Revoke and Let Live

A Secure Key Revocation API for Cryptographic Devices

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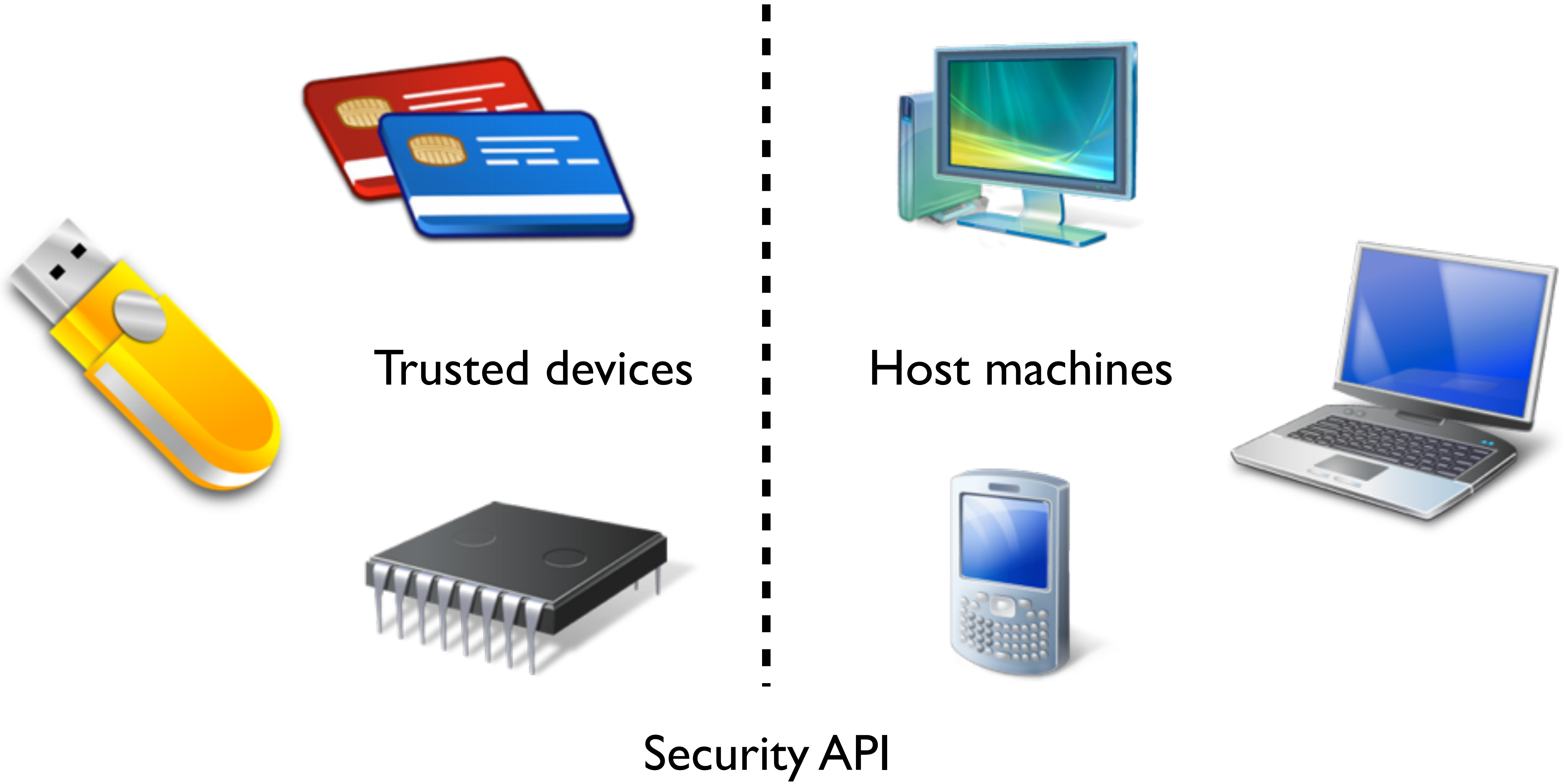
Séminaire Méthodes Formelles et Sécurité

Rennes, May 24th, 2013

Funded by

Security APIs



Trusted devices

Host machines

Security API

Goal : Enforce security of data stored inside the trusted device, even when connected to untrusted host machines.

Applications

- Smartphones,

- Online Banking, Asynchronous Transfer Mode,

- Electronic Ticketing Systems,

- Vehicle-to-vehicle networking.

- ...

How does it work ?

Host machine

Trusted device

h_1	🔑
h_2	🔑

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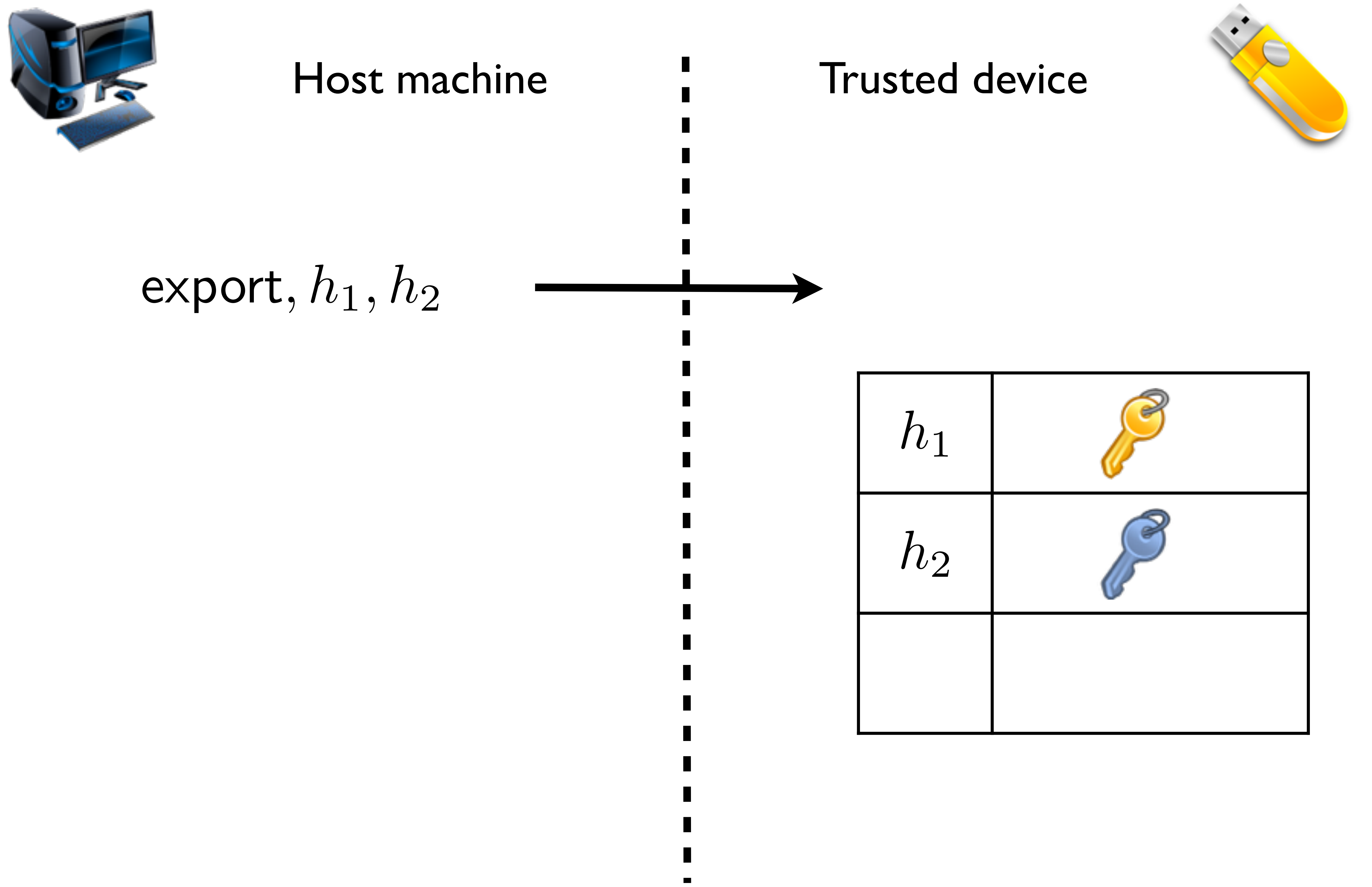

Host machine

Trusted device

export, h_1, h_2

h_1	🔑
h_2	🔑

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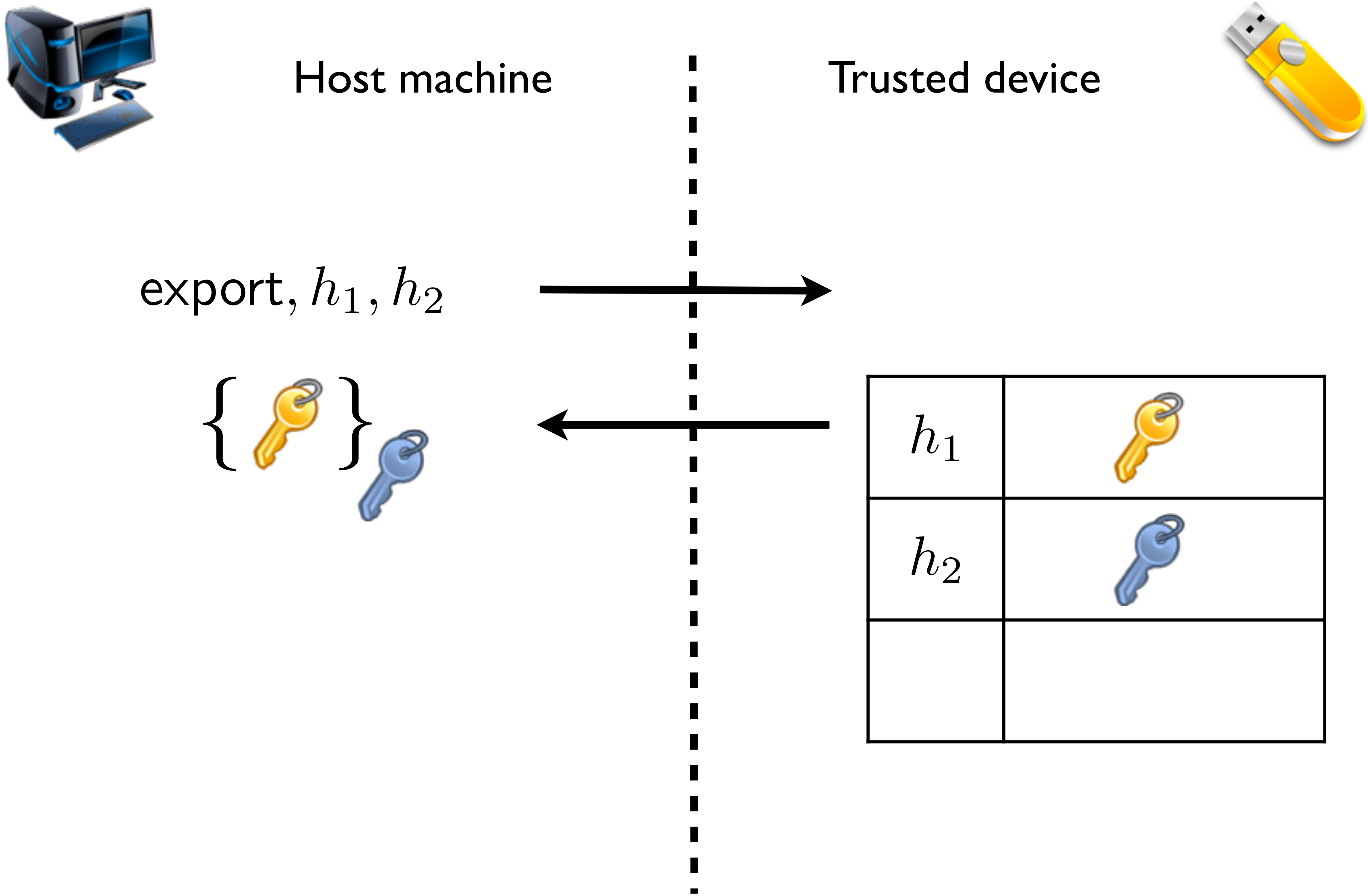

