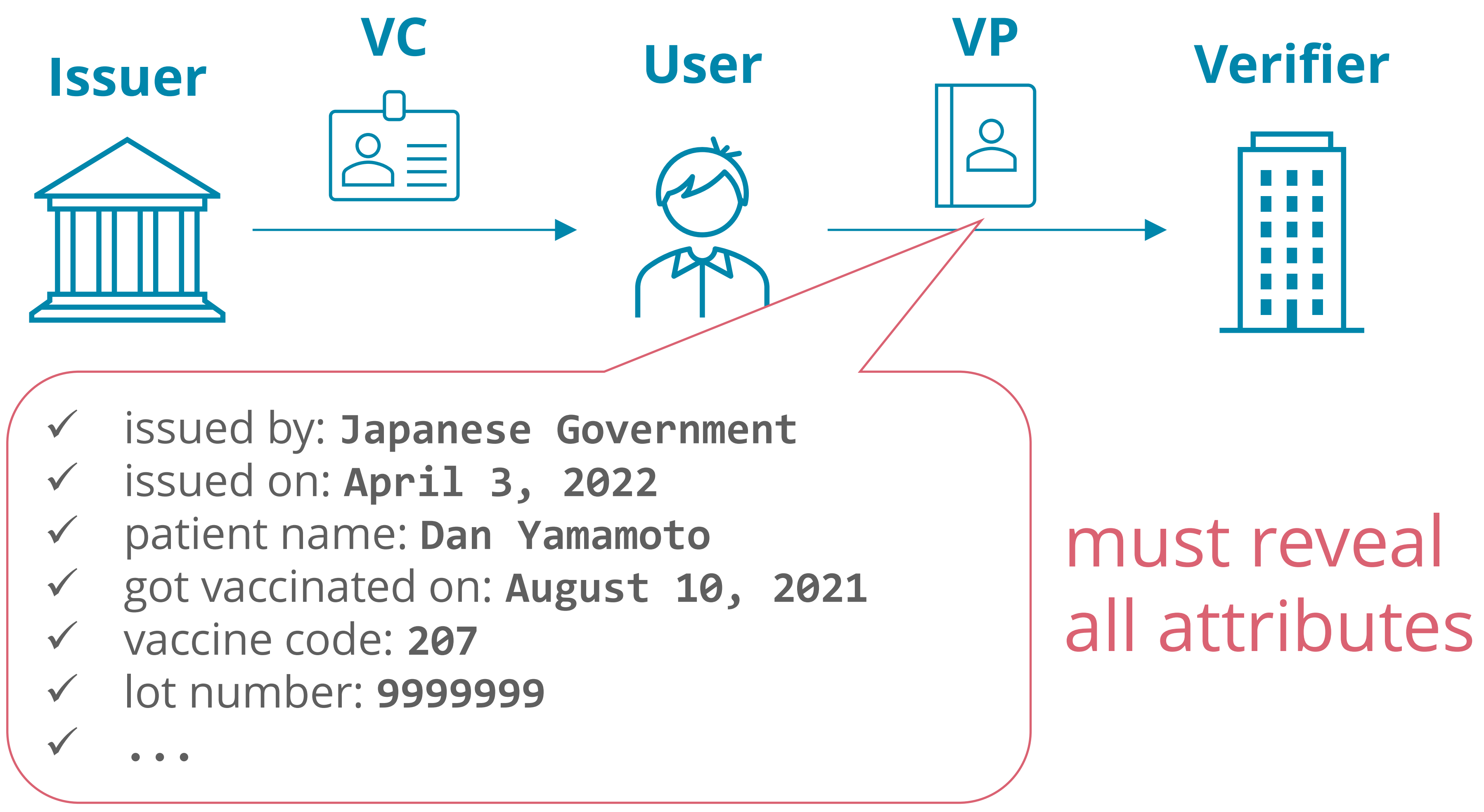
| 接与日 | 接与日 | 接与日 |
|---|---|---|
| 2021/08/10 | 2021/09/07 | 2022/03/30 |

発行元
Government of Japan

doc format = **JSON**
proof format = **JWT**
sig scheme = **RSA, ECDSA, EdDSA, …**

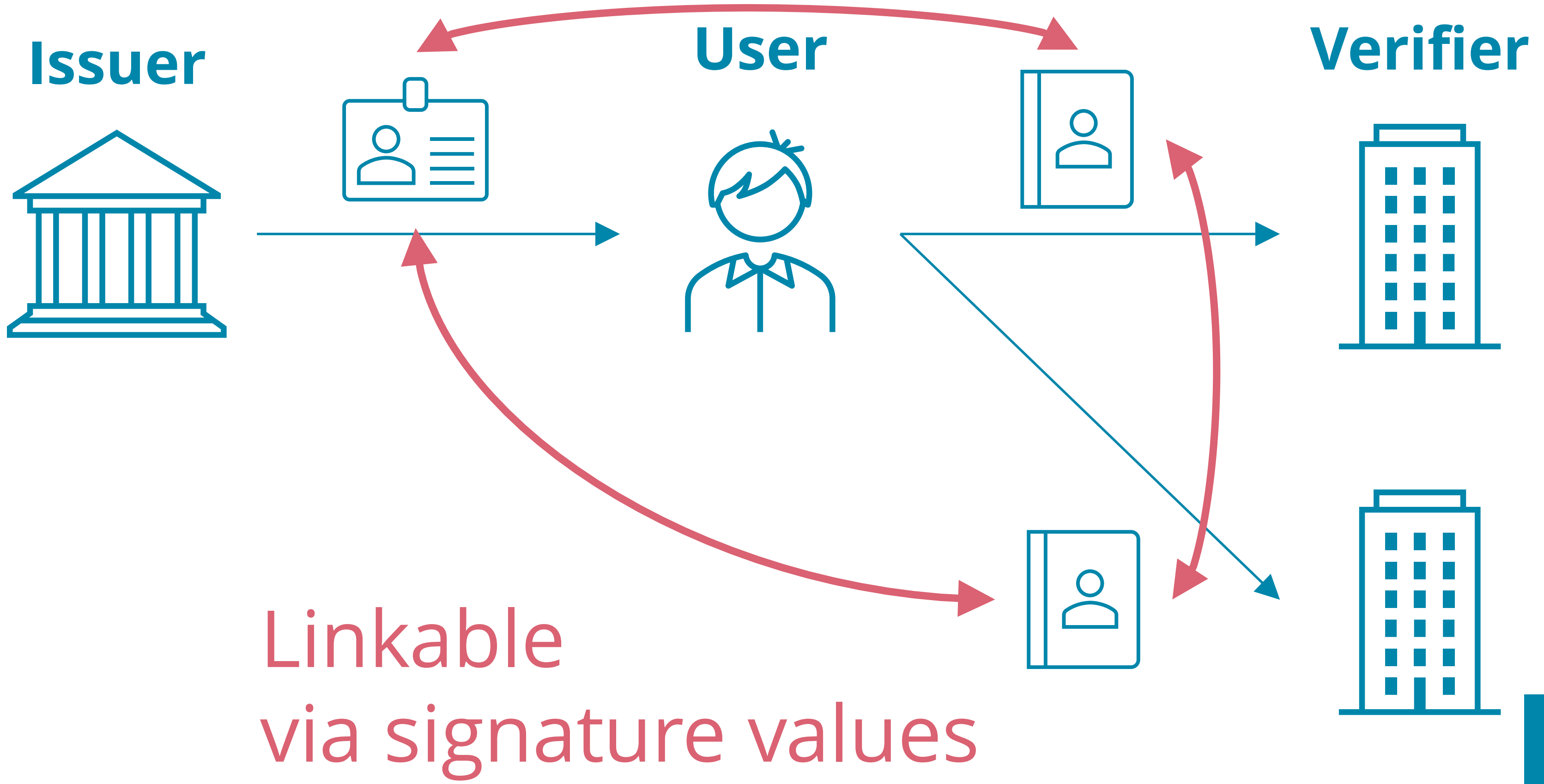
- ✓ Simple, easy to develop
- ✓ Many real world instances
- ✗ No selective disclosure
- ✗ Presentations are linkable

**Not privacy-preserving**



- ✓ issued by: `Japanese Government`
- ✓ issued on: `April 3, 2022`
- ✓ patient name: `Dan Yamamoto`
- ✓ got vaccinated on: `August 10, 2021`
- ✓ vaccine code: `207`
- ✓ lot number: `9999999`
- ✓ `...`

must reveal all attributes

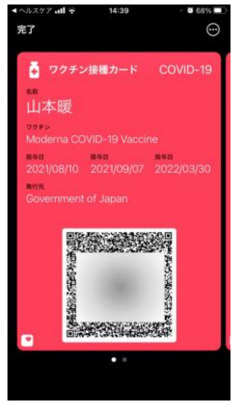


Linkable
via signature values

# VC flavors

## JWT-based VC

**(e.g., SMART Health Cards)**



ワクチン接種カード COVID-19

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|---|---|---|
| 2021/08/10 | 2021/09/07 | 2022/03/30 |

発行元
Government of Japan

| | |
|---|---|
| doc format | = **JSON** |
| proof format | = **JWT** |
| sig scheme | = **RSA, ECDSA, EdDSA, …** |

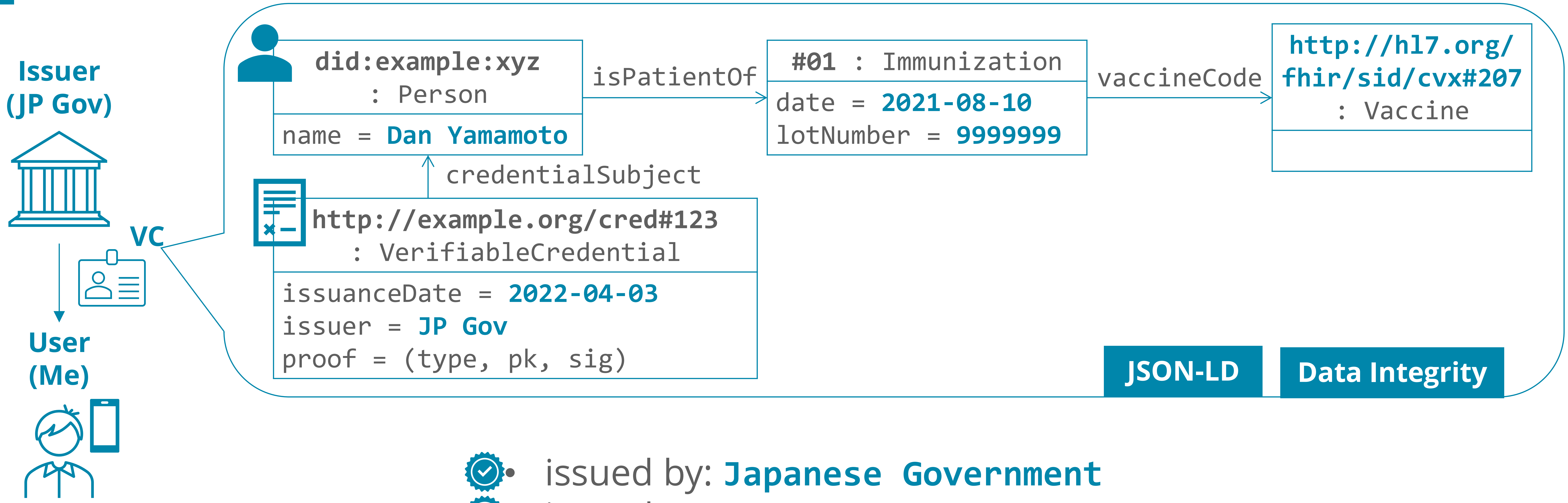
- ✓ Simple, easy to develop
- ✓ Many real world instances
- ✗ No selective disclosure
- ✗ Presentations are linkable

