dRR: A Decentralized, Scalable, and Auditable Architecture for RPKI Repository

NDSS ’24

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Resource Public Key Infrastructure (RPKI)

- **RPKI** is an **infrastructure for securing Internet number resources** (e.g., IP prefixes or AS numbers) and improving security of BGP routing

- Two key objects in RPKI
  - Resource Certificate (RC): enables resource holders to assert their legitimate ownership of Internet number resources
  - Route Origin Authorization (ROA): provides a binding of IP prefixes to their legitimate origin ASes

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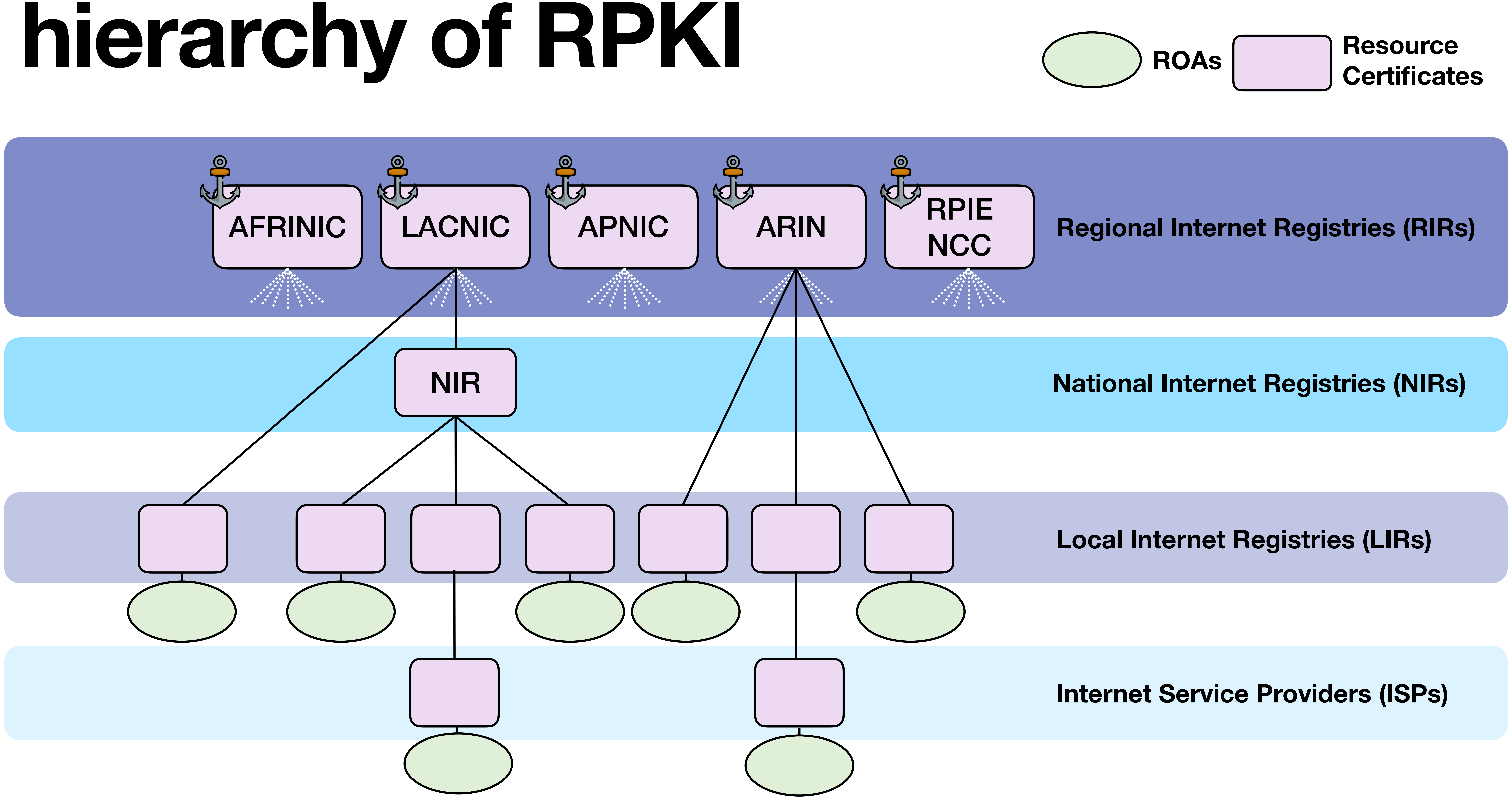
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- RPKI is structured hierarchically
  - five RIRs are root CAs and NIRs/LIRs/ISPs are sub-CAs

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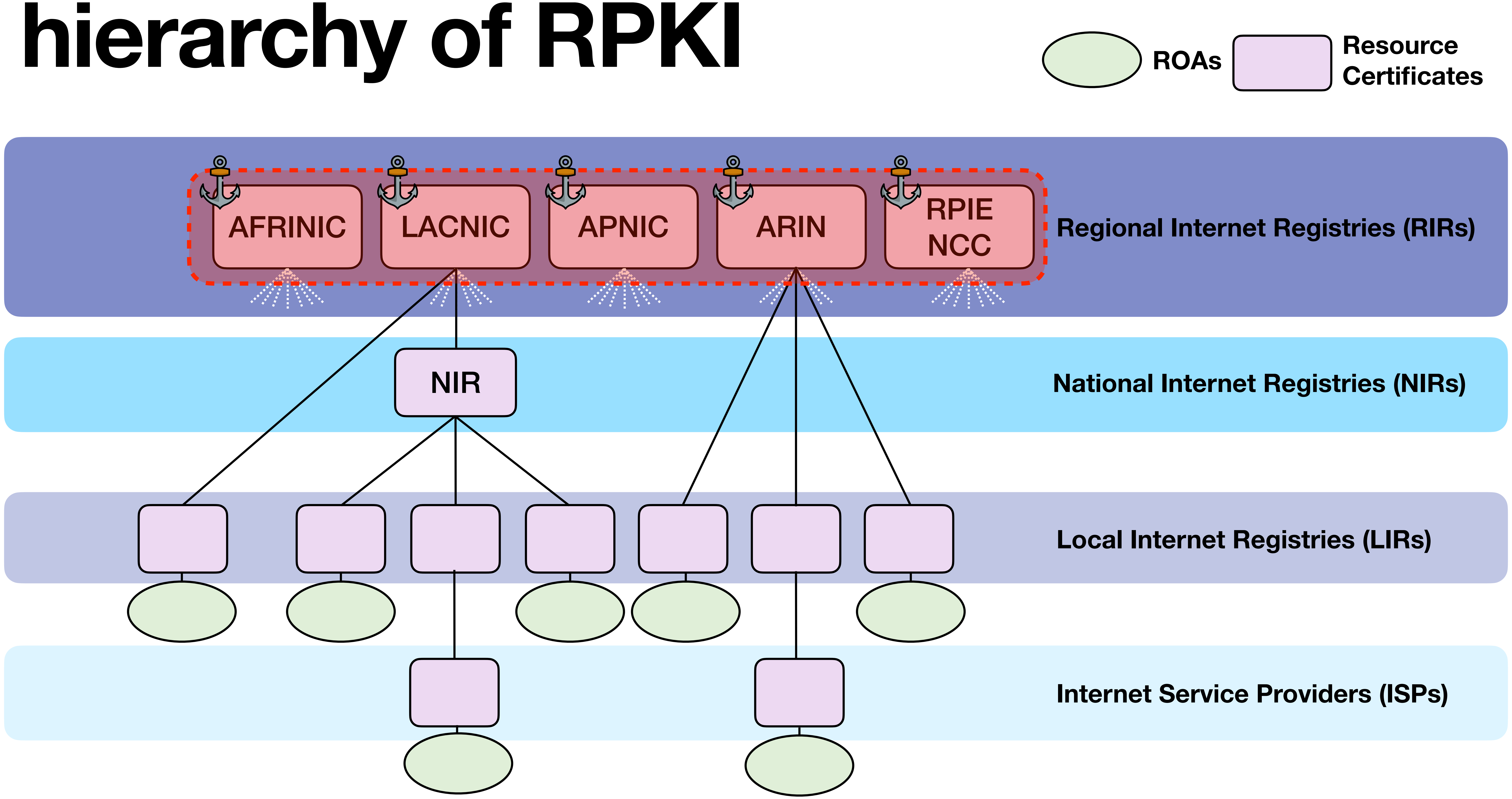
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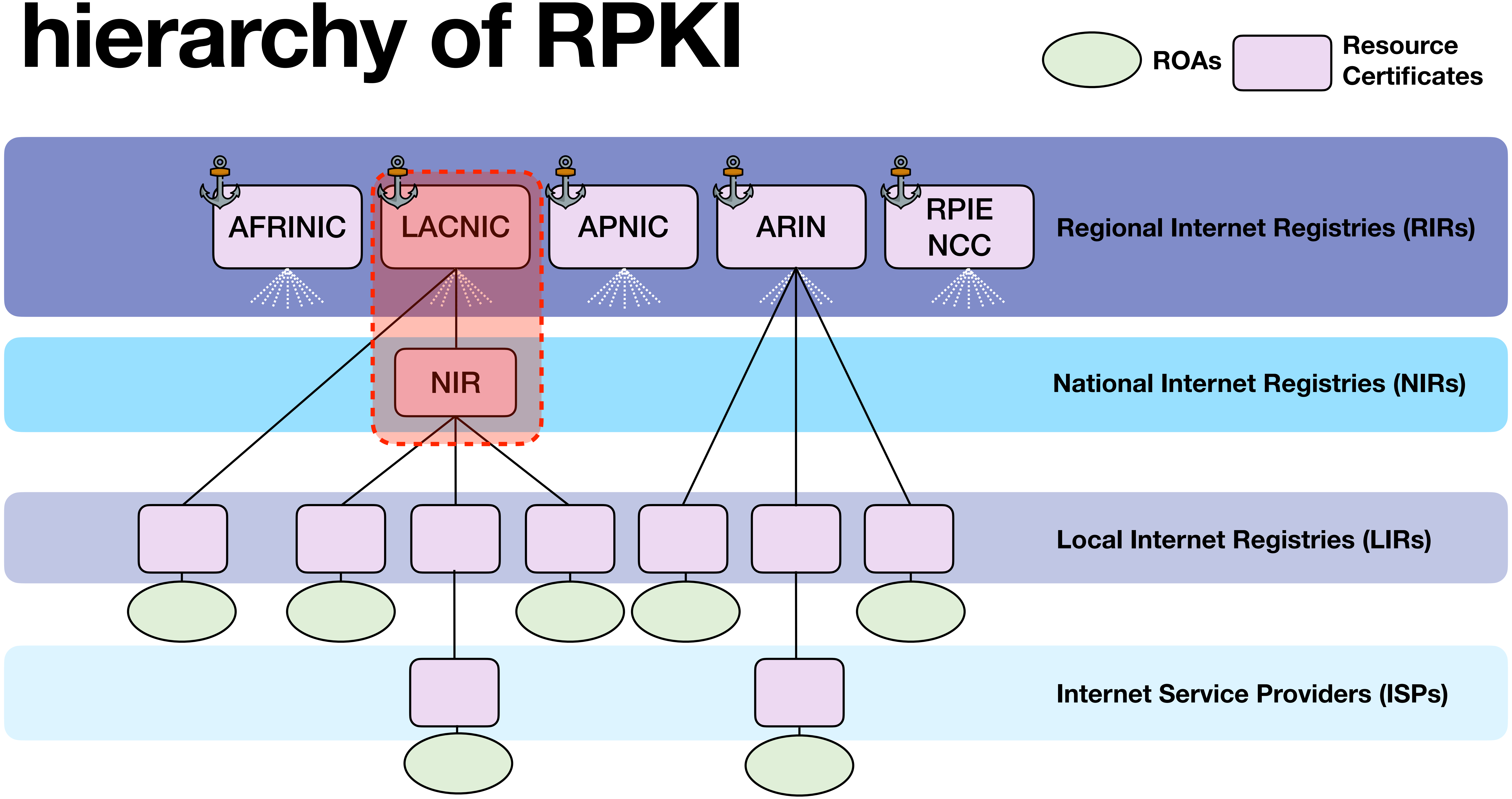
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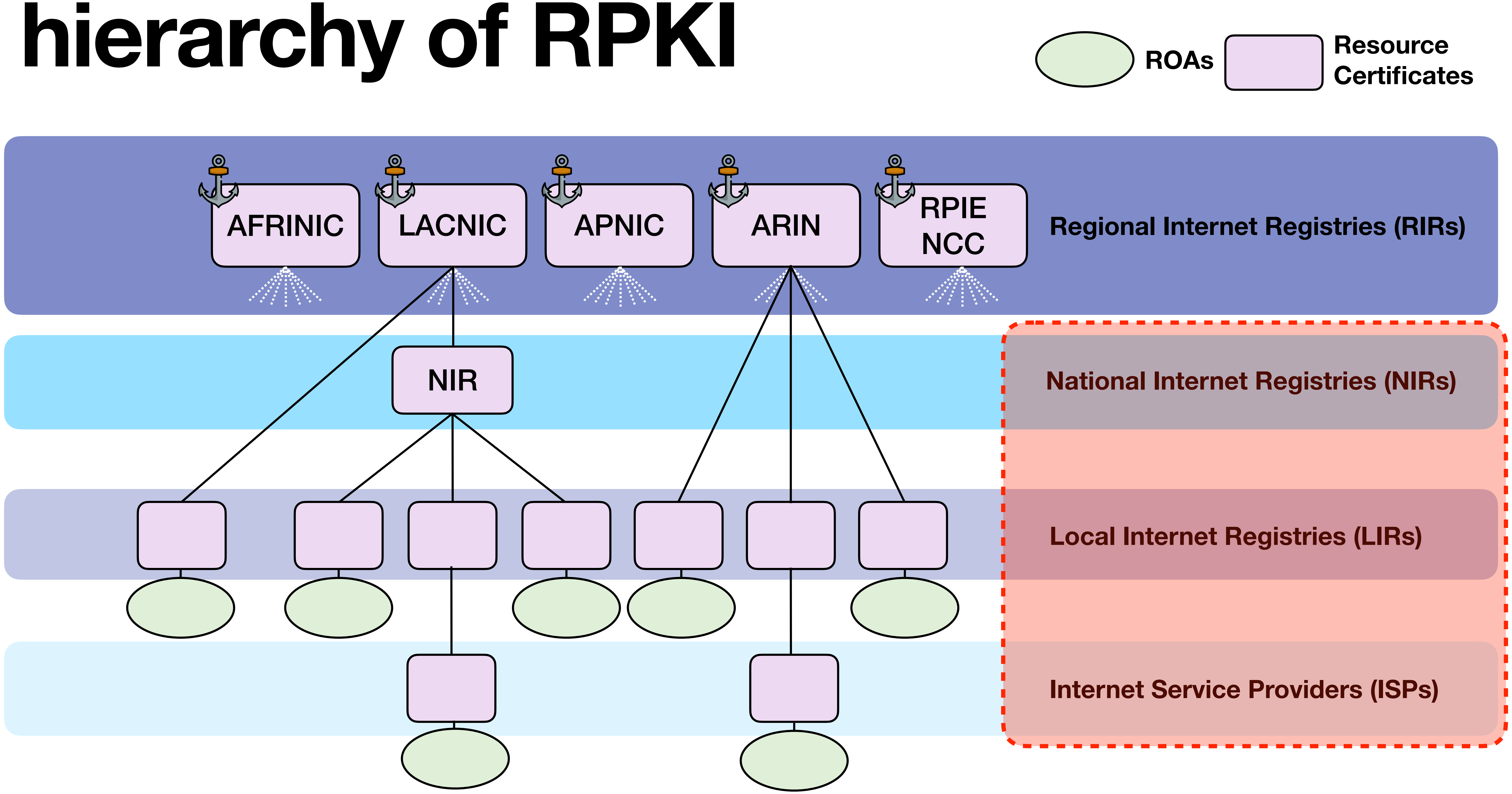
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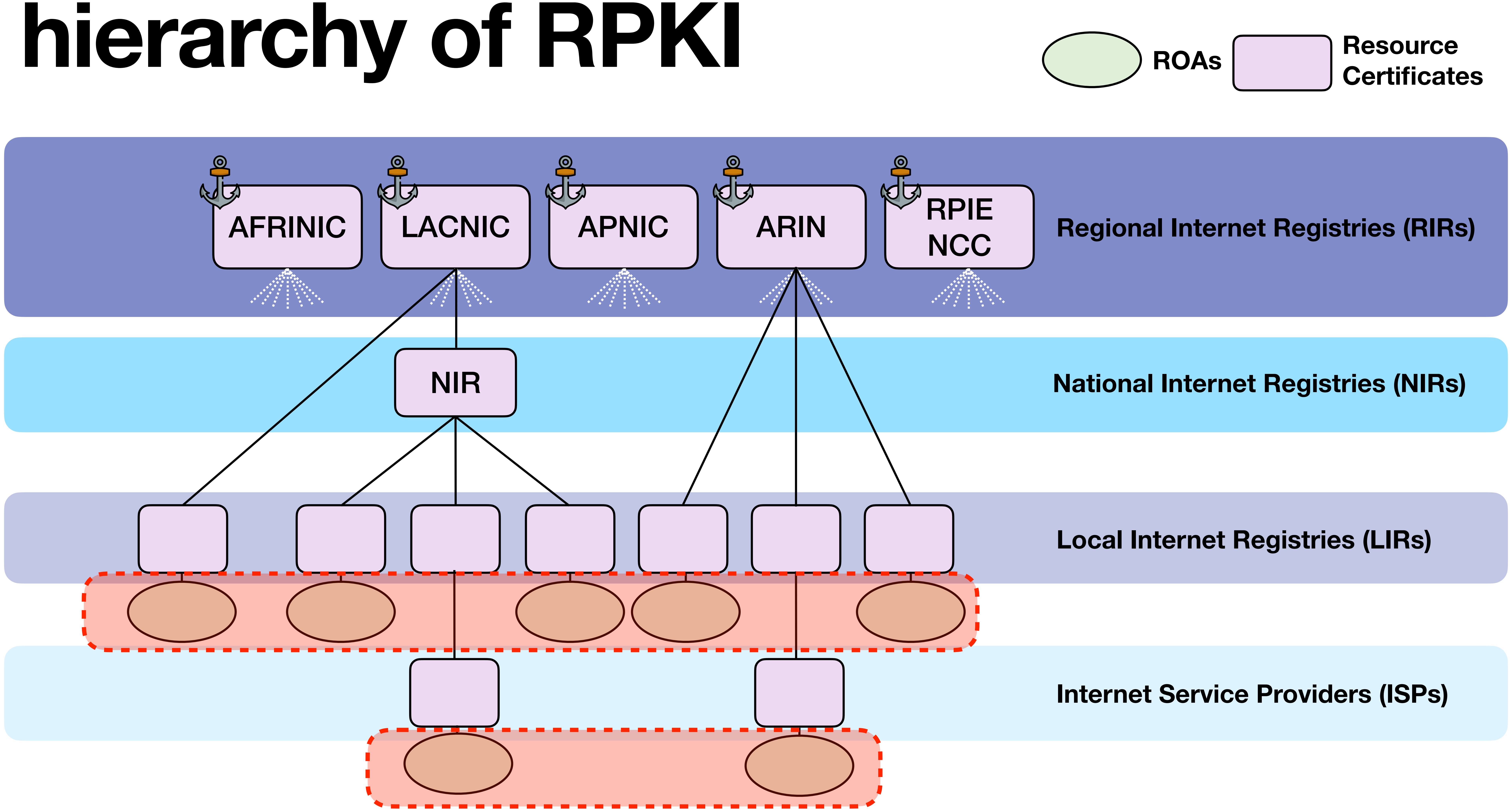
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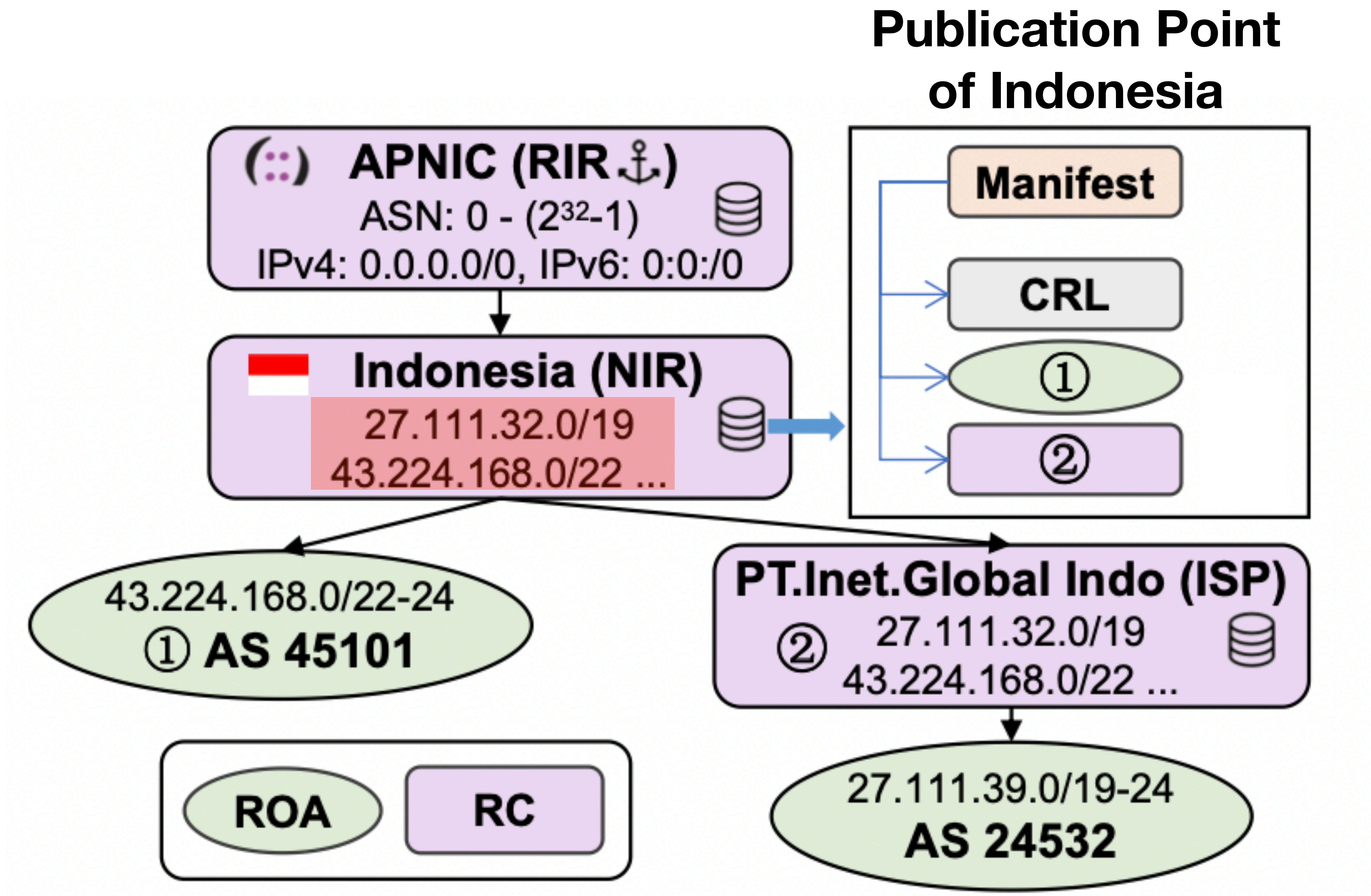
Example of RPKI hierarchical structure



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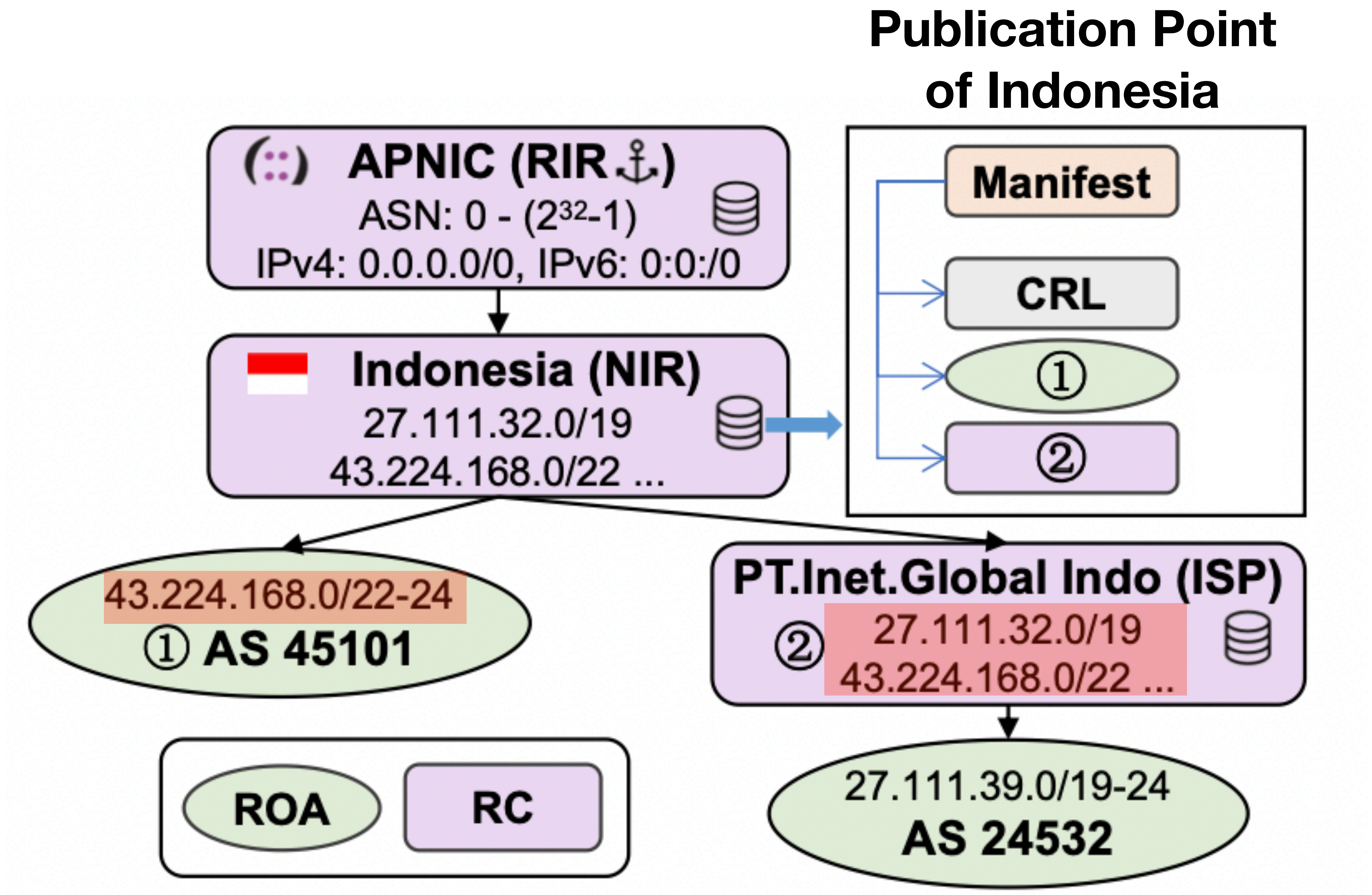

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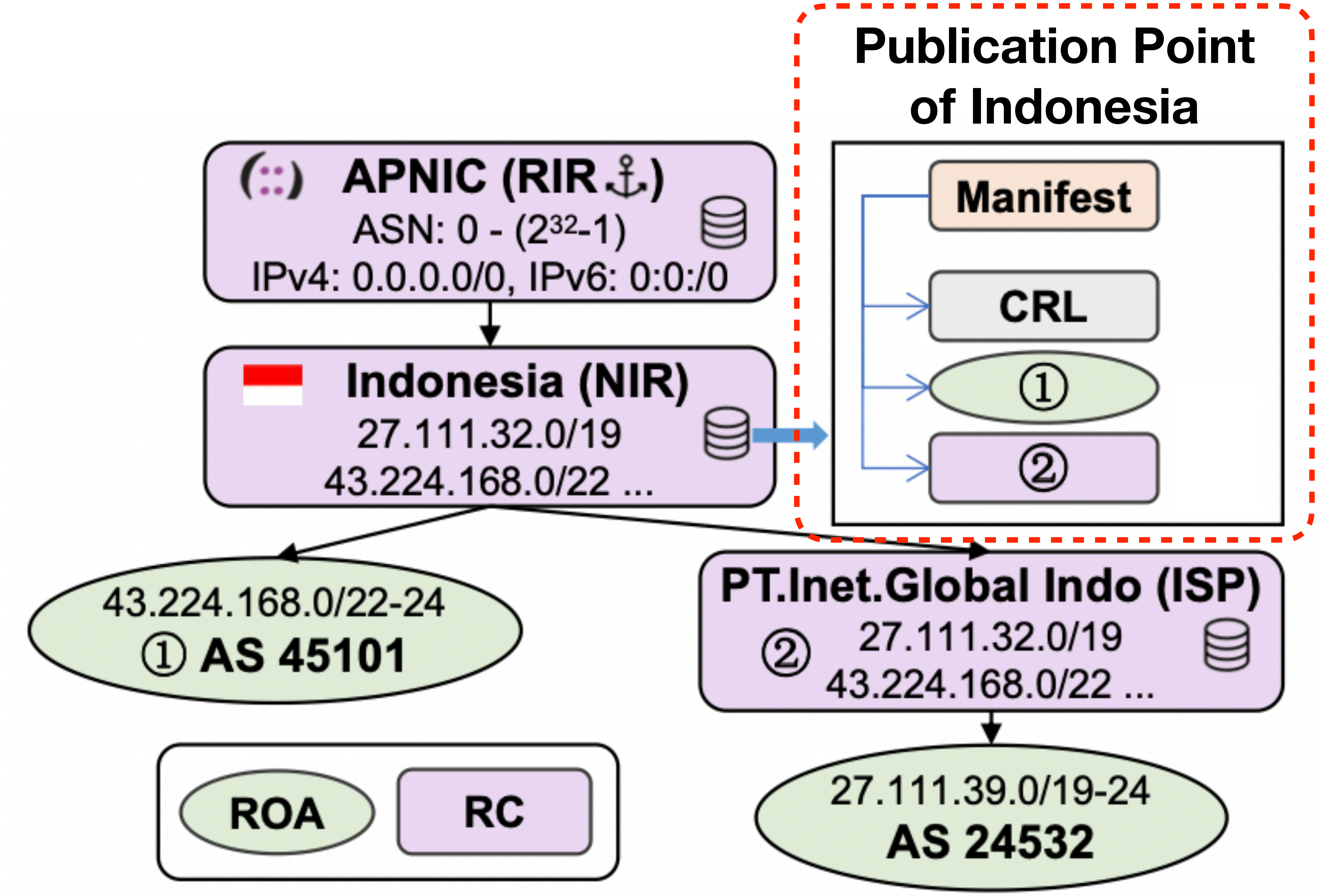
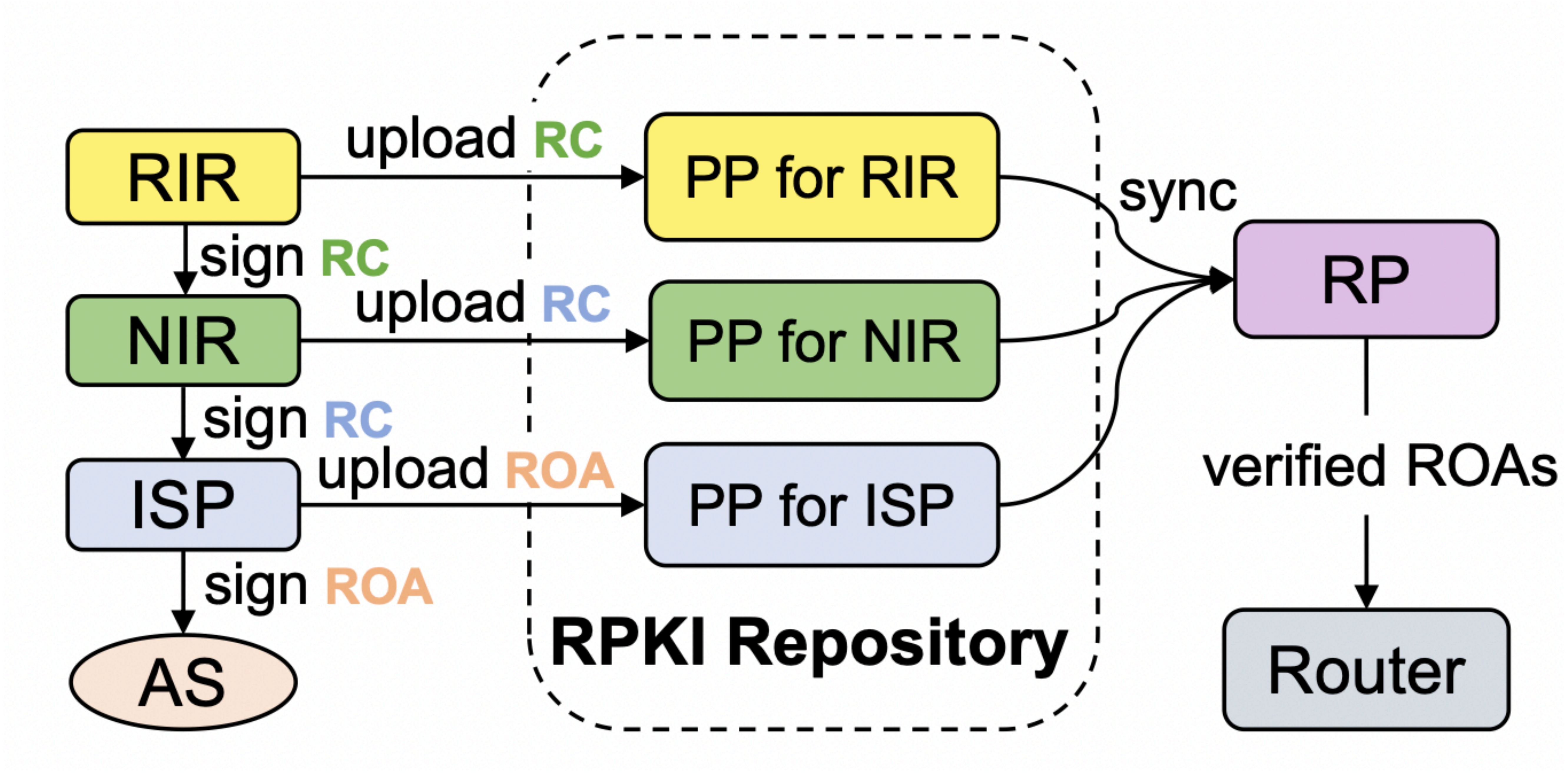