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Trusted device

export, h_1, h_2

$\{$🔑$\}$🔑

h_1	🔑
h_2	🔑

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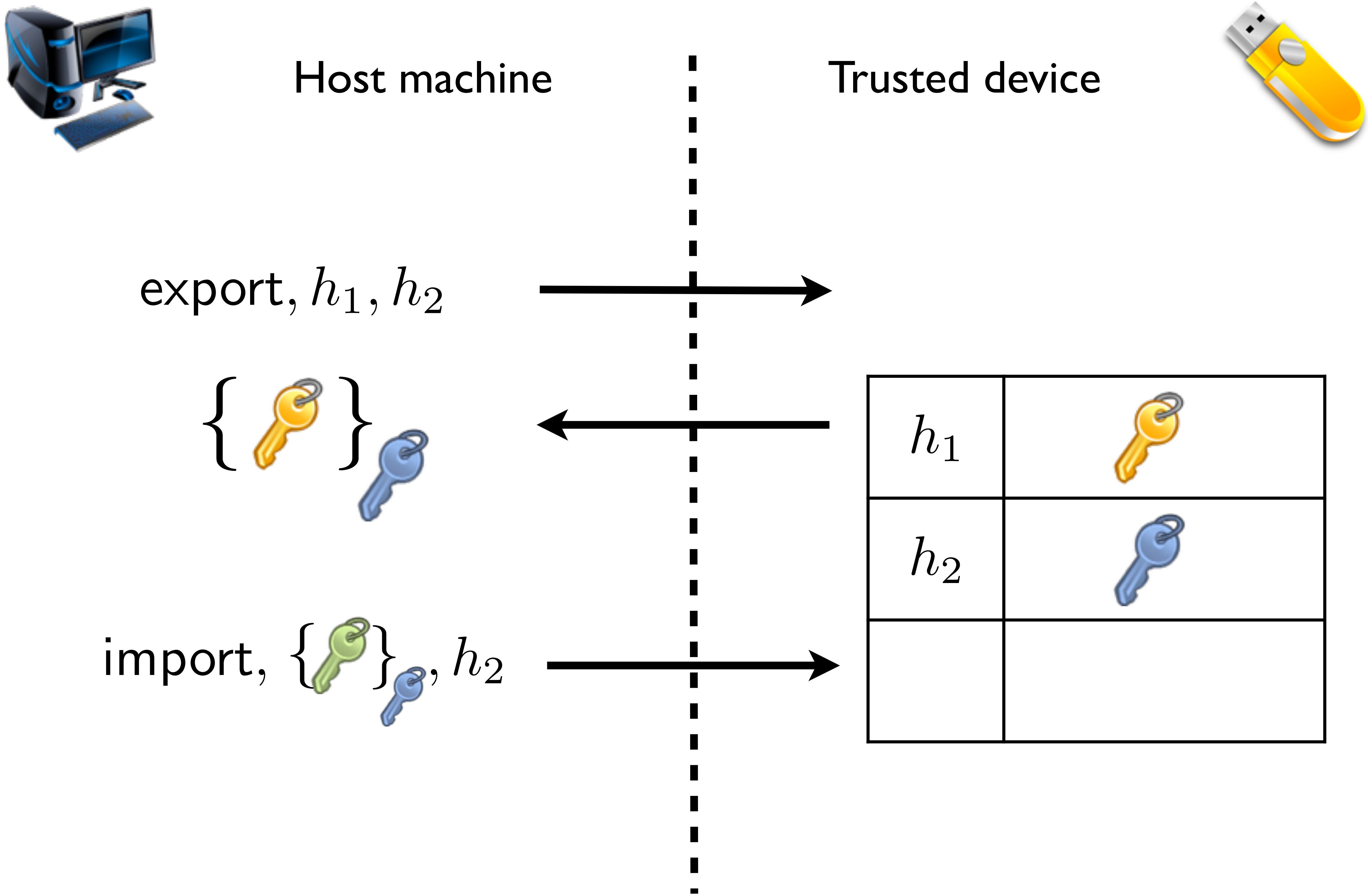


Host machine

Trusted device

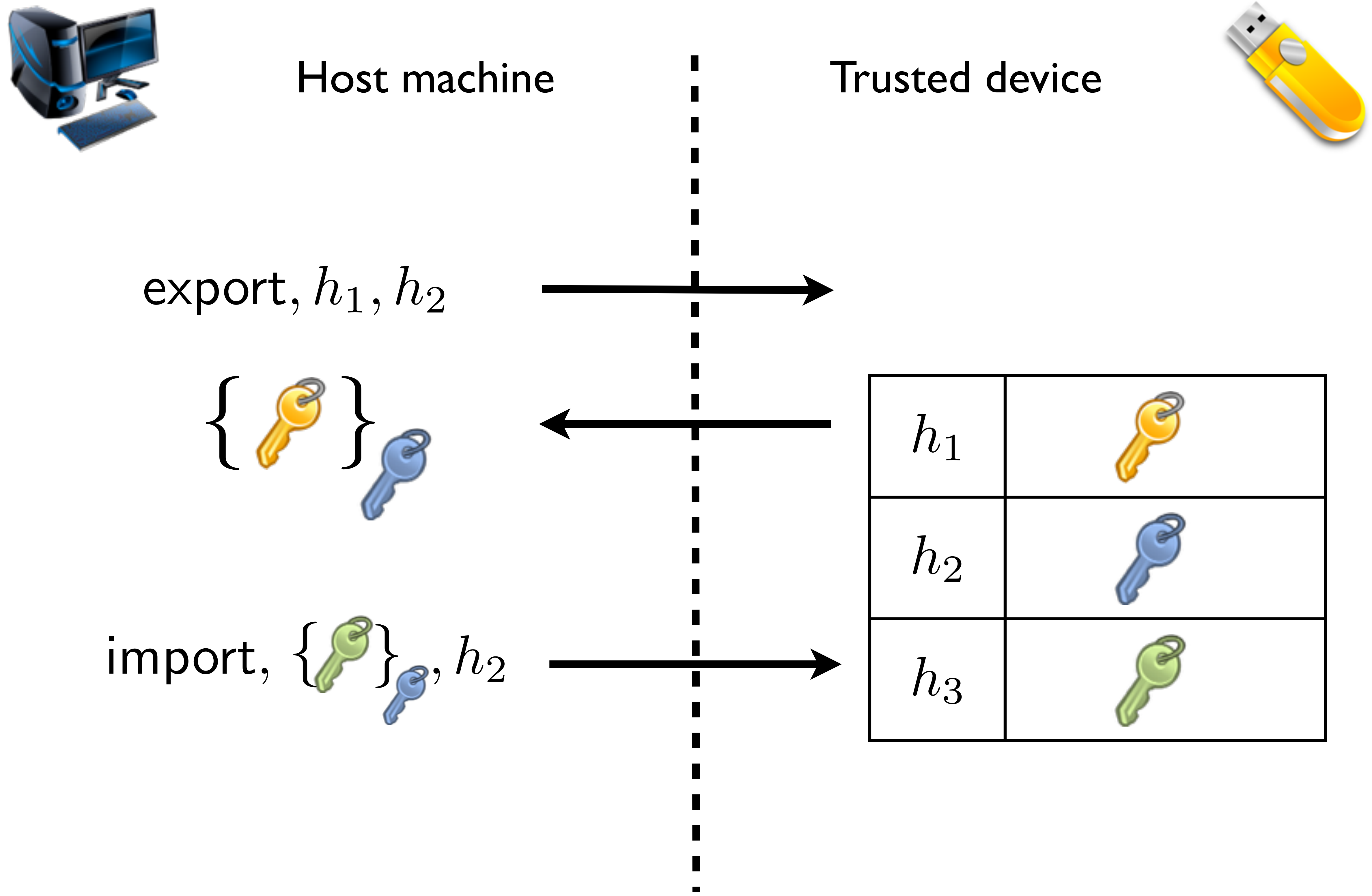
export, h_1, h_2

import, $\{\ \}$, h_2

h_1

h_2

How does it work ?



Host machine

Trusted device

export, h_1, h_2

$\{\ \}$

import, $\{\ \}$, h_2

h_1

h_2

h_3

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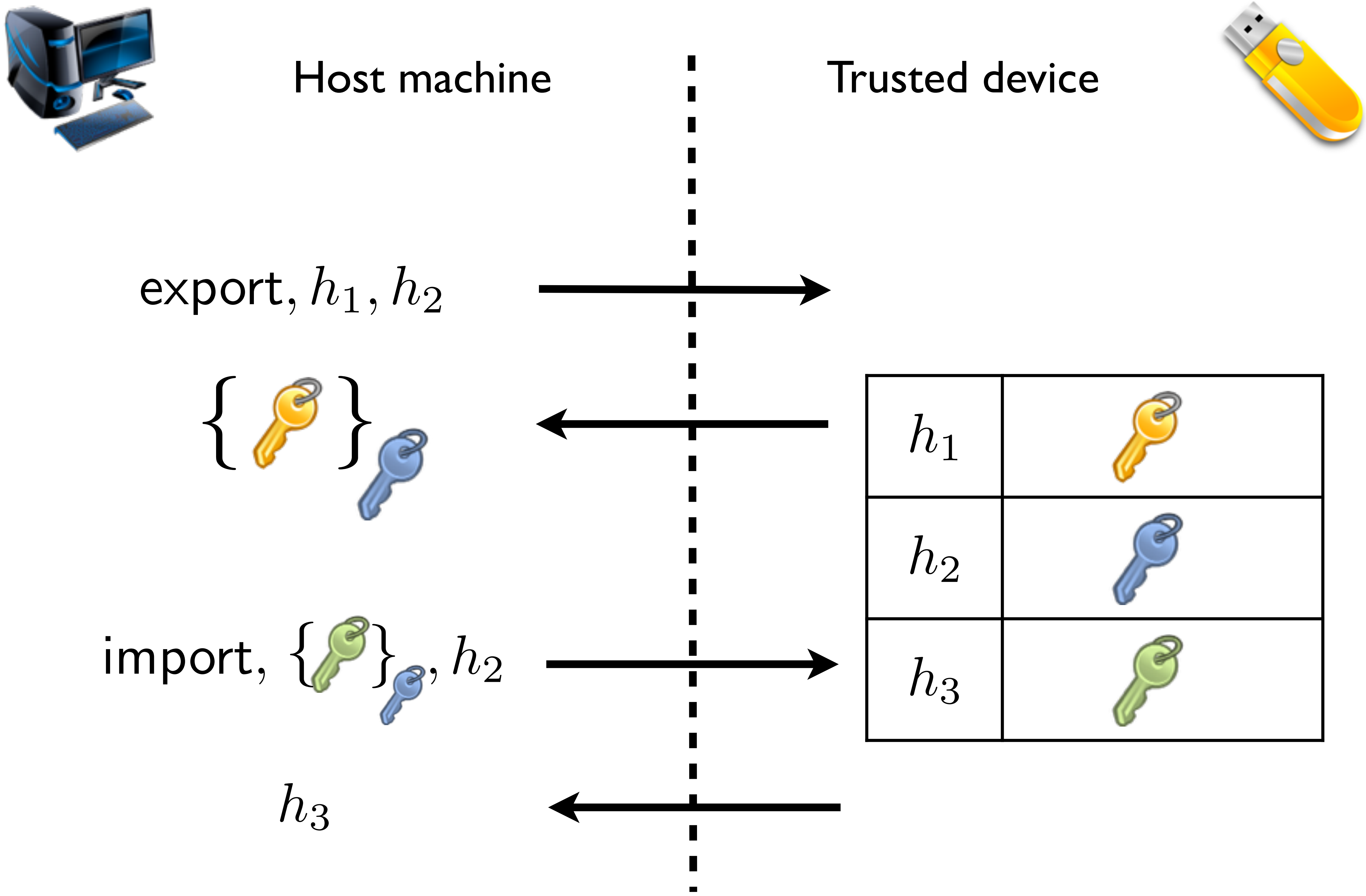

Host machine

Trusted device

export, h_1, h_2

import, h_2

h_3

h_1	🔑
h_2	🔑
h_3	🔑

Related Work

Many flaws found on **PKCS #11** security tokens.