## Linked-Data based VC (LDP-BBS+)

| | |
|---|---|
| doc format | = **JSON-LD** |
| proof format | = **Data Integrity** (LD Proof) |
| sig scheme | = **BBS+** |

- ✗ Relatively complicated
- ✗ Still work in progress
- ✓ Selective disclosure
- ✓ Unlinkable Presentations

# LD-based Health Cards



did:example:xyz
: Person

name = **Dan Yamamoto**

isPatientOf

**#01** : Immunization

date = **2021-08-10**
lotNumber = **9999999**

vaccineCode

**http://hl7.org/fhir/sid/cvx#207**
: Vaccine

credentialSubject

**http://example.org/cred#123**
: VerifiableCredential

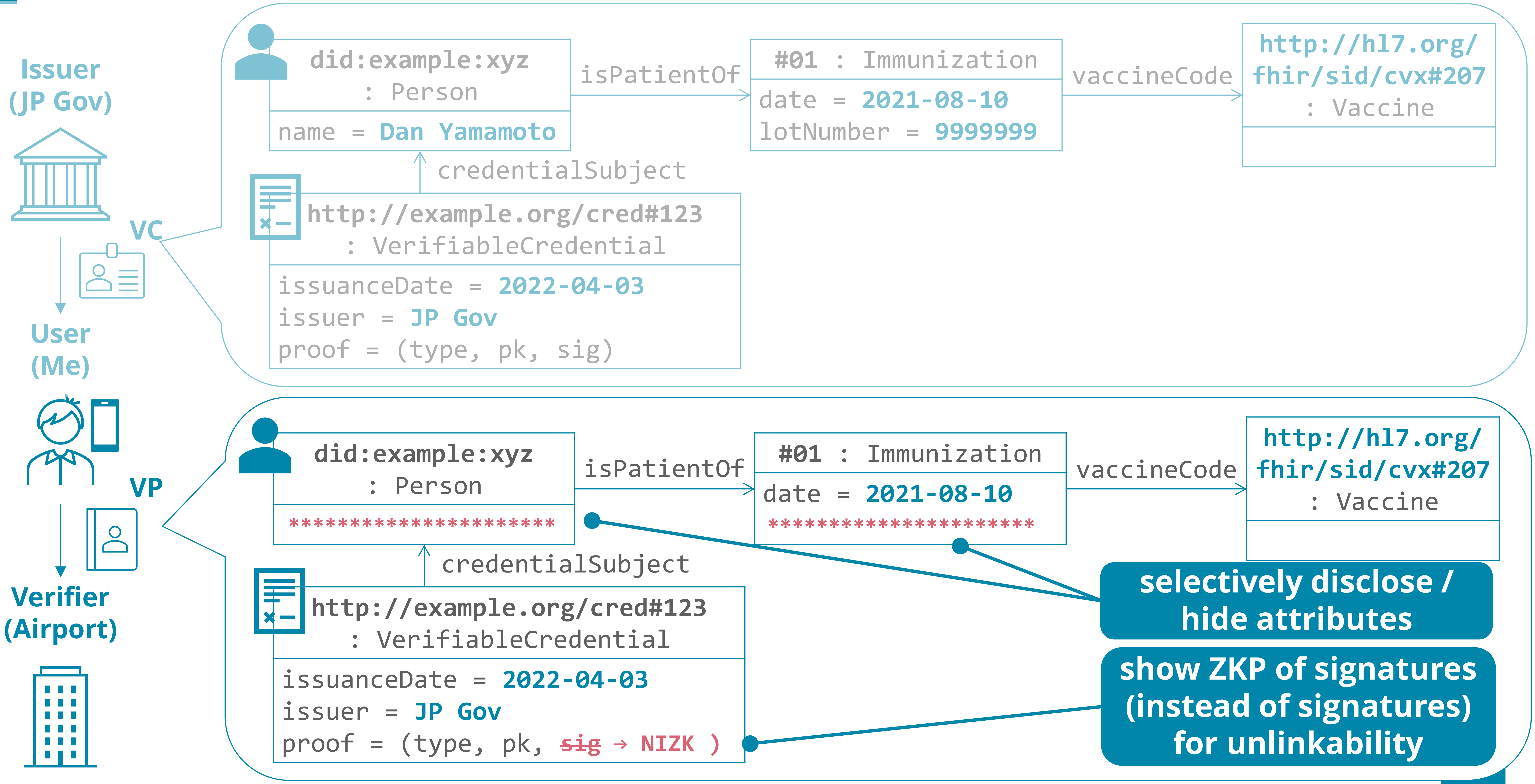
issuanceDate = **2022-04-03**
issuer = **JP Gov**
proof = (type, pk, sig)

**JSON-LD**

**Data Integrity**

- ✓ issued by: **Japanese Government**
- ✓ issued on: **April 3, 2022**
- ✓ patient name: **Dan Yamamoto**
- ✓ got vaccinated on: **August 10, 2021**
- ✓ vaccine code: **207**
- ✓ lot number: **9999999**

# Selective Disclosure & Unlinkable Presentations



Issuer
(JP Gov)

VC

User
(Me)

VP

Verifier
(Airport)

did:example:xyz
: Person

name = Dan Yamamoto

isPatientOf

#01 : Immunization

date = 2021-08-10
lotNumber = 9999999

vaccineCode

http://hl7.org/
fhir/sid/cvx#207
: Vaccine

credentialSubject

http://example.org/cred#123
: VerifiableCredential

issuanceDate = 2022-04-03
issuer = JP Gov
proof = (type, pk, sig)

did:example:xyz
: Person

**********************

isPatientOf

#01 : Immunization

date = 2021-08-10
**********************

vaccineCode

http://hl7.org/
fhir/sid/cvx#207
: Vaccine

credentialSubject

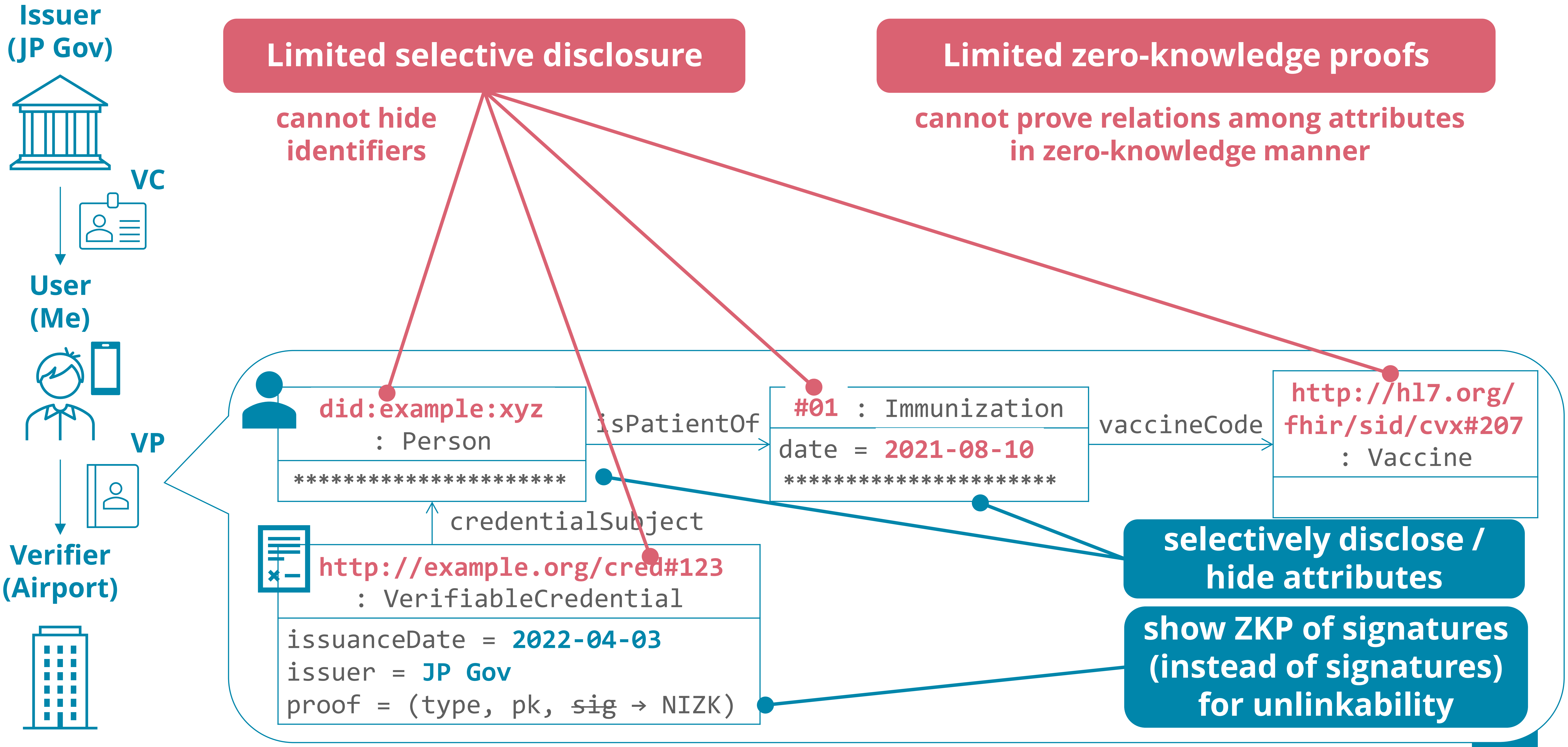
http://example.org/cred#123
: VerifiableCredential

issuanceDate = 2022-04-03
issuer = JP Gov
proof = (type, pk, ~~sig~~ → NIZK )

selectively disclose /
hide attributes

show ZKP of signatures
(instead of signatures)
for unlinkability

# Limitations of Existing Construction (LDP-BBS+)



Issuer (JP Gov)

VC

User (Me)

VP

Verifier (Airport)