Each CA runs
a Publication Point (PP)
to store RCs and ROAs
issues for Internet
Number Resource
holders (INR holders)

RPKI Repository



- **All PPs collectively form the RPKI Repository**
    - each CA's PP exclusively stores the RPKI objects issued by the respective CA
- Relying Parties (RPs) periodically traverse all PPs, download and validate all RPKI objects

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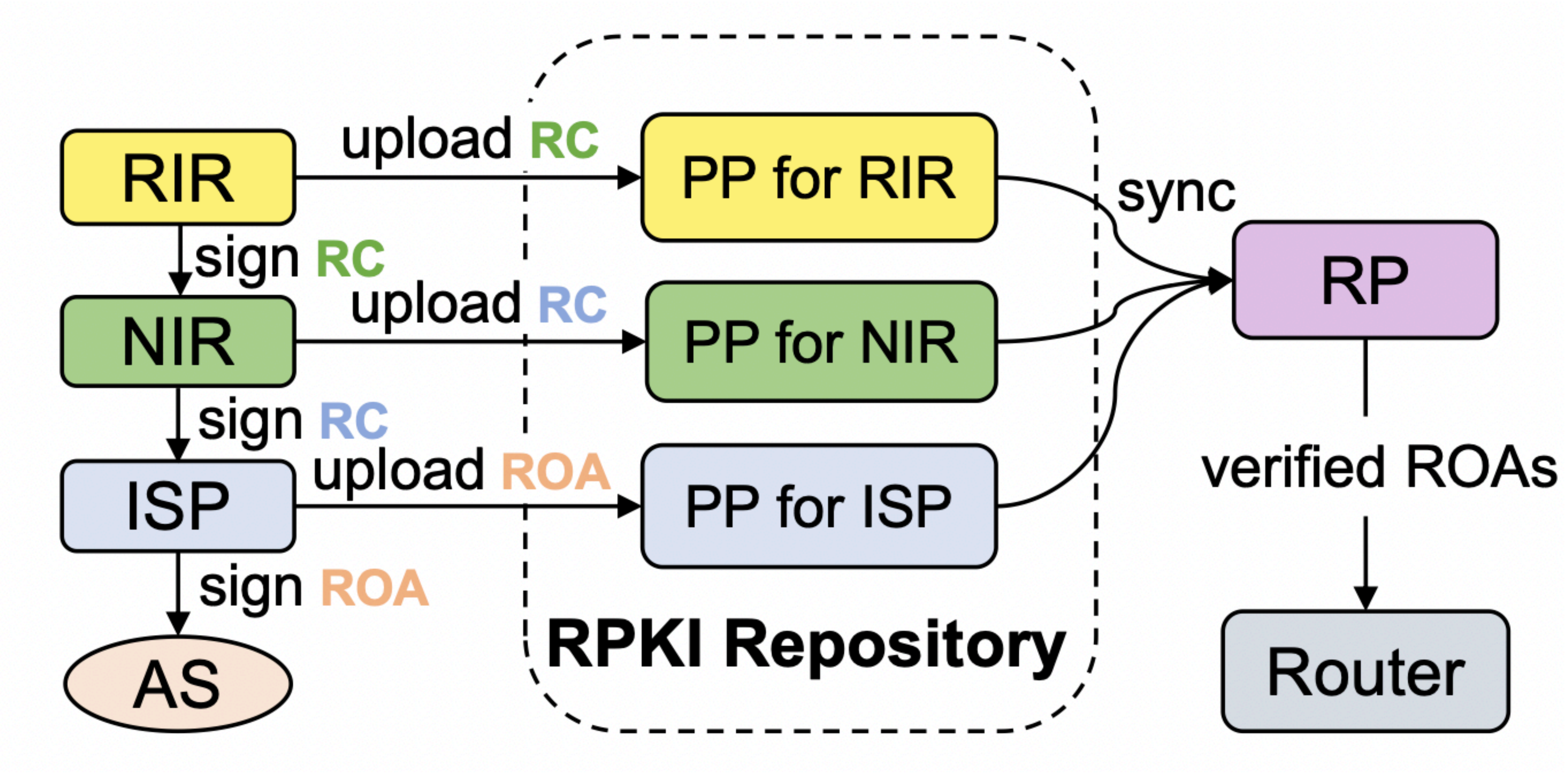

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Three Key Problems of RPKI Repository

P1. Unilateral Reliance on RPKI Authority

- CAs can unilaterally undermine any RPKI objects without INR holders' consent

P2. Single Point of Failure

- Any PPs' failure will hinder RPs from obtaining complete RPKI object views
- Introduce inter-dependency between the accessibility of a PP and the reachability of the PP's AS

P3. Poor Scalability

- RP local cache refresh involves traversing all PPs to fetch updated data
- The number of PPs is expected to increase dramatically with the further deployment of RPKI

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Data-driven Security Analysis

P1. “Unilateral Reliance on RPKI Authority"

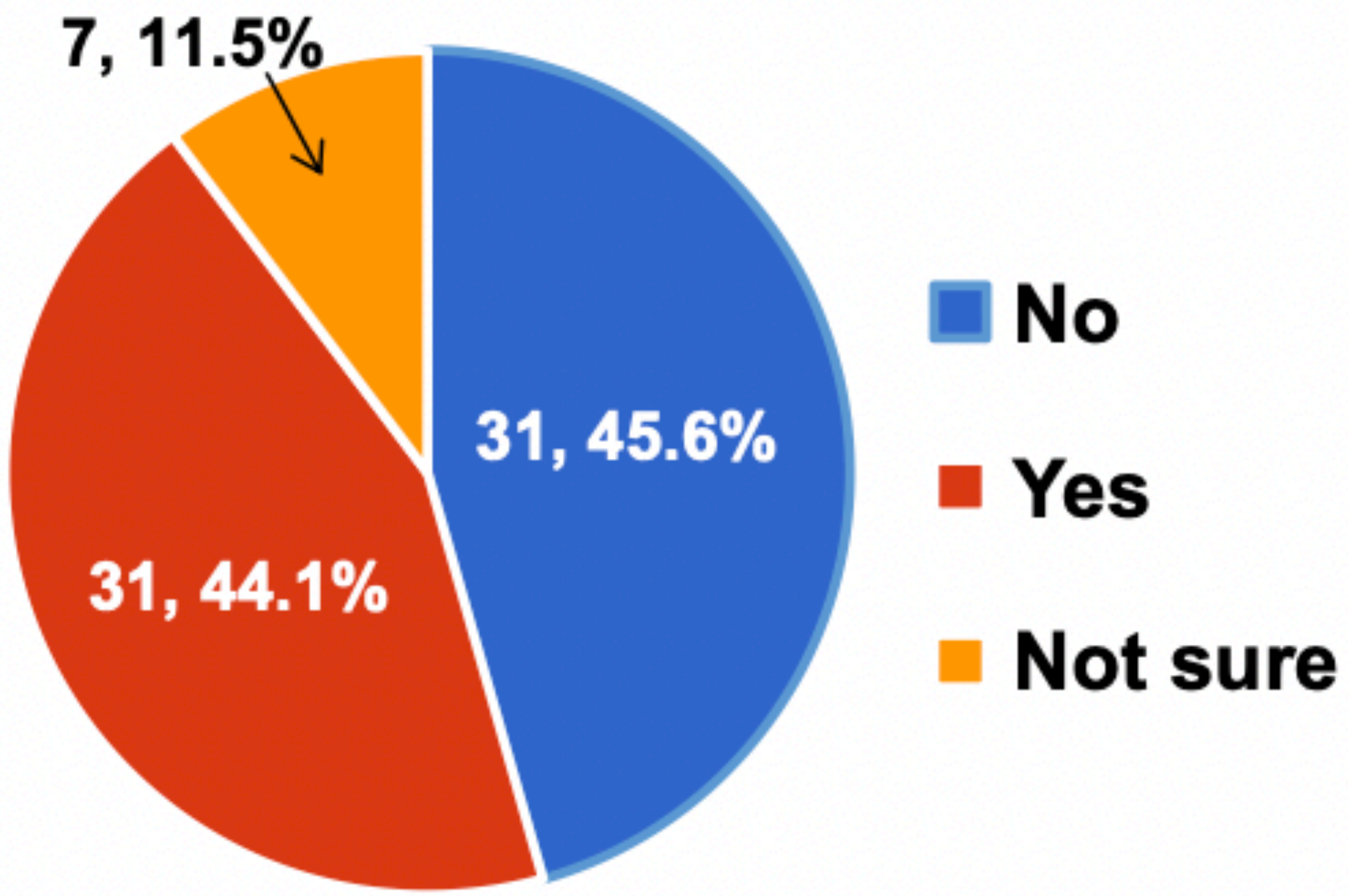


Fig. 21: For P1. Are you worried that RPKI authorities maliciously compromise your certificates, which could affect the legitimacy of your BGP updates? (w/ROA).

- Real-world concerns
  - **44% of AS operators** expressed **concerns** about **malicious authorities**
  - **two operators** consider the threat from authorities to be **the most serious problem**
  - **one operator had lost all their ROAs** due to administrative/human reasons

responses from administrators of 68 ASes that have deployed ROA and 35 ASes that have not deployed ROA

Data-driven Security Analysis

P2. “Vulnerable to Single Point of Failure"

- **only 8** out of 61 PPs are **hosted in CDNs***
  - hosted in Cloudflare AS13335 or Amazon AS16509

*** RPKI Repository Delta Protocol (RRDP)**

- used by Relying Parties to retrieve the RPKI objects from the RPKI repository,
- designed to leverage CDN infrastructure for resilient service

- **58** out of 61 PPs are **hosted in a single AS**
  - The accessibility of these PPs is highly dependent on the reachability of a single AS

- **14** PPs **carry the ROAs of the ASes where PPs are located**
  - The accessibility of these PPs will form a circular dependency on the reachability of the ASes

Data-driven Security Analysis

P3. “Poor Scalability"

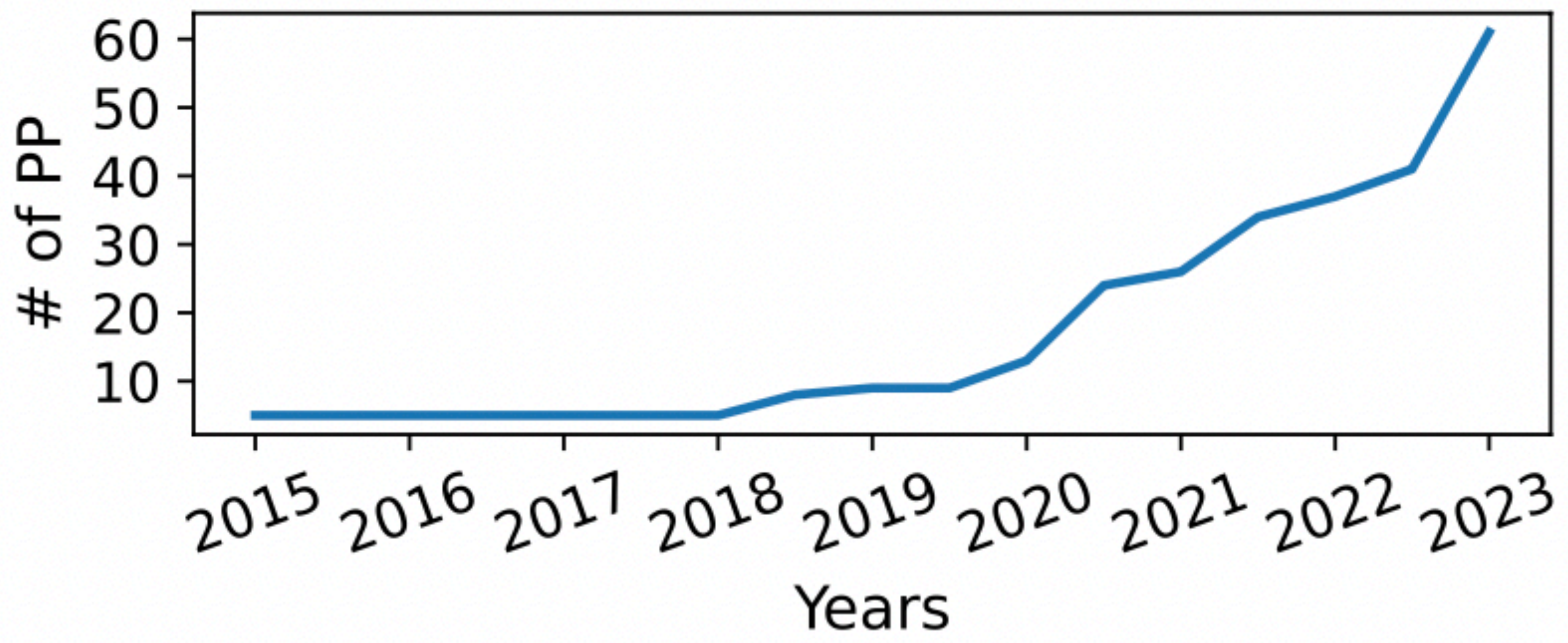


Fig. 4: The number of independent PPs over nine years.

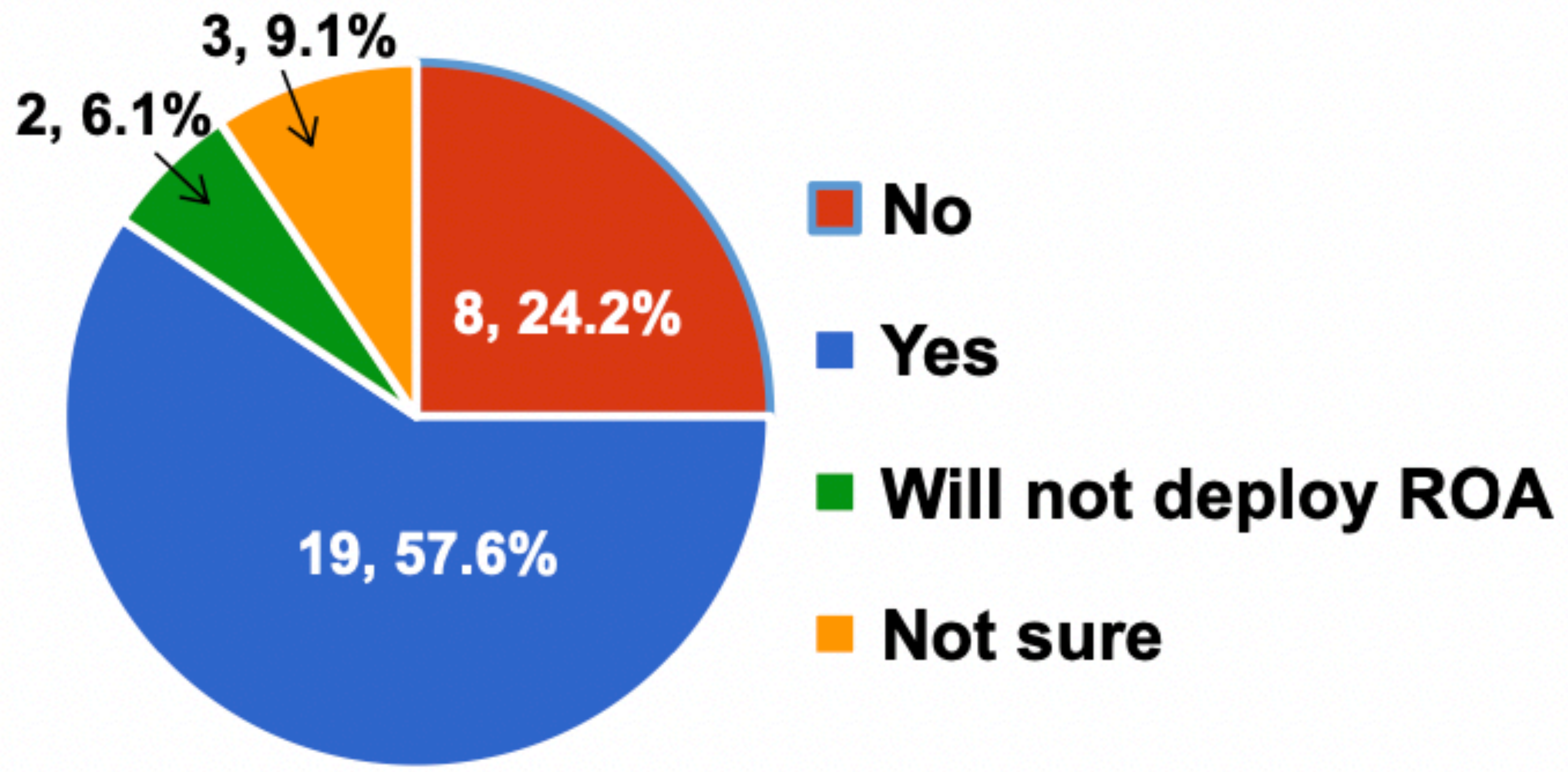


Fig. 22: For P3. If you deploy ROA in the future, would you consider adopting delegated RPKI and running your own PP? (wo/ROA).

- Analysis
  - **the number of PPs** has **grown** more than **12 times**
  - **many AS operators** are **considering running PPs**
  - when RPKI is fully deployed, **the number of PPs will inevitably increase**
- Potential Problems
  - threaten the scalability of RPKI
  - increase the cost of RP refreshing

Design Goal of dRR *(**d**ecentralized **R**PKI **R**epository)*

P1

- **Defend against RPKI authorities' malicious behavior**
  - Allow RPs verify certificate status
  - Allow resource holders verify the integrity of RPKI views
  - RPKI historical data can be audited

P2

- **Defend against single point of failure**
  - Truly distributed data storage
  - PP accessibility is independent of AS accessibility

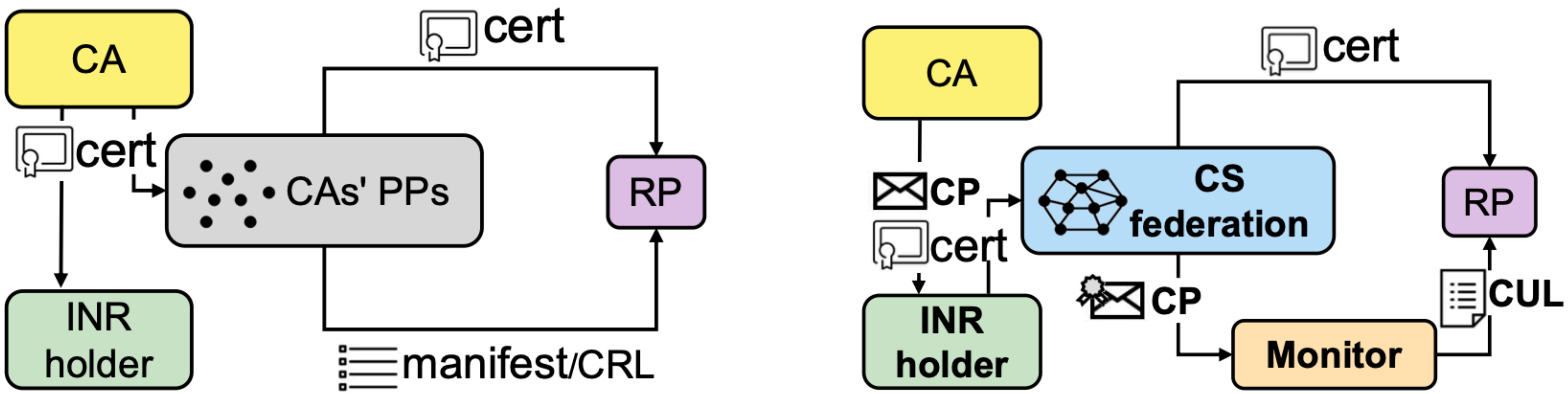
P3

- **Prevent unlimited growth in the number of PPs**
  - Improve the reliability of RPKI Repository system

Be compatible with RPKI architecture and support incremental deployment

Key Idea of dRR

- **Separating RPKI object distribution from signing**
  - decouple PP and RPKI Authority and design a third-party repository for RPKI



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(b) dRR

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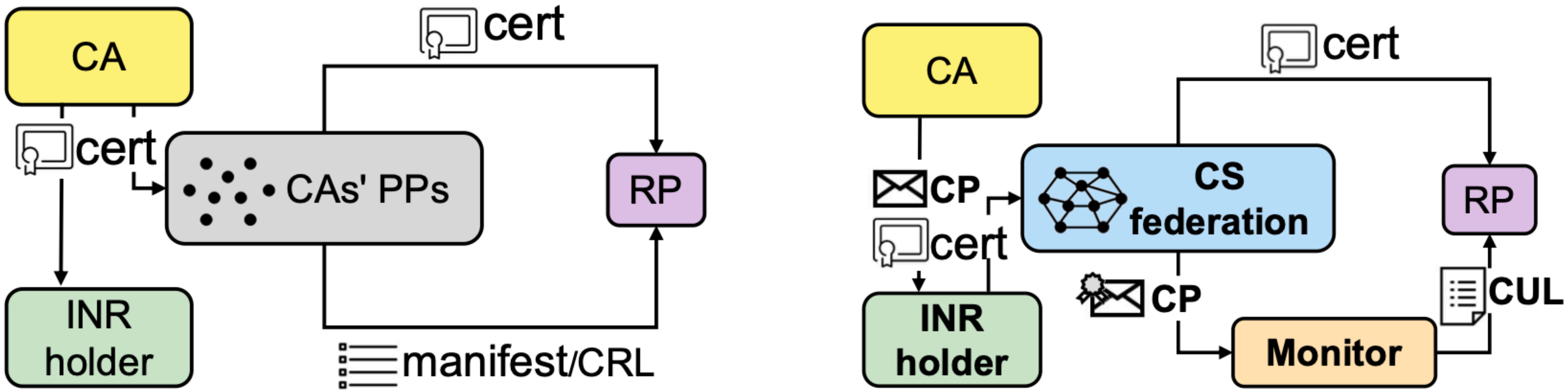

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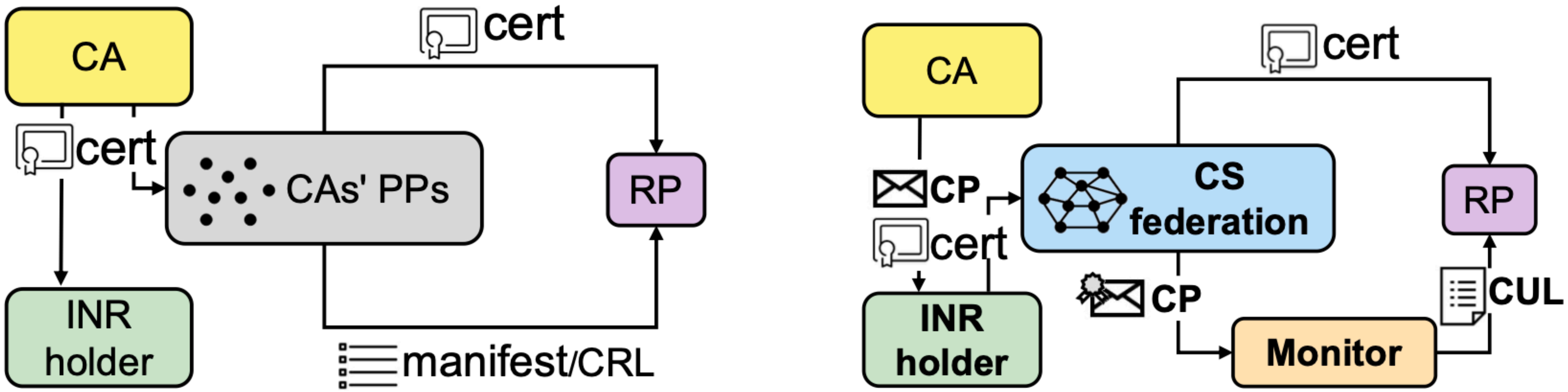

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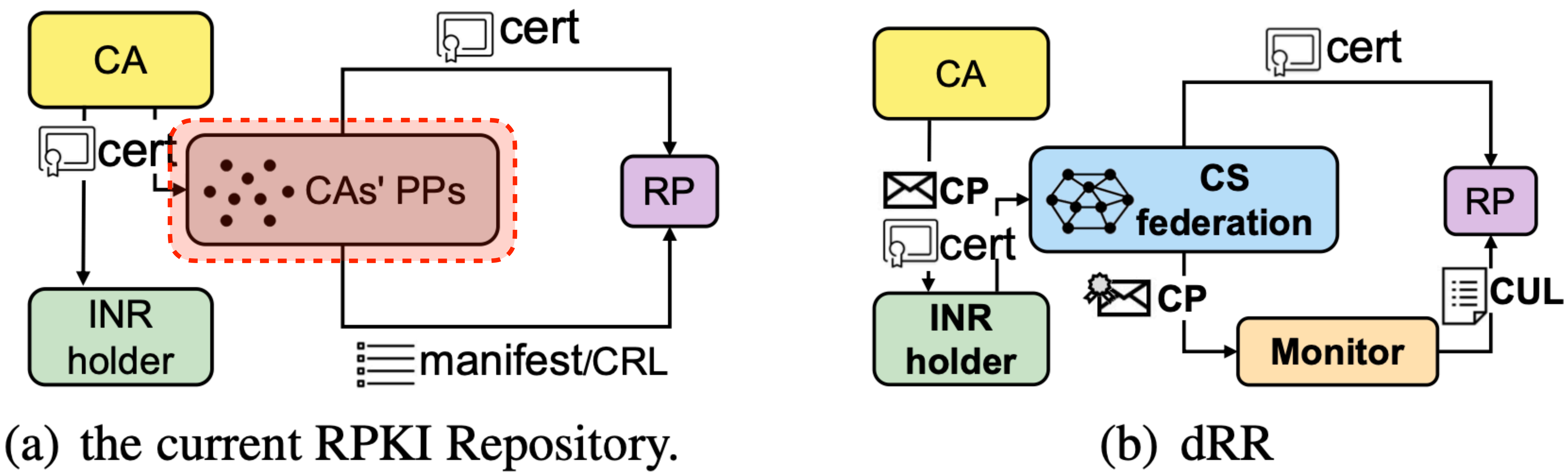

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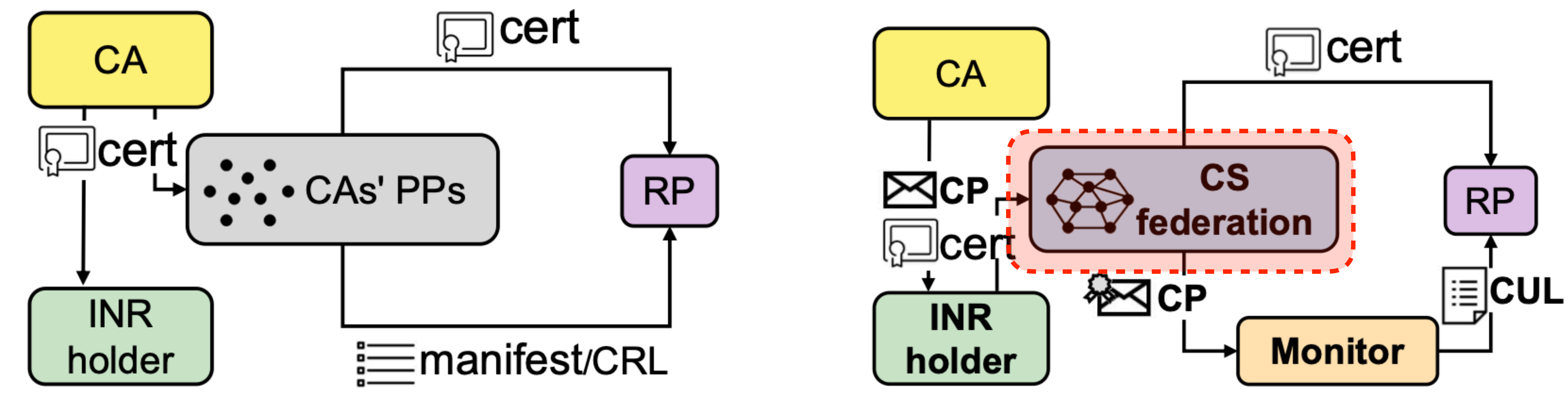

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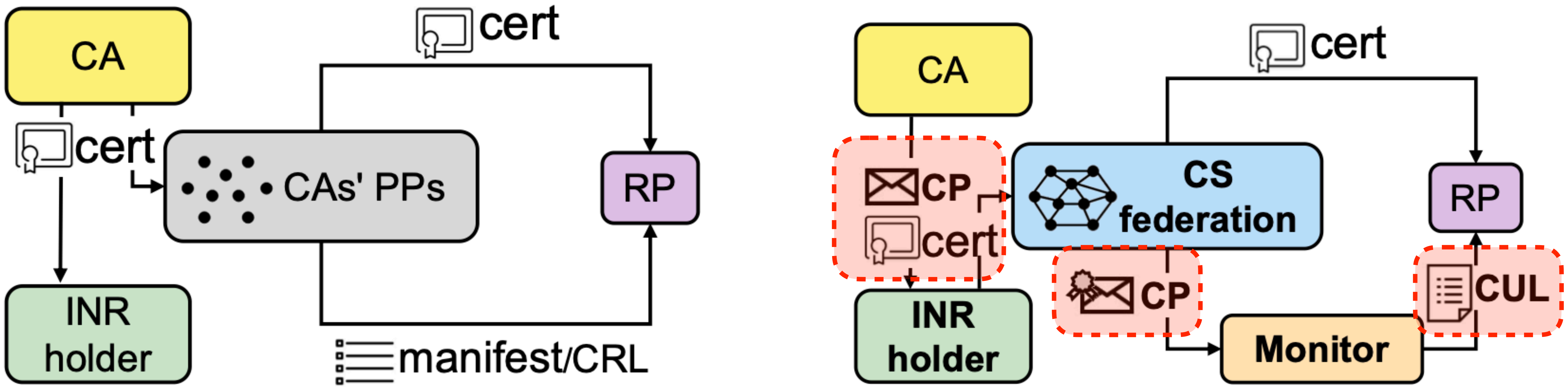