M. Bortolozzo, M. Centenaro,
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TOOKAN

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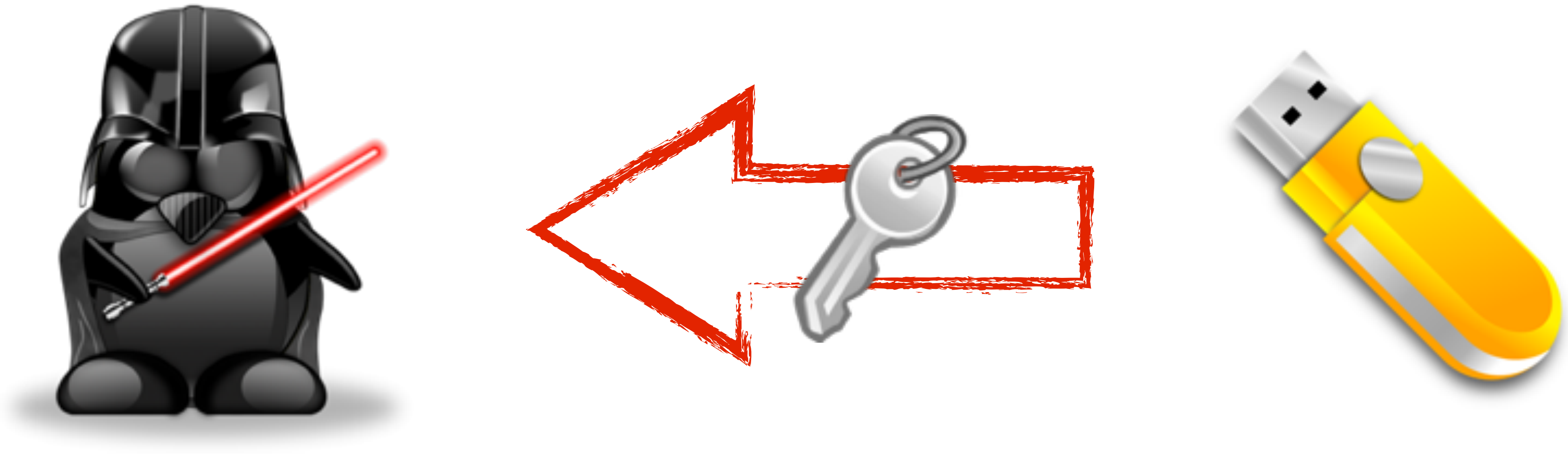
Use of long-term keys implying
unrecoverable loss of devices if keys are lost

Breaking Keys in a TRD

«Because I’m bad, really really bad !»



There are ways for the attacker to **break some keys** of a Tamper-Resistant Device (TRD):

- Bruteforcing,
- Side-channel attack,
- ...

(More) Related Work

Proposals for key management APIs **with revocation**:

L. Eschenauer, V. D. Gligor, CCS'02.

(Using a control server)

X. Z. Yong Wan, B. Ramamurthy, ICC'07.

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F. E. Kargl, Sevecom, 2009...

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⚠ **Attacked by S. Möderschein & P. Modesti**

(solution proposed but no security proof)

Ideal Key Revocation API

Keys must remain **confidential**:

Information about key should not be recovered by the intruder.

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Any key should be **revocable**:

The more sensitive a key is, the more an attacker will try to break it.

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Information about key should not be recovered by the intruder.

Any key should be **revocable**:

The more sensitive a key is, the more an attacker will try to break it.

The device should remain **functional**:

A revocation of a key should not prevent the user from using his/her device.

Our Contributions

- **Design** of an API satisfying previous properties with :
  - **update** functionality,
  - **revocation** functionality.

- A **formal proof of security** ensuring three properties :
  - A **key remains secret** unless it is broken (brute forced),
  - the system is able to **recover itself** from an attack,
  - a **revocation immediately secures** the device.

Description of the API

Some **assumptions** on the tamper-resistant devices:

Description of the API

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A **clock** assumed synchronized with a global clock

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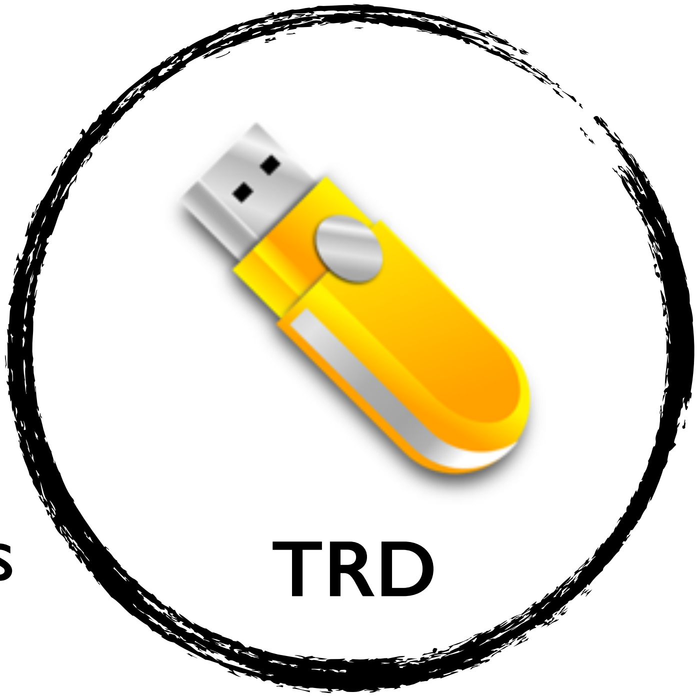

A **table** indexed by handles to store keys' information (level, validity date, value, ...)

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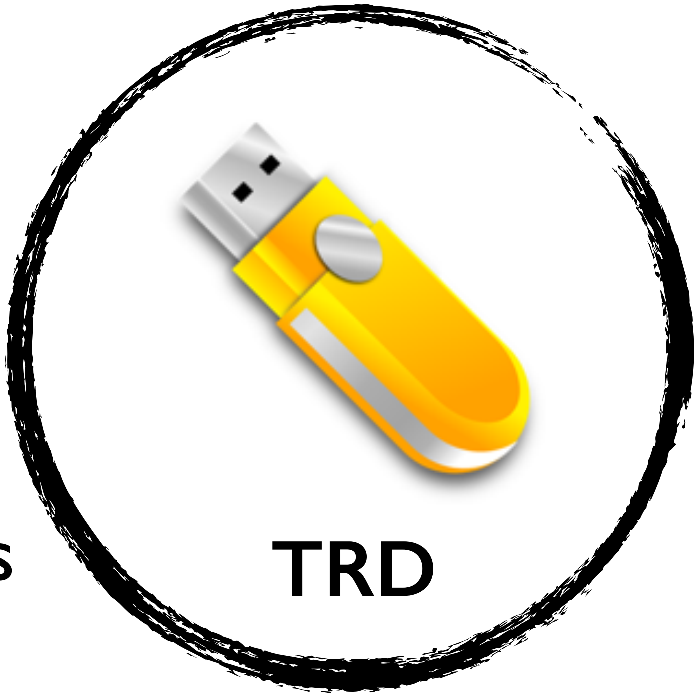

TRD

A **blacklist** of elements of the form (l, t)

A **clock** assumed synchronized with a global clock

Description of the API

We also assume a **hierarchy of levels** for keys:

- with a (partial) order,
- with a maximal and a minimal element.

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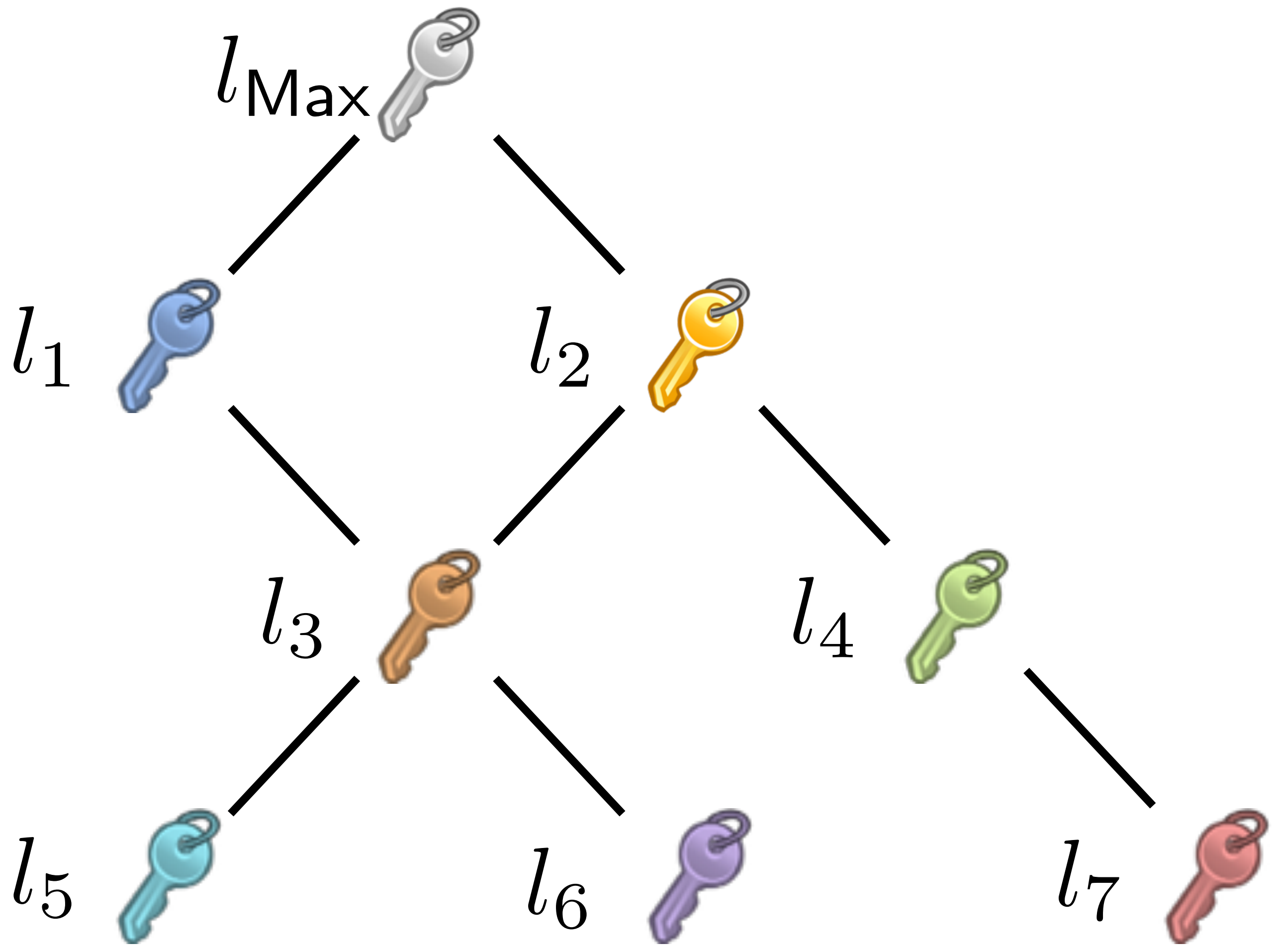