**Limited selective disclosure**

cannot hide identifiers

**Limited zero-knowledge proofs**

cannot prove relations among attributes in zero-knowledge manner

did:example:xyz : Person

*********************

isPatientOf

#01 : Immunization

date = 2021-08-10

*********************

vaccineCode

http://hl7.org/fhir/sid/cvx#207 : Vaccine

credentialSubject

http://example.org/cred#123 : VerifiableCredential

issuanceDate = 2022-04-03

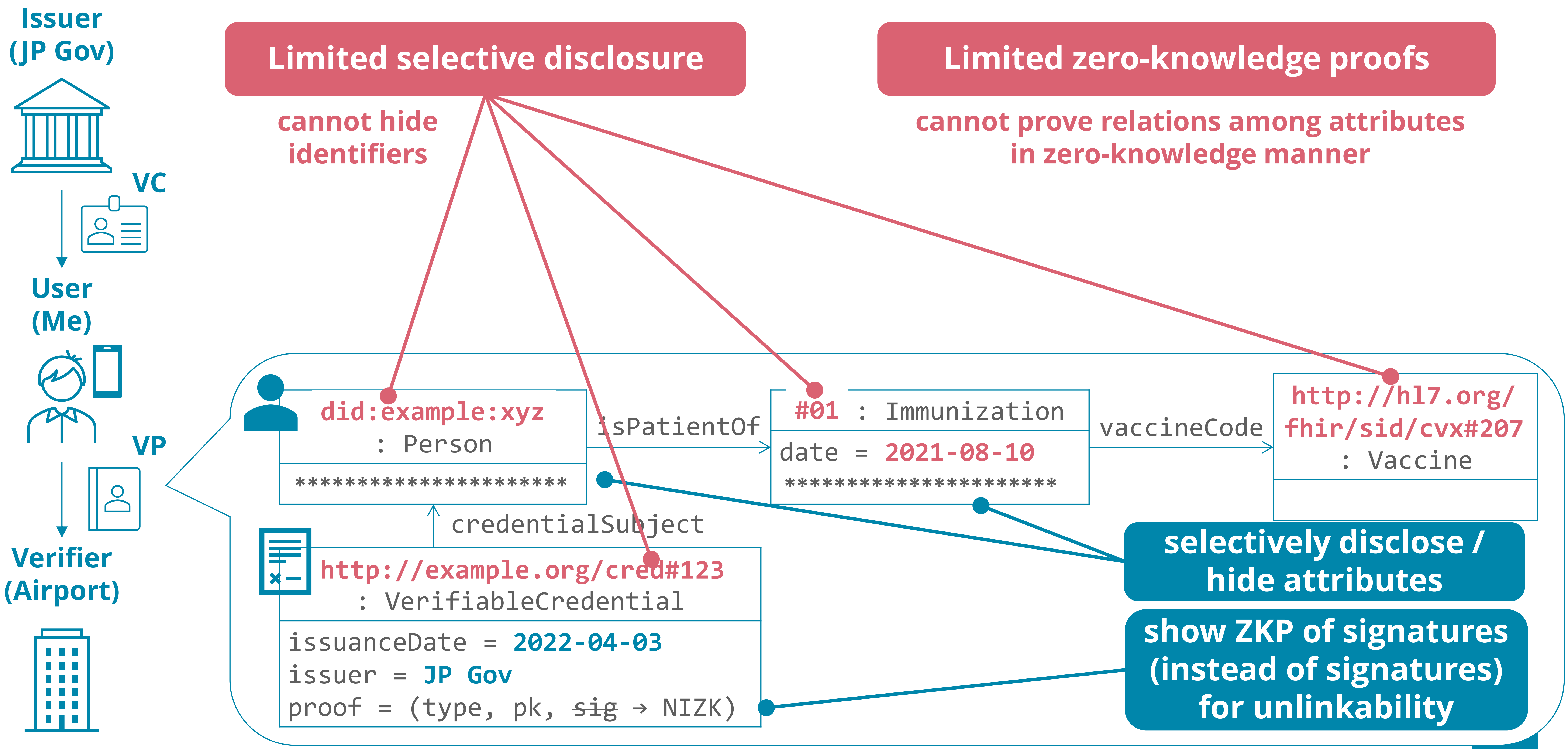
issuer = JP Gov

proof = (type, pk, ~~sig~~ → NIZK)

**selectively disclose / hide attributes**

**show ZKP of signatures (instead of signatures) for unlinkability**

# Our Contribution



Issuer (JP Gov)

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User (Me)

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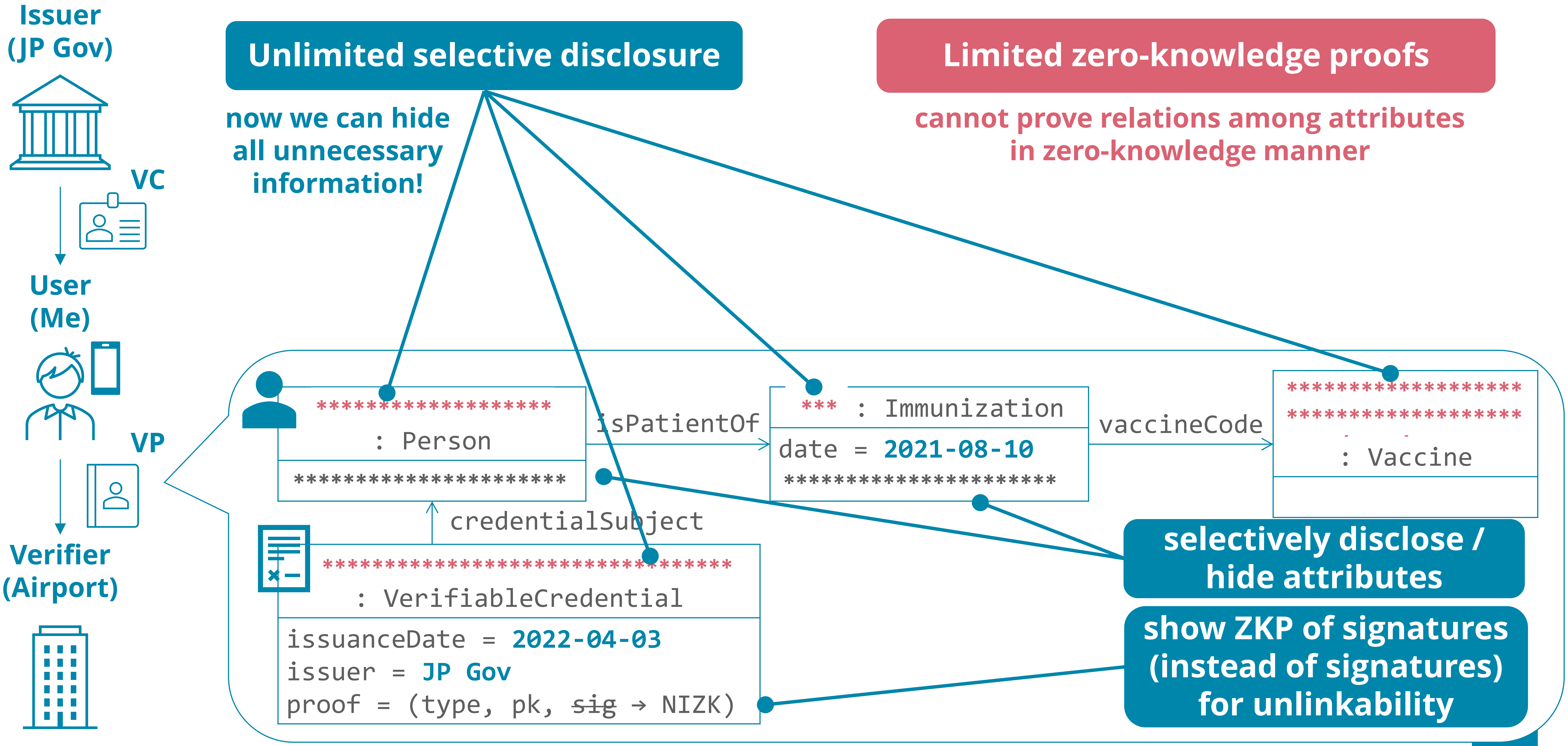


Issuer (JP Gov)

VC

User (Me)

VP

Verifier (Airport)

**Unlimited selective disclosure**

now we can hide all unnecessary information!

**Limited zero-knowledge proofs**

cannot prove relations among attributes in zero-knowledge manner

```
******************
      : Person
*********************
```

isPatientOf

```
***  : Immunization
date = 2021-08-10
*********************
```

vaccineCode

```
******************
******************
   : Vaccine
```

credentialSubject

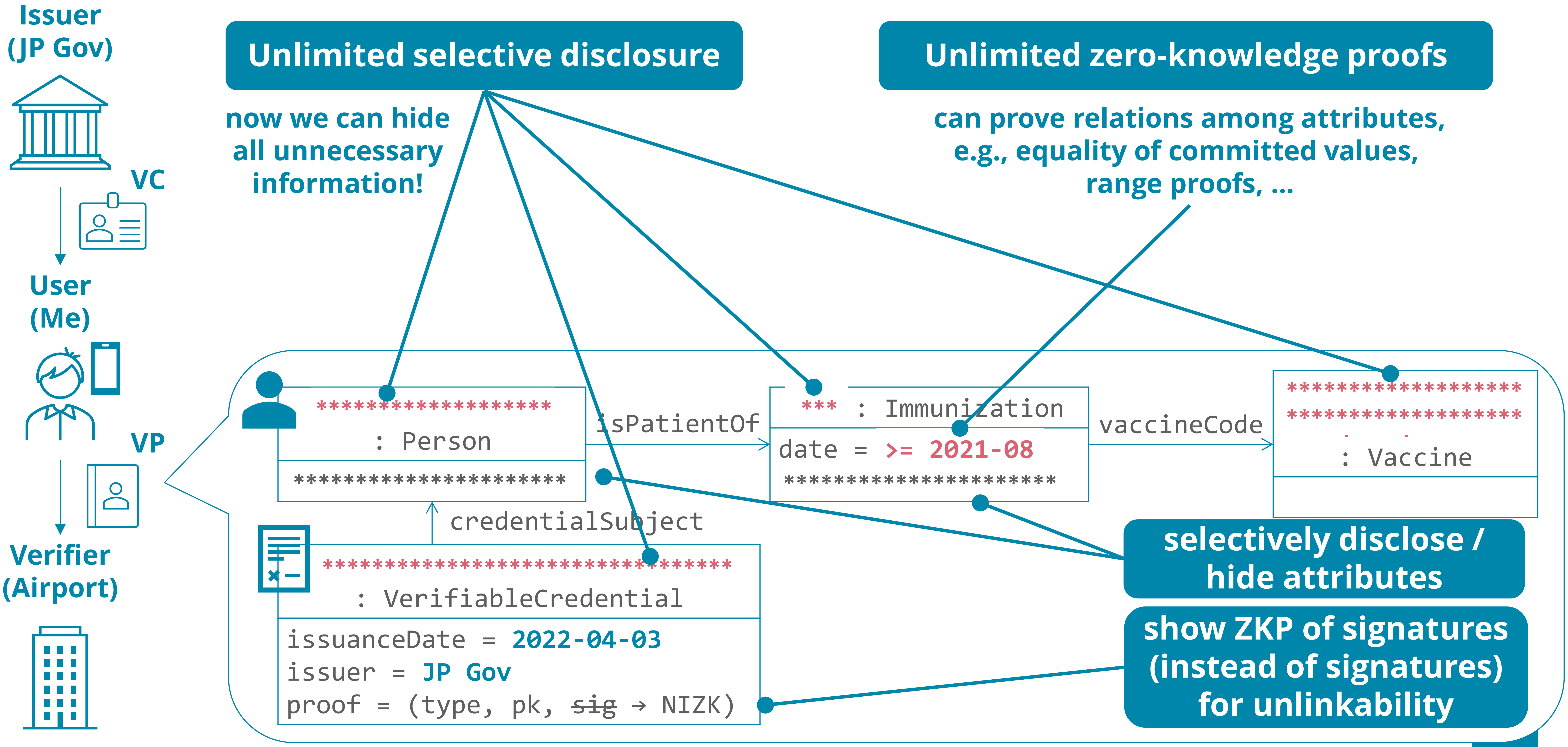
```
********************************
   : VerifiableCredential
issuanceDate = 2022-04-03
issuer = JP Gov
```

proof = (type, pk, ~~sig~~ → NIZK)

**selectively disclose / hide attributes**

**show ZKP of signatures (instead of signatures) for unlinkability**

# Our Contribution



Issuer
(JP Gov)

VC

User
(Me)

VP

Verifier
(Airport)

**Unlimited selective disclosure**

now we can hide
all unnecessary
information!