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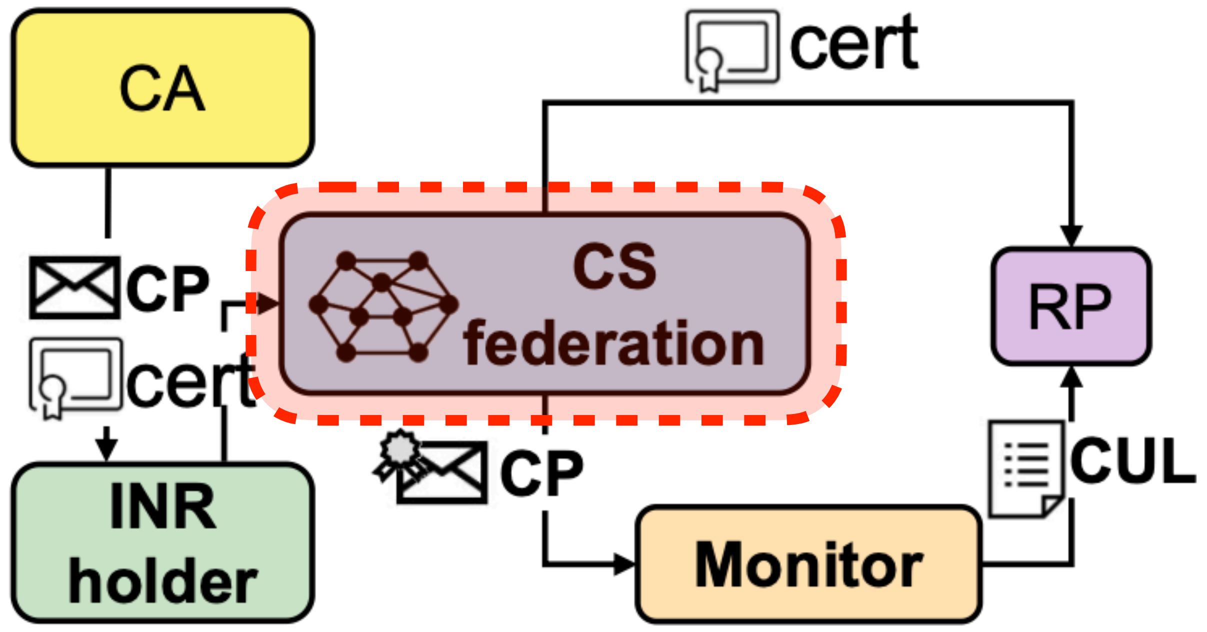
Certificate Server (CS) Federation

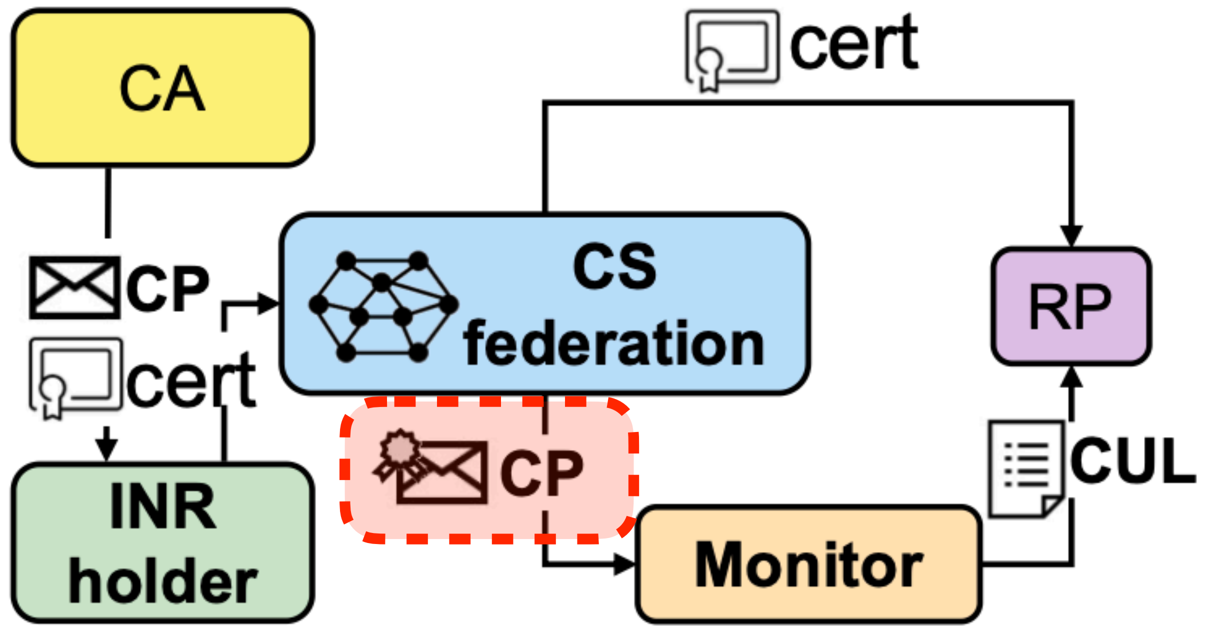


(b) dRR

- Hosting resource certificates and ROAs for resource holders

- Two main improvements of the CS, compared to the traditional publication point (PP)
  - **independent of CAs**, all certificate servers are equal and together form the CS federation
  - **resource holders can freely choose any CSs** they trust to provide certificate hosting services for them
    - not only host the certificates, but also **publicize certificate policies**

Certificate Policy (CP)



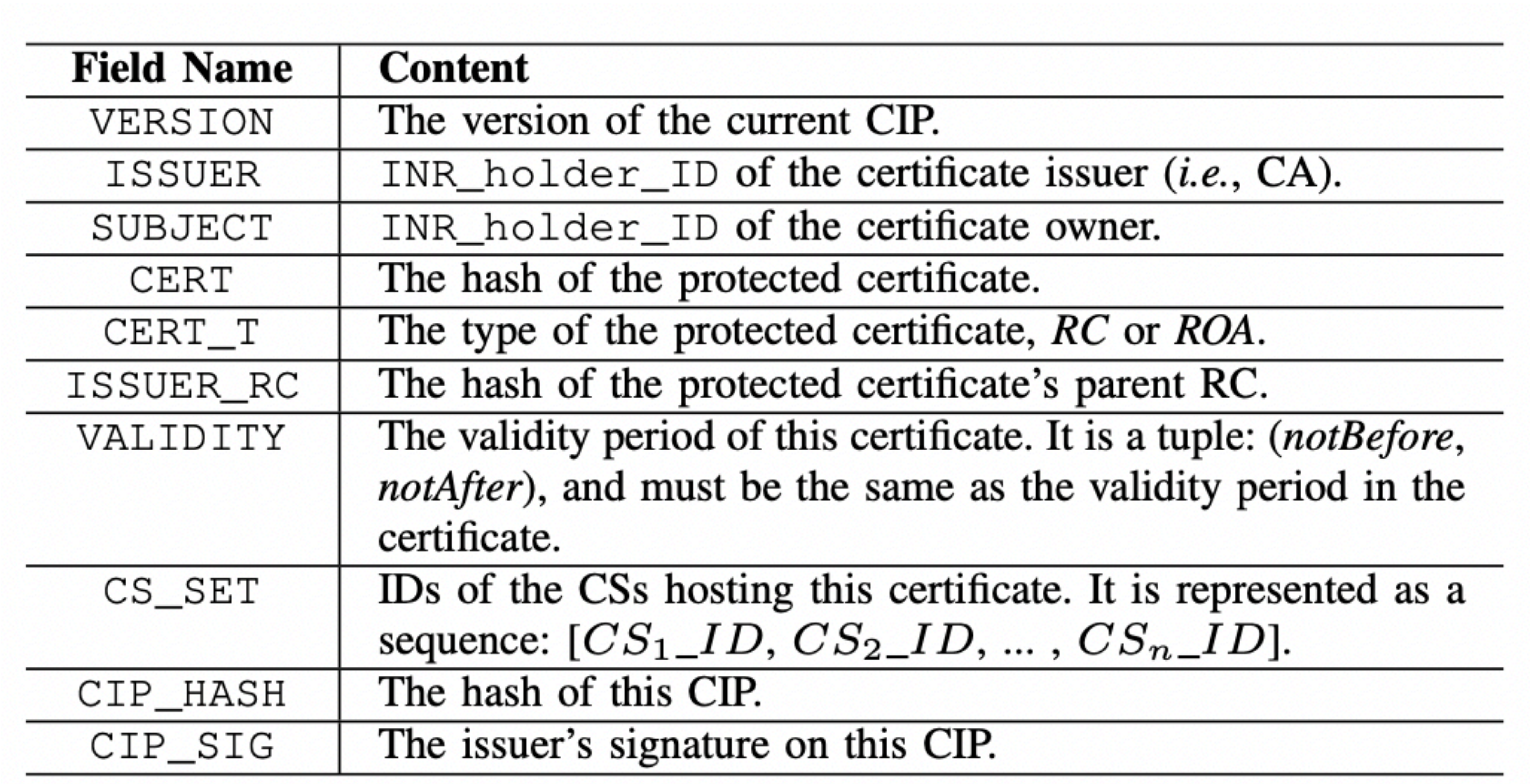
(b) dRR

- Any certificate issuance and revocation will be publicized in the CS federation in the form of Certificate Policies

- Two types of CPs
  - **certificate issuance policy (CIP)**
  - **certificate revocation policy (CRP)**

Certificate Issuance Policy (CIP)

- CAs provide CIPs to resource holders to **prove the authenticity of the issuance** of certificates

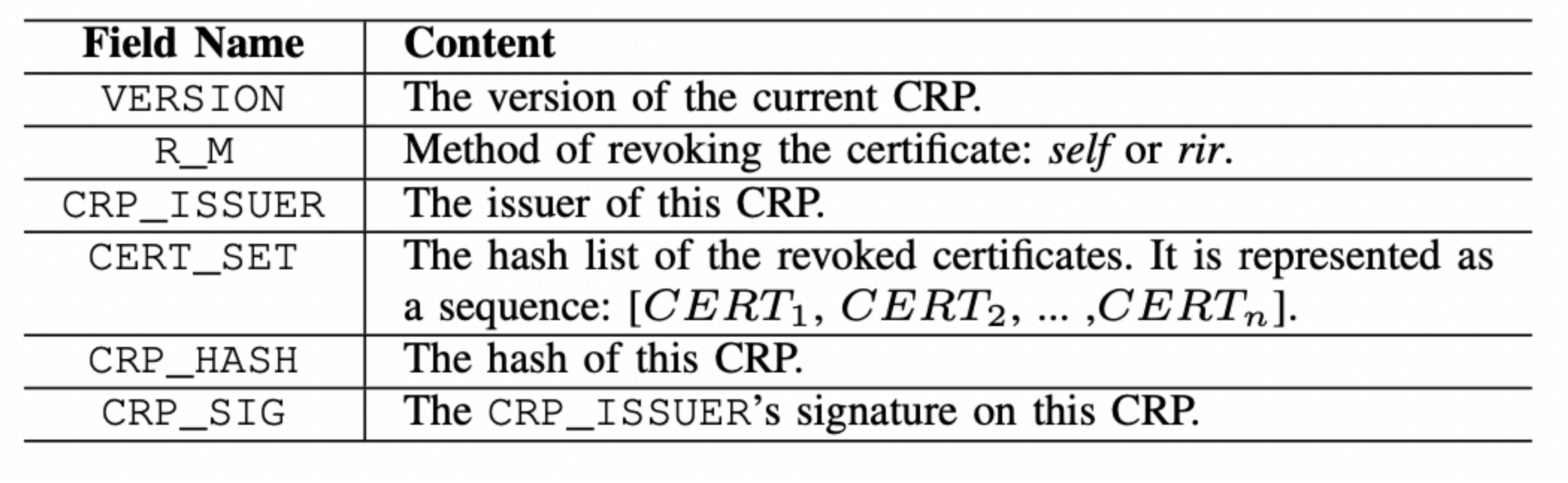


Field Name	Content
`VERSION`	The version of the current CIP.
`ISSUER`	`INR_holder_ID` of the certificate issuer (*i.e.*, CA).
`SUBJECT`	`INR_holder_ID` of the certificate owner.
`CERT`	The hash of the protected certificate.
`CERT_T`	The type of the protected certificate, *RC* or *ROA*.
`ISSUER_RC`	The hash of the protected certificate's parent RC.
`VALIDITY`	The validity period of this certificate. It is a tuple: (*notBefore*, *notAfter*), and must be the same as the validity period in the certificate.
`CS_SET`	IDs of the CSs hosting this certificate. It is represented as a sequence: [CS_1_ID, CS_2_ID, ... , CS_n_ID].
`CIP_HASH`	The hash of this CIP.
`CIP_SIG`	The issuer's signature on this CIP.

Certificate Revocation Policy (CRP)

- Resource holders provide CRPs to confirm that **the revocation has obtained the consent** of all affected parties

- **Five RIRs** can jointly sign CRPs for **mandatory certificate revocation**



Field Name	Content
`VERSION`	The version of the current CRP.
`R_M`	Method of revoking the certificate: *self* or *rir*.
`CRP_ISSUER`	The issuer of this CRP.
`CERT_SET`	The hash list of the revoked certificates. It is represented as a sequence: [$CERT_1$, $CERT_2$, ... ,$CERT_n$].
`CRP_HASH`	The hash of this CRP.
`CRP_SIG`	The `CRP_ISSUER`'s signature on this CRP.

The Global Ledger Maintained by the CS Federation

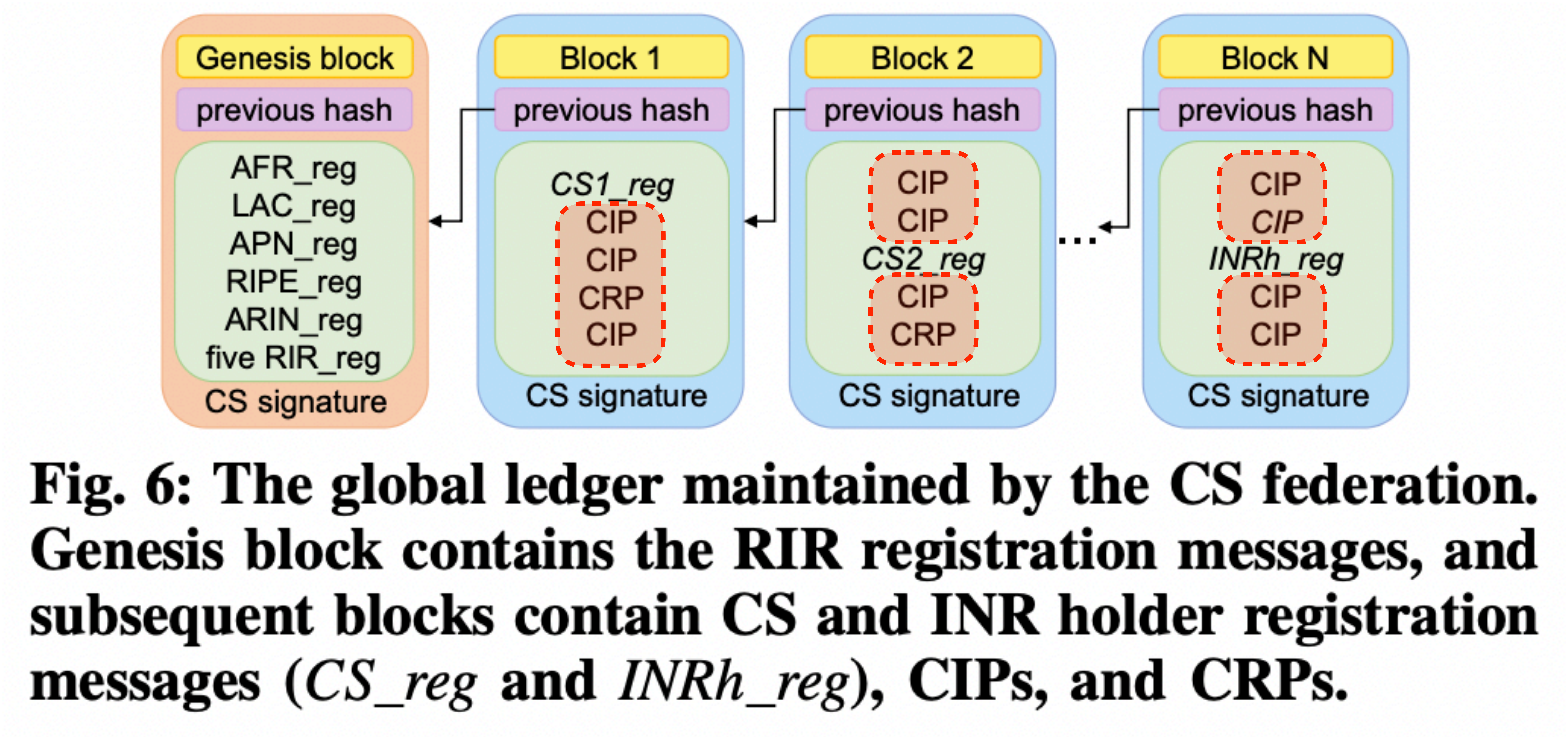


Fig. 6: The global ledger maintained by the CS federation. Genesis block contains the RIR registration messages, and subsequent blocks contain CS and INR holder registration messages (*CS_reg* and *INRh_reg*), CIPs, and CRPs.

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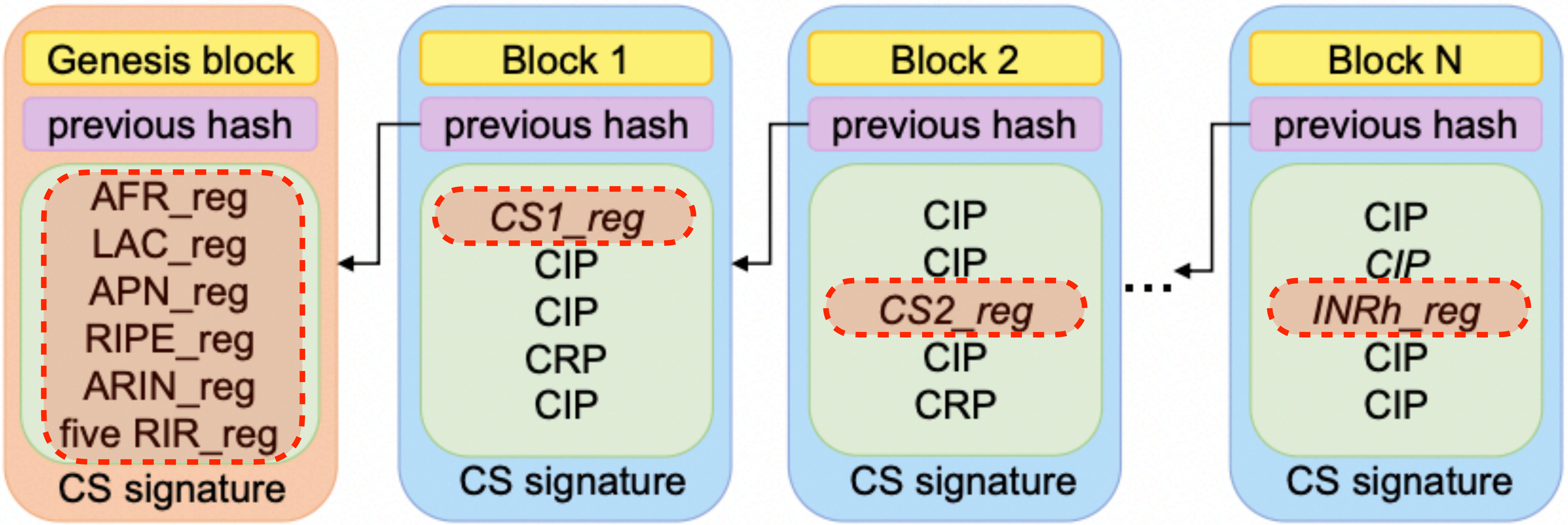

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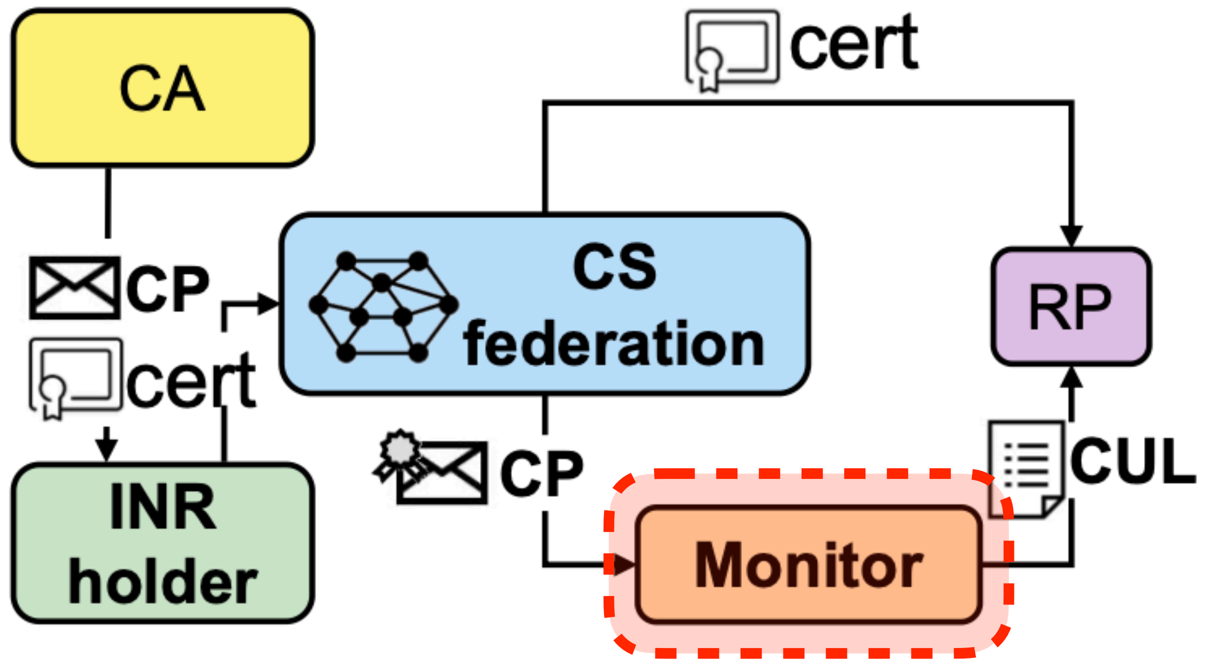

(b) dRR

- The Monitor in dRR provides proofs of the status of a specific certificate and the trustworthiness of the monitor
    - proof of presence, proof of absence, proof of consistency

- M-Tree
    - a Merkle Hash Tree (MHT) with leaf nodes containing CPs
    - generate a *commitment* (root hash of the tree) after inserting a block’s CIPs and CRPs
    - the newly added CIPs in one block will be appended into the M-Tree according to the lexicographical order of their certificate hashes
    - the revocation of the certificates in the newly added CRP is recorded by modifying the CIP entries of the respective certificates

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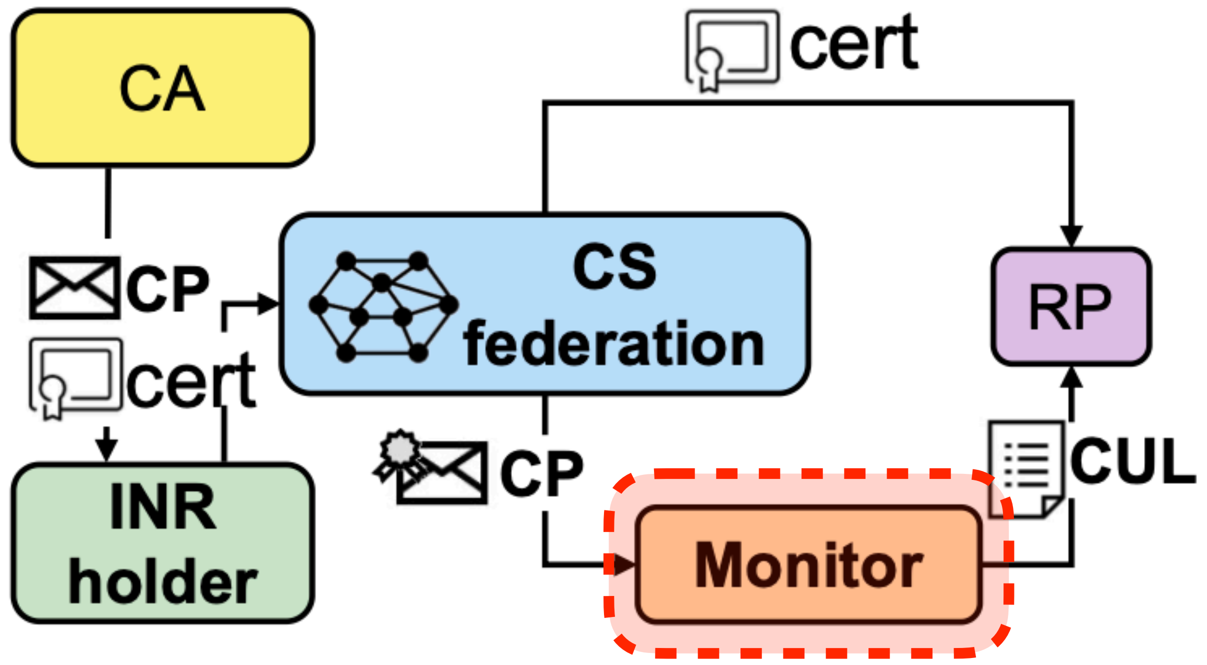

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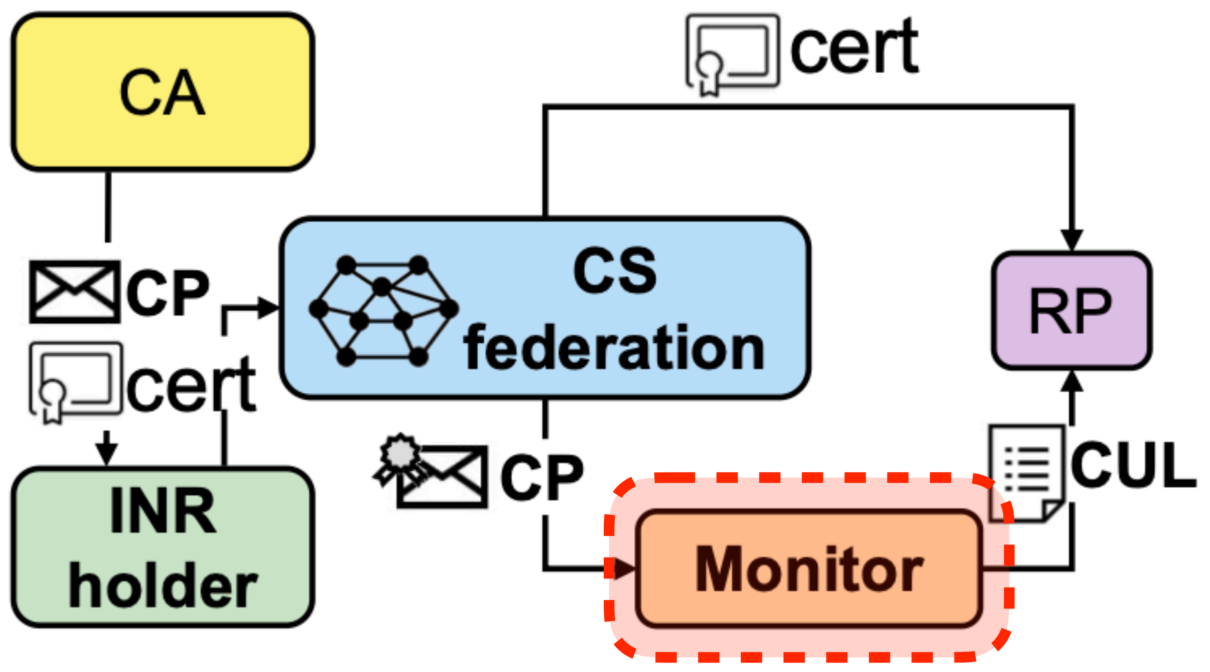

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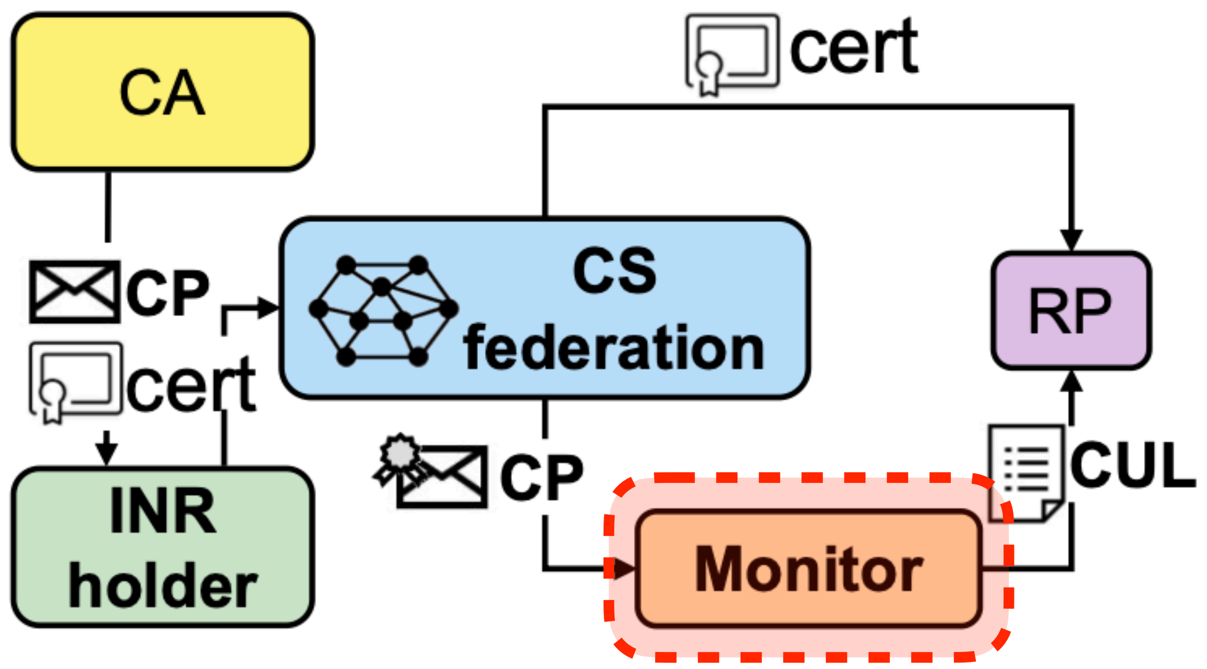

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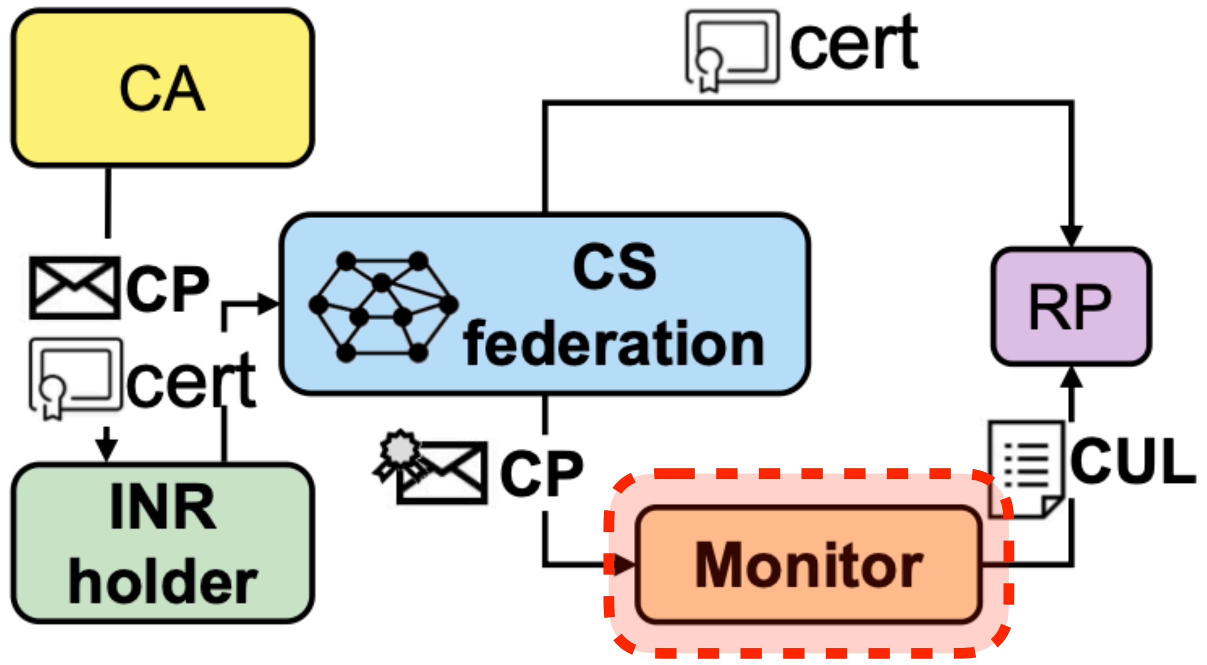