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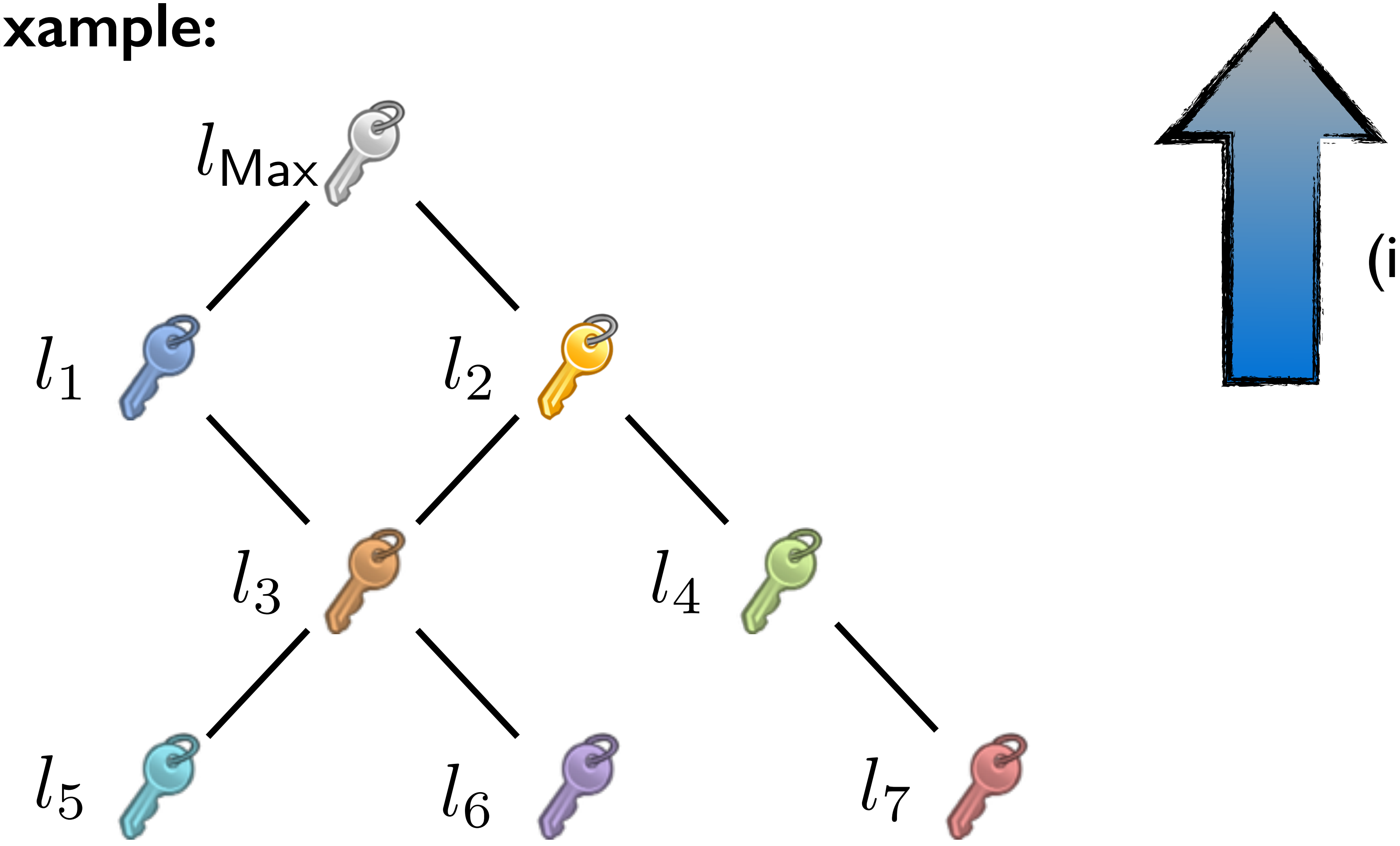

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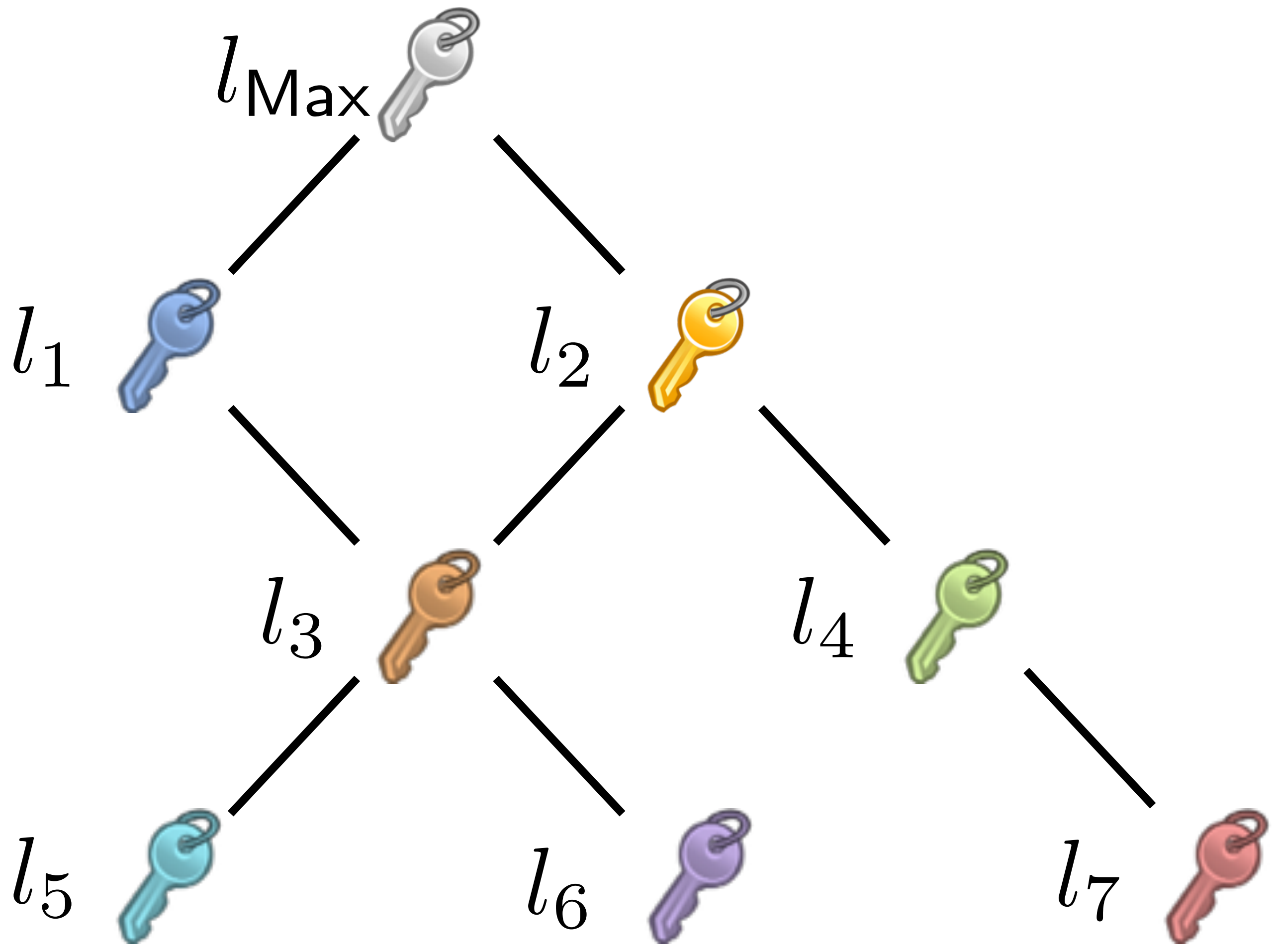

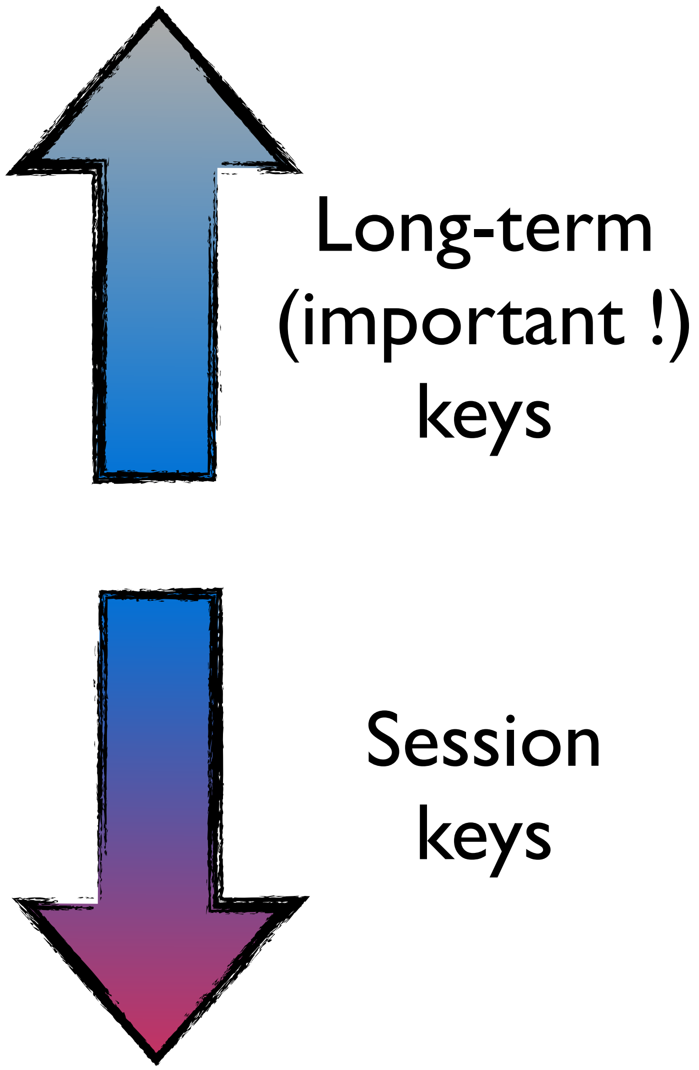

User’s Commands

We have a set of **basic commands**.