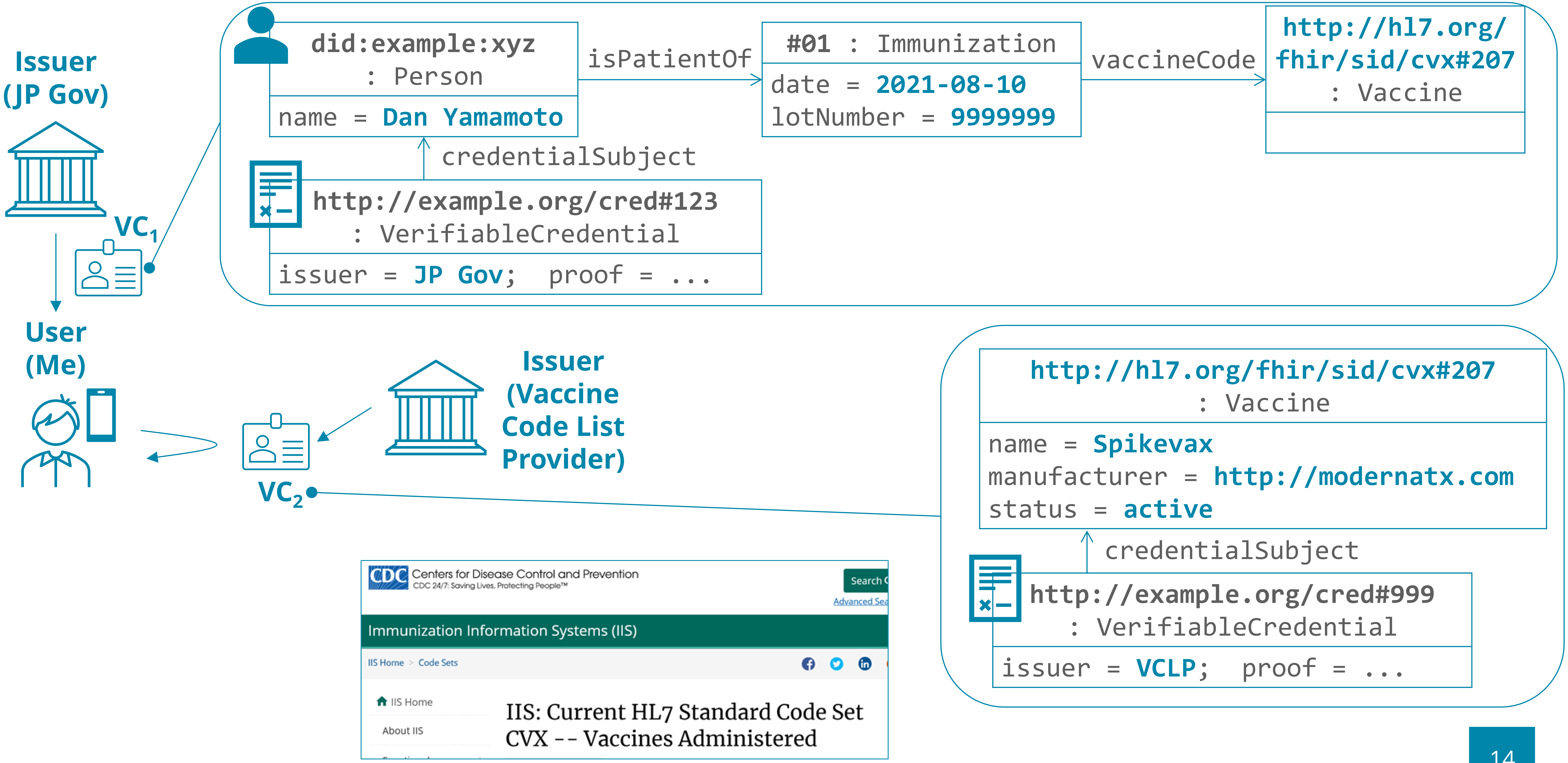
**Unlimited zero-knowledge proofs**

can prove relations among attributes,
e.g., equality of committed values,
range proofs, ...

**selectively disclose / hide attributes**

**show ZKP of signatures (instead of signatures) for unlinkability**

# Possible Future Use Cases



Issuer (JP Gov)

VC$_1$

User (Me)

did:example:xyz : Person

name = **Dan Yamamoto**

isPatientOf

#01 : Immunization

date = **2021-08-10**
lotNumber = **9999999**

vaccineCode

**http://hl7.org/fhir/sid/cvx#207** : Vaccine

credentialSubject

**http://example.org/cred#123** : VerifiableCredential

issuer = **JP Gov**; proof = ...

Issuer (Vaccine Code List Provider)

VC$_2$

**http://hl7.org/fhir/sid/cvx#207** : Vaccine

name = **Spikevax**
manufacturer = **http://modernatx.com**
status = **active**

credentialSubject

**http://example.org/cred#999** : VerifiableCredential

issuer = **VCLP**; proof = ...

CDC Centers for Disease Control and Prevention
CDC 24/7: Saving Lives, Protecting People™

Search

Advanced Sea

Immunization Information Systems (IIS)

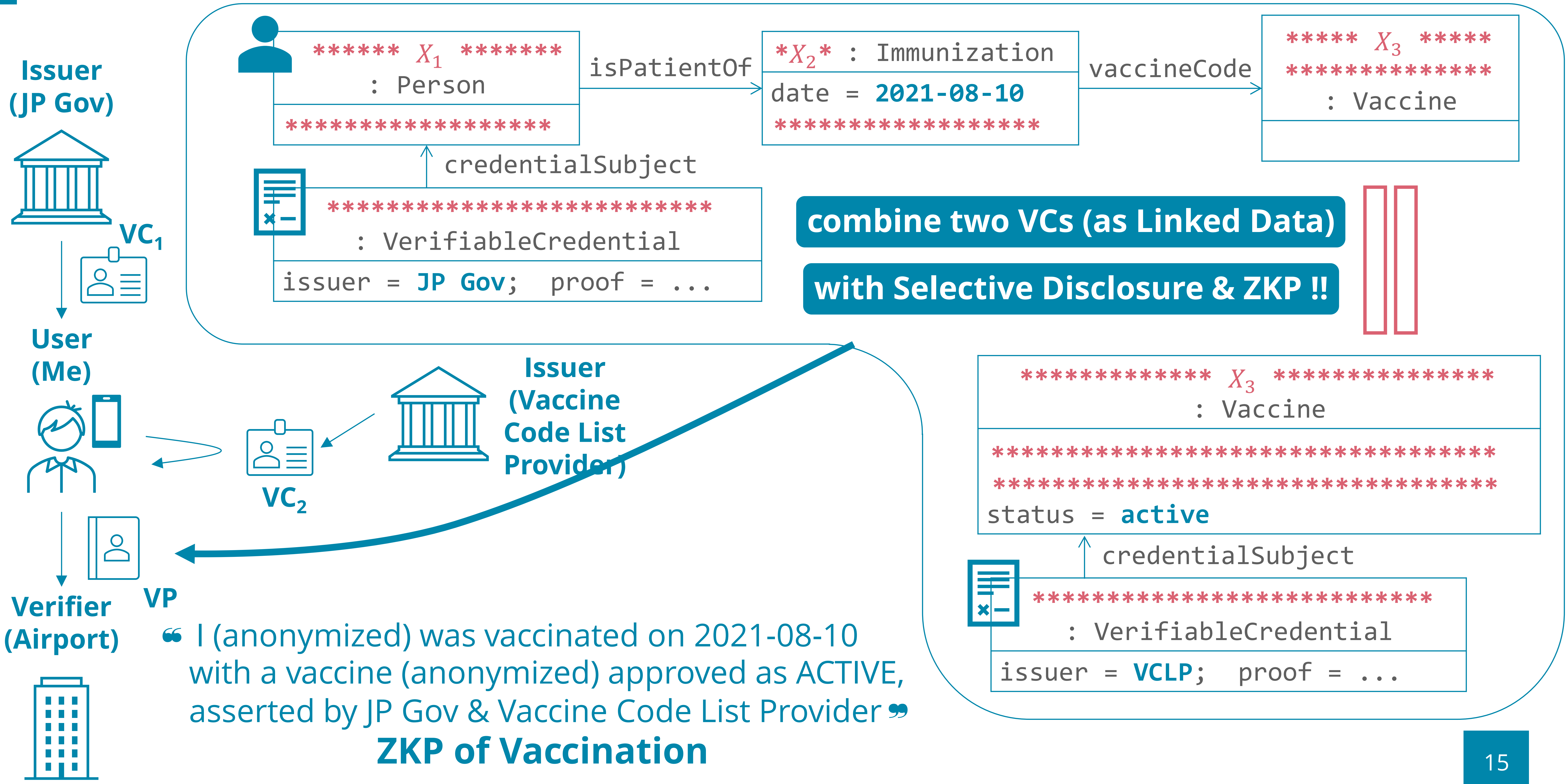
IIS Home > Code Sets

IIS Home

About IIS

IIS: Current HL7 Standard Code Set CVX -- Vaccines Administered

# Possible Future Use Cases



Issuer (JP Gov)

VC$_1$

User (Me)

VC$_2$

Issuer (Vaccine Code List Provider)

Verifier (Airport)

VP

```
****** X1 *******
: Person
******************
```

isPatientOf

```
*X2* : Immunization
date = 2021-08-10
******************
```

vaccineCode

```
***** X3 *****
**************
: Vaccine
```

credentialSubject

```
**************************
: VerifiableCredential
issuer = JP Gov;  proof = ...
```

**combine two VCs (as Linked Data)**

**with Selective Disclosure & ZKP !!**

```
************* X3 ***************
: Vaccine
**********************************
**********************************
status = active
```

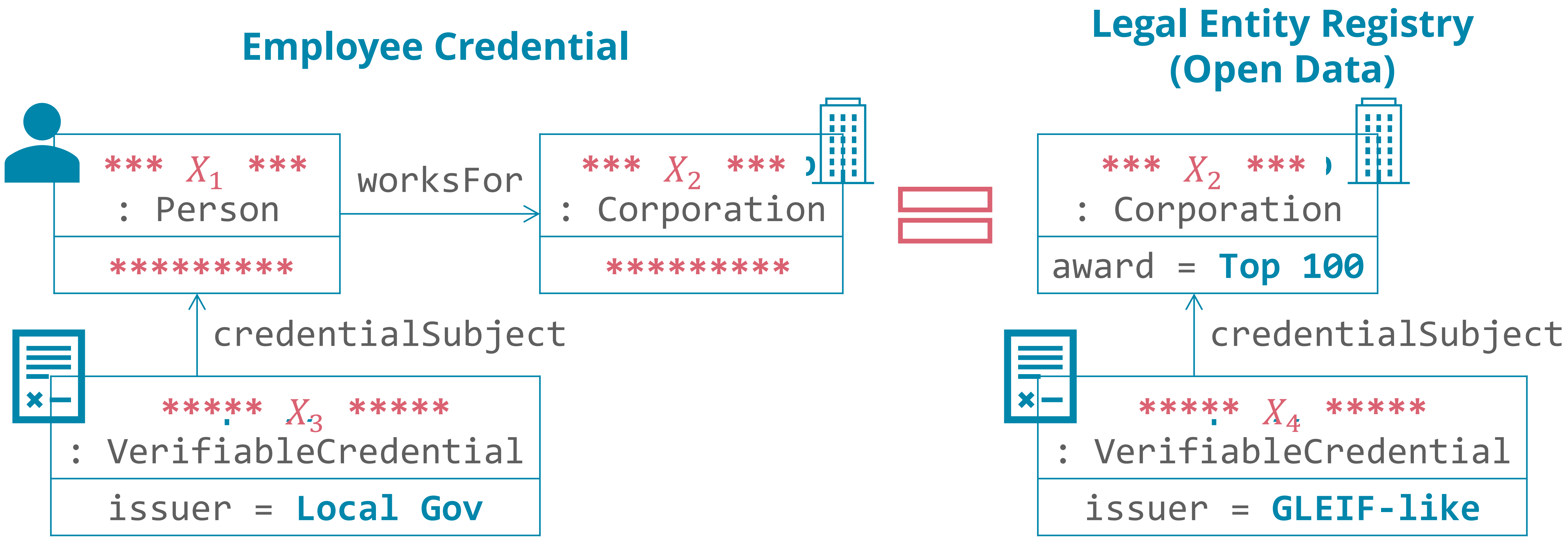
credentialSubject

```
***************************
: VerifiableCredential
issuer = VCLP;  proof = ...
```

“ I (anonymized) was vaccinated on 2021-08-10 with a vaccine (anonymized) approved as ACTIVE, asserted by JP Gov & Vaccine Code List Provider ”