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- **A pruned tree** that contains the leaf entry of the requested certificate and the intermediate nodes needed to reconstruct the commitment

- Verification process
  - an INR holder asks whether a certificate exists
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  - the INR holder reconstructs a *commitment* C'
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  - then the INR holder accesses *the commitment update files* provided by other Monitors to check the authenticity of *C′*

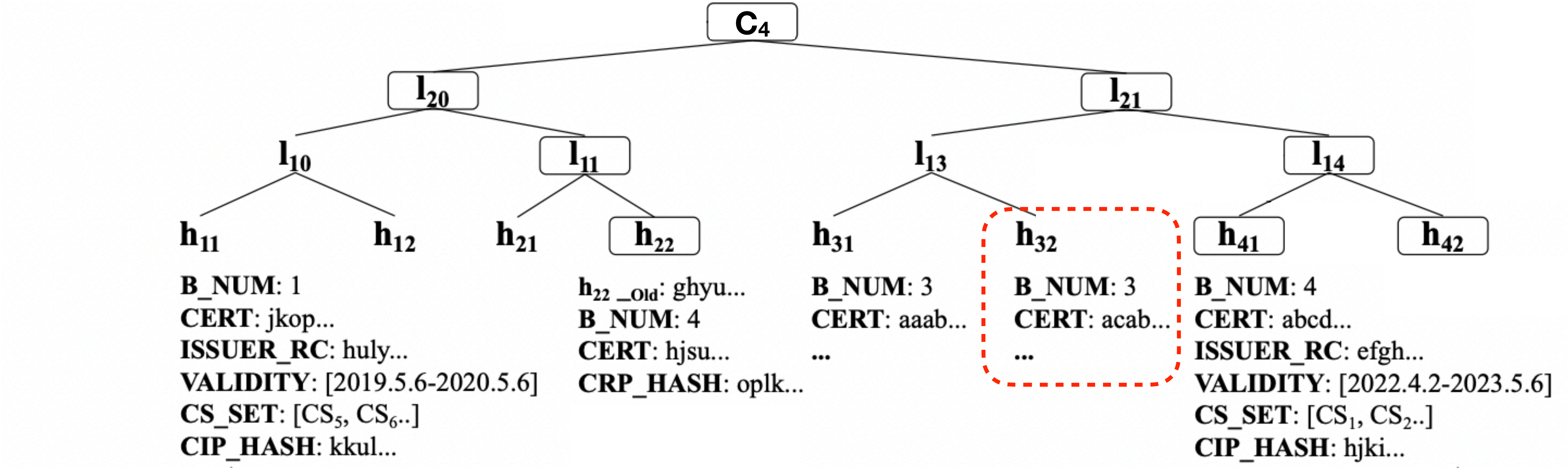
Proof of Presence

- A pruned tree that contains the leaf entry of the requested certificate and the intermediate nodes needed to reconstruct the commitment

- **Verification process**
  - an INR holder asks whether a certificate exists
  - the Monitor will return a proof of presence
  - the INR holder reconstructs a *commitment C′*
  - **then the INR holder accesses *the commitment update files* provided by other Monitors to check the authenticity of *C′***

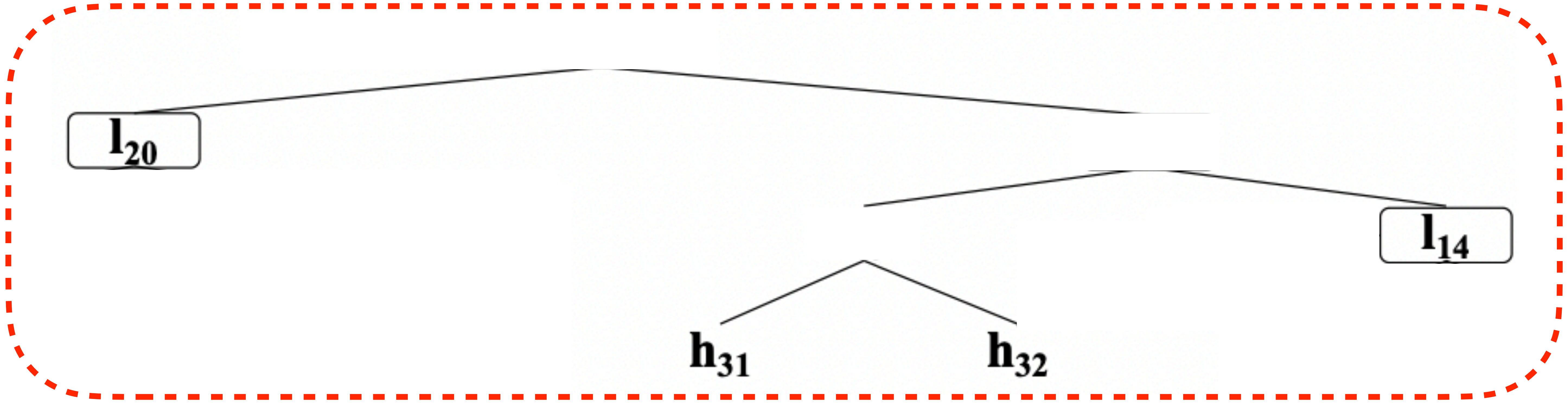
Proof of Presence: example

- INR holder asks whether the certificate in h32=⟨B_NUM = 3,CERT = acab…⟩ exists



Proof of Presence: example

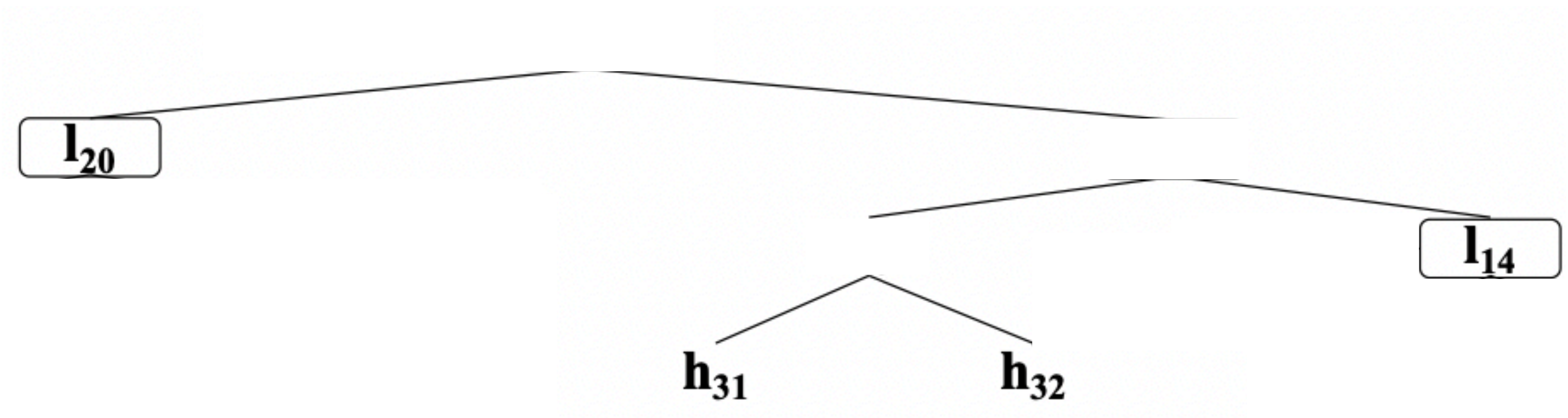
- The Monitor will return a pruned tree that contains the entry of h_{32} and the hash of h_{31}, intermediate nodes l_{14} and l_{20} to the INR holder



proof of presence

Proof of Presence: example

- The INR holder can easily reconstruct the *commitment C_4'*



Proof of Presence: example

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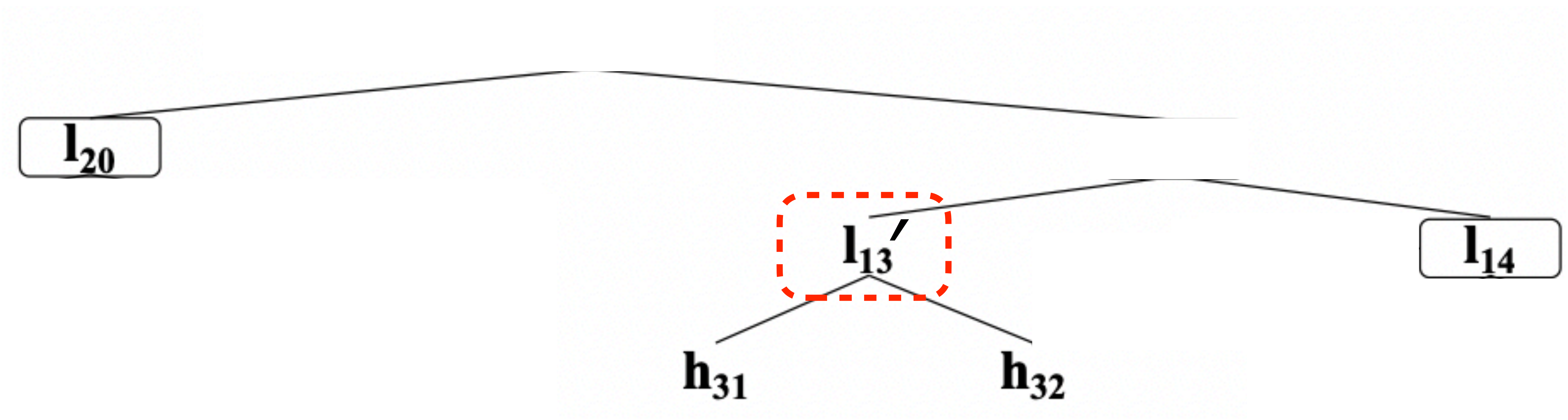
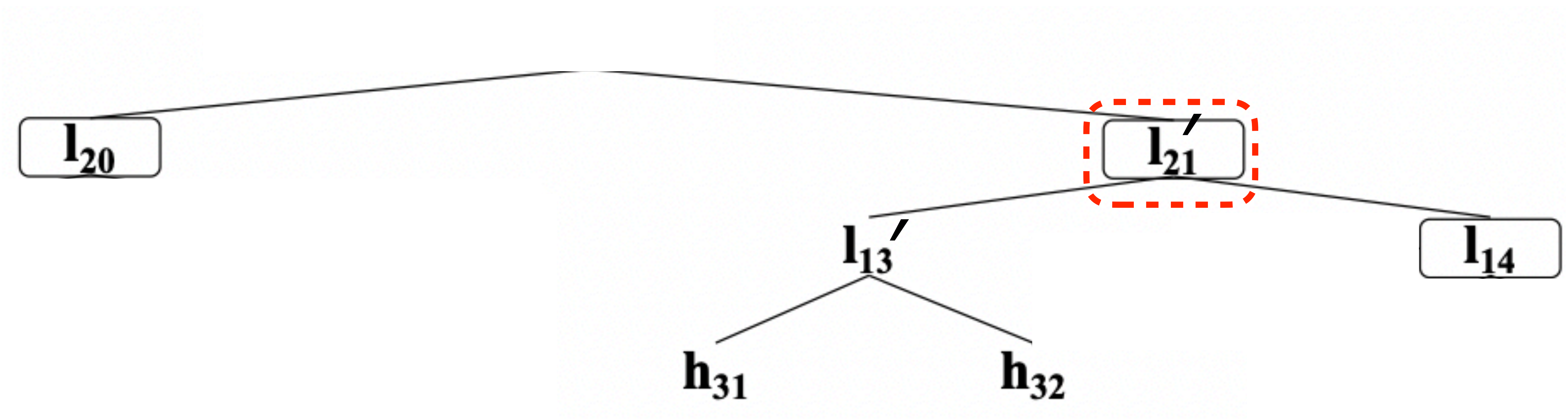


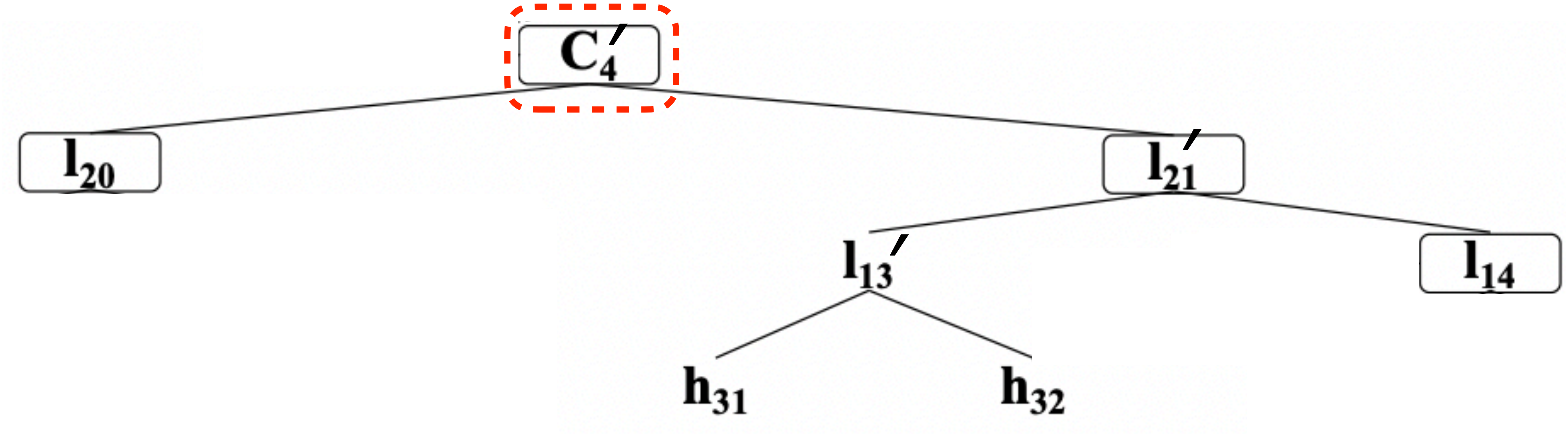
Proof of Presence: example

- The INR holder can easily reconstruct the *commitment C_4'*



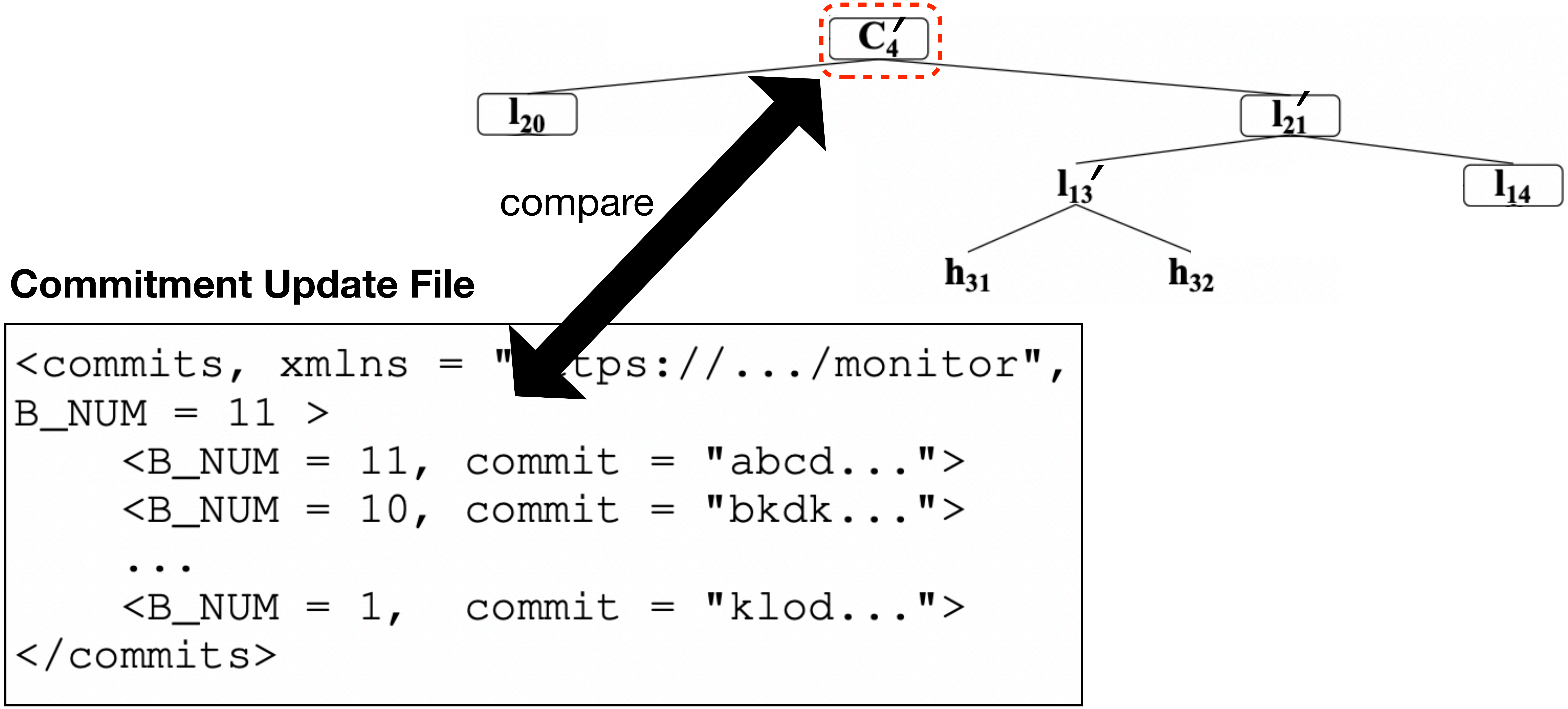
Proof of Presence: example

- The INR holder can easily reconstruct the *commitment C_4'*



Proof of Presence: example

- Then the INR holder accesses the commitment update files provided by other Monitors to check the authenticity of C_4'



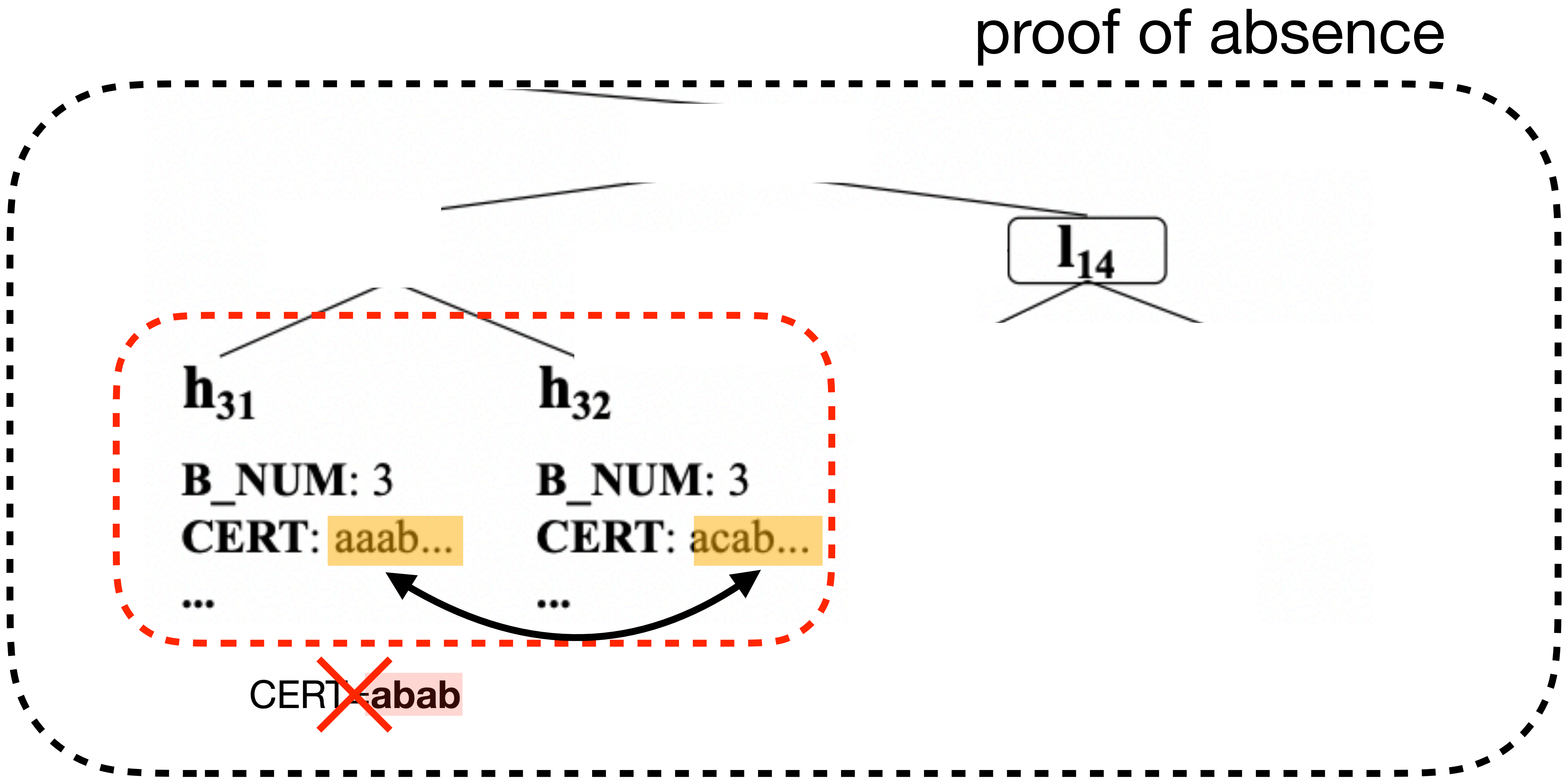
Commitment Update File

```
<commits, xmlns = "  tps://.../monitor",
B_NUM = 11 >
    <B_NUM = 11, commit = "abcd...">
    <B_NUM = 10, commit = "bkdk...">
    ...
    <B_NUM = 1,  commit = "klod...">
</commits>
```

Proof of Absence

- A pruned tree
  - contains **two consecutive leaf nodes** where **the hash of the queried certificate is between the hashes of them**
  - and the intermediate nodes needed to reconstruct the commitment
- Verification process is the same as that of the proof of presence

<B_NUM=3, CERT=**abab**> ?



Proof of Absence

- A pruned tree
  - contains **two consecutive leaf nodes** where **the hash of the queried certificate is between the hashes of them**
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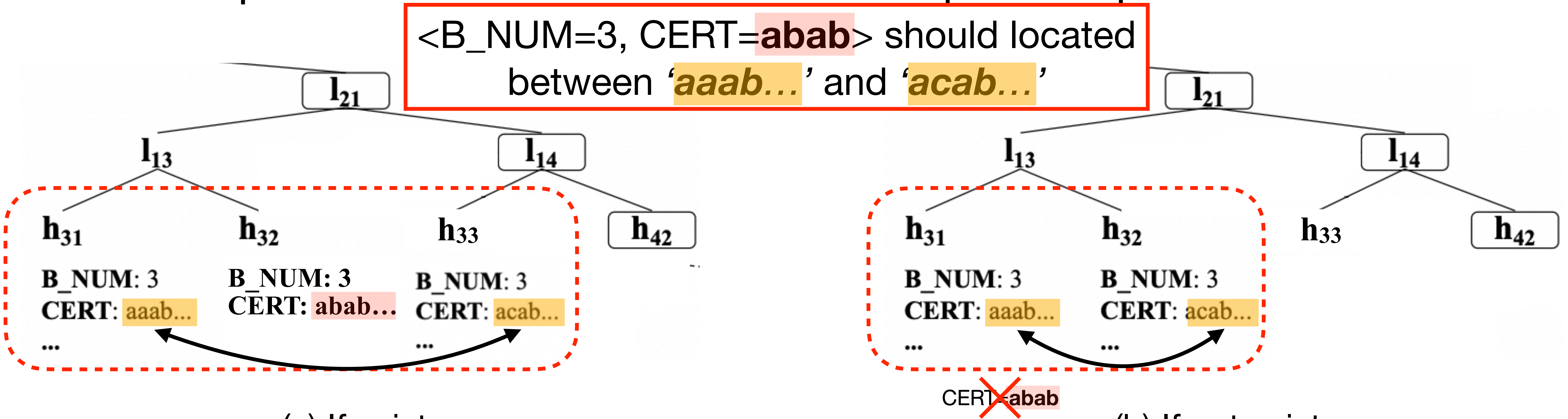


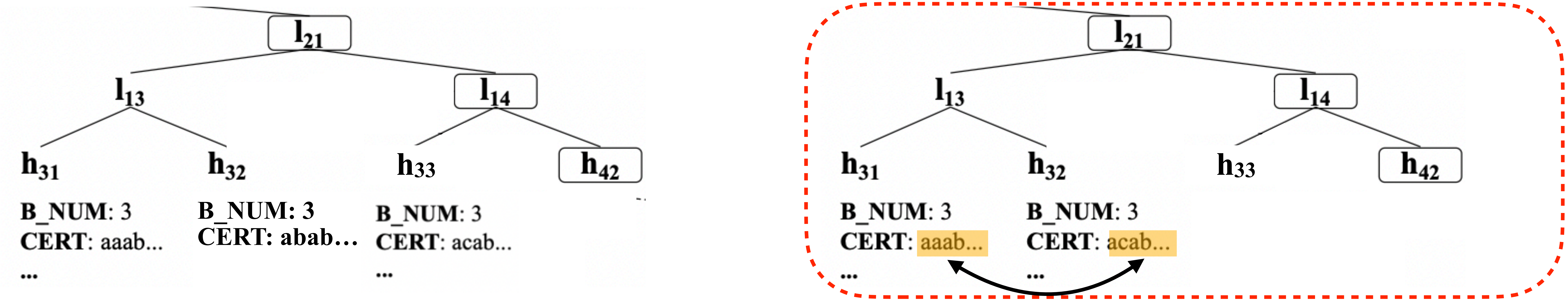
<B_NUM=3, CERT=**abab**> should located between '***aaab…***' and '***acab…***'

(a) If exist

(b) If not exist

Proof of Absence

- A pruned tree
  - contains **two consecutive leaf nodes** where **the hash of the queried certificate is between the hashes of them**
  - and the intermediate nodes needed to reconstruct the commitment
- Verification process is the same as that of the proof of presence



(a) If exist

no such certificate exists → proof of absence

(b) If not exist

Proof of Consistency

- A pruned tree
  - contains a **Certificate Update List** (**CUL**, a list of newly inserted or updated entries) and a proof (hashes needed to reconstruct a commitment)
  - prove that the commitment of the current M-tree is indeed evolved from the previous commitment

Proof of Consistency

- Verification process
  - **A Relying Party (RP) submits <B_num=3, c=C_3>, the RP has completed the synchronization of the first three blocks**
  - The Monitor will return a proof of consistency whose commitment is C_4
  - The RP verify that the reconstructed commitment C'_4 is trusted
  - The RP verify that the reconstructed commitment C'_4 is evolved from C_3

Proof of Consistency

- Verification process
  - A Relying Party (RP) submits <B_num=3, c=C_3>, the RP has completed the synchronization of the first three blocks
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  - The RP verify that the reconstructed commitment C'_4 is trusted
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Proof of Consistency

- Verification process
  - A Relying Party (RP) submits <B_num=3, c=C_3>, the RP has completed the synchronization of the first three blocks
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  - **The RP verify that the reconstructed commitment C'_4 is trusted**
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Proof of Consistency

- Verification process
  - A Relying Party (RP) submits <B_num=3, c=C_3>, the RP has completed the synchronization of the first three blocks
  - The Monitor will return a proof of consistency whose commitment is C_4
  - The RP verify the authenticity of the reconstructed commitment C'_4
  - **The RP verify whether the reconstructed commitment C'_4 is evolved from C_3**