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Running example:

Alice

h_1	🔑$, l, v, m$
h_2	
h_3	

Bob

h'_1	🔑$, l, v, m$
h'_2	
h'_3	

User’s Commands

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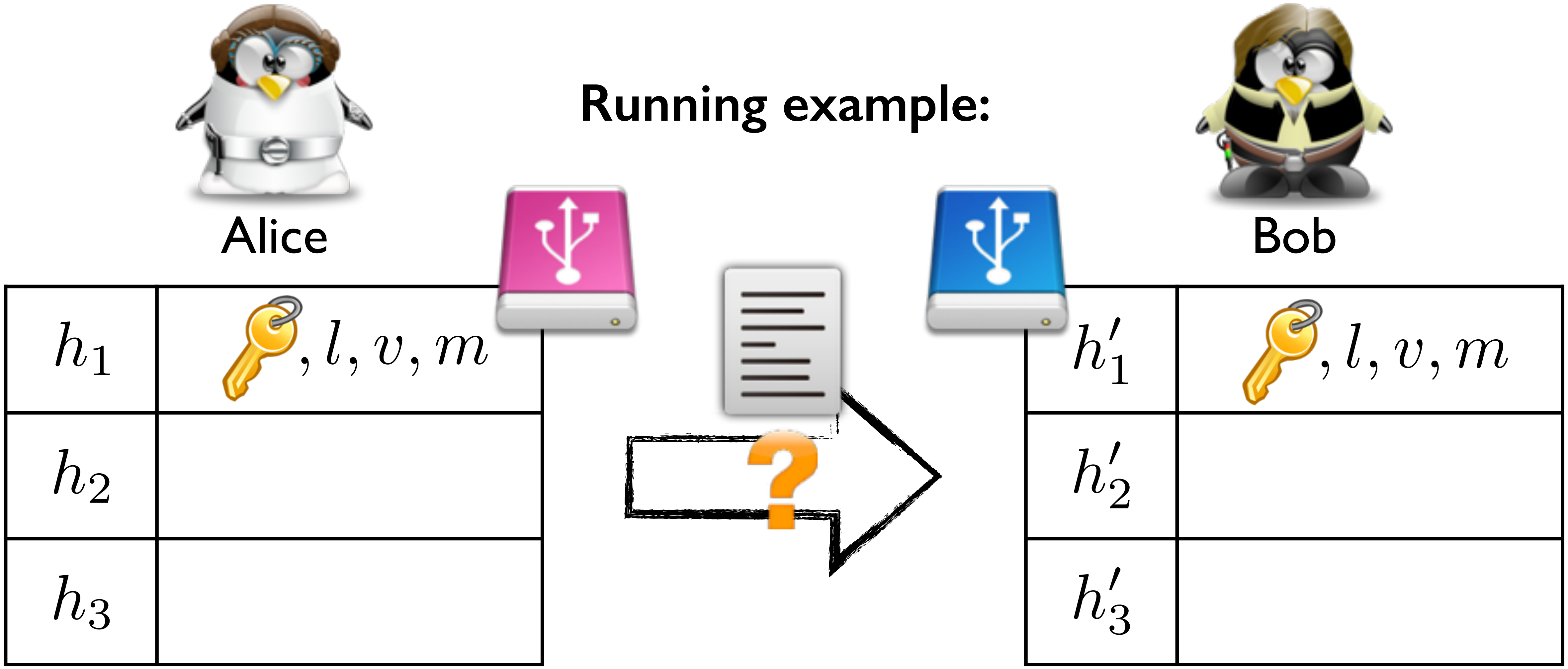


h_1	🔑$, l, v, m$
h_2	
h_3	

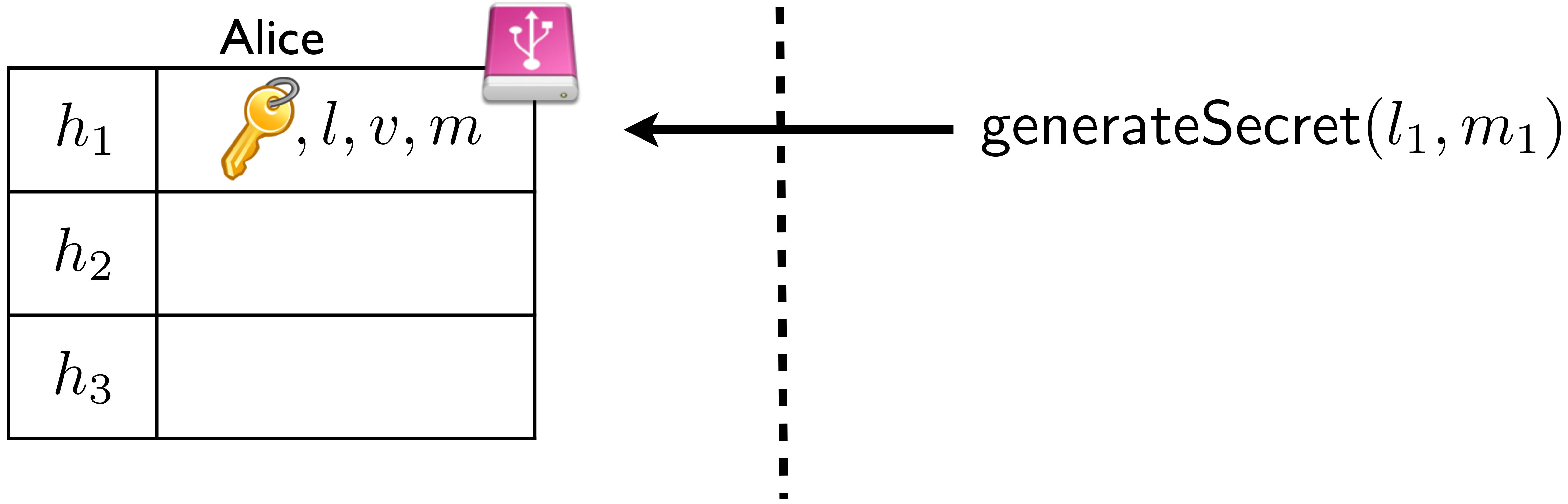
h'_1	🔑$, l, v, m$
h'_2	
h'_3	

Alice and Bob share a key and wish to securely exchange a message.

User’s Commands

	Alice
h_1	🔑$, l, v, m$
h_2	
h_3	

User's Commands

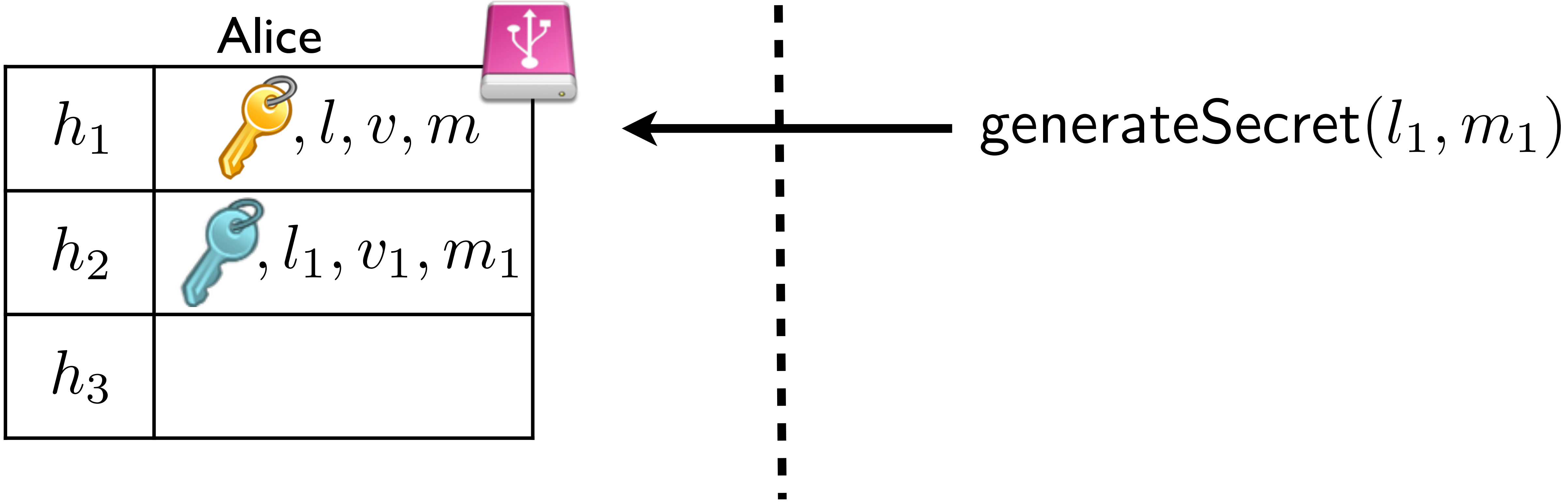


Alice

h_1	🔑$, l, v, m$
h_2	
h_3	

generateSecret(l_1, m_1)

User's Commands



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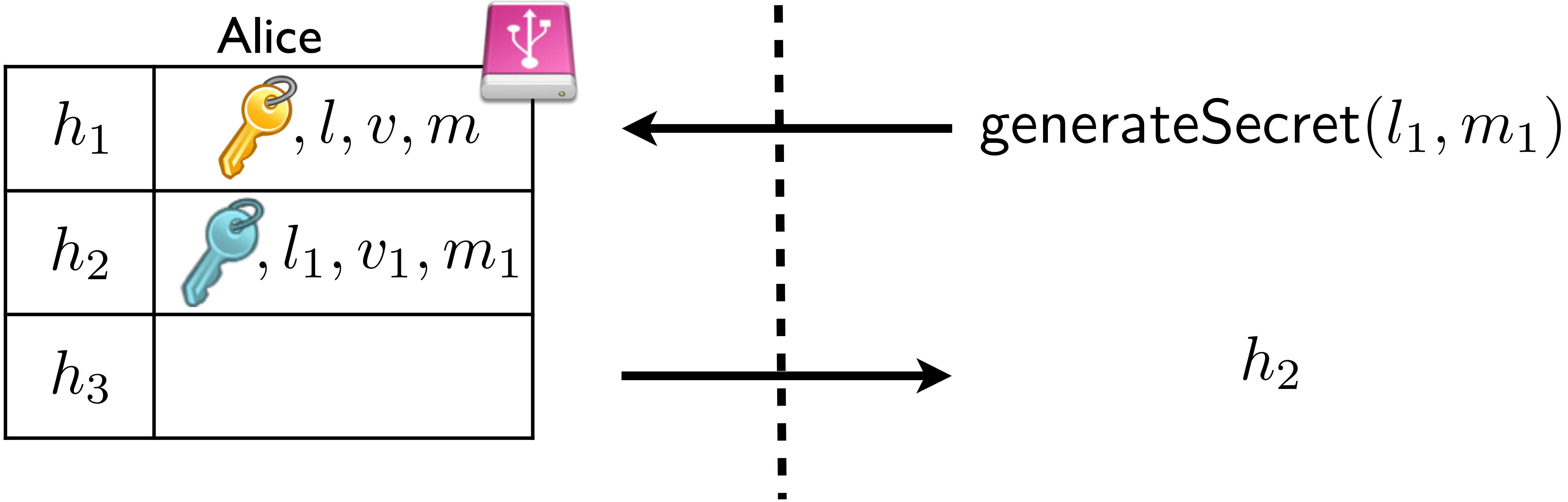

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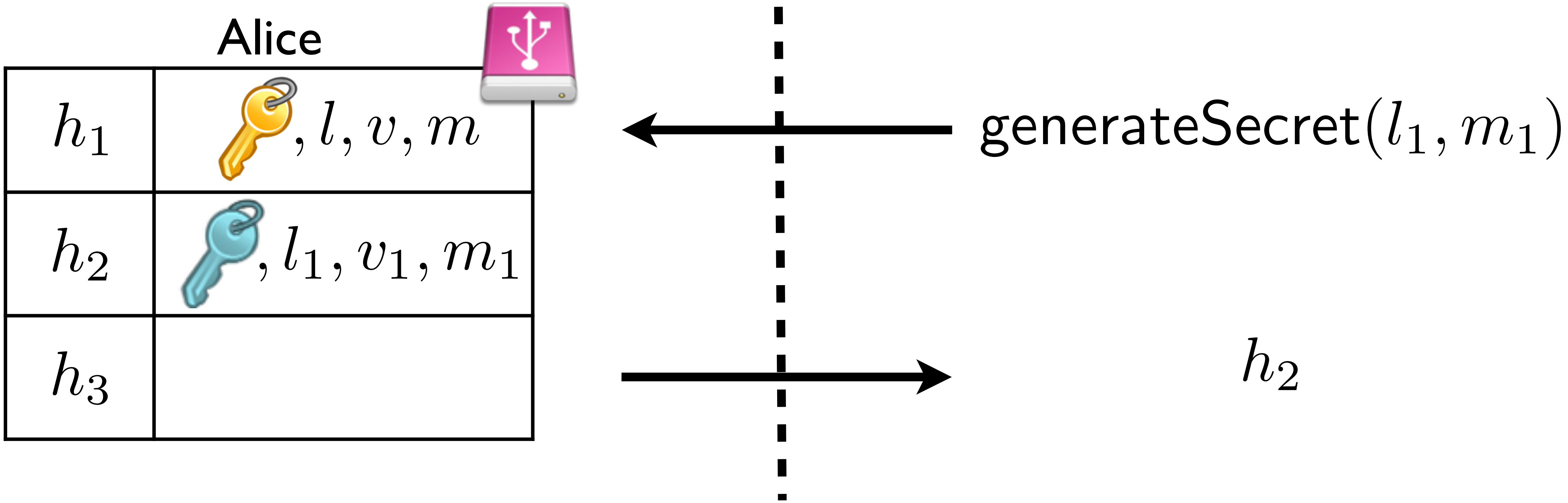