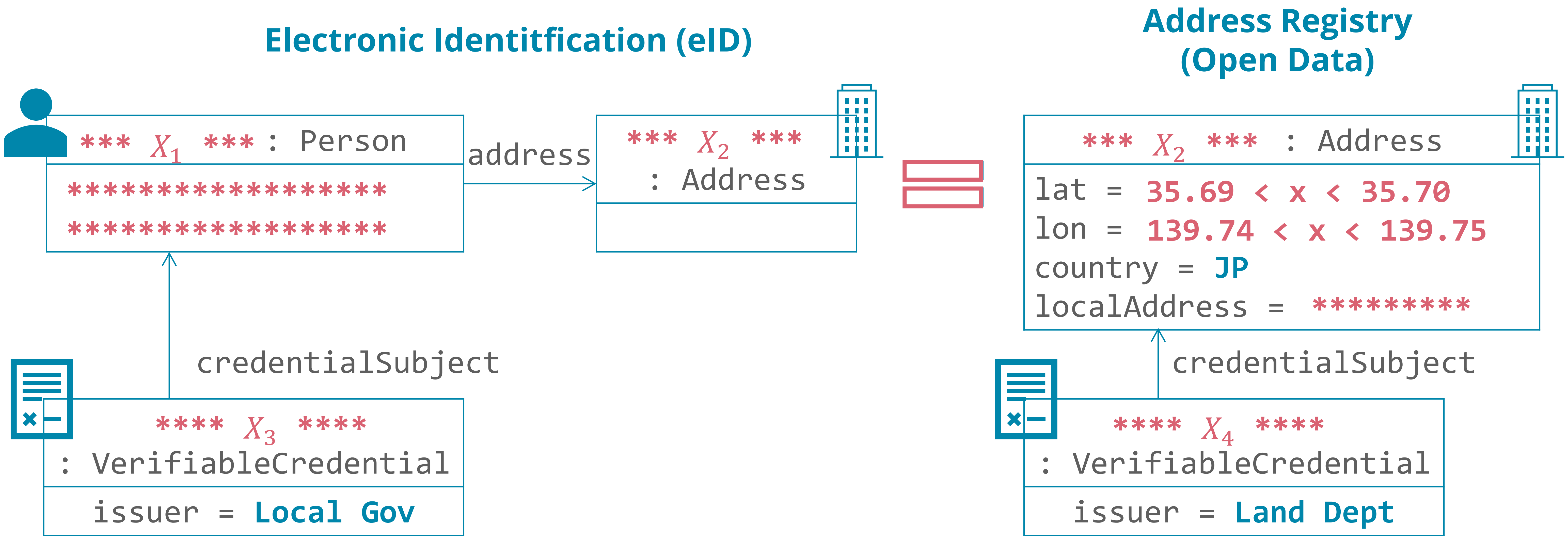
**ZKP of Vaccination**

# Other Use Cases: ZKP of Employer



❝ I (anonymized) work for
a company (anonymized) that received the Top 100 award,
asserted by Local Gov & GLEIF-like organization ❞

# Other Use Cases: ZKP of Residence



**Electronic Identitfication (eID)**

*** $X_1$ *** : Person
*****************
*****************

address

*** $X_2$ ***
: Address

credentialSubject

**** $X_3$ ****
: VerifiableCredential
issuer = **Local Gov**

=

**Address Registry**
**(Open Data)**

*** $X_2$ *** : Address
lat = **35.69 < x < 35.70**
lon = **139.74 < x < 139.75**
country = **JP**
localAddress = *********

credentialSubject

**** $X_4$ ****
: VerifiableCredential
issuer = **Land Dept**

> “ I (anonymized) live in a place (anonymized)
> that is geographically located in (35.69, 139.74) --- (35.70, 139.75),
> asserted by Local Gov & Land Department ”

# Related Standardization Efforts

W3C JSON-LD, RDF, …

**Verifiable Credentials Data Model**
W3C Recommendation

**Data Integrity**
W3C Draft Community Group Report (in Progress)

**BBS+ Signatures 2020 (LDP-BBS+)**
W3C Draft Community Group Report (in Progress)

OpenID

**OpenID Connect for SSI**
(in Progress)

DIF

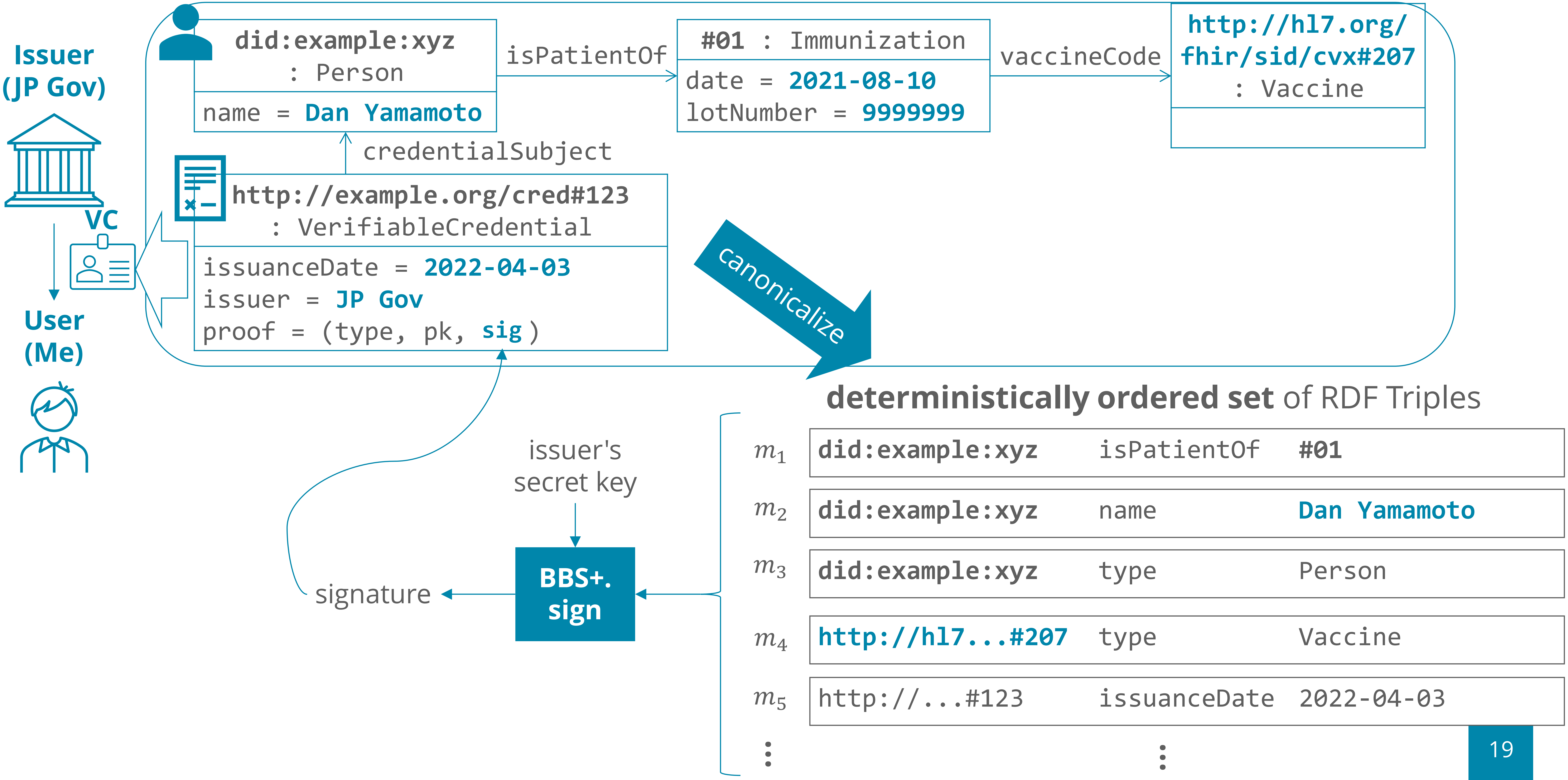
**The BBS Signature Scheme**
(in Progress)

⋮

**Ours: LDP-BBS++?**
(not on any standardization process yet)

*this work formalizes security & privacy notions for future standardization

# Existing Construction (LDP-BBS+)



Issuer (JP Gov)

VC

User (Me)

did:example:xyz
: Person

name = **Dan Yamamoto**

isPatientOf

#01 : Immunization

date = **2021-08-10**
lotNumber = **9999999**

vaccineCode

**http://hl7.org/fhir/sid/cvx#207**
: Vaccine

credentialSubject

**http://example.org/cred#123**
: VerifiableCredential

issuanceDate = **2022-04-03**
issuer = **JP Gov**
proof = (type, pk, **sig**)

canonicalize

**deterministically ordered set** of RDF Triples

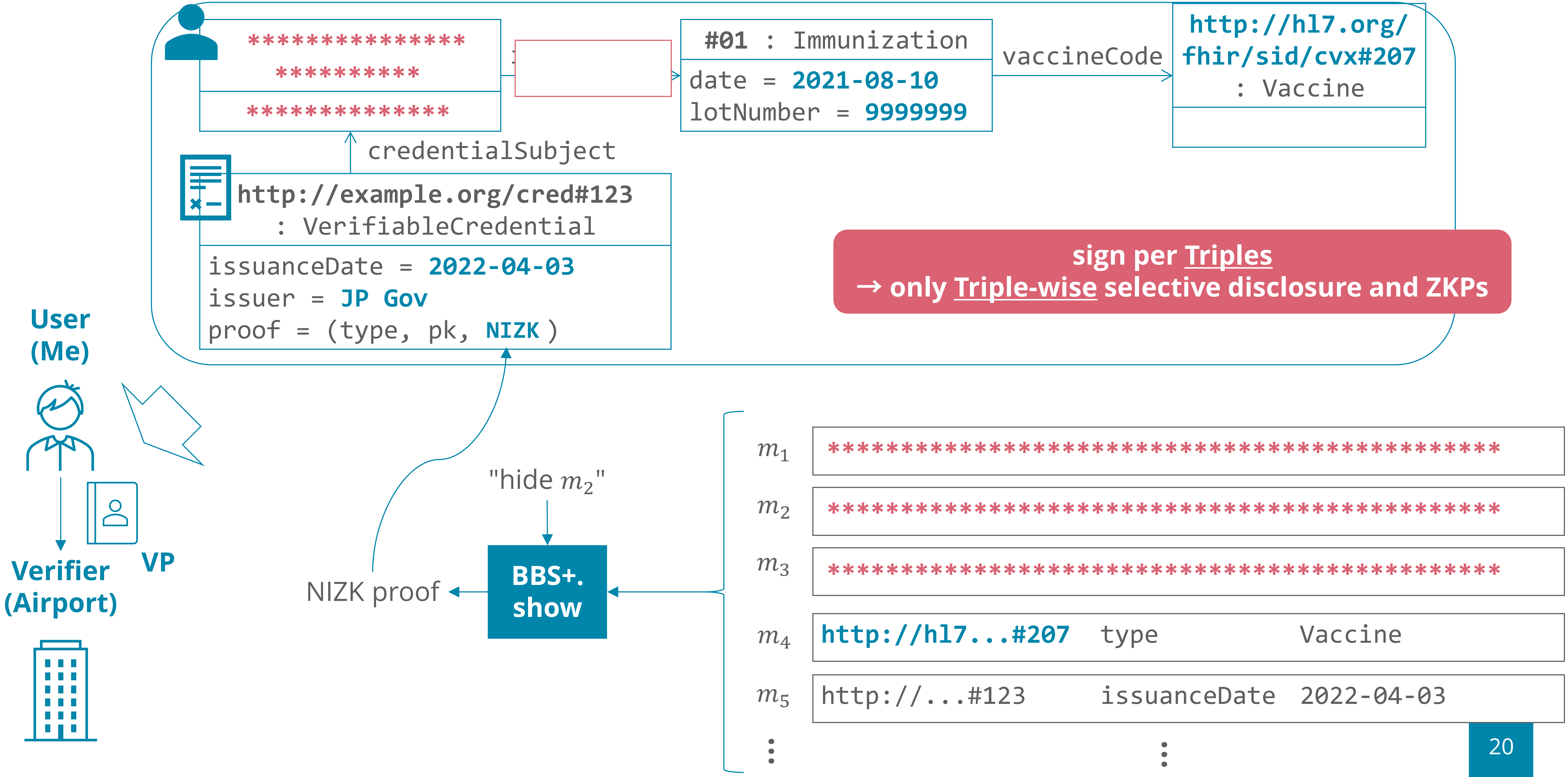
| | | | |
|---|---|---|---|
| $m_1$ | **did:example:xyz** | isPatientOf | **#01** |
| $m_2$ | **did:example:xyz** | name | **Dan Yamamoto** |
| $m_3$ | **did:example:xyz** | type | Person |
| $m_4$ | **http://hl7...#207** | type | Vaccine |
| $m_5$ | http://...#123 | issuanceDate | 2022-04-03 |
| ⋮ | ⋮ | | |

issuer's secret key

**BBS+.sign**

signature

# Existing Construction (LDP-BBS+) = **Triple-wise** Encoding



***************
**********
**************

#01 : Immunization
date = 2021-08-10
lotNumber = 9999999

vaccineCode

http://hl7.org/
fhir/sid/cvx#207
: Vaccine

credentialSubject

http://example.org/cred#123
: VerifiableCredential
issuanceDate = 2022-04-03
issuer = JP Gov
proof = (type, pk, NIZK )