Proof of Consistency

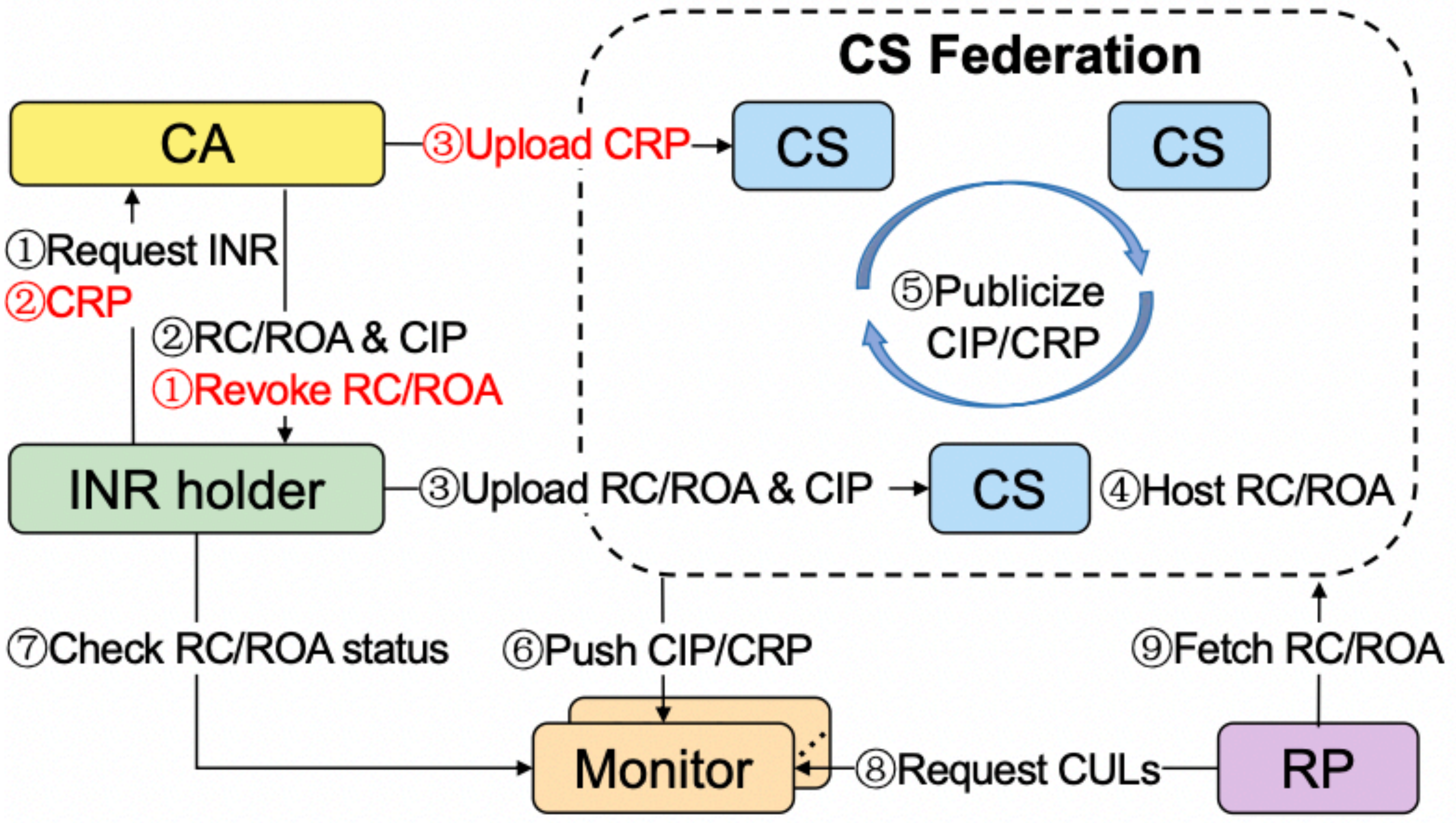
- Verification process
  - A Relying Party (RP) submits <B_num=3, c=C_3>, the RP has completed the synchronization of the first three blocks
  - The Monitor will return a proof of consistency whose commitment is C_4
  - The RP verify the authenticity of the reconstructed commitment C'_4
  - **The RP verify whether the reconstructed commitment C'_4 is evolved from C_3**

    deletes inserted entries and reverts the updated entries from the pruned tree

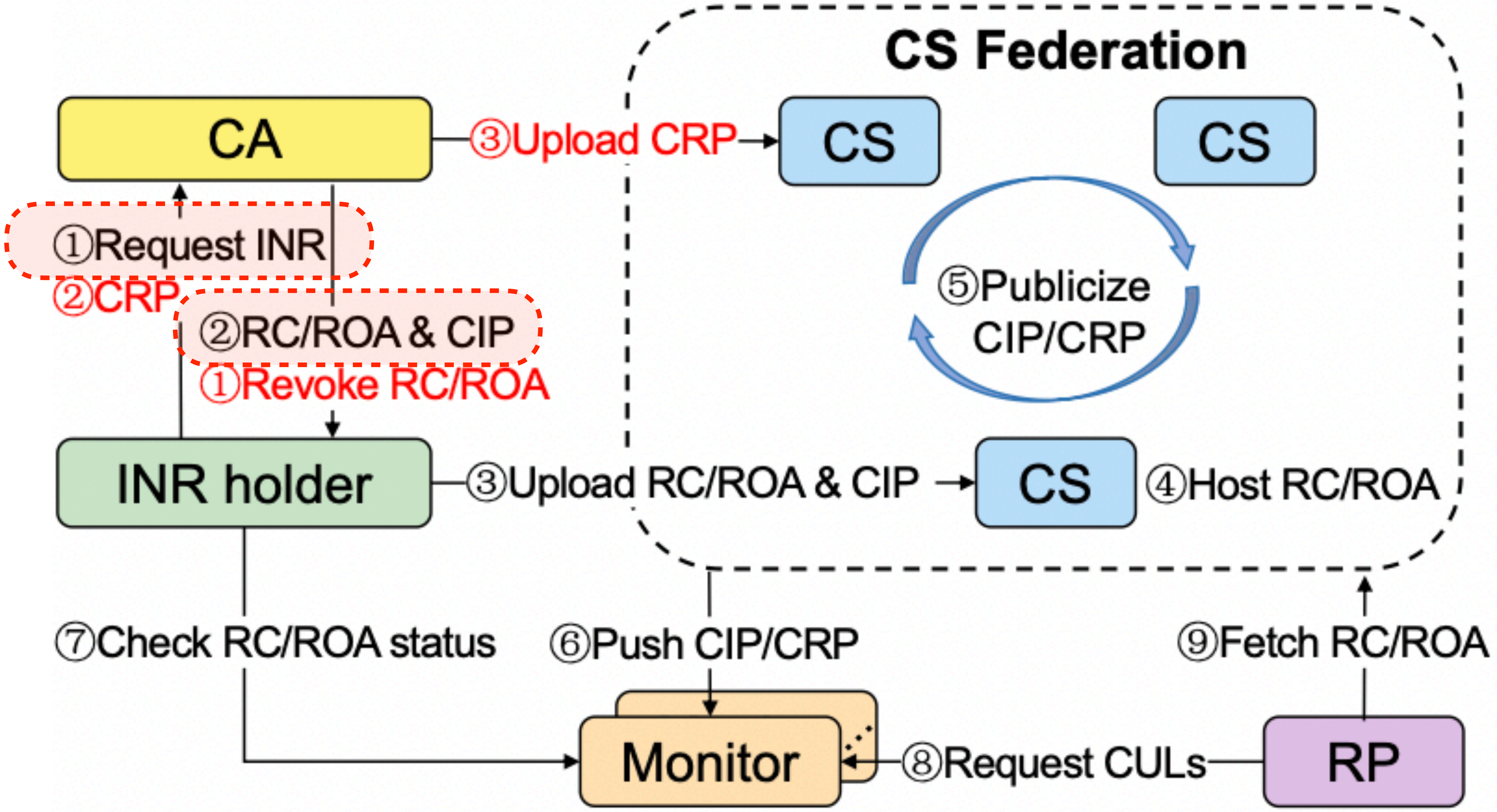
    re-calculates the commitments C′3

    checks whether it is equal to C3

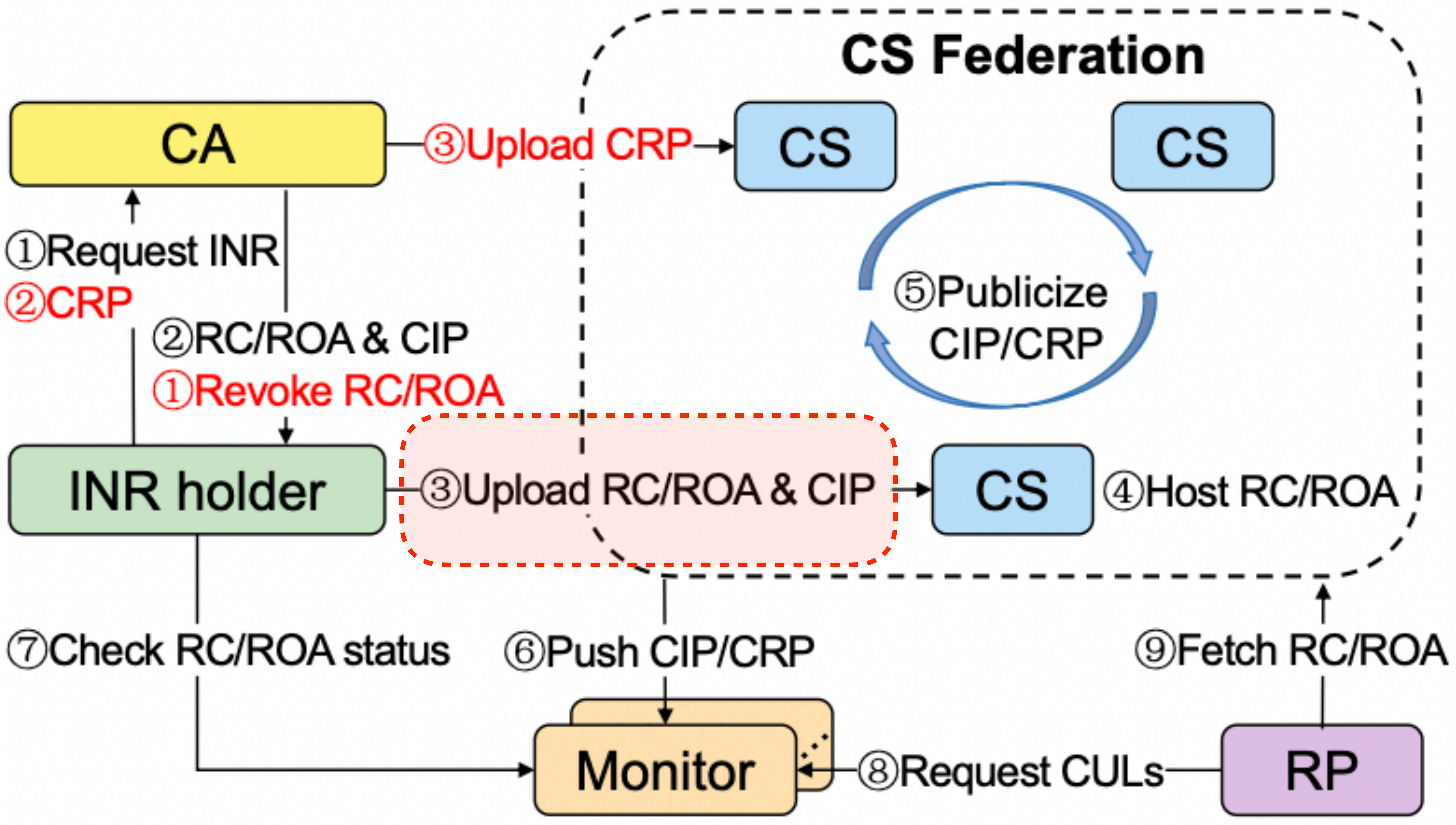
dRR Workflow



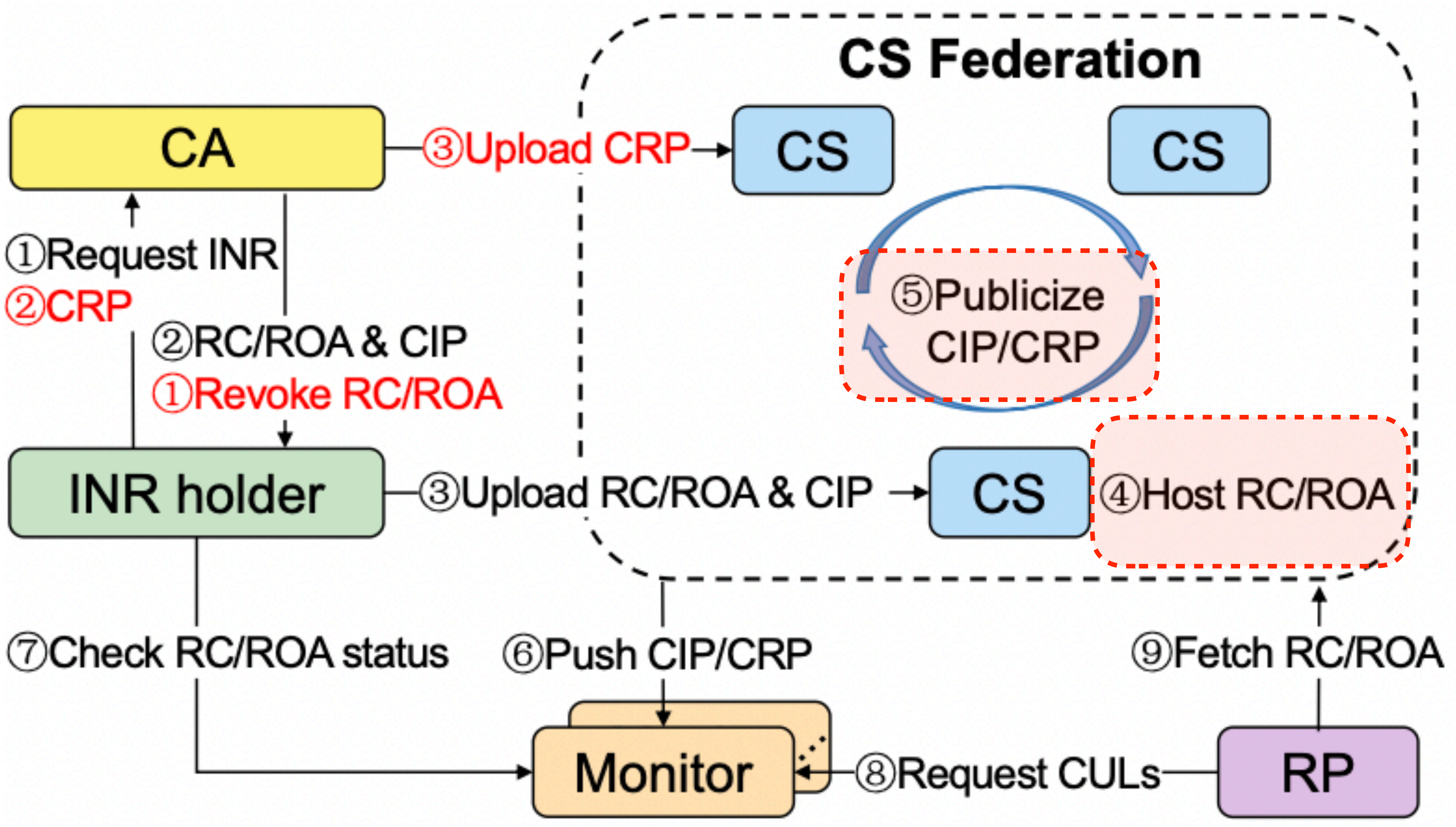
dRR Workflow



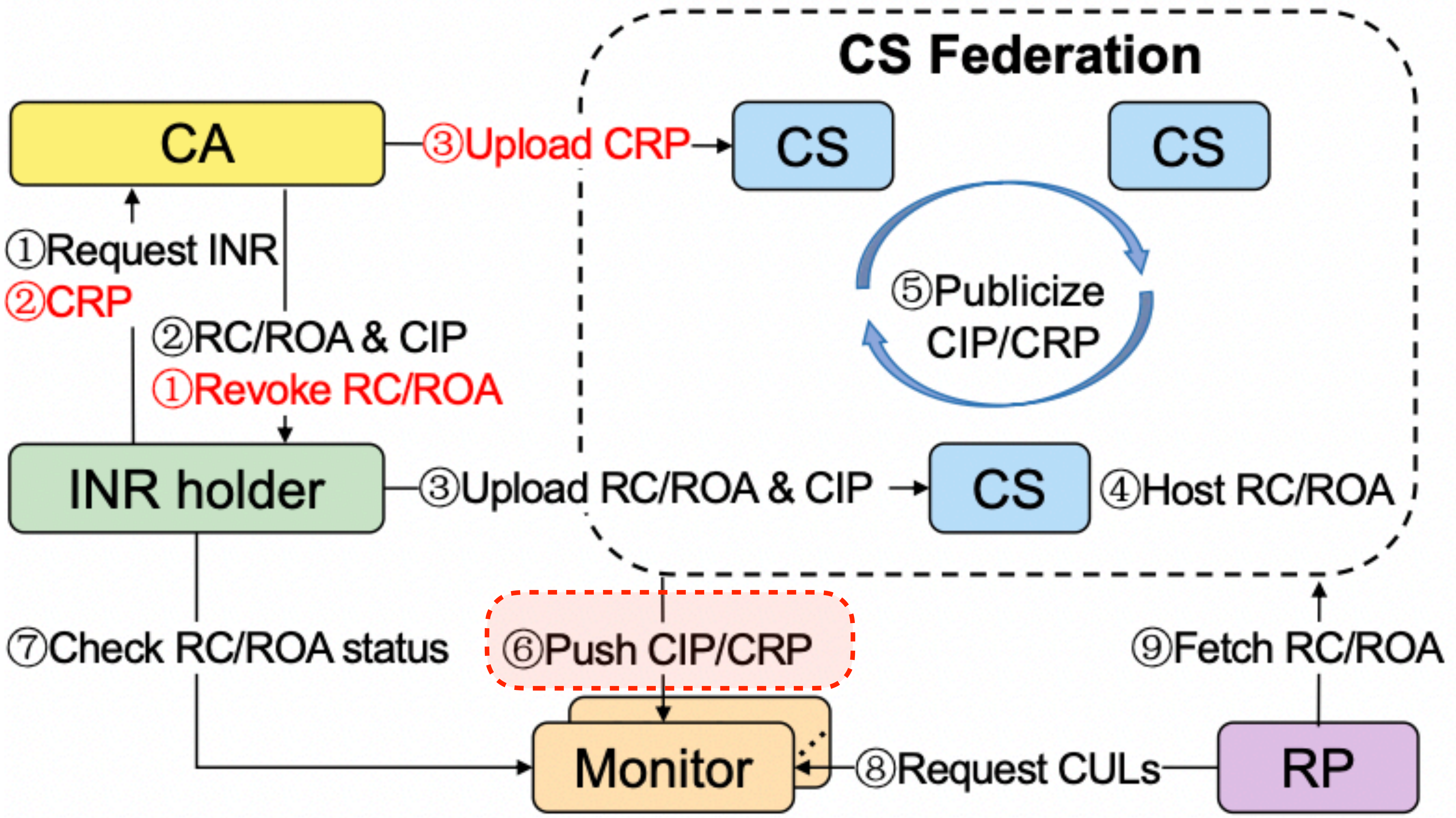
dRR Workflow



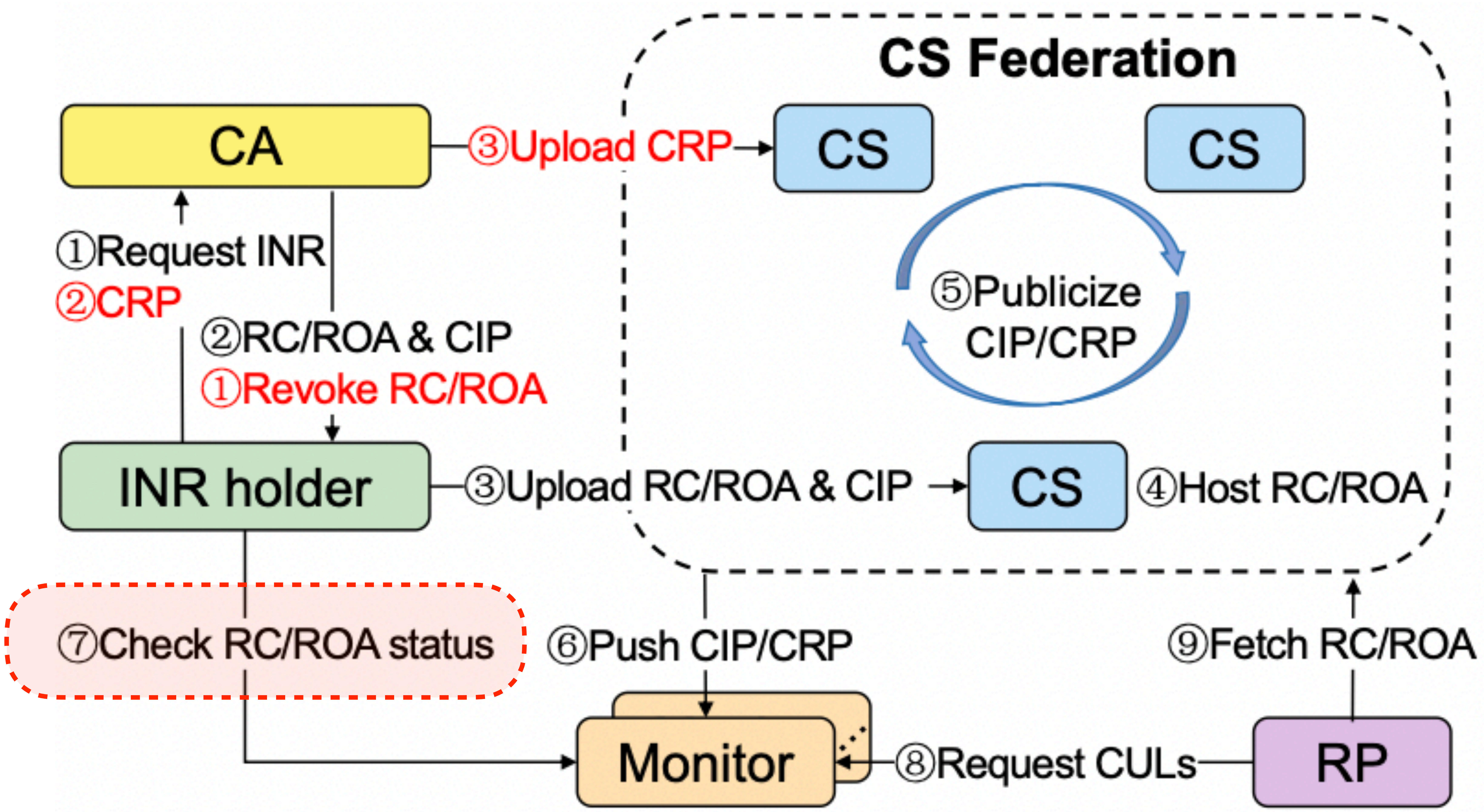
dRR Workflow



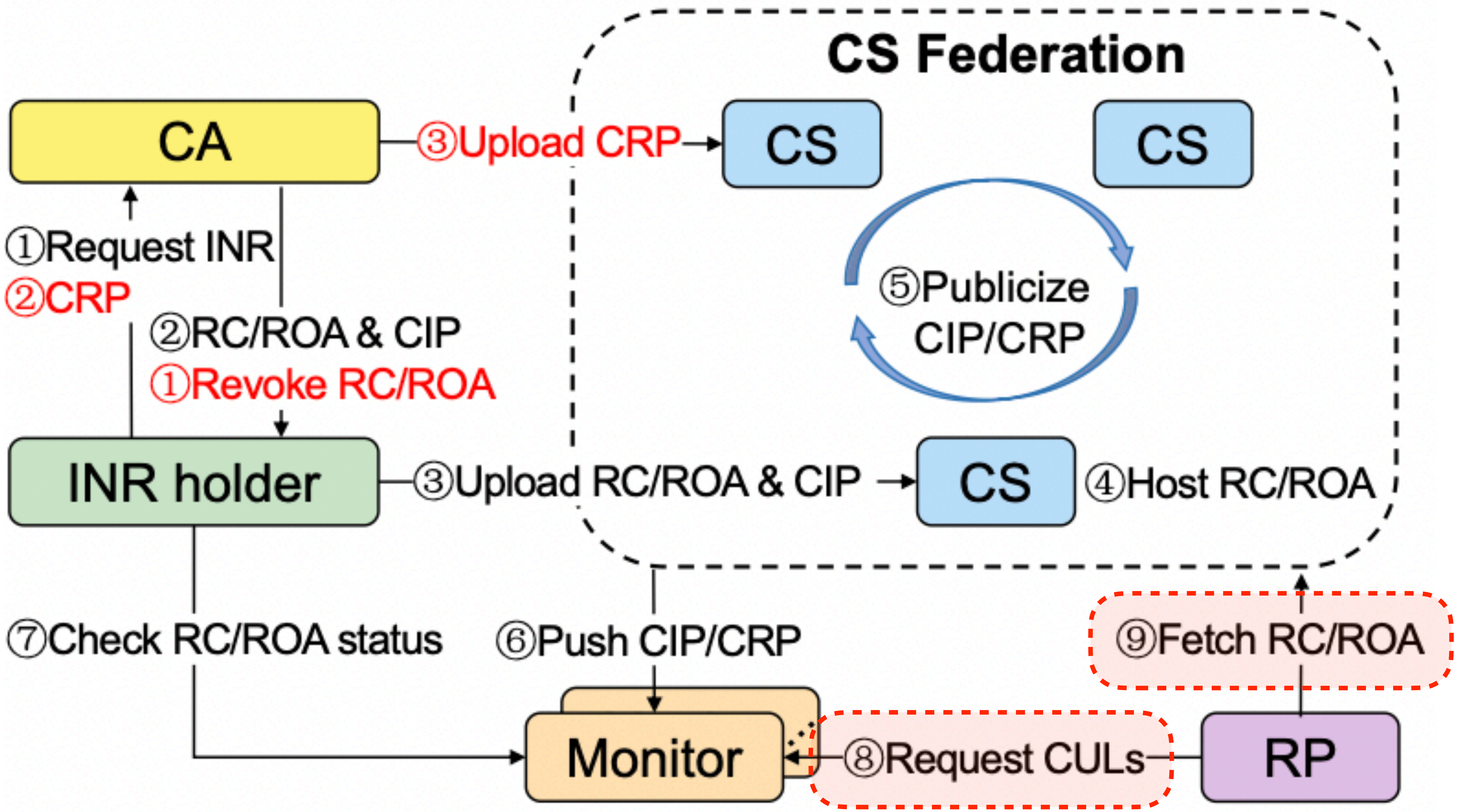
dRR Workflow



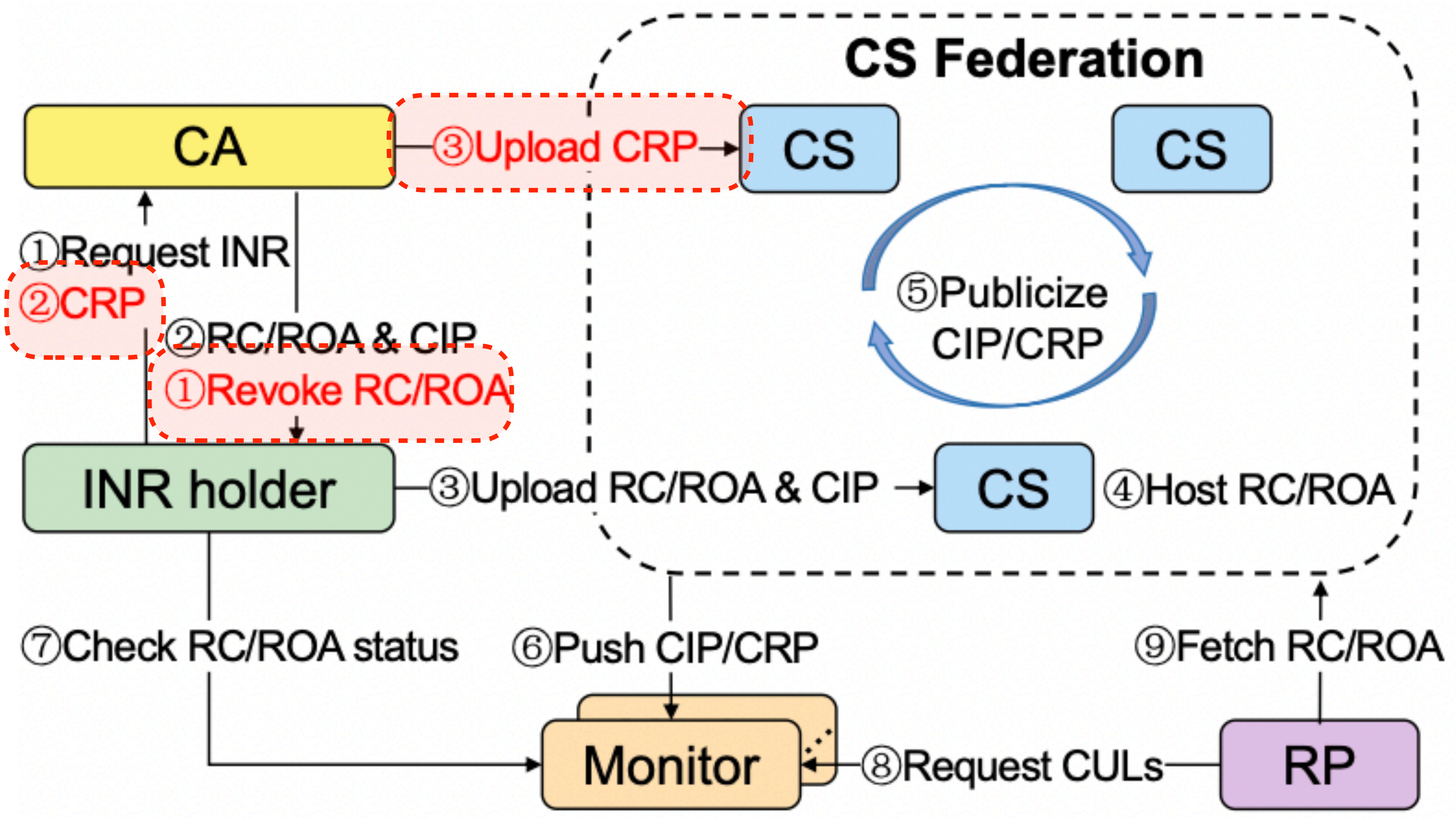
dRR Workflow



dRR Workflow



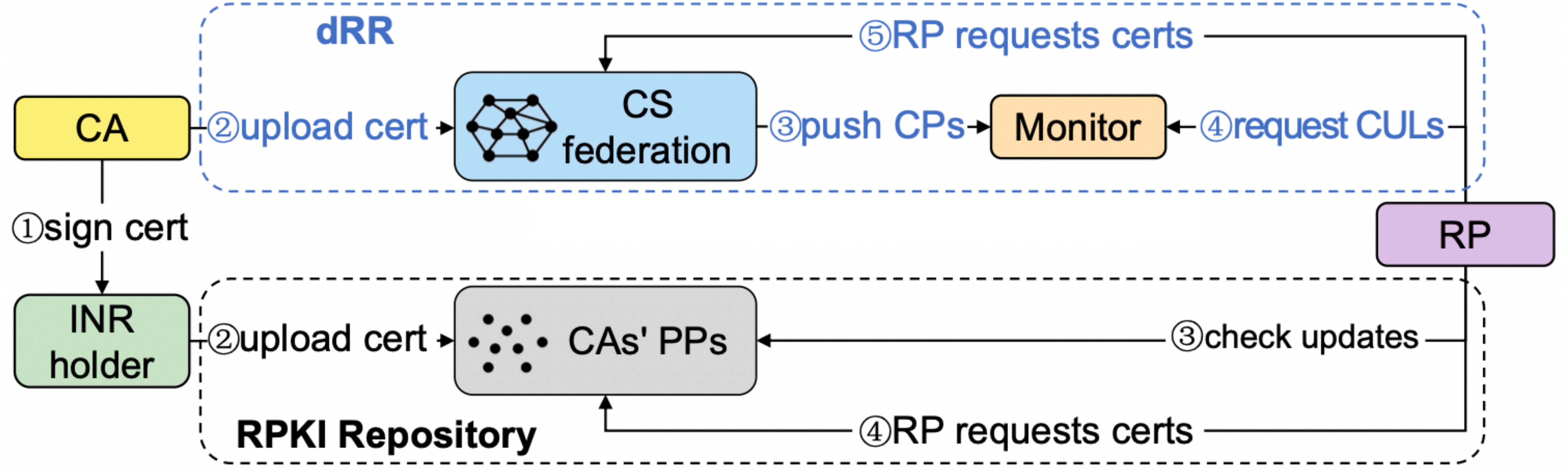
dRR Workflow



Evaluation

- Global Testbed
  - 100 server nodes across 15 countries
  - 50 nodes for CS federation and 50 nodes for Monitors

- Goal: evaluate the overhead of dRR



Evaluating CS Federation

- **Metrics**
  - throughput of the CS federation
  - the latency from a submission of a certificate policy to the confirmation
- **Baseline:**
  - the frequency of the issuance and the revocation in the current RPKI system
  - the **peak** reaches **60k/day (issued 30K + revoked 30K)**

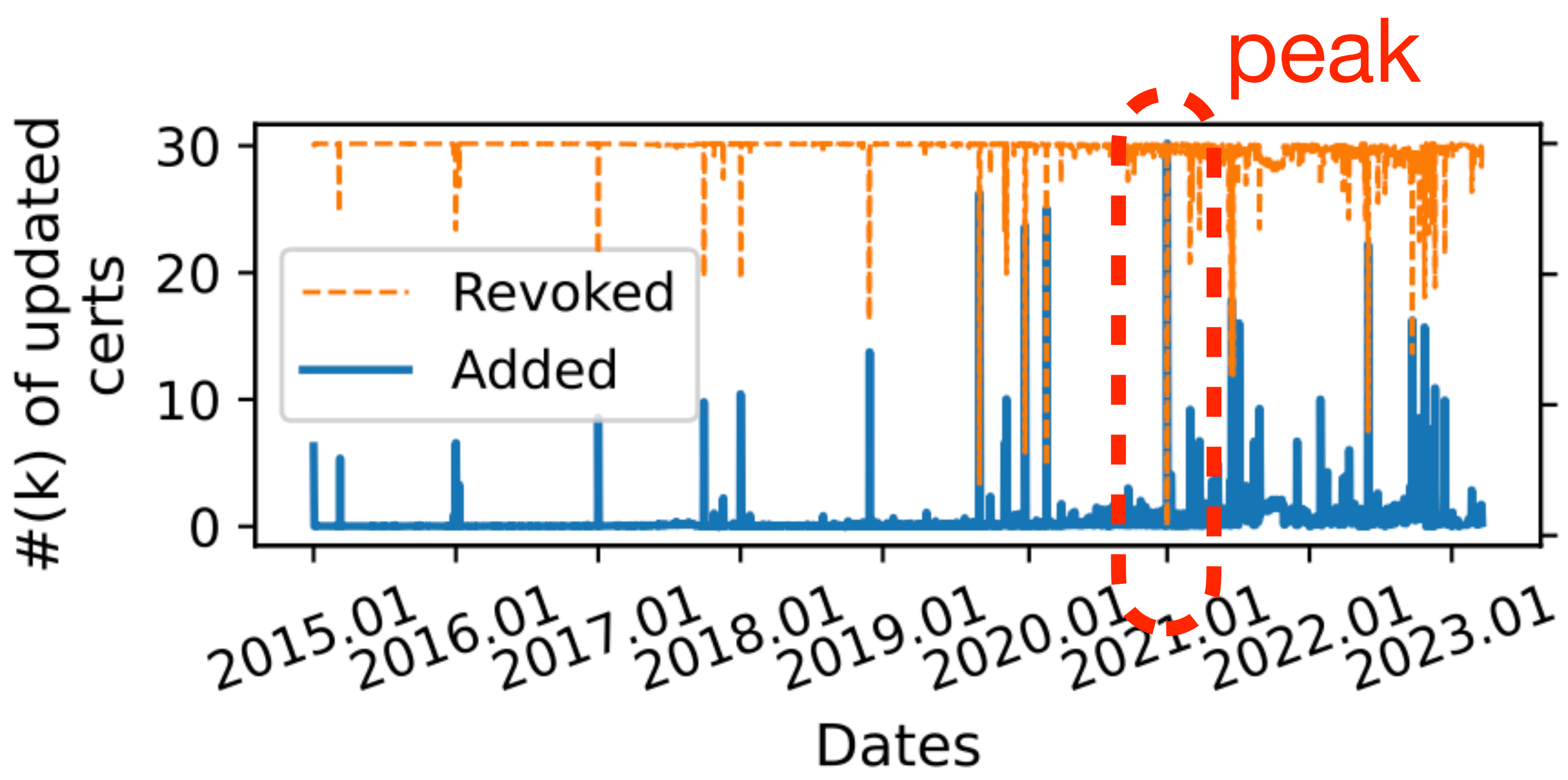


Fig. 9: The number of added and revoked certificates per day from Jan 1, 2015 to Apr 1, 2023.