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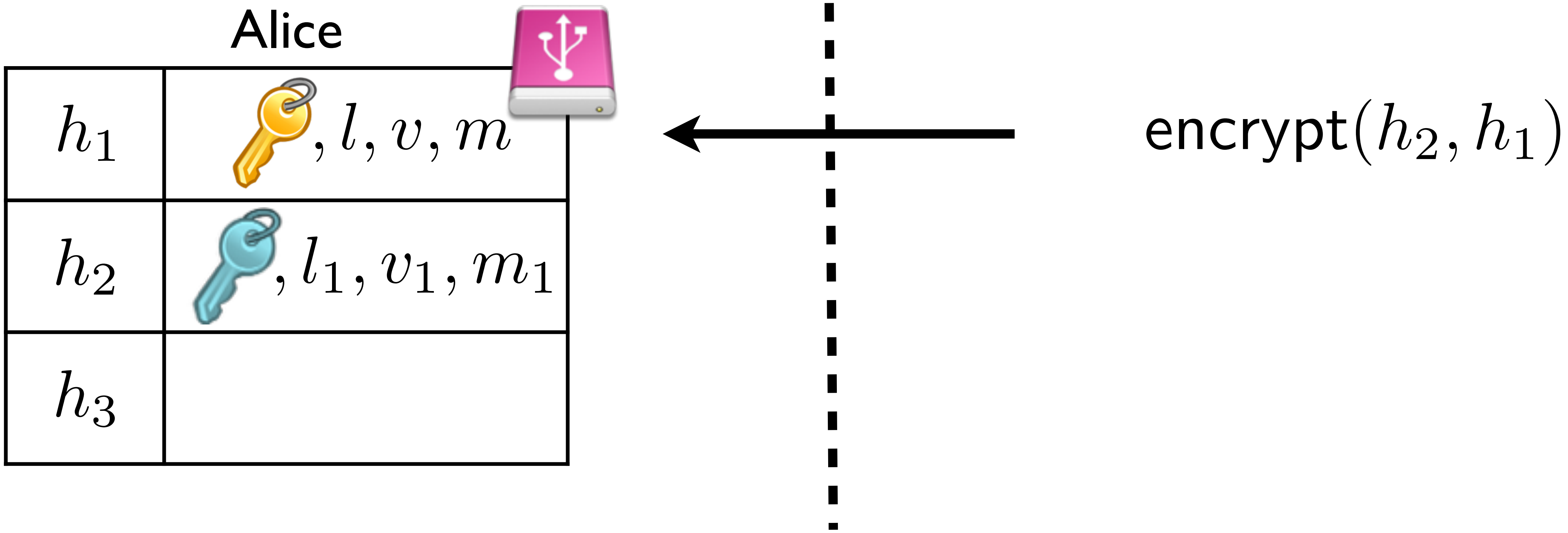
To share the new session key with Bob, Alice needs to « export » the new key.



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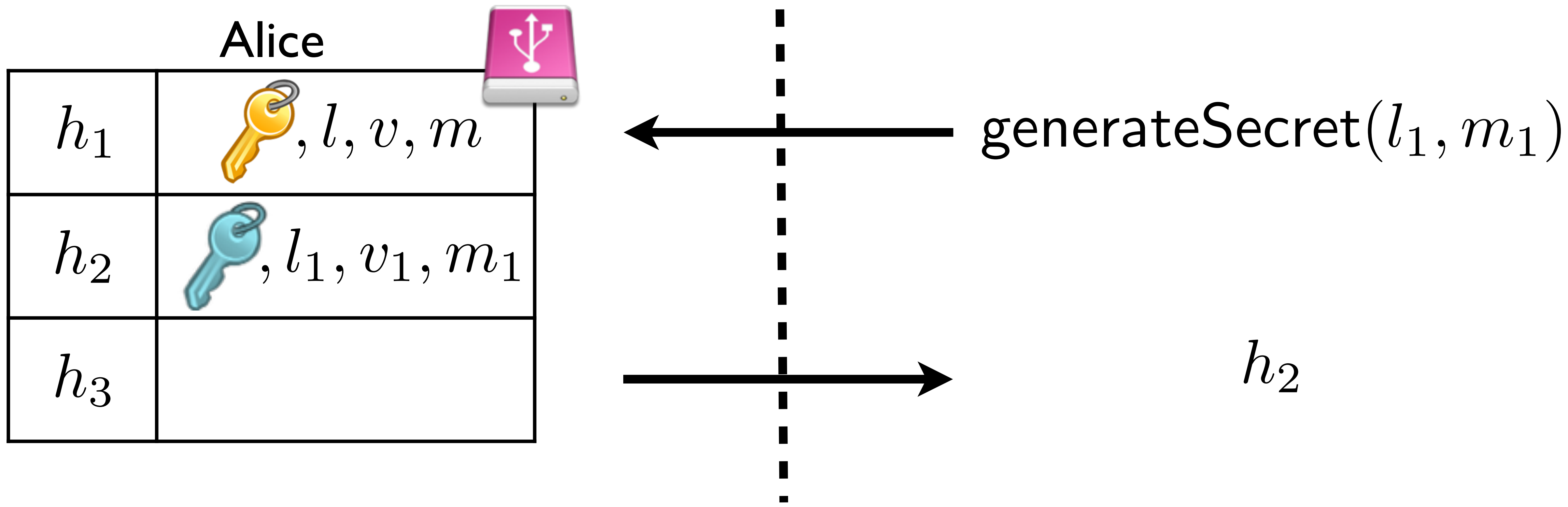
encrypt(h_2, h_1)

User's Commands



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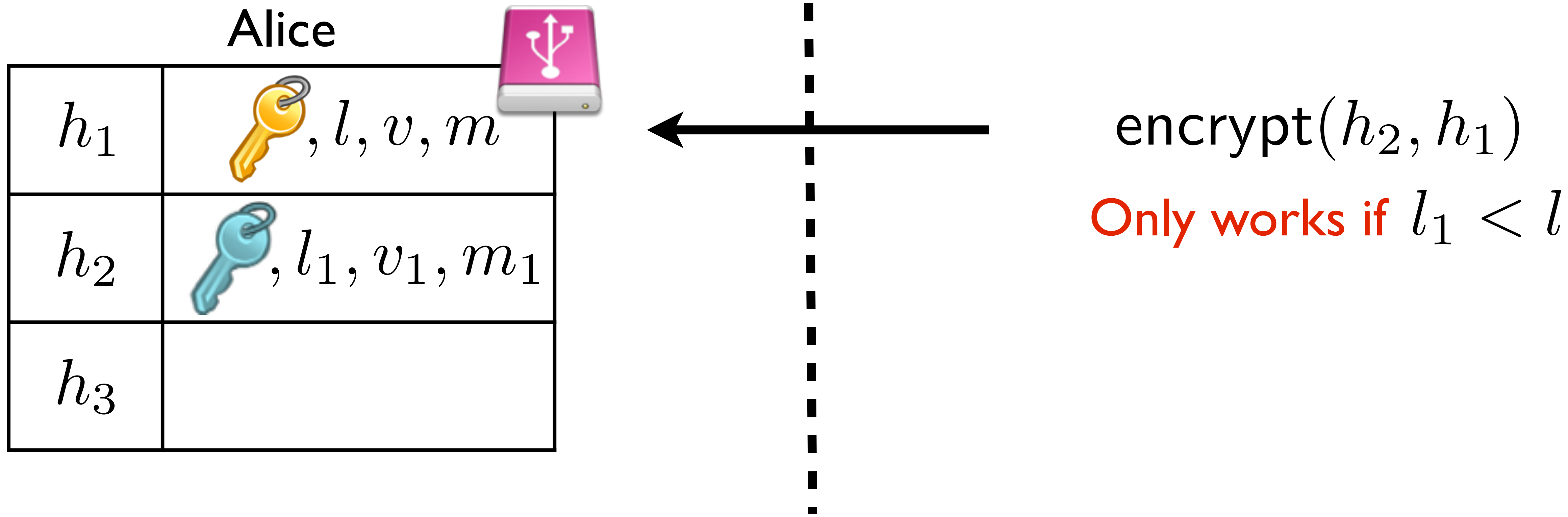

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h_1	🔑$, l, v, m$
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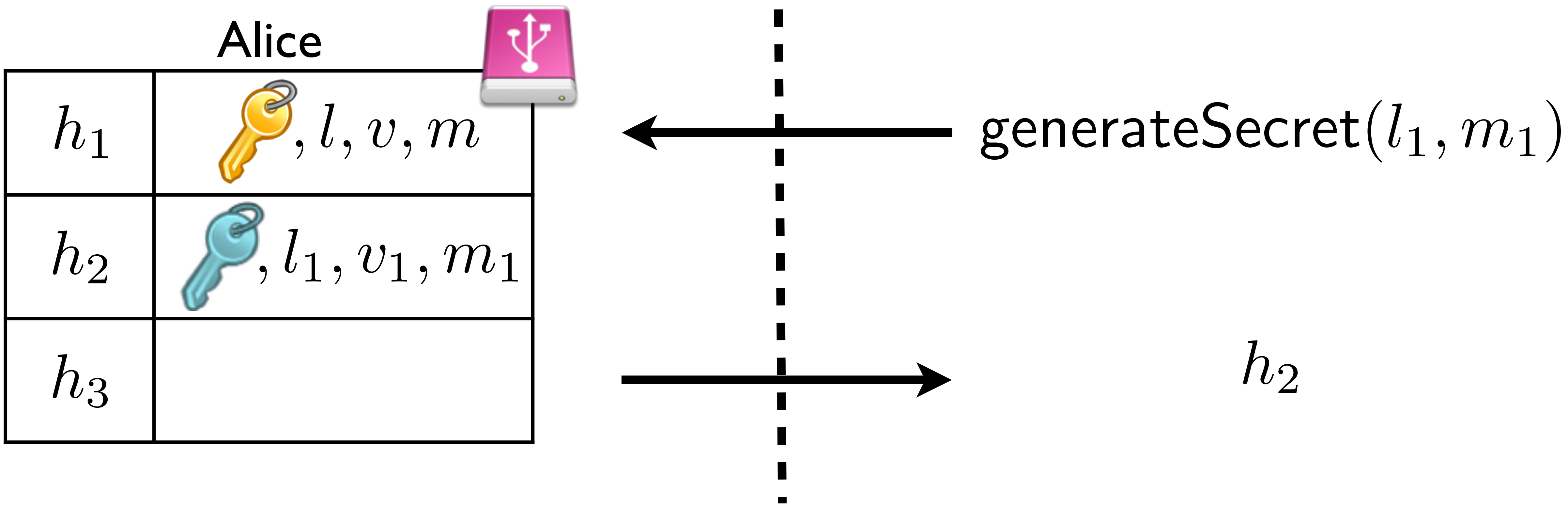
Only works if $l_1 < l$