**sign per Triples**
**→ only Triple-wise selective disclosure and ZKPs**

**User (Me)**

**Verifier (Airport)**

**VP**

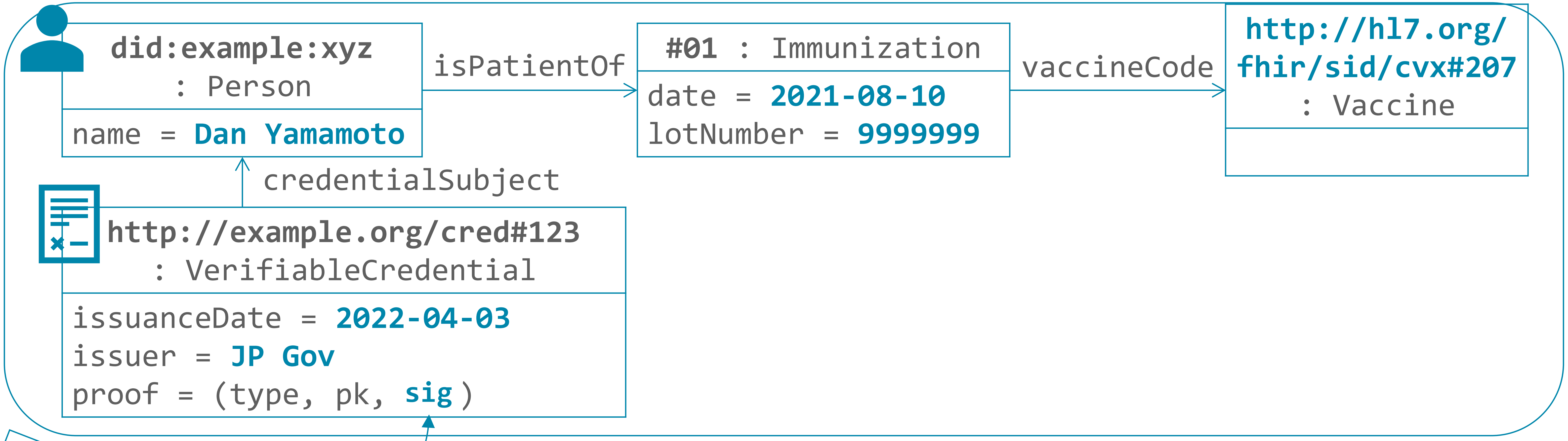
"hide $m_2$"

**BBS+. show**

NIZK proof

| | | | |
|---|---|---|---|
| $m_1$ | ********************************************** | | |
| $m_2$ | ********************************************** | | |
| $m_3$ | ********************************************** | | |
| $m_4$ | http://hl7...#207 | type | Vaccine |
| $m_5$ | http://...#123 | issuanceDate | 2022-04-03 |
| ⋮ | ⋮ | | |

# Our Construction = **Term-wise** Encoding



did:example:xyz
: Person

name = **Dan Yamamoto**

isPatientOf

**#01** : Immunization

date = **2021-08-10**
lotNumber = **9999999**

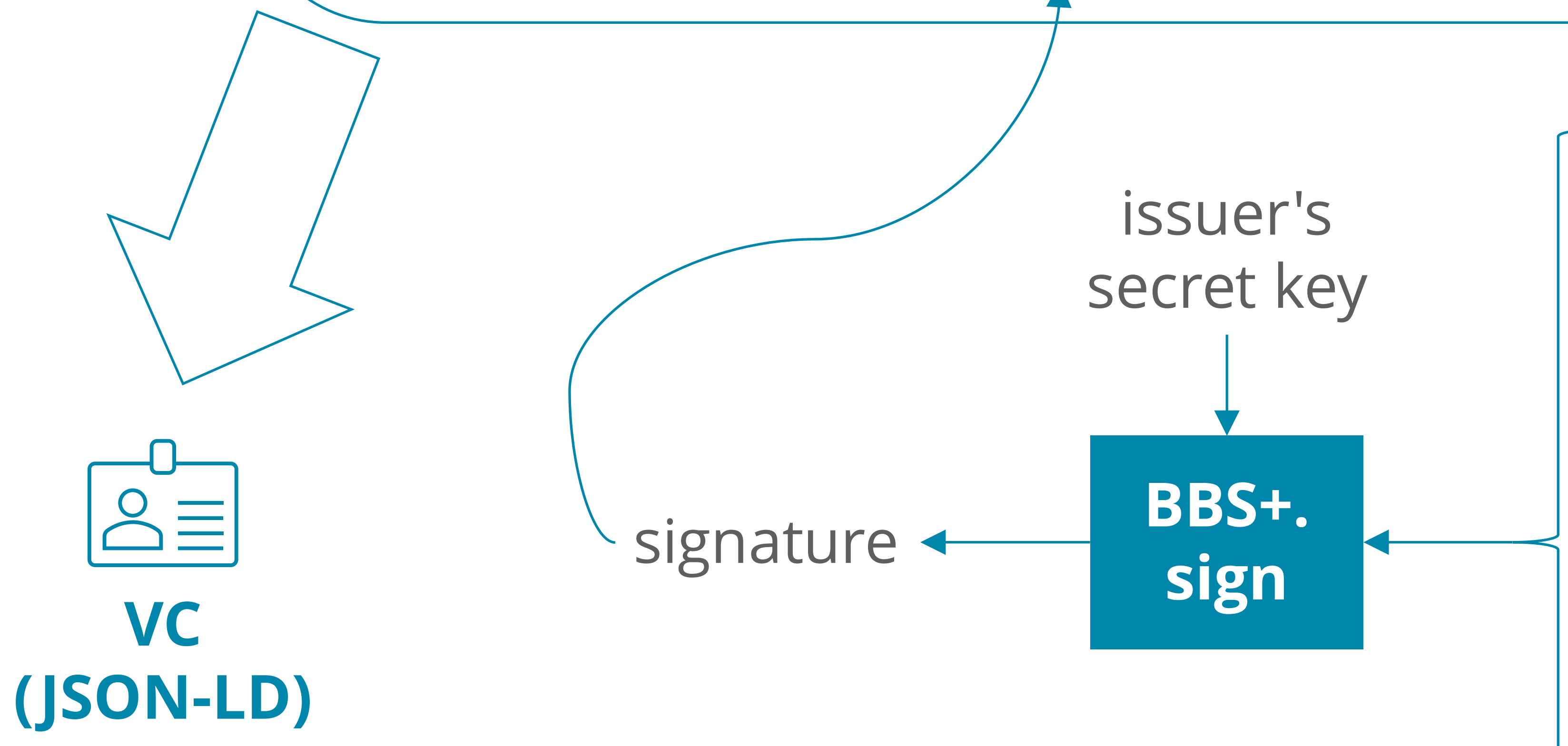
vaccineCode

**http://hl7.org/fhir/sid/cvx#207**
: Vaccine

credentialSubject

http://example.org/cred#123
: VerifiableCredential

issuanceDate = **2022-04-03**
issuer = **JP Gov**
proof = (type, pk, **sig**)



**VC**
**(JSON-LD)**

issuer's
secret key

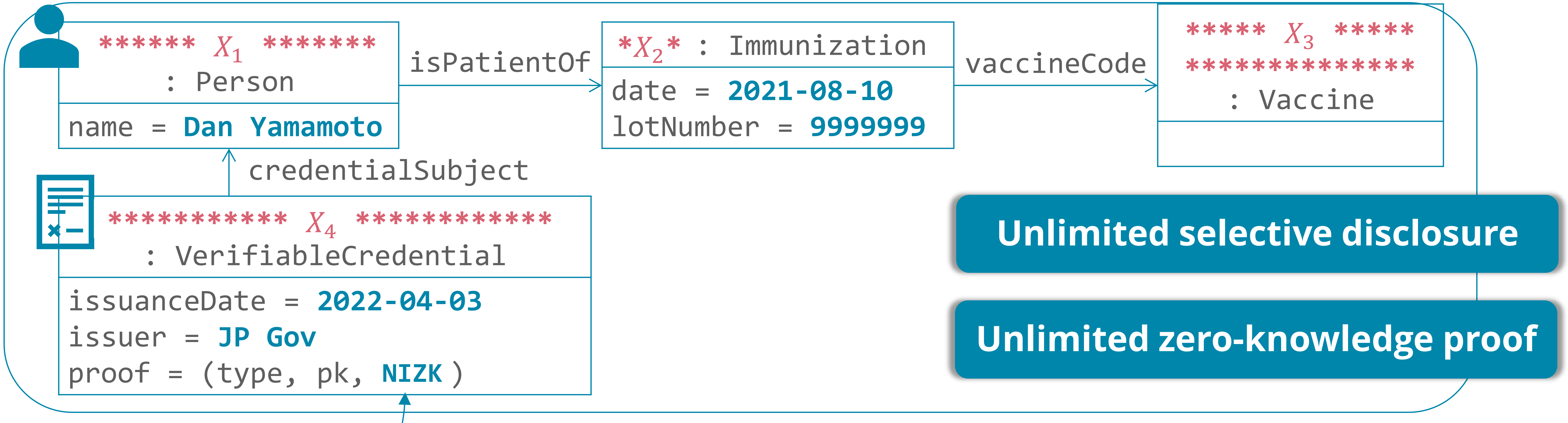
**BBS+.**
**sign**

signature

| | | | | | |
|---|---|---|---|---|---|
| $m_1$ | **did:example:xyz** | $m_2$ | isPatientOf | $m_3$ | **#01** |
| $m_4$ | **did:example:xyz** | $m_5$ | name | $m_6$ | **Dan Yamamoto** |
| $m_7$ | **did:example:xyz** | $m_8$ | type | $m_9$ | Person |
| $m_{10}$ | **http://hl7...#207** | $m_{11}$ | type | $m_{12}$ | Vaccine |
| $m_{13}$ | http://...#123 | $m_{14}$ | issuanceDate | $m_{15}$ | 2022-04-03 |
| ⋮ | ⋮ | ⋮ | ⋮ | ⋮ | ⋮ |