Evaluating CS Federation

- **Results**
  - throughput ≈ **310/s** (i.e., 26.78 M/day) which is **450 times faster than that of the baseline**
  - **latency < 2s**

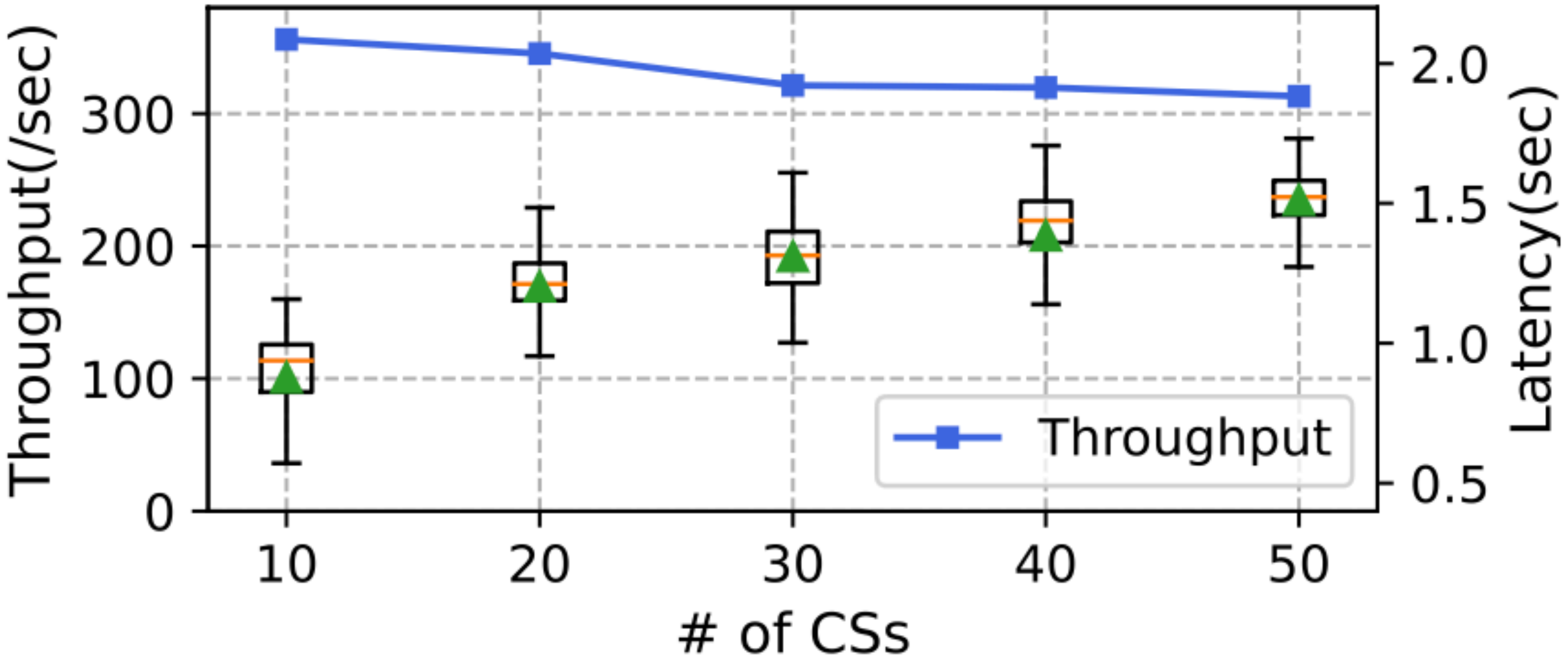


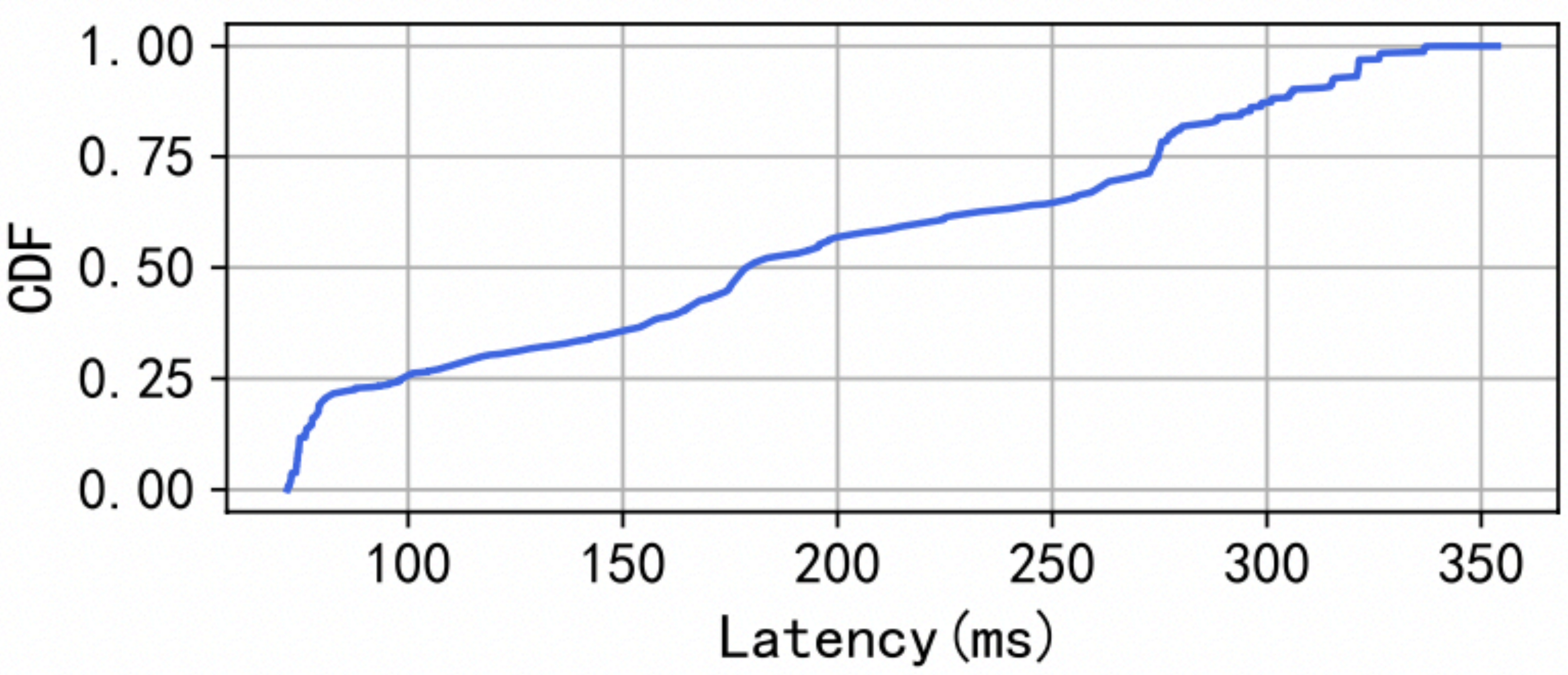
Fig. 12: The maximum throughput and the corresponding latency distribution of the system under different CS scales. Candlesticks show the maximum and minimum latency and the average latency (green triangle).

Evaluating Monitors

- **Latency**
  - from sending a block by a CS to a Monitor completing the M-Tree update about the block

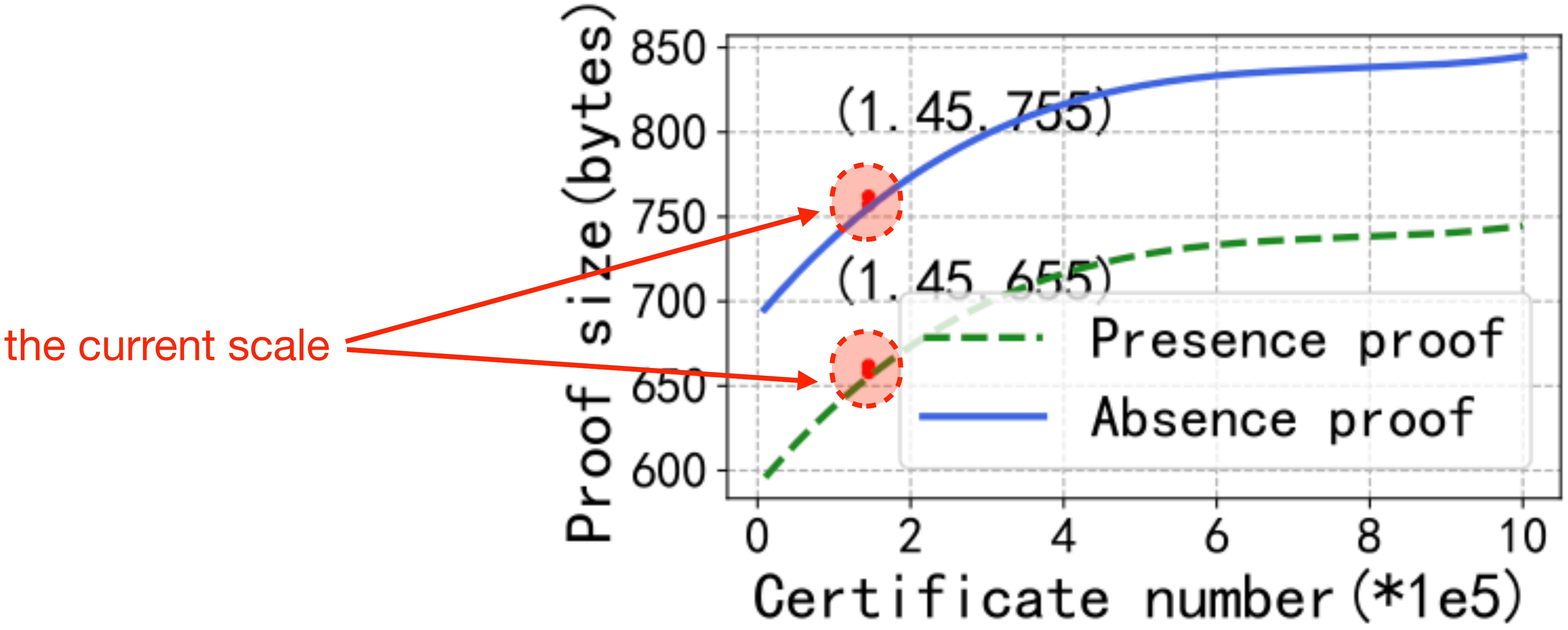
- **Setup**
  - a CS server in Silicon Valley serves 50 Monitors distributed in 15 countries (regions)
  - the CS continuously pushes 10,000 new blocks to 50 Monitors

- **Result**
  - the Monitor can **complete the update** of its M-Tree for this block **within 500ms**



Evaluating Monitors

- ***The size of proofs***
  - grows logarithmically with the number of total certificates
  - at the current RPKI certificate scale, both presence and absence proof sizes are within 1 KB



Summary

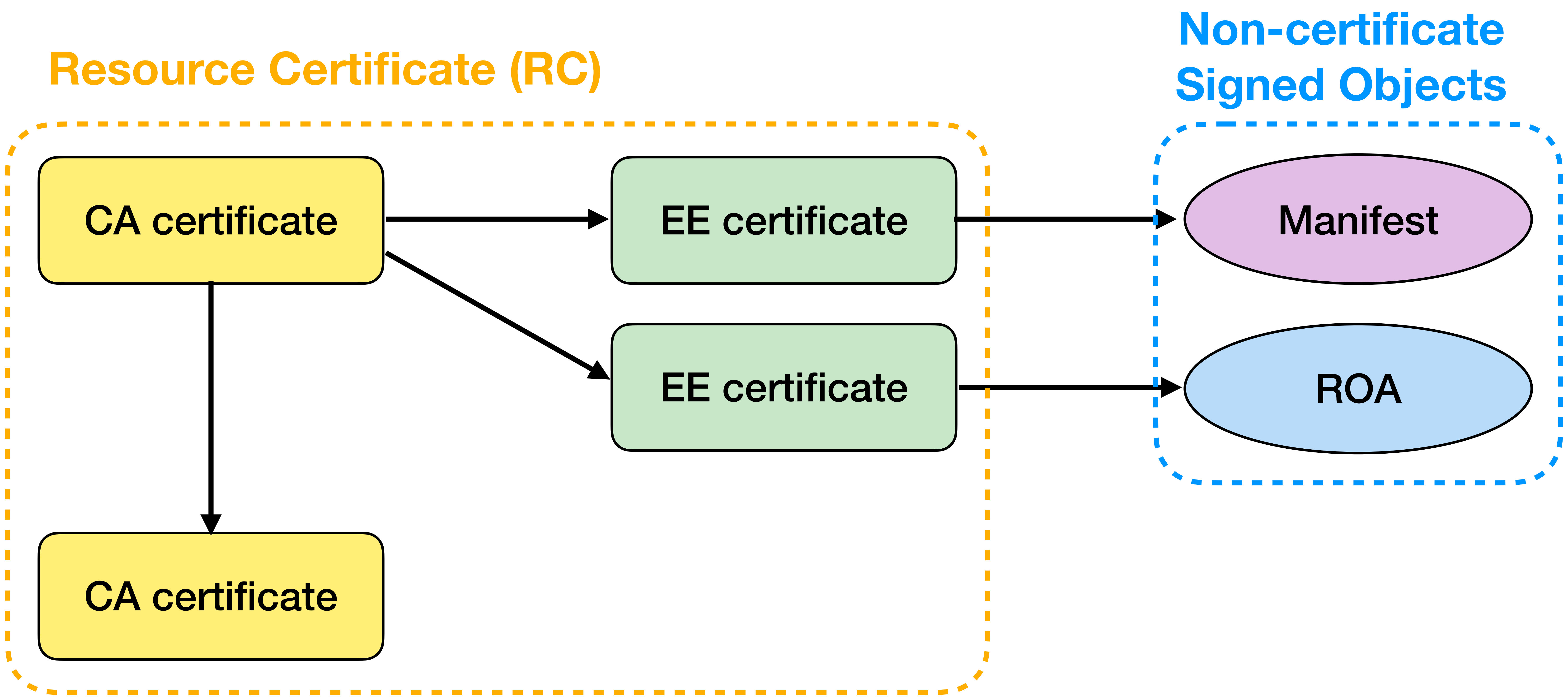
- Conduct the first data-driven RPKI-threat analysis
  - uncover three key problems of the current RPKI repository
- Propose dRR to tackle the problems of the RPKI repository
  - design an RPKI-compatible architecture to enhance security, robustness, and scalability of the RPKI Repository
- Implement a prototype of dRR and evaluate it on a global testbed with 100 nodes
  - show that the new security features of dRR introduce minimal overhead

Q&A

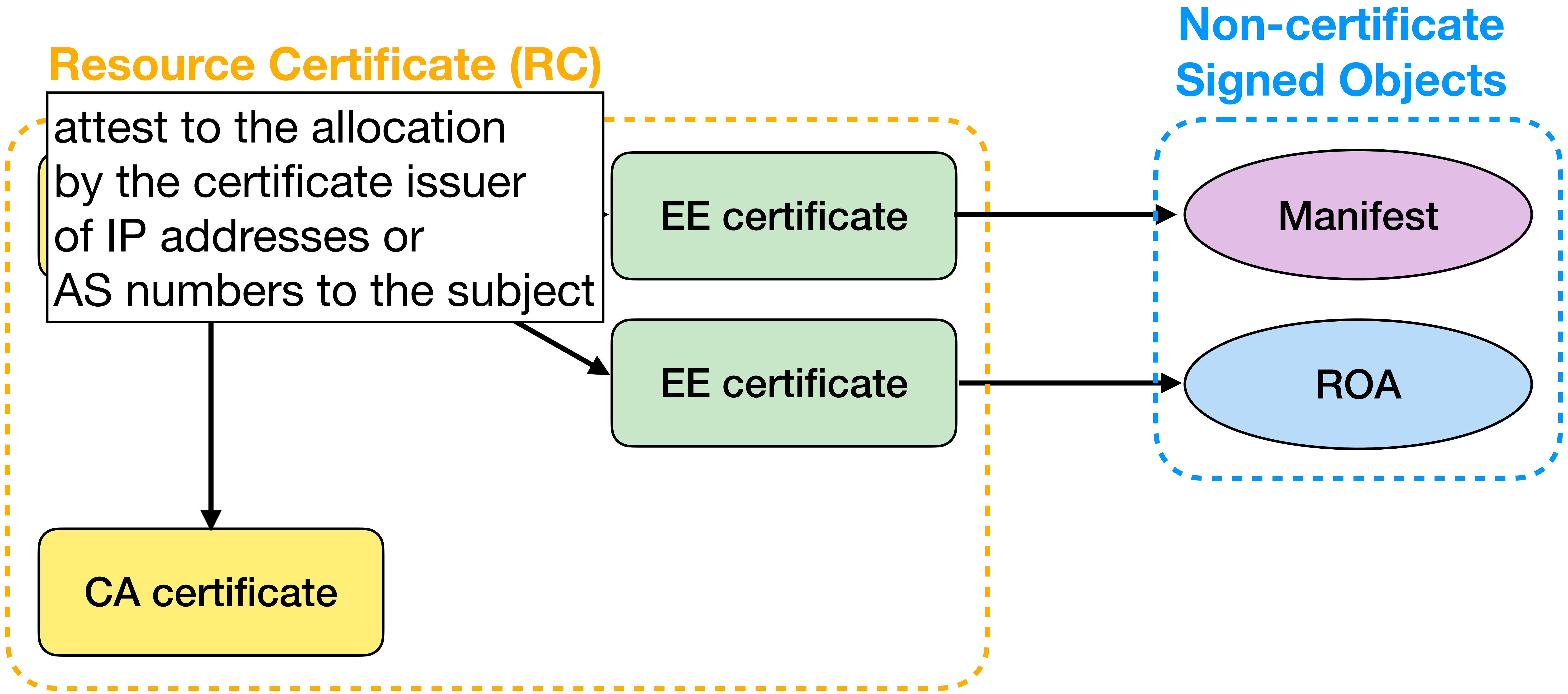
Backup

RPKI

RPKI Objects

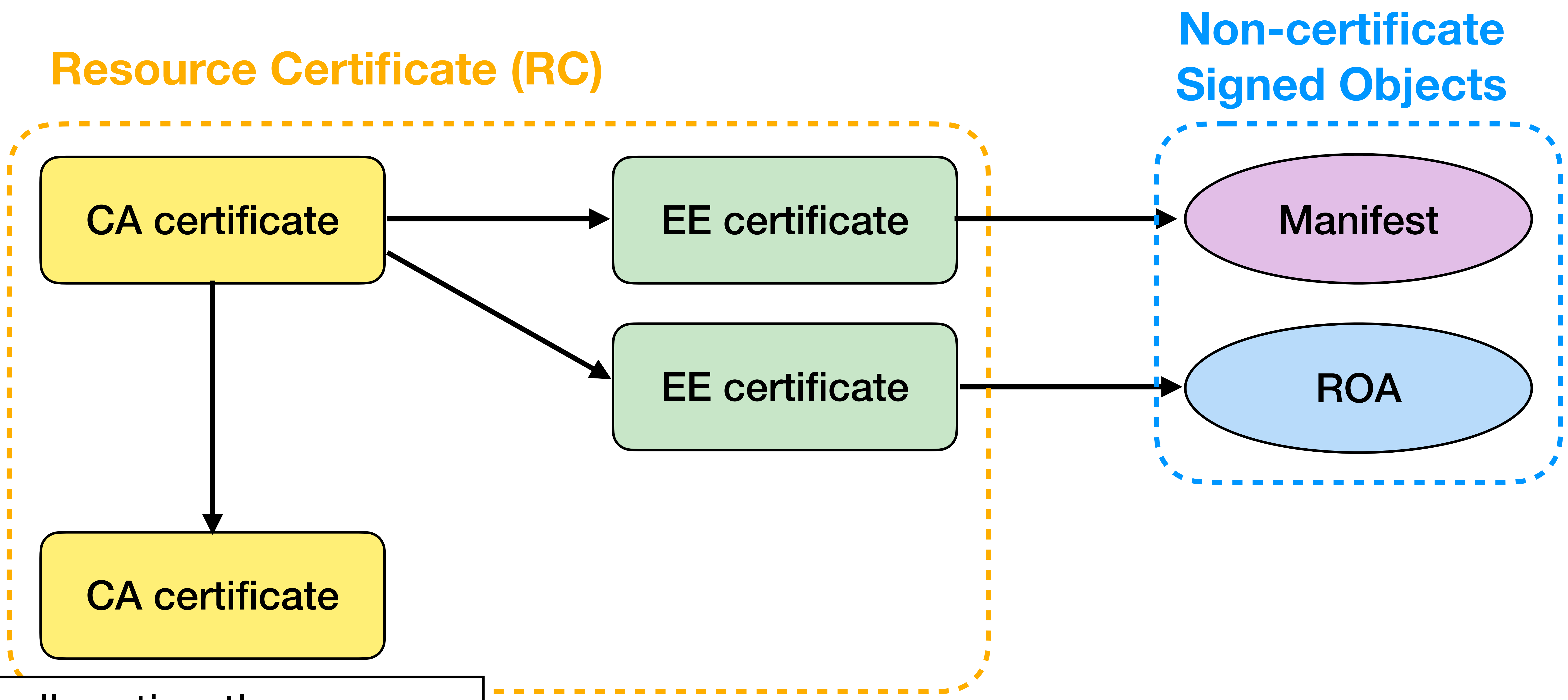


RPKI Objects



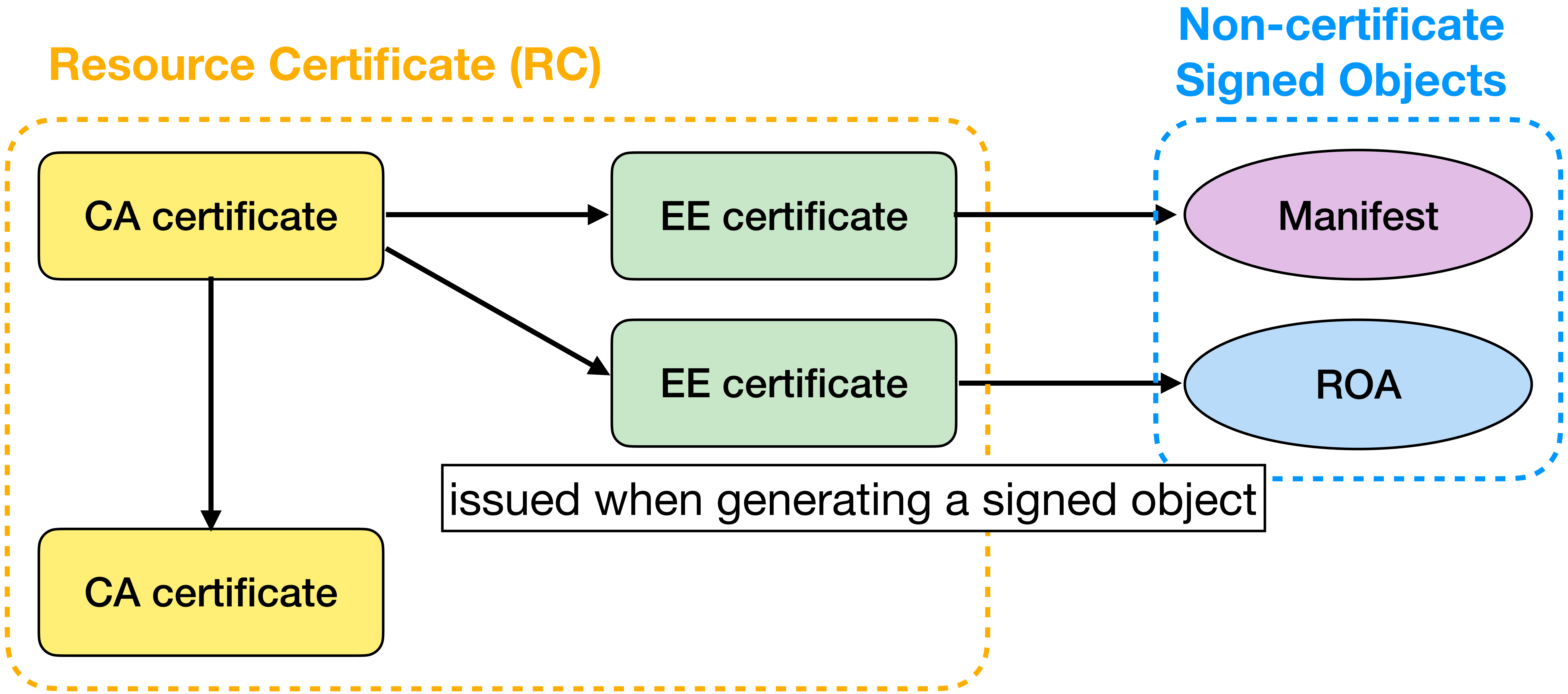
attest to the allocation by the certificate issuer of IP addresses or AS numbers to the subject