User's Commands



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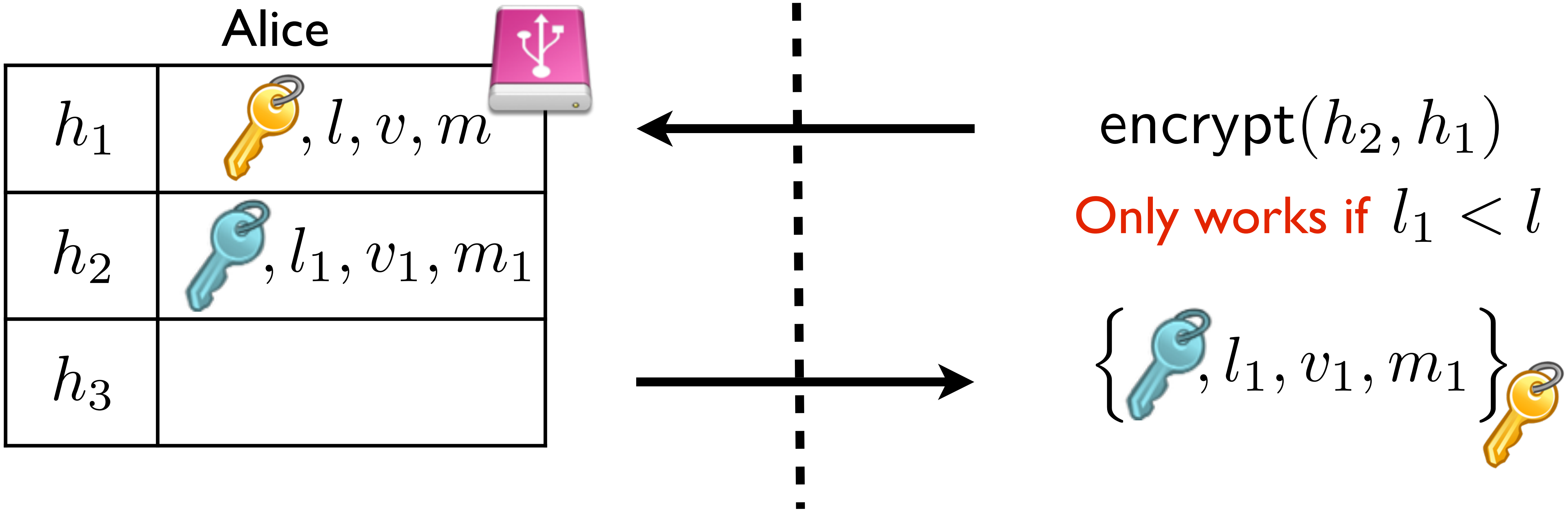

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encrypt(h_2, h_1)

Only works if $l_1 < l$

{🔑, l_1, v_1, m_1}🔑

User’s Commands

Alice sends the new session key to Bob which can « import » it in his TRD.

Bob

h'_1	🔑$, l, v, m$
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h'_3	

User’s Commands

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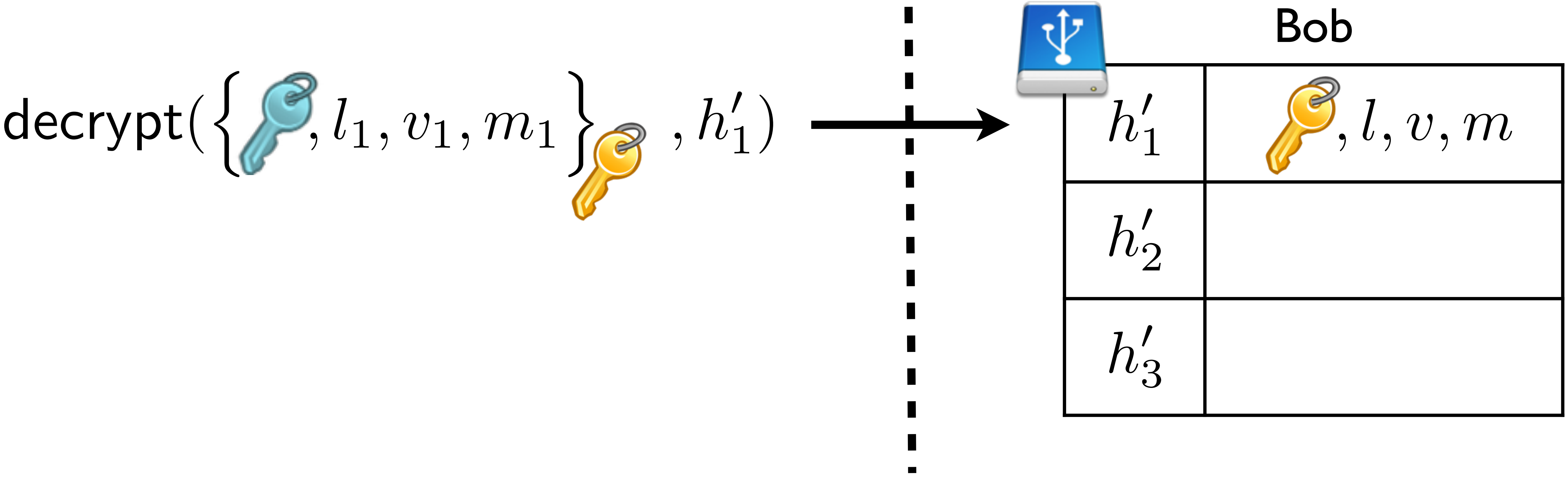

decrypt($\{$🔑$, l_1, v_1, m_1\}_{🔑}$ $, h'_1$)

Bob

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h'_2	
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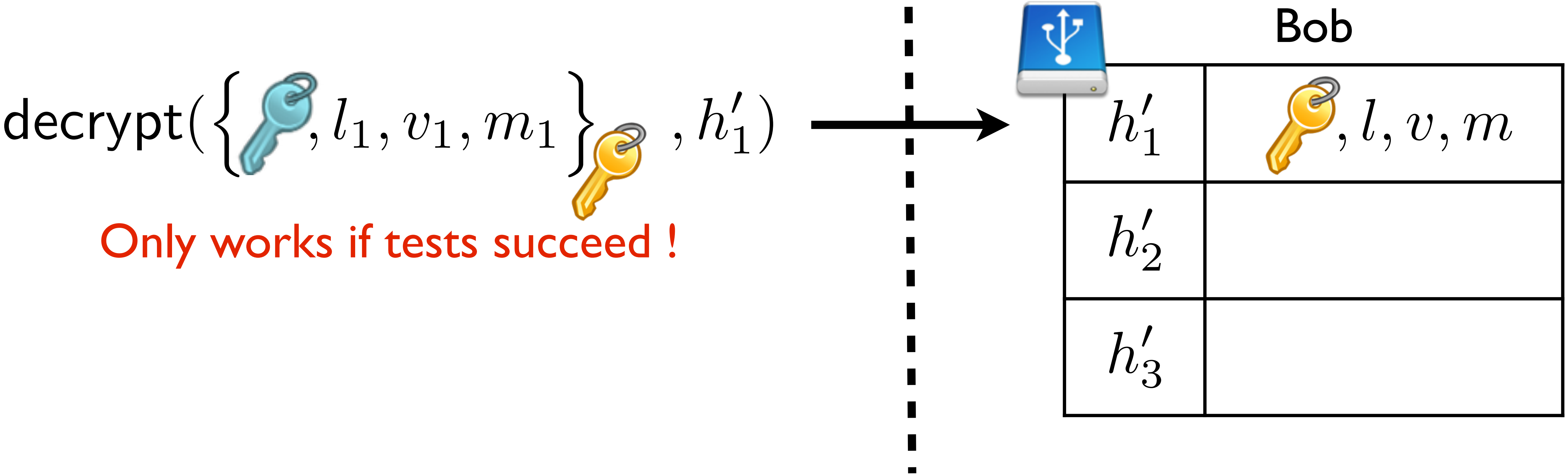

decrypt($\{$🔑$, l_1, v_1, m_1\}_{🔑}, h'_1)$

Only works if tests succeed !

Bob

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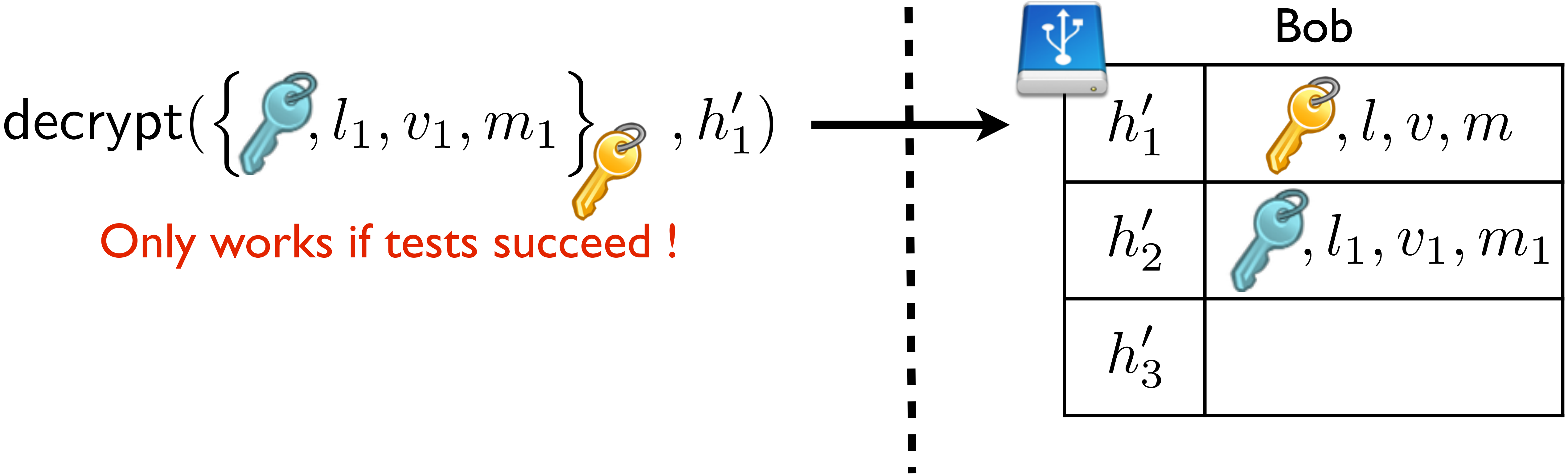
User's Commands

Alice sends the new session key to Bob which can « import » it in his TRD.



decrypt({🔑, l_1, v_1, m_1}🔑, h'_1)

Only works if tests succeed !

Bob

h'_1	🔑, l, v, m
h'_2	🔑, l_1, v_1, m_1
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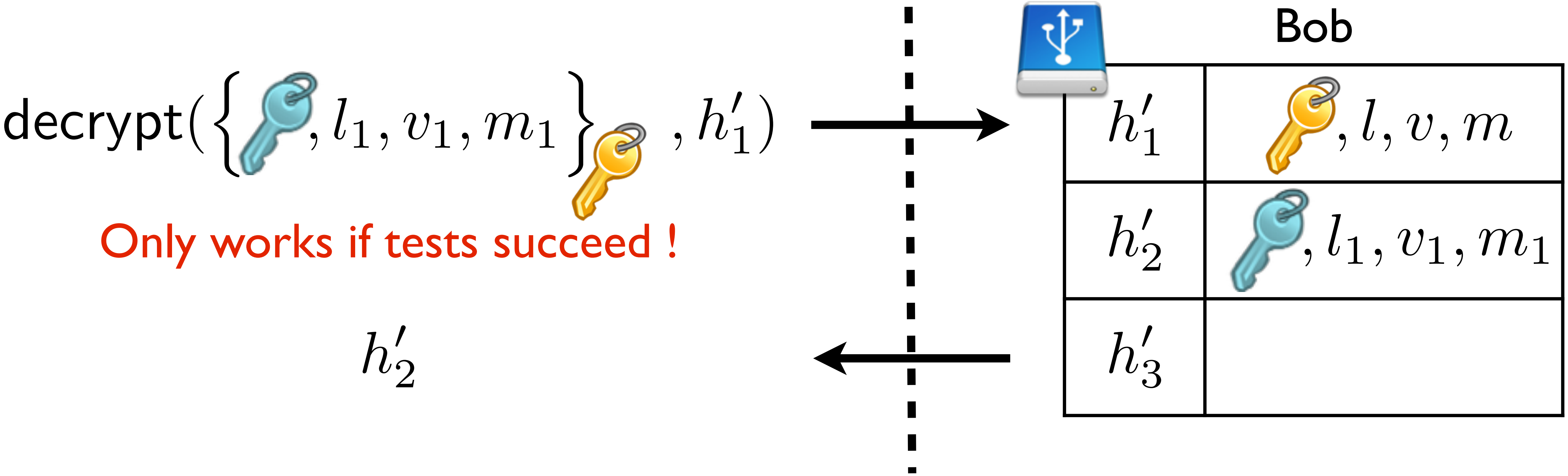


decrypt({🔑, $l_1, v_1, m_1\}_{🔑}, h'_1)$

Only works if tests succeed !