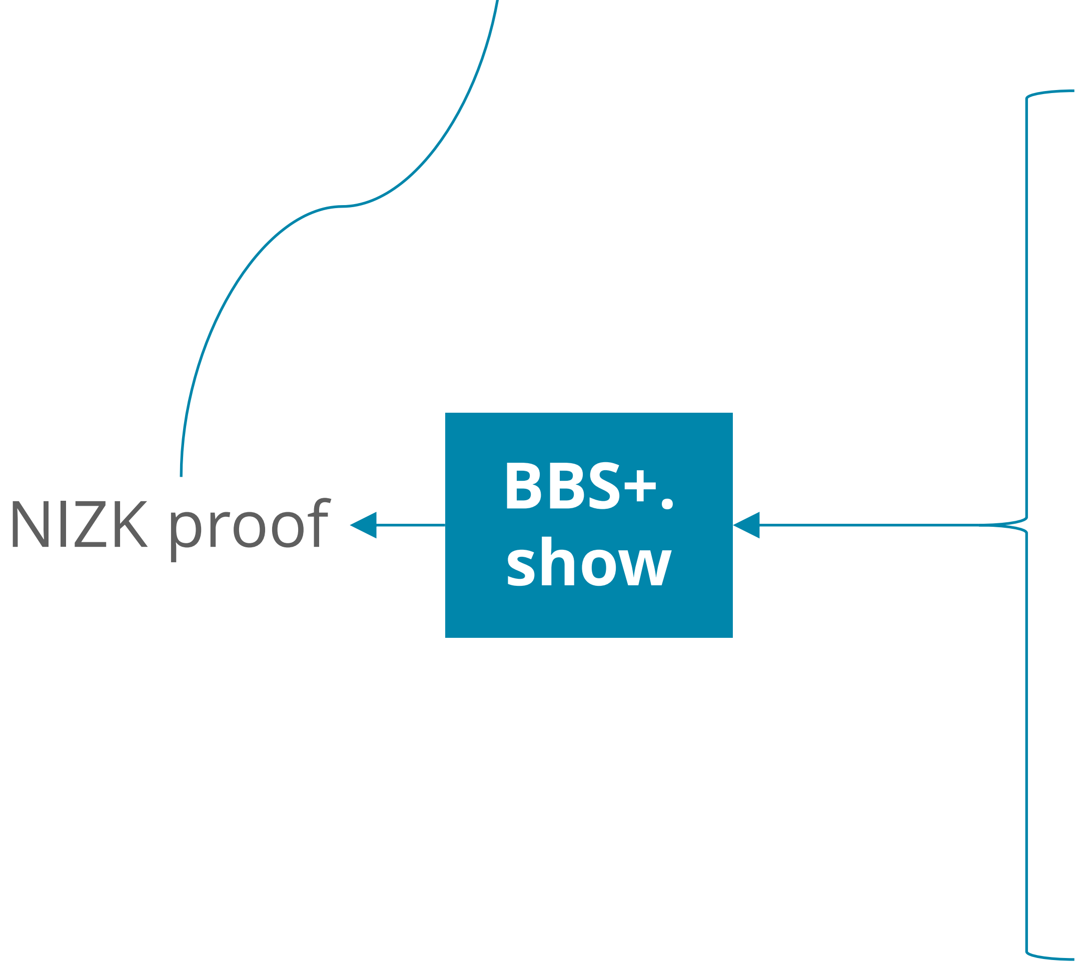
**sign per Terms**
**→ Term-wise selective disclosure and ZKPs**

# Our Construction = **Term-wise** Encoding


****** $X_1$ ******* : Person
name = Dan Yamamoto
isPatientOf
*$X_2$* : Immunization
date = 2021-08-10
lotNumber = 9999999
vaccineCode
***** $X_3$ ***** ************* : Vaccine
credentialSubject
*********** $X_4$ ************ : VerifiableCredential
issuanceDate = 2022-04-03
issuer = JP Gov
proof = (type, pk, NIZK )

**Unlimited selective disclosure**

**Unlimited zero-knowledge proof**



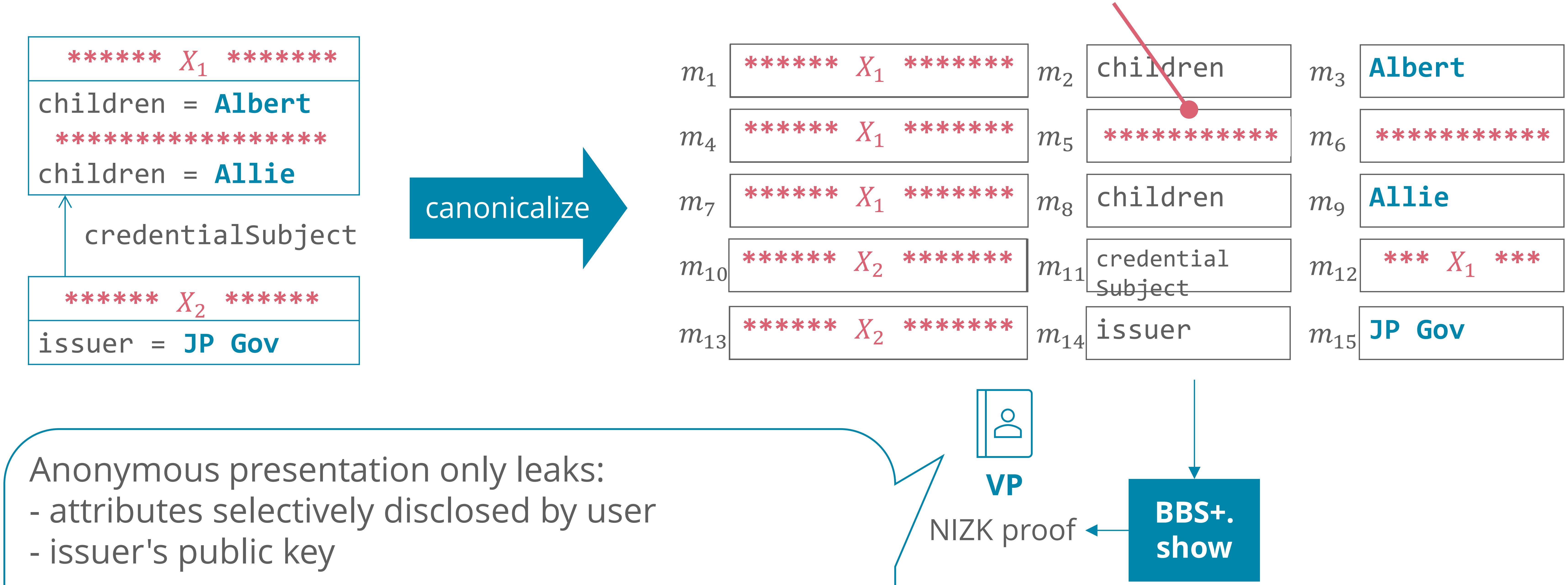
| | | | | | |
|---|---|---|---|---|---|
| $m_1$ | ****** $X_1$ ******* | $m_2$ | isPatientOf | $m_3$ | #01 |
| $m_4$ | ****** $X_1$ ******* | $m_5$ | name | $m_6$ | Dan Yamamoto |
| $m_7$ | ****** $X_1$ ******* | $m_8$ | type | $m_9$ | Person |
| $m_{10}$ | ****** $X_3$ ******* | $m_{11}$ | type | $m_{12}$ | Vaccine |
| $m_{13}$ | ****** $X_4$ ******* | $m_{14}$ | issuanceDate | $m_{15}$ | ≥2022-01-01 |
| ⋮ | ⋮ | ⋮ | ⋮ | ⋮ | ⋮ |

# Security and Privacy

- We defined game-based notions of **unforgeability** and **anonymity** based on Sanders' definition (@ PKC '20)
- and proved:
  - Our construction is **unforgeable**
    **if** the underlying anonymous credential (e.g., BBS+) is unforgeable
  - Our construction is **weakly anonymous**
    **if** the underlying anonymous credential (e.g., BBS+) is anonymous

# Anonymity vs. Weak Anonymity

**Adversary knows:**
$m_5$ **must be lexicographically larger than** $m_2$
(if lexicographically sort is used for canonicalization)



Anonymous presentation only leaks:
- attributes selectively disclosed by user
- issuer's public key

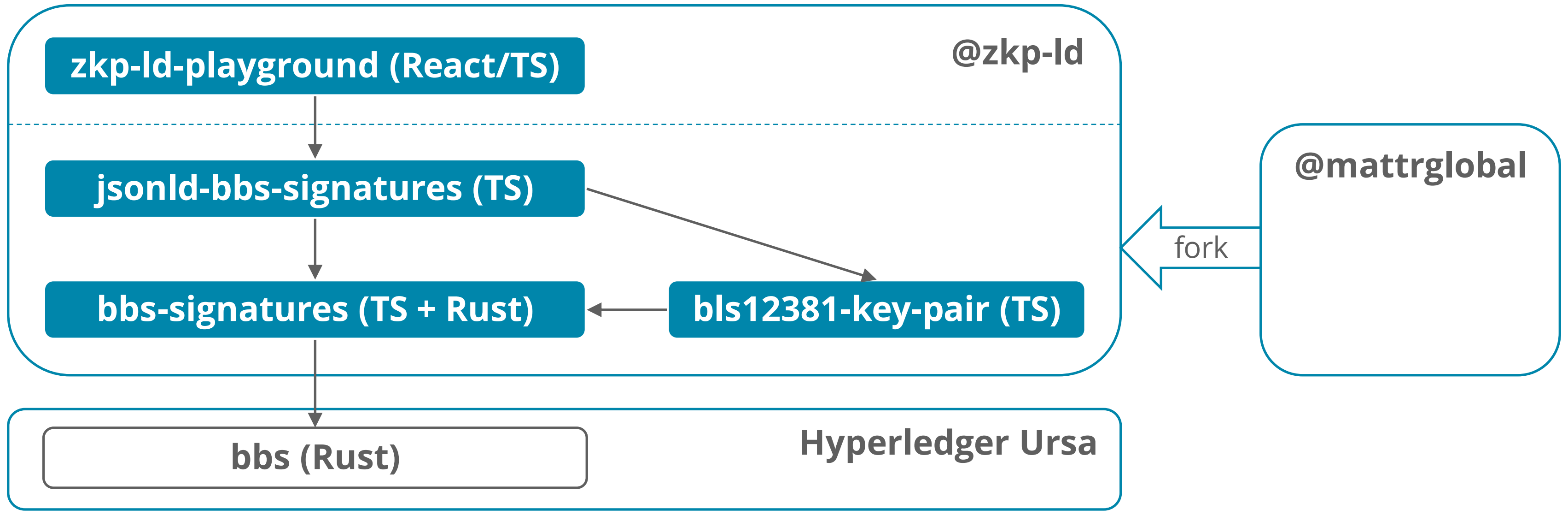
Weakly anonymous presentation additionally leaks:
- total number of attributes: $|\{m_i\}| = 15$
- index $i$ of canonicalized attributes $\{m_i\}$

**workarounds:**
**add dummy attributes**
**& random permutations**

# Implementations and Demo

## Implementations (published on Github and npm)

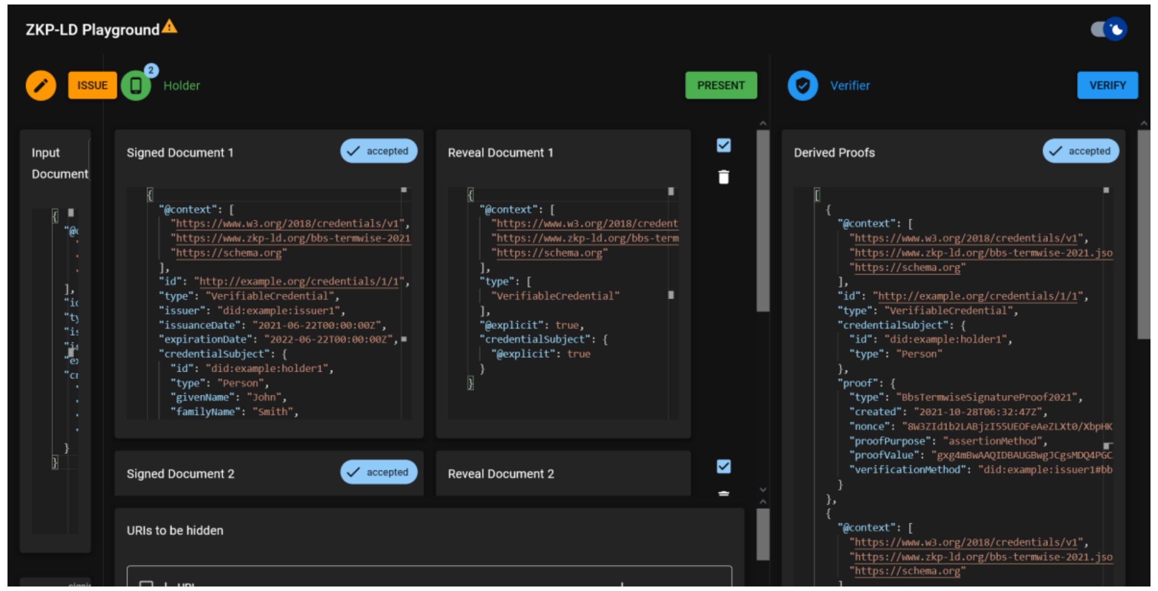
- @zkp-ld/jsonld-signatures-bbs
- @zkp-ld/bls12381-key-pair
- @zkp-ld/bbs-signatures