RPKI Objects

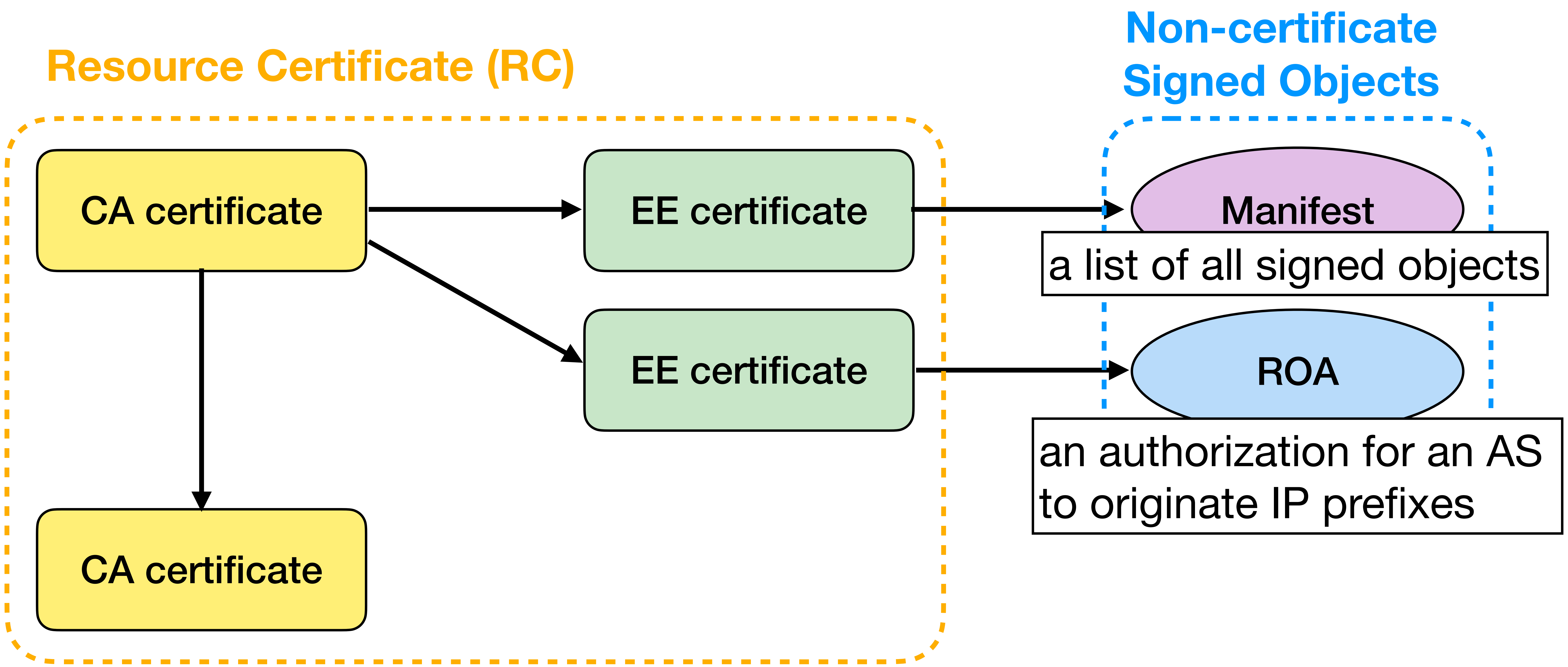


issued when sub-allocating the resource

RPKI Objects



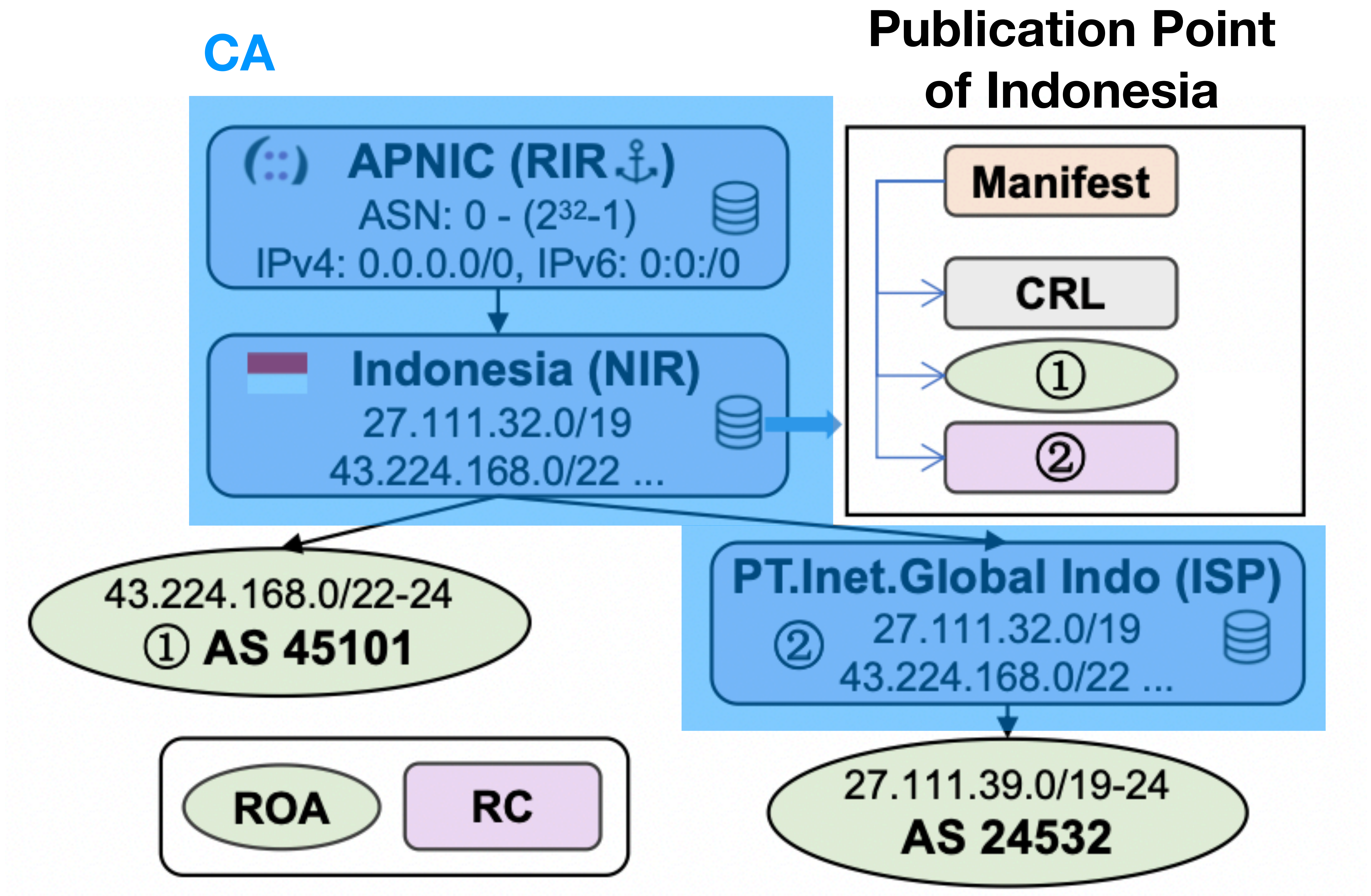
RPKI Objects



a list of all signed objects

an authorization for an AS
to originate IP prefixes

Example of RPKI hierarchical structure



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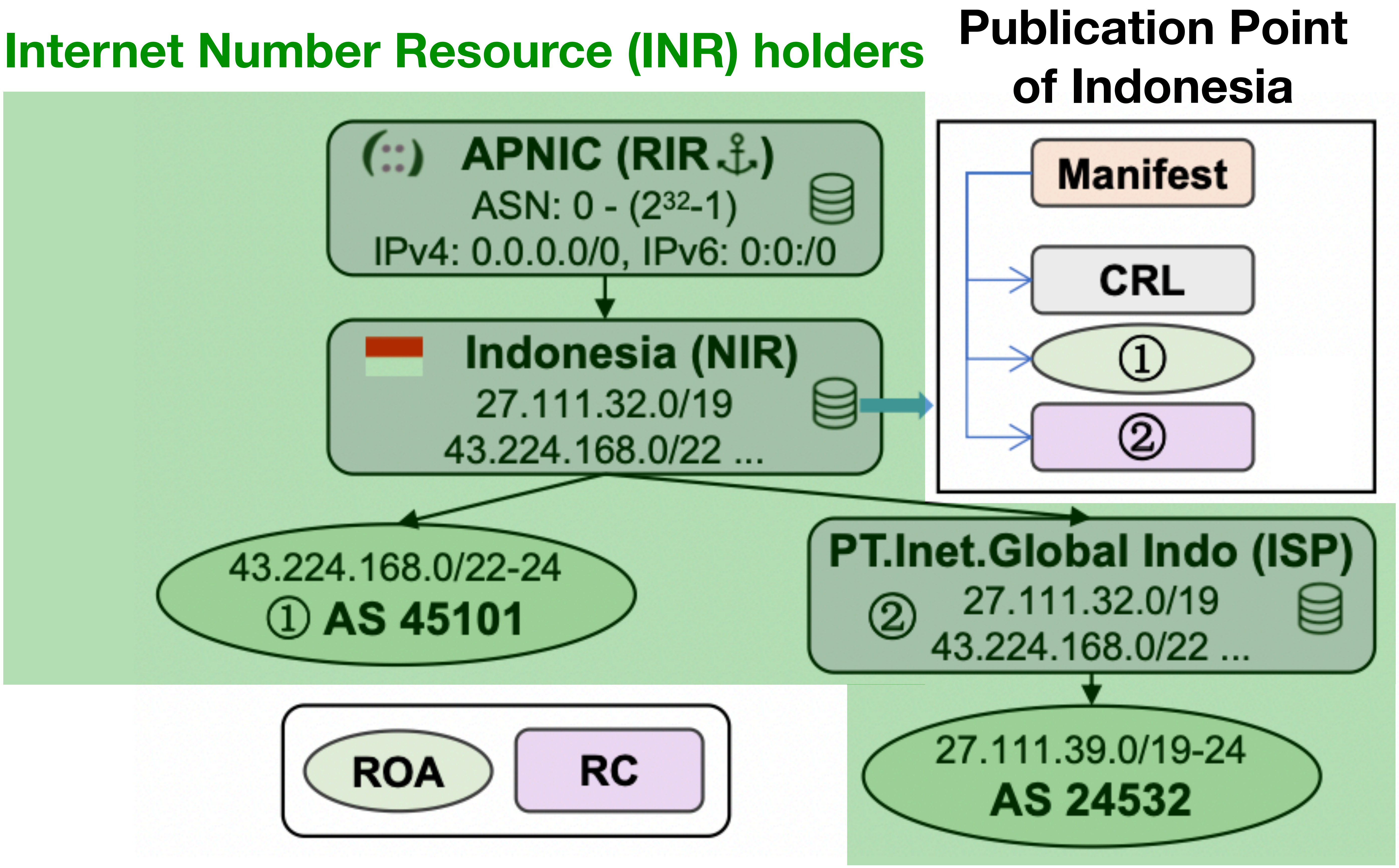
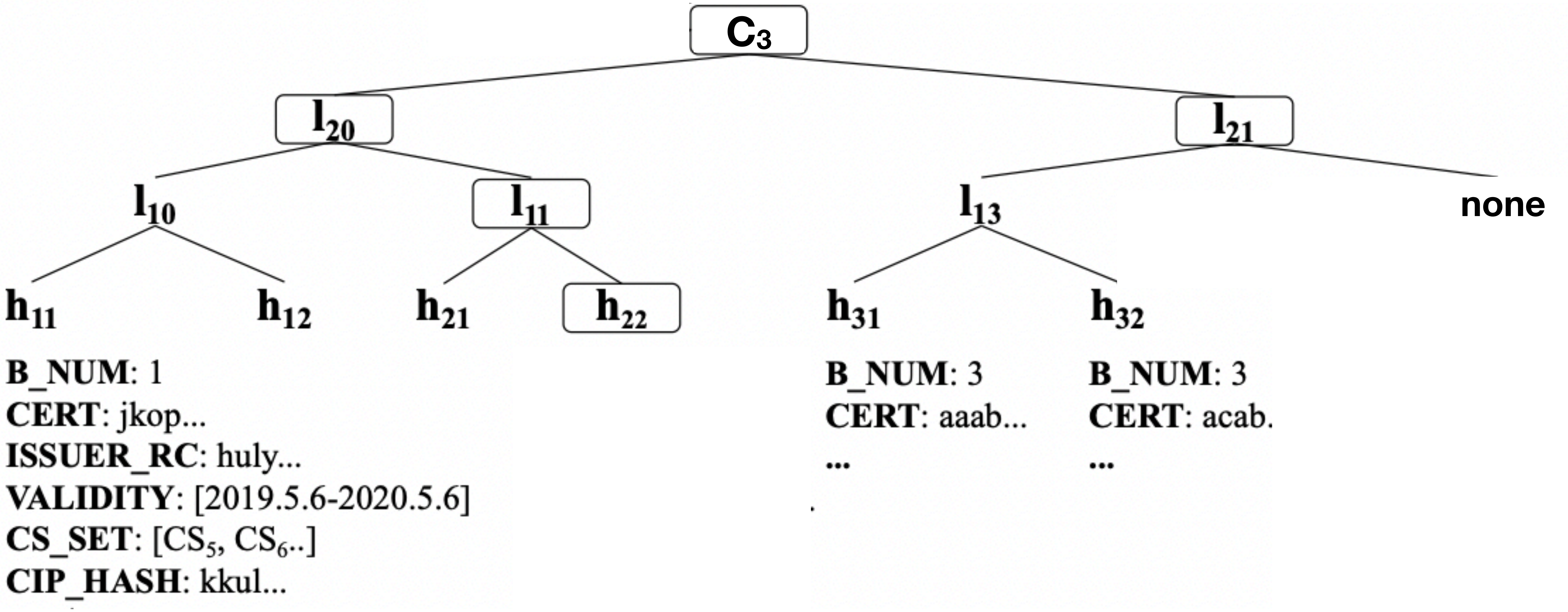
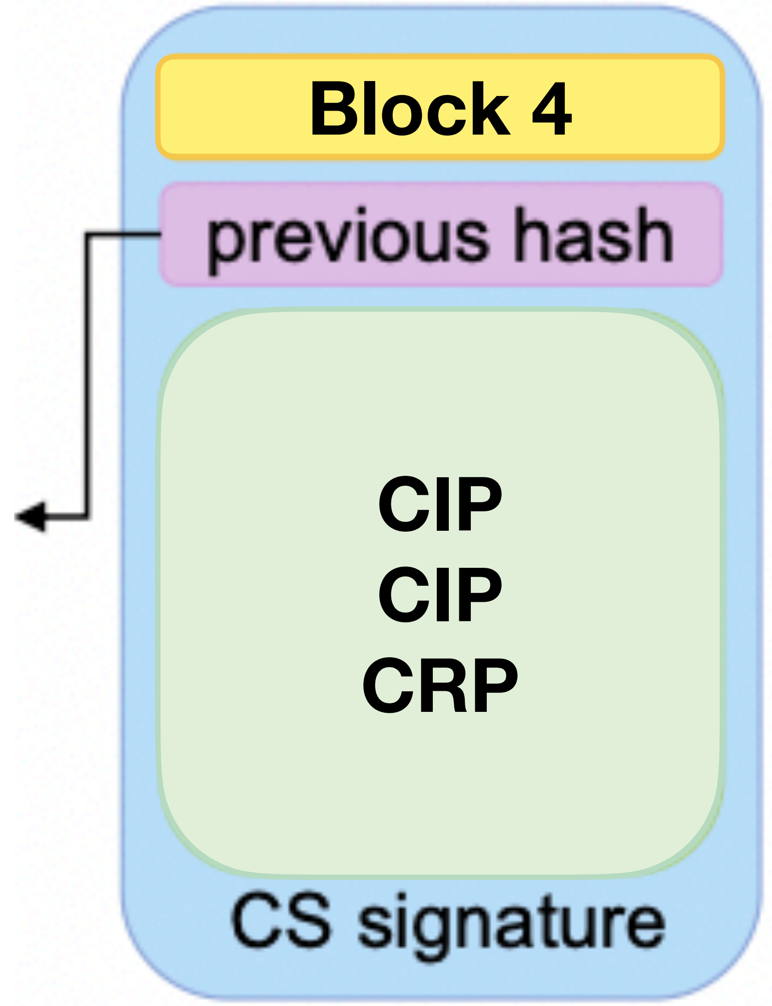


Internet Number Resource (INR) holders

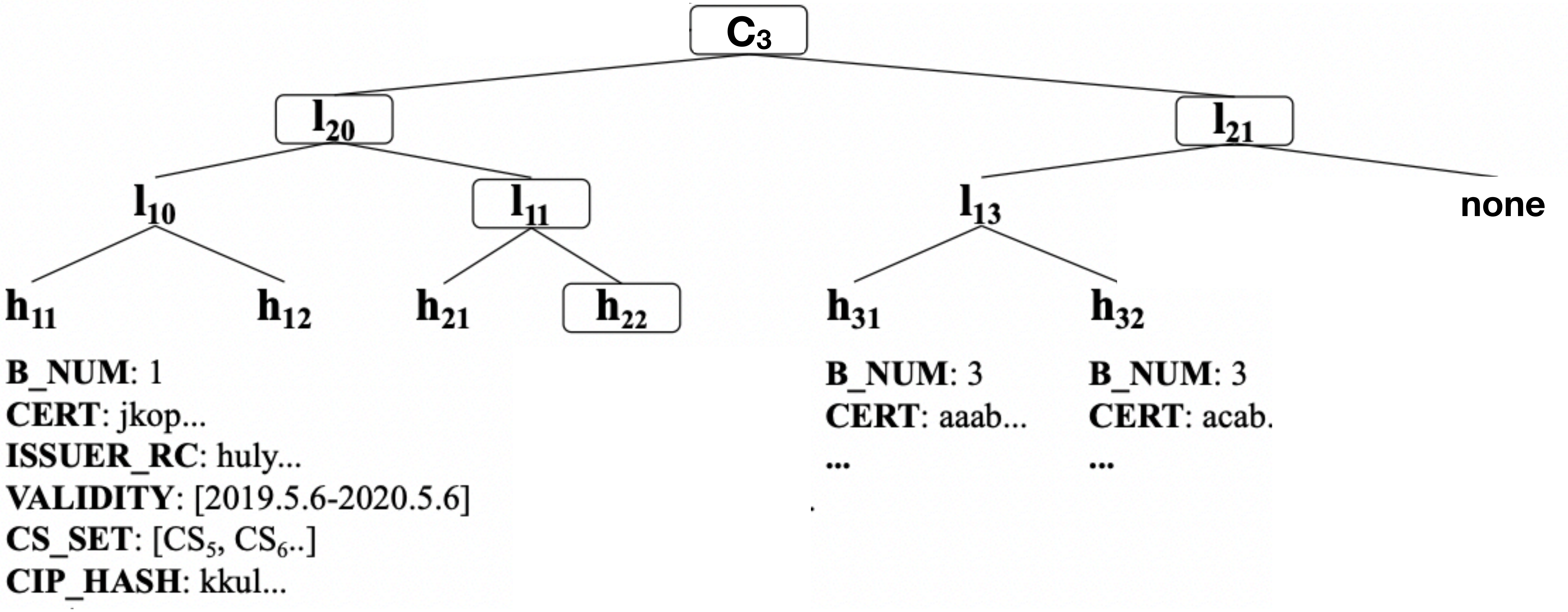
Monitor: Insert a block

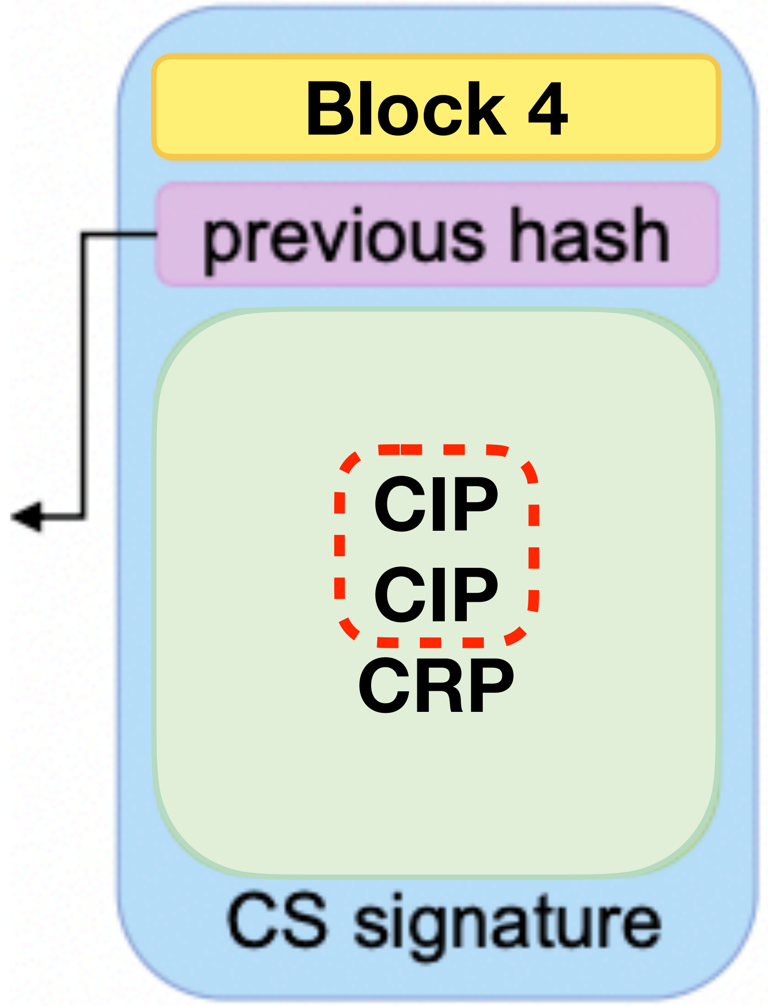
Monitor: CIPs → insert entries



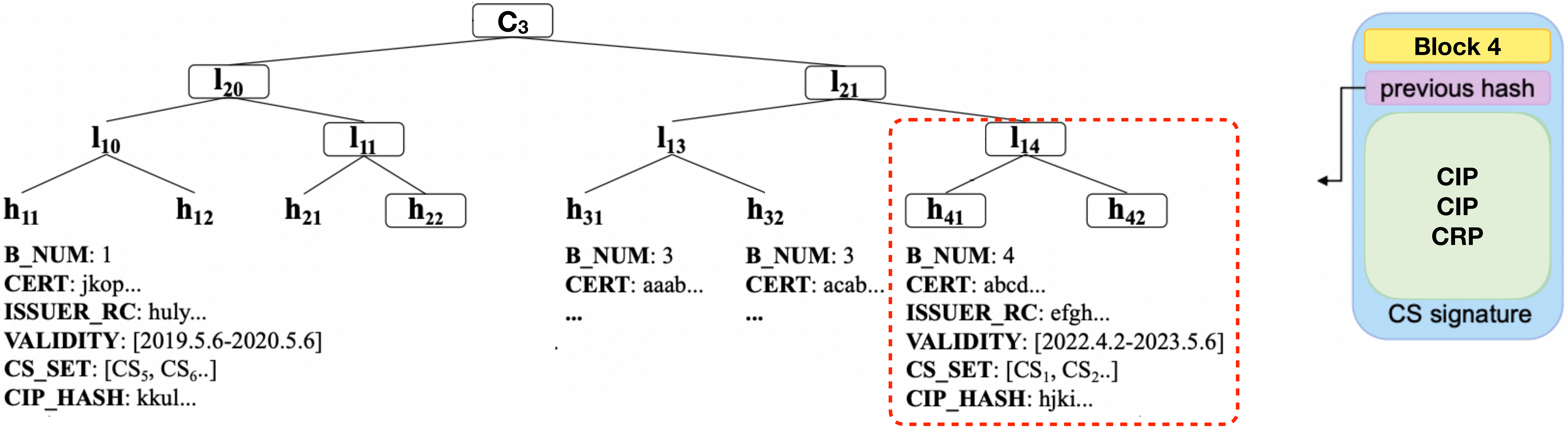


Monitor: CIPs → insert entries

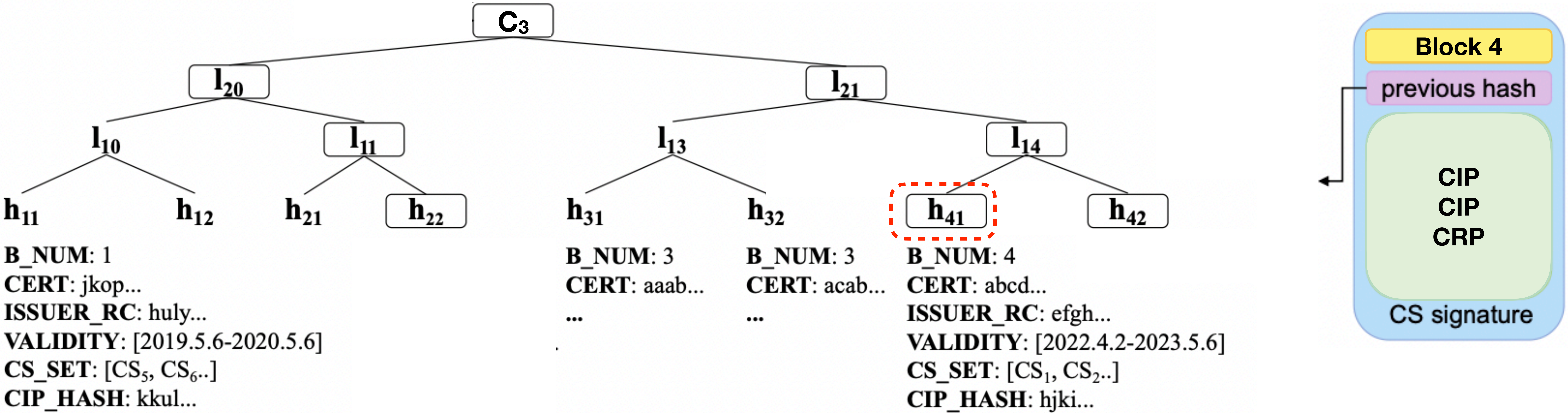




Monitor: CIPs → insert entries



Monitor: CIPs → insert entries



B_NUM: 1
CERT: jkop...
ISSUER_RC: huly...
VALIDITY: [2019.5.6-2020.5.6]
CS_SET: [CS_5, CS_6..]
CIP_HASH: kkul...

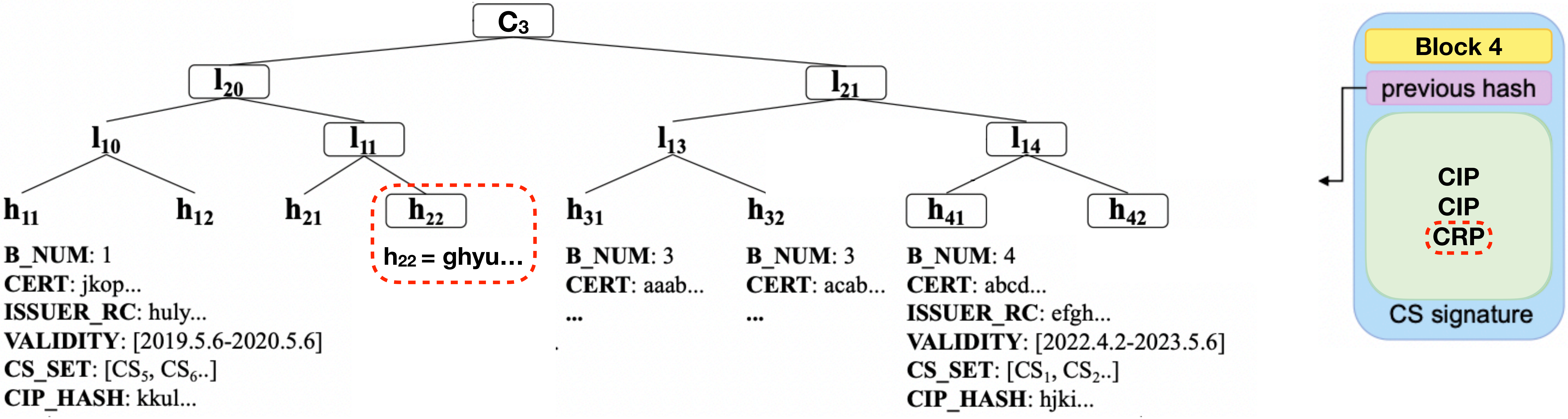
B_NUM: 3
CERT: aaab...
...

B_NUM: 3
CERT: acab...
...

B_NUM: 4
CERT: abcd...
ISSUER_RC: efgh...
VALIDITY: [2022.4.2-2023.5.6]
CS_SET: [CS_1, CS_2..]
CIP_HASH: hjki...

$$h_{41} = HASH(\texttt{B\_NUM} \mathbin{||} \texttt{ISSUER\_RC} \mathbin{||} \texttt{CERT} \mathbin{||} \texttt{VALIDITY} \mathbin{||} \texttt{CS\_SET} \mathbin{||} \texttt{CIP\_HASH})$$

Monitor: CRPs → update entries



B_NUM: 1
CERT: jkop...
ISSUER_RC: huly...
VALIDITY: [2019.5.6-2020.5.6]
CS_SET: [CS$_5$, CS$_6$..]
CIP_HASH: kkul...

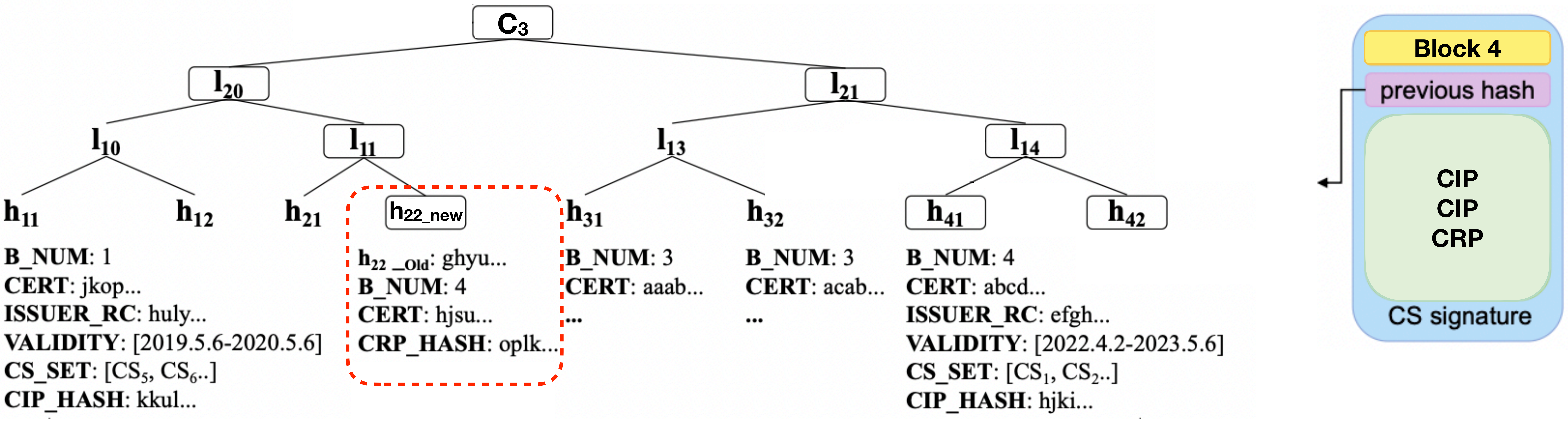
h_{22} = ghyu…

B_NUM: 3
CERT: aaab...
...

B_NUM: 3
CERT: acab...
...

B_NUM: 4
CERT: abcd...
ISSUER_RC: efgh...
VALIDITY: [2022.4.2-2023.5.6]
CS_SET: [CS$_1$, CS$_2$..]
CIP_HASH: hjki...

Monitor: CRPs → update entries



B_NUM: 1
CERT: jkop...
ISSUER_RC: huly...
VALIDITY: [2019.5.6-2020.5.6]
CS_SET: [CS_5, CS_6..]
CIP_HASH: kkul...

h_{22} _Old: ghyu...
B_NUM: 4
CERT: hjsu...
CRP_HASH: oplk...

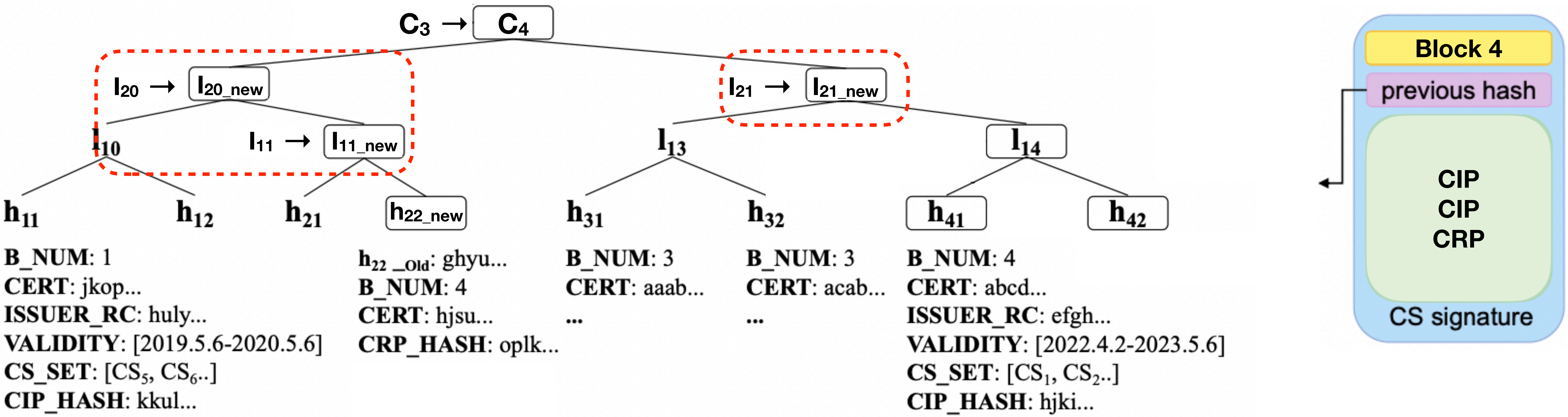
B_NUM: 3
CERT: aaab...
...

B_NUM: 3
CERT: acab...
...

B_NUM: 4
CERT: abcd...
ISSUER_RC: efgh...
VALIDITY: [2022.4.2-2023.5.6]
CS_SET: [CS_1, CS_2..]
CIP_HASH: hjki...

$$\boxed{h_{22\_new} = HASH(h_{22\_old} \mid\mid \texttt{B\_NUM} \mid\mid \texttt{CERT} \mid\mid \texttt{CRP\_HASH})}$$

Monitor: generate commitment



B_NUM: 1
CERT: jkop...
ISSUER_RC: huly...
VALIDITY: [2019.5.6-2020.5.6]
CS_SET: [CS_5, CS_6..]
CIP_HASH: kkul...

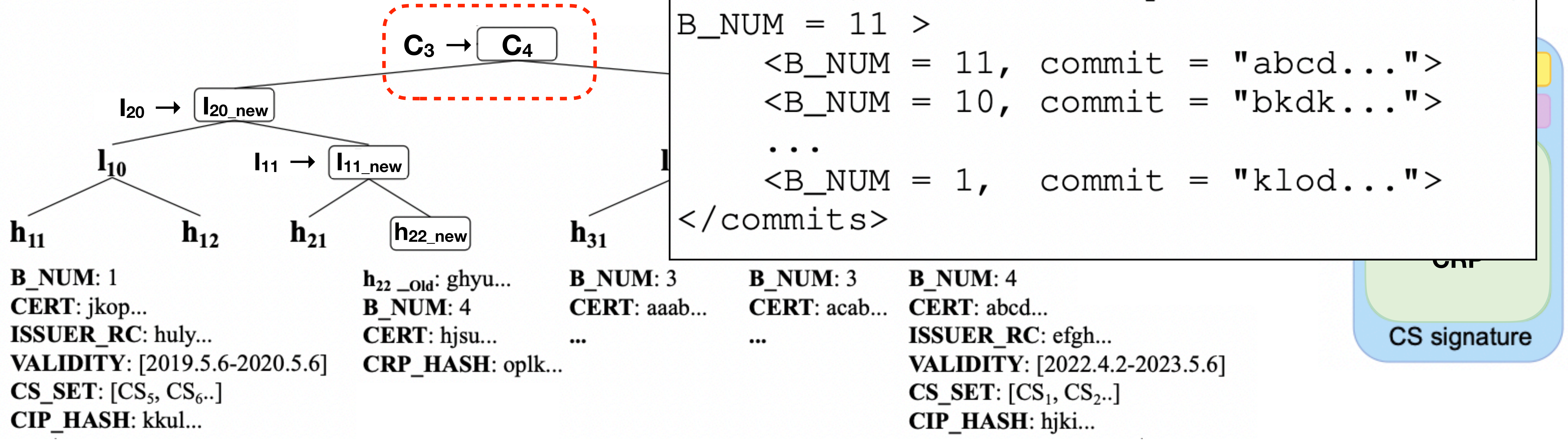
h_{22_Old}: ghyu...
B_NUM: 4
CERT: hjsu...
CRP_HASH: oplk...

B_NUM: 3
CERT: aaab...
...

B_NUM: 3
CERT: acab...
...

B_NUM: 4
CERT: abcd...
ISSUER_RC: efgh...
VALIDITY: [2022.4.2-2023.5.6]
CS_SET: [CS_1, CS_2..]
CIP_HASH: hjki...

Monitor: generate commitment



B_NUM: 1
CERT: jkop...
ISSUER_RC: huly...
VALIDITY: [2019.5.6-2020.5.6]
CS_SET: [CS_5, CS_6..]
CIP_HASH: kkul...

h_{22} **_Old**: ghyu...
B_NUM: 4
CERT: hjsu...
CRP_HASH: oplk...

B_NUM: 3
CERT: aaab...
...

B_NUM: 3
CERT: acab...
...

B_NUM: 4
CERT: abcd...
ISSUER_RC: efgh...
VALIDITY: [2022.4.2-2023.5.6]
CS_SET: [CS_1, CS_2..]
CIP_HASH: hjki...

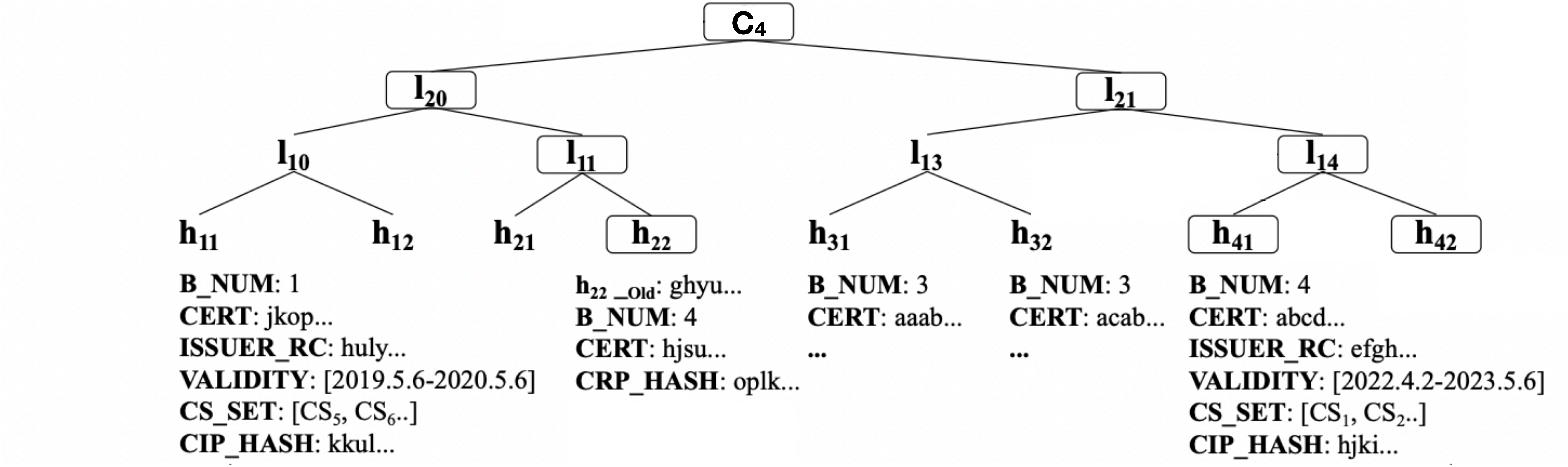
Commitment Update File

```
<commits, xmlns = "https://.../monitor",
B_NUM = 11 >
    <B_NUM = 11, commit = "abcd...">
    <B_NUM = 10, commit = "bkdk...">
    ...
    <B_NUM = 1,  commit = "klod...">
</commits>
```

Monitor: proof of absence

Proof of Absence: example

- INR holder asks whether the certificate in⟨B_NUM = 3,CERT = abab…⟩ exists



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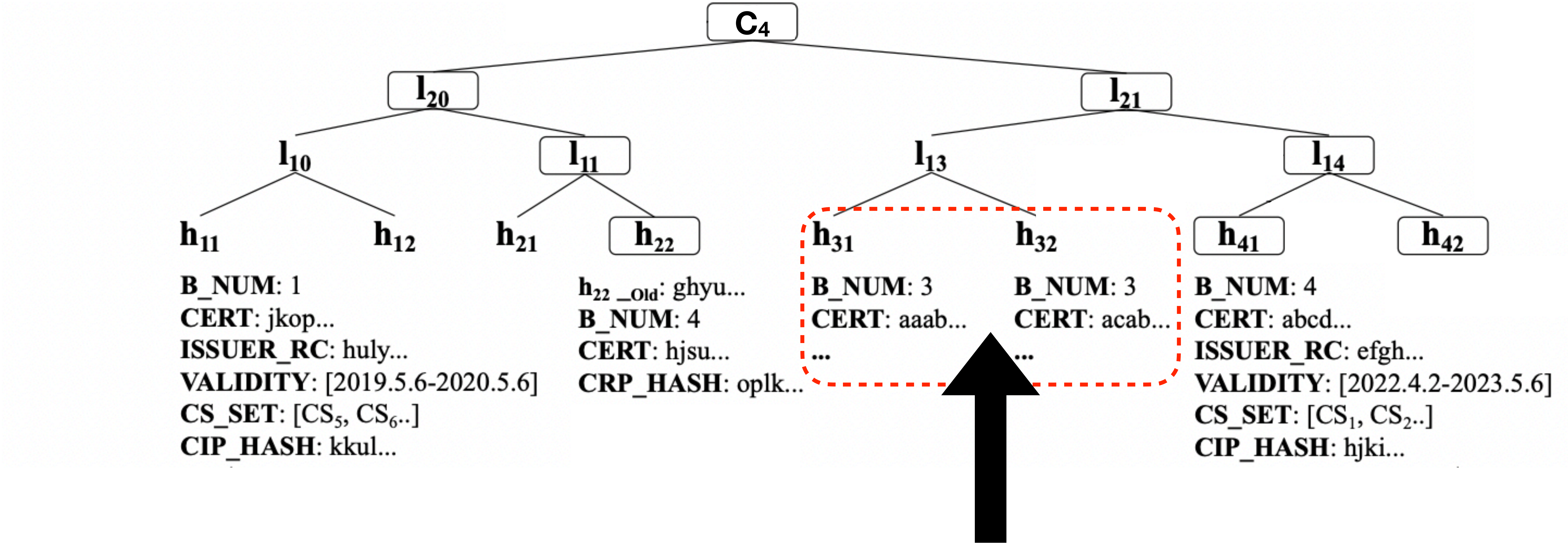
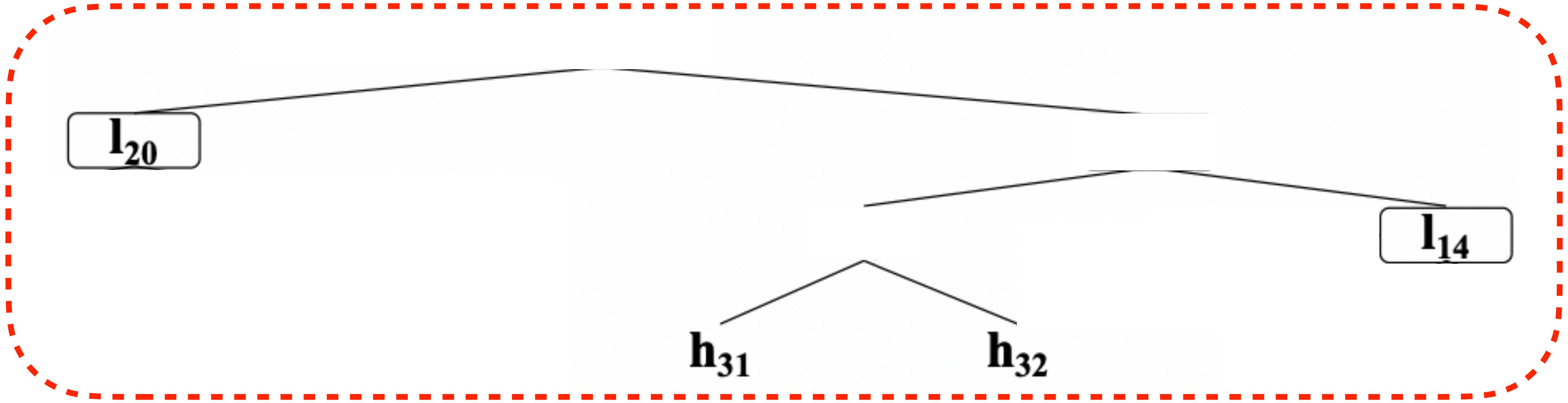


<B_NUM=3, CERT=abab> should located here
since monitors insert CIPs of one block with lexicographic order

Proof of Absence: example

- The Monitor will return a pruned tree that contains the entry of h_{32} and the hash of h_{32}, intermediate nodes l_{14} and l_{20} the INR holder

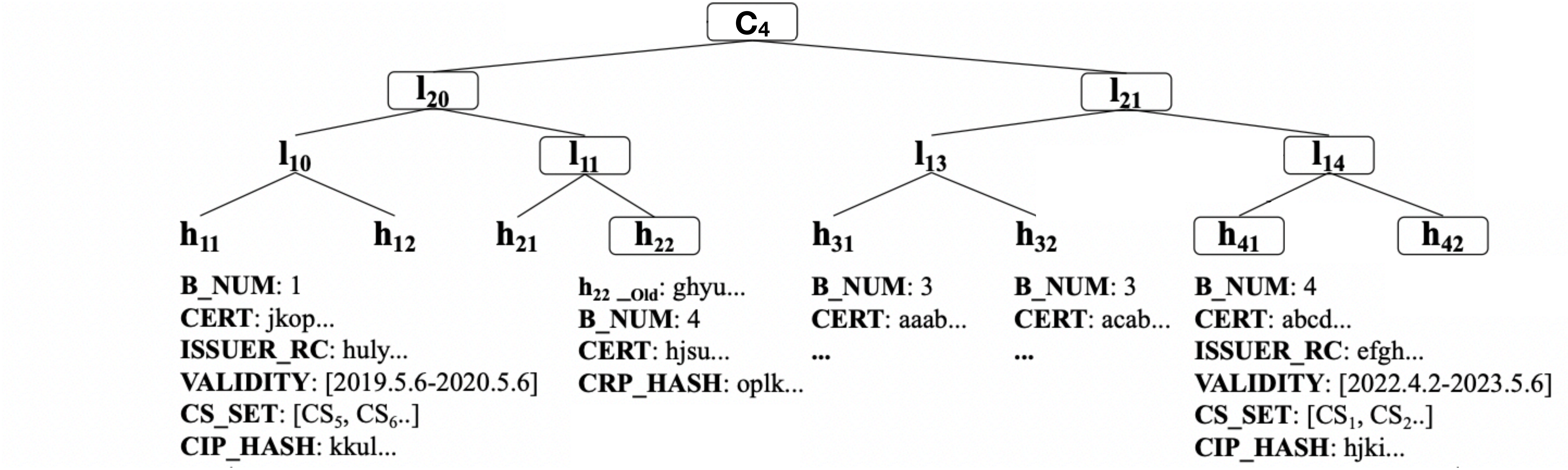


proof of absence

Monitor: proof of consistency

Proof of Consistency: example

- The RP has completed the synchronization of the first three blocks and now needs to synchronize the *block 4* incrementally
  - A Relying Party (RP) submits <B_num=3, c=C_3> to the monitor



B_NUM: 1
CERT: jkop...
ISSUER_RC: huly...
VALIDITY: [2019.5.6-2020.5.6]
CS_SET: [CS_5, CS_6..]
CIP_HASH: kkul...

h_{22} _Old: ghyu...
B_NUM: 4
CERT: hjsu...
CRP_HASH: oplk...

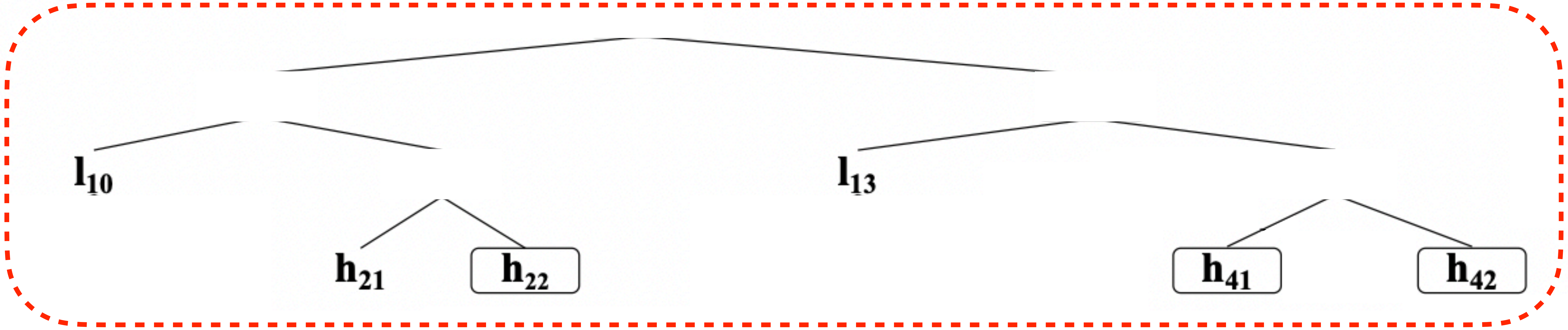
B_NUM: 3
CERT: aaab...
...

B_NUM: 3
CERT: acab...
...

B_NUM: 4
CERT: abcd...
ISSUER_RC: efgh...
VALIDITY: [2022.4.2-2023.5.6]
CS_SET: [CS_1, CS_2..]
CIP_HASH: hjki...

Proof of Consistency: example

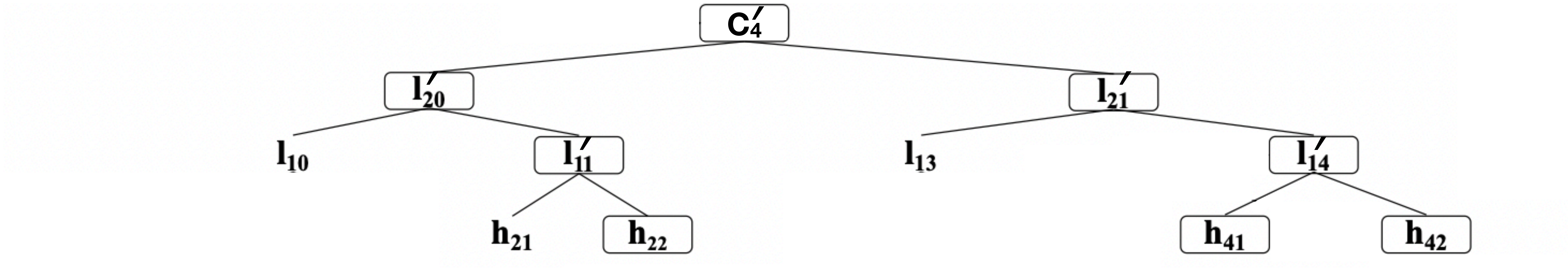
- The Monitor will return a proof of consistency



proof of consistency

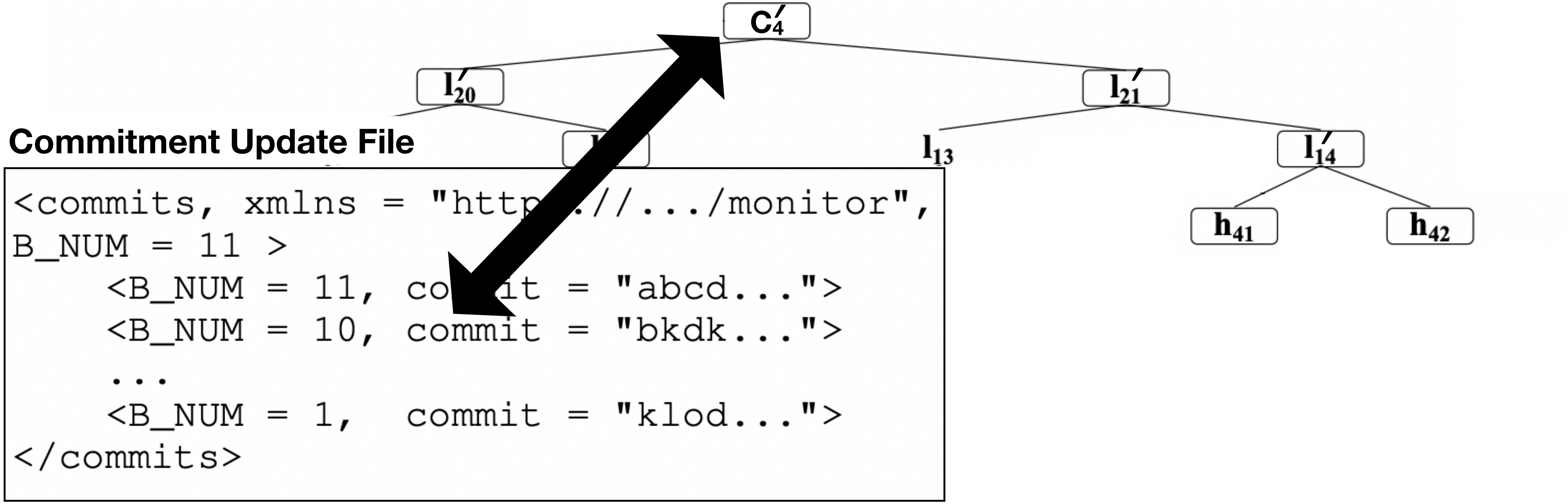
Proof of Consistency: example

- The RP reconstructs C₄′ and verify it



Proof of Consistency: example

- The RP reconstructs C_4' and verify it

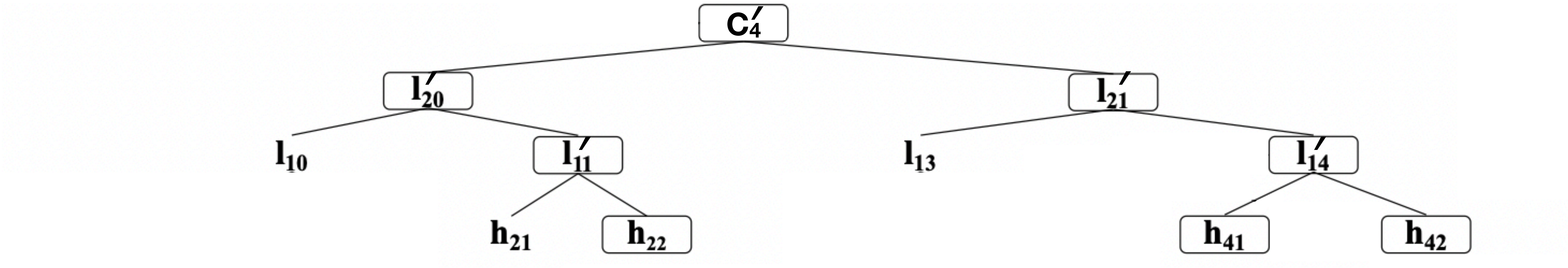


Commitment Update File

```
<commits, xmlns = "http .//.../monitor",
B_NUM = 11 >
    <B_NUM = 11, co   it = "abcd...">
    <B_NUM = 10, commit = "bkdk...">
    ...
    <B_NUM = 1,  commit = "klod...">
</commits>
```

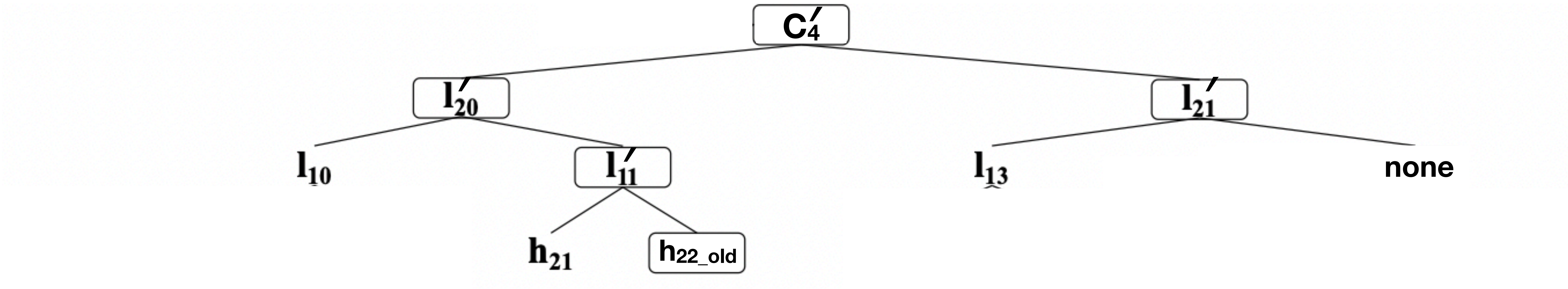
Proof of Consistency: example

- The RP Verify that C_3 can be deduced from C_4'



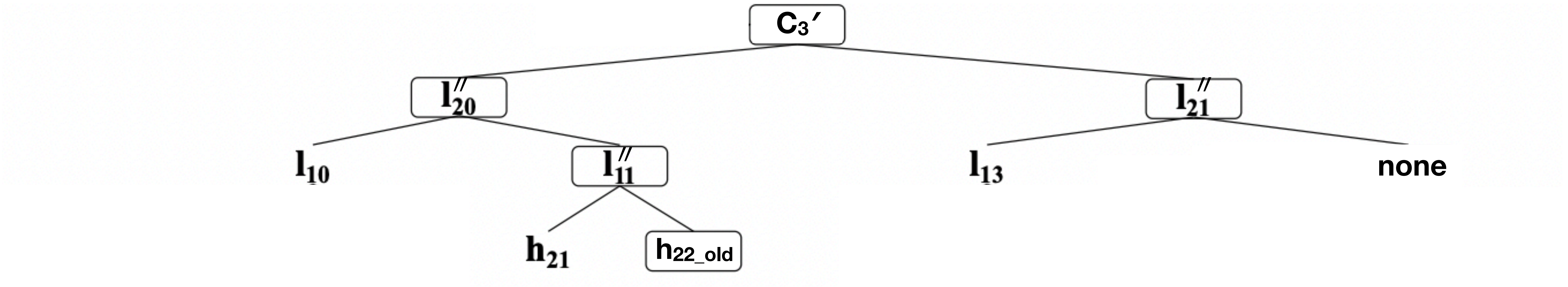
Proof of Consistency: example

- The RP Verify that C_3 can be deduced from C_4'
  - by replacing h_{22} with h_{22_old} and delete h_{41} and h_{42}



Proof of Consistency: example

- The RP Verify that *C_3* can be deduced from C_4'
    - by replacing h_{22} with h_{22_old} and delete h_{41} and h_{42}
    - reconstruct C_3' and check whether it is equal to C_3



Evaluating dRR Parameter

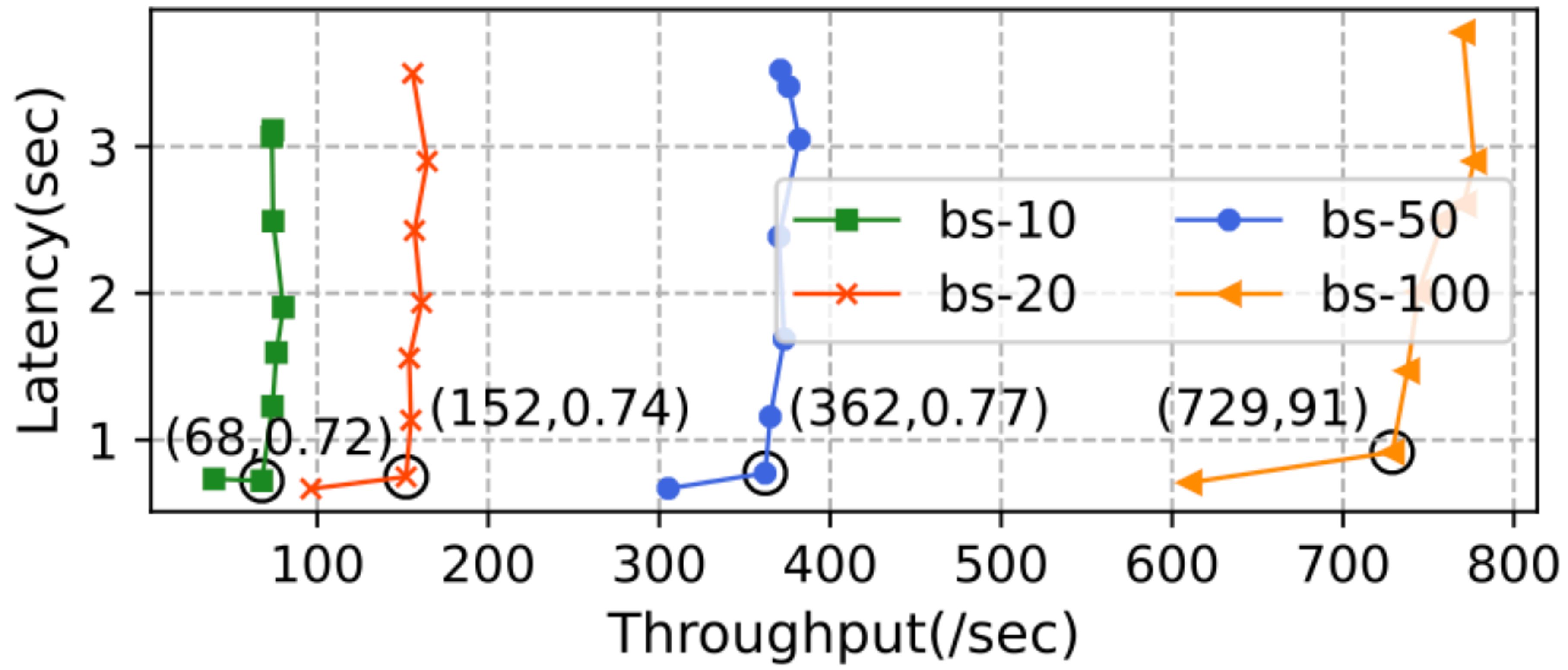


Fig. 10: The throughput and average latency under different batch sizes. Data in the circle represents the maximum throughput and the corresponding average latency.

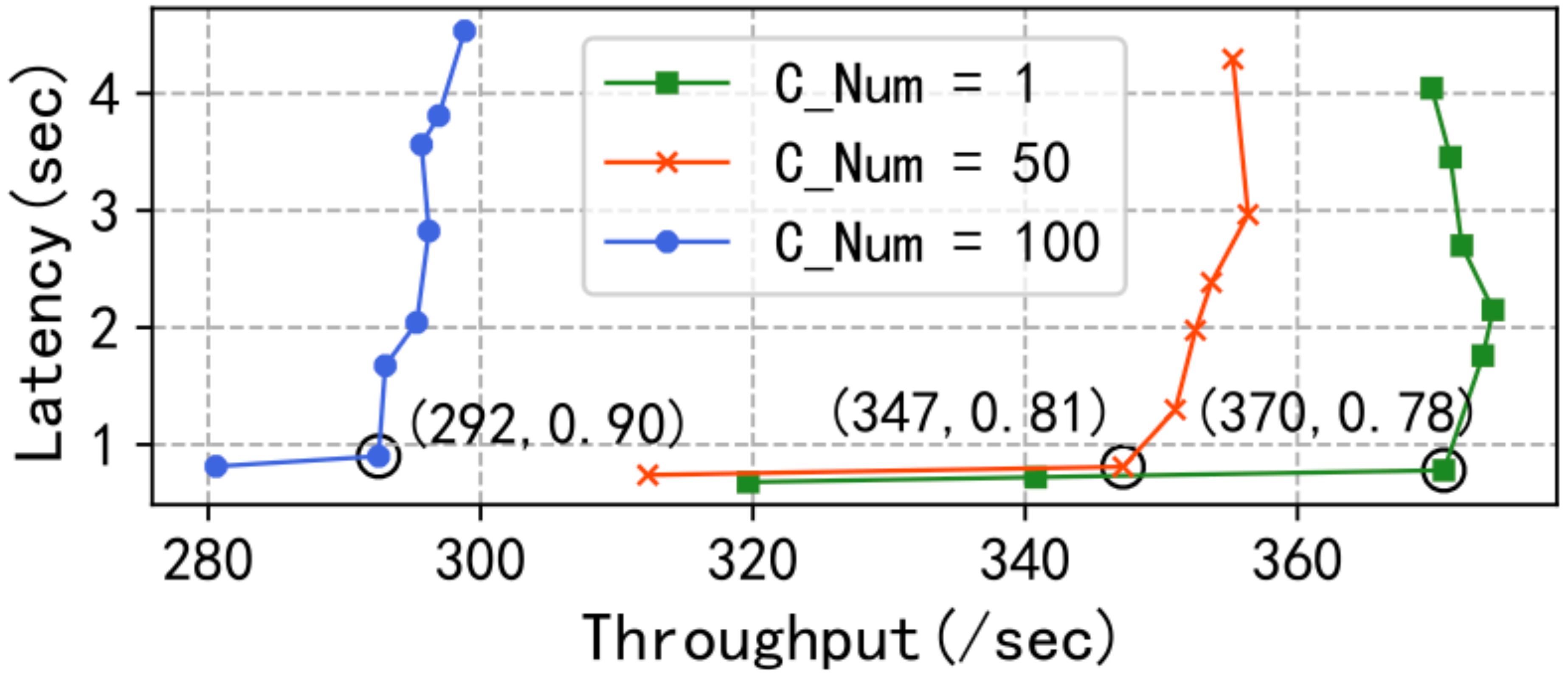
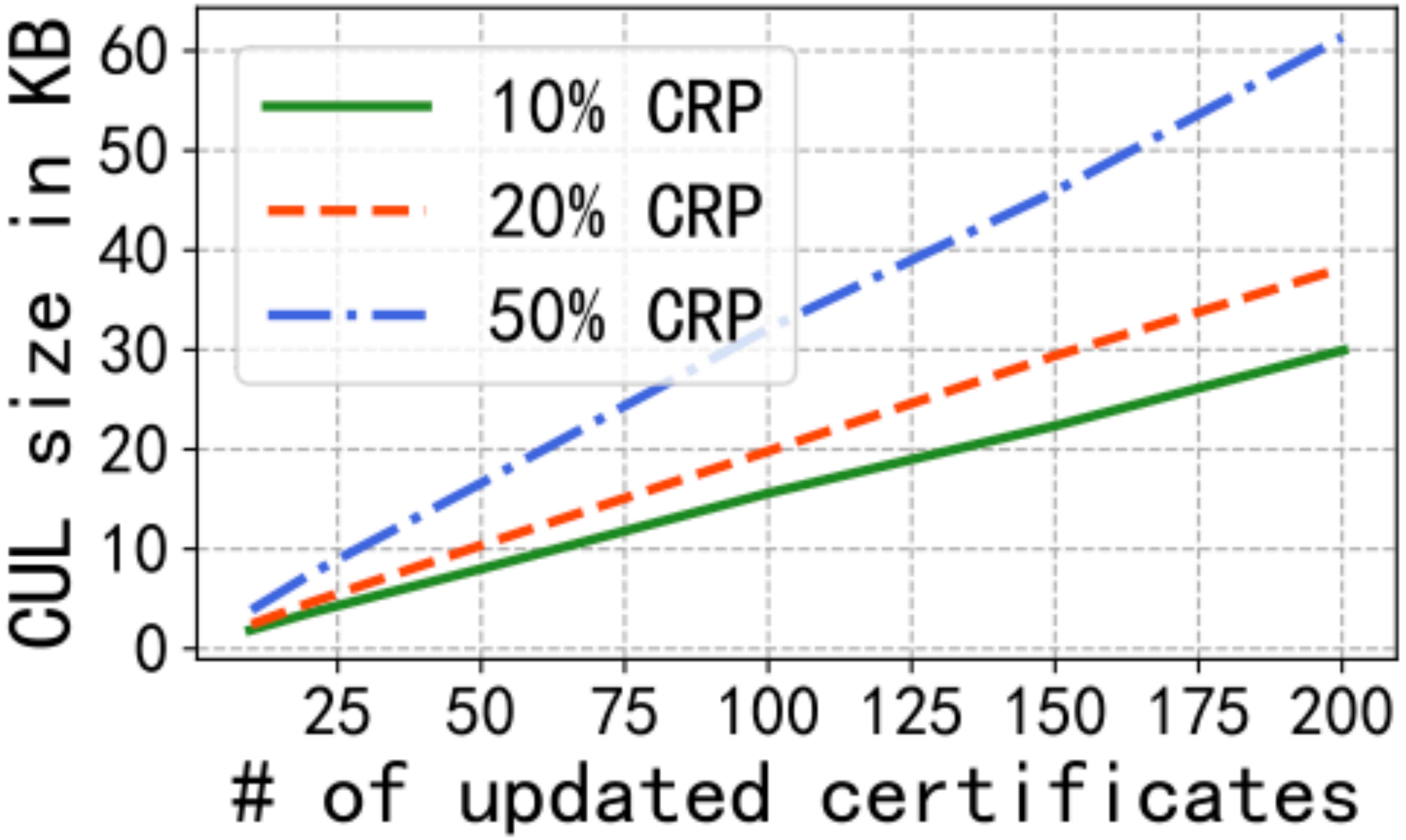


Fig. 11: The throughput and average latency under different numbers of revoked certificates in one CRP.

Evaluating Monitors

- **The size of CULs**
  - the size of the CUL is positively correlated with the number of updated certificates


CUL size in KB
# of updated certificates
10% CRP
20% CRP
50% CRP