@zkp-ld
zkp-ld-playground (React/TS)
jsonld-bbs-signatures (TS)
bbs-signatures (TS + Rust)
bls12381-key-pair (TS)
fork
@mattrglobal
bbs (Rust)
Hyperledger Ursa

## ZKP-LD Playground <https://playground.zkp-ld.org>

- a playground for developers
- you can sign & verify LD-based credential and show & verify presentations on browser



Signed Document 1

```
{
  "@context": [
    "https://www.w3.org/2018/credentials/v1",
    "https://www.zkp-ld.org/bbs-termwise-2021
    "https://schema.org"
  ],
  "id": "http://example.org/credentials/1/1",
  "type": "VerifiableCredential",
  "issuer": "did:example:issuer1",
  "issuanceDate": "2021-06-22T00:00:00Z",
  "expirationDate": "2022-06-22T00:00:00Z",
  "credentialSubject": {
    "id": "did:example:holder1",
    "type": "Person",
    "givenName": "John",
    "familyName": "Smith",
```

Reveal Document 1

```
{
  "@context": [
    "https://www.w3.org/2018/credent
    "https://www.zkp-ld.org/bbs-term
    "https://schema.org"
  ],
  "type": [
    "VerifiableCredential"
  ],
  "@explicit": true,
  "credentialSubject": {
    "@explicit": true
  }
}
```

Derived Proofs

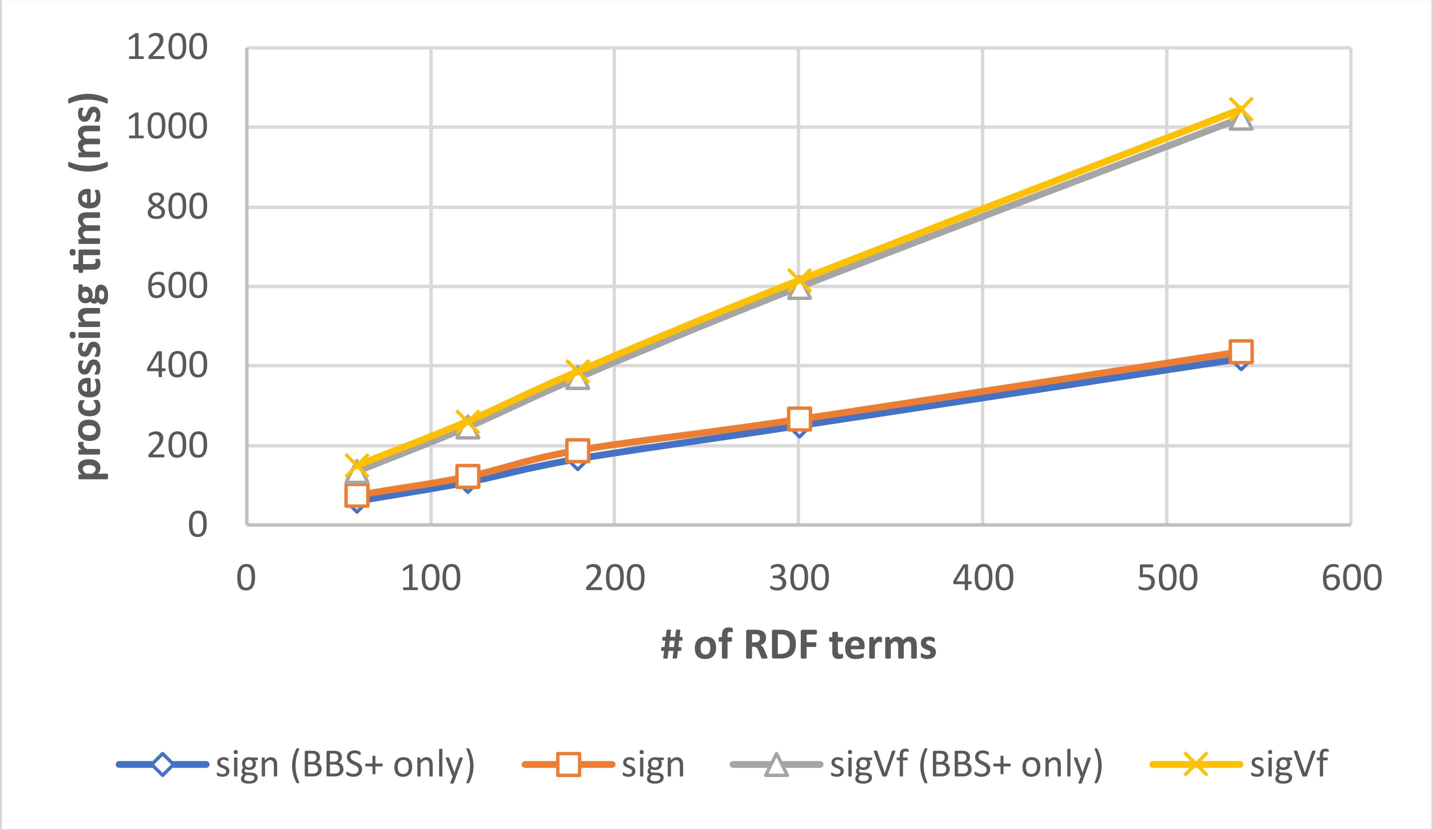
```
[
  {
    "@context": [
      "https://www.w3.org/2018/credentials/v1",
      "https://www.zkp-ld.org/bbs-termwise-2021.jso
      "https://schema.org"
    ],
    "id": "http://example.org/credentials/1/1",
    "type": "VerifiableCredential",
    "credentialSubject": {
      "id": "did:example:holder1",
      "type": "Person"
    },
    "proof": {
      "type": "BbsTermwiseSignatureProof2021",
      "created": "2021-10-28T06:32:47Z",
      "nonce": "8W3ZId1b2LABjzI55UEOFeAeZLXt0/XbpHK
      "proofPurpose": "assertionMethod",
      "proofValue": "gxg4mBwAAQIDBAUGBwgJCgsMDQ4PGC
      "verificationMethod": "did:example:issuer1#bb
    }
  },
  {
    "@context": [
      "https://www.w3.org/2018/credentials/v1",
      "https://www.zkp-ld.org/bbs-termwise-2021.jso
      "https://schema.org"
```

# Performance Evaluation

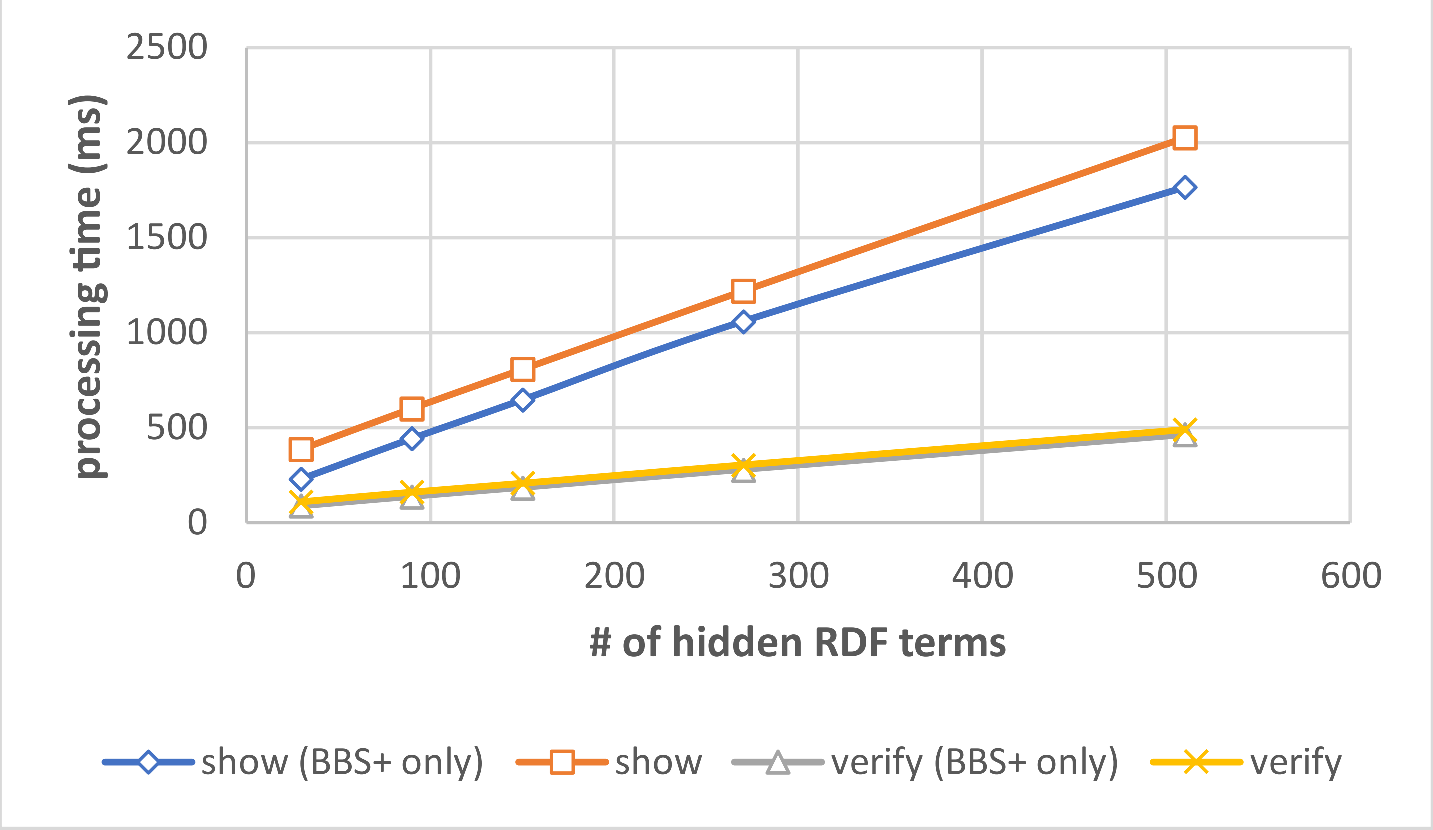
| | size (bits) |
|---|---|
| secret key | 256 |
| public key | 768 |
| signature | 896 |
| proof | $2944 + 256\,n$ |

($n$ : # of hidden terms)

## VC: sign / sigVf



## VP: show / verify



- i7-10750H (6 cores 12 threads) CPU, 32GB RAM, Google Chrome
- takes at most 1 sec to handle < 200 RDF terms
- (the issuance of bound credentials has not yet been implemented & evaluated)

# Conclusions

1. Constructed a LD-based VC scheme with fully selective disclosure
2. Proposed novel use cases using LD-based VCs with ZKP
3. Formalized LD-based VC and its security and privacy notion
4. Proved the security and privacy of our construction
5. Provided OSS implementations and Web-based demo

**Future Work**

- Fully anonymous construction
- Revocation, Delegation, Pseudonyms, Issuer-Hiding
- Constant proof sizes and verification times