h'_2

Bob

h'_1	🔑, l, v, m
h'_2	🔑, l_1, v_1, m_1
h'_3	

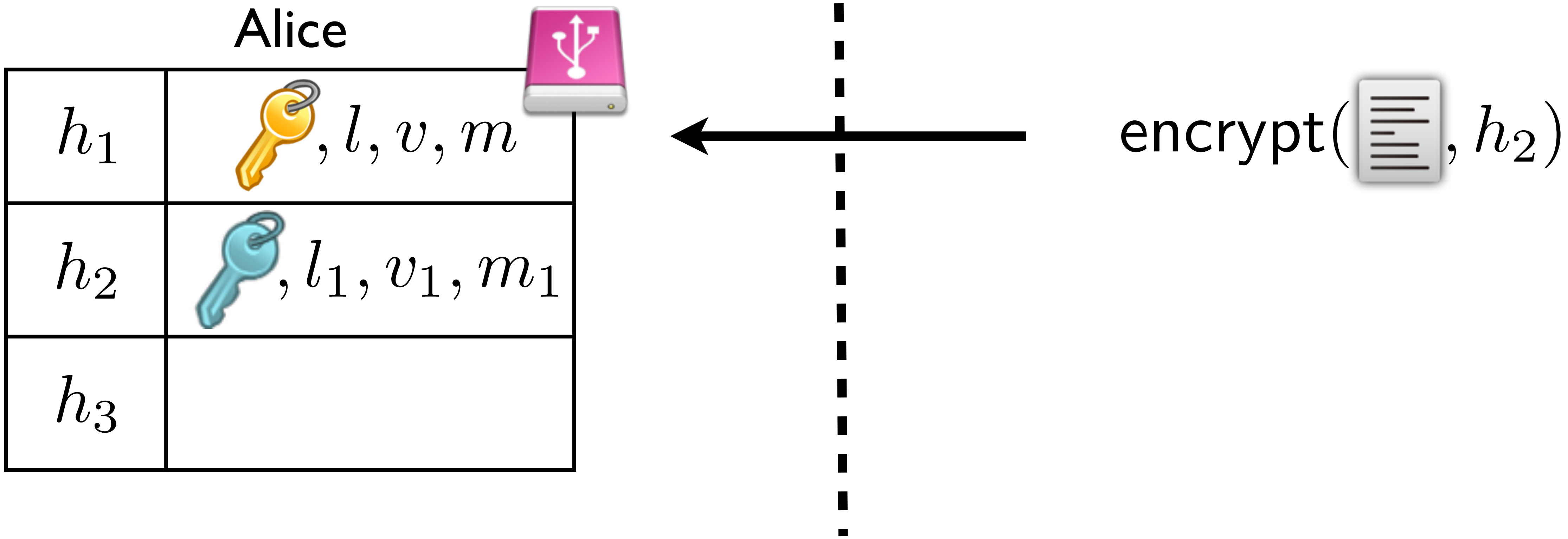
User’s Commands

Alice can now encrypt the message using the session key.

	Alice
h_1	🔑$, l, v, m$
h_2	🔑$, l_1, v_1, m_1$
h_3	

User’s Commands

Alice can now encrypt the message using the session key.



Alice

h_1	🔑$, l, v, m$
h_2	🔑$, l_1, v_1, m_1$
h_3	

encrypt(📄$, h_2)$

User’s Commands

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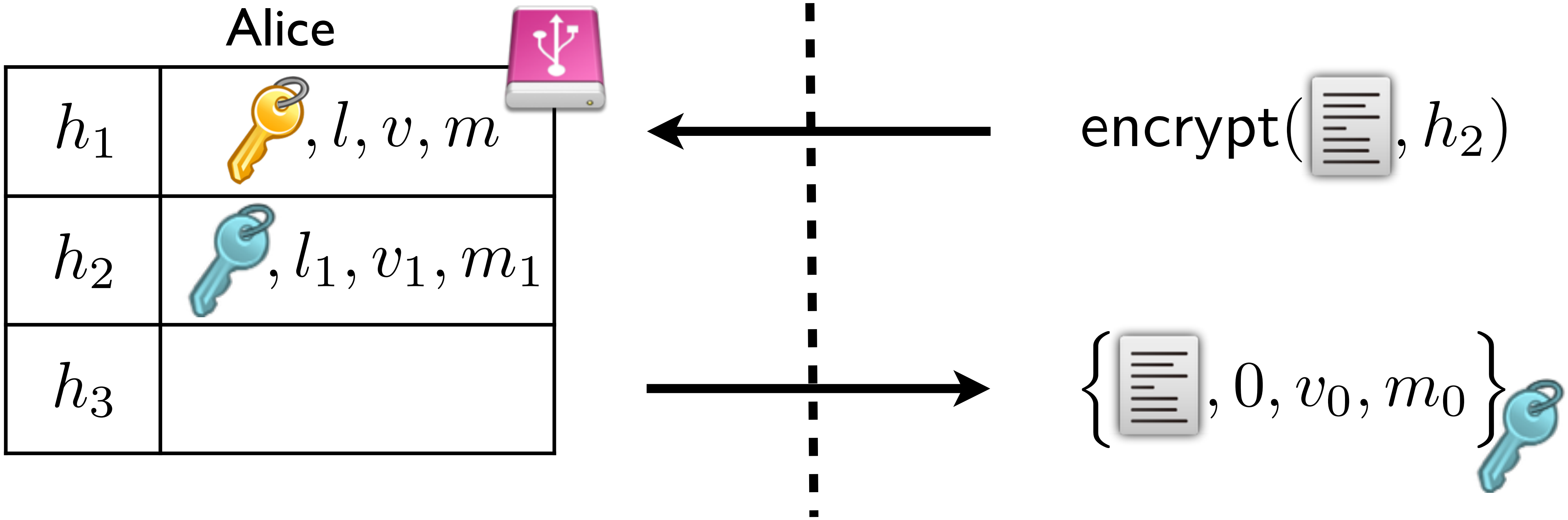

Alice

h_1	🔑, l, v, m
h_2	🔑, l_1, v_1, m_1
h_3	

encrypt(📄, h_2)

$\{$📄$, 0, v_0, m_0\}$🔑

User’s Commands

And, finally, Alice sends the encrypted message to Bob, which decrypts it.

Bob

h'_1	🔑$, l, v, m$
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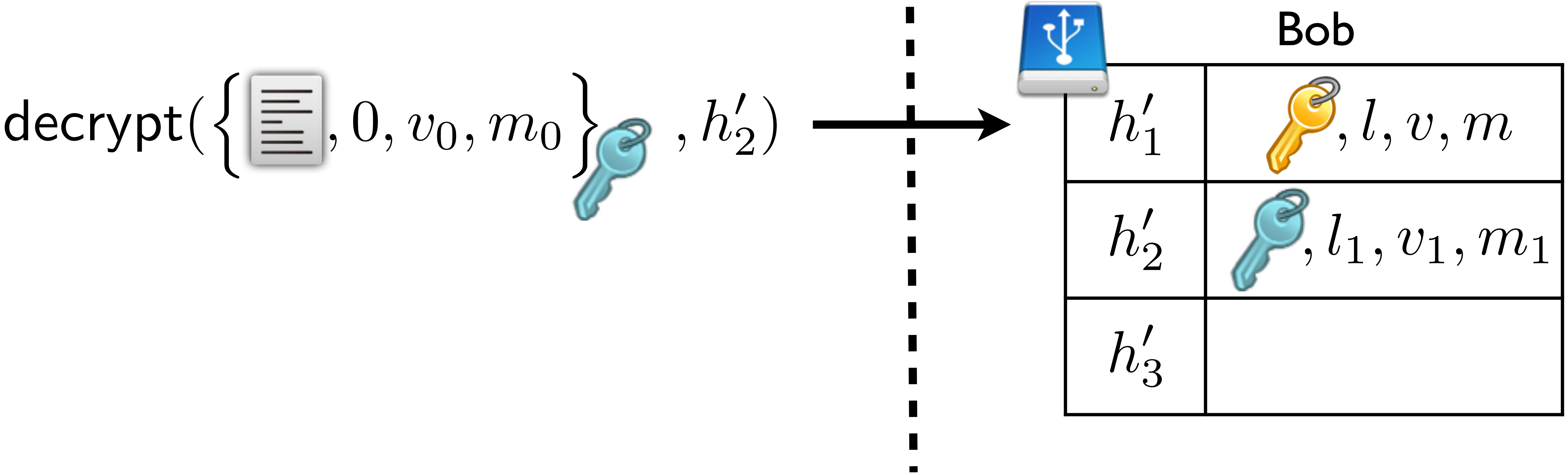

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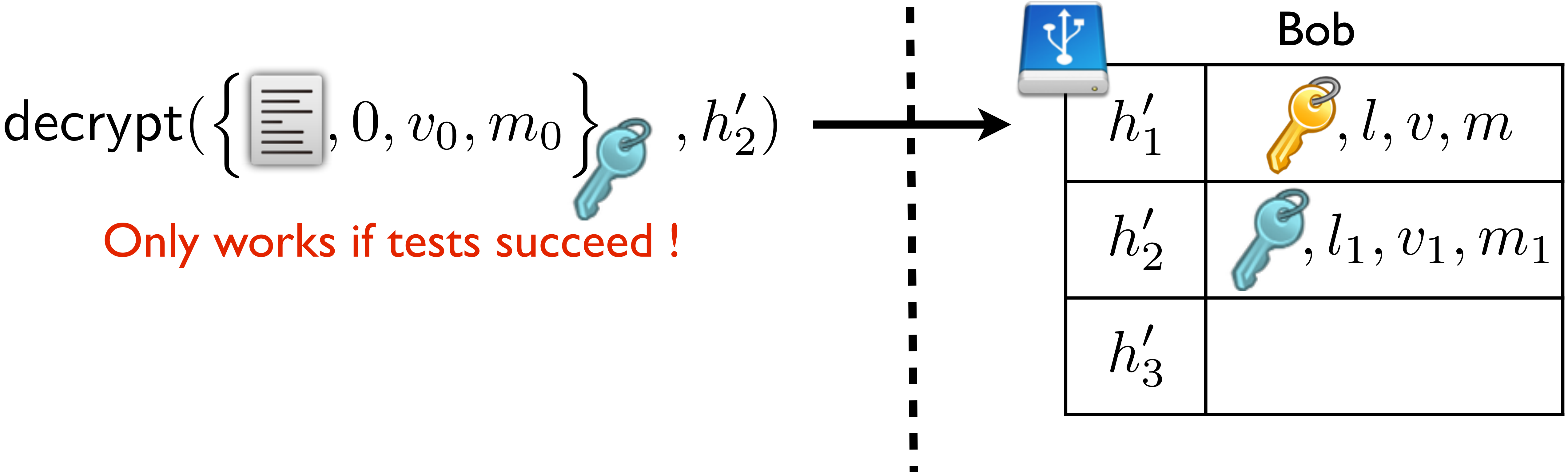

decrypt($\{$ 📄 $, 0, v_0, m_0\}$ 🔑 $, h'_2)$

Only works if tests succeed !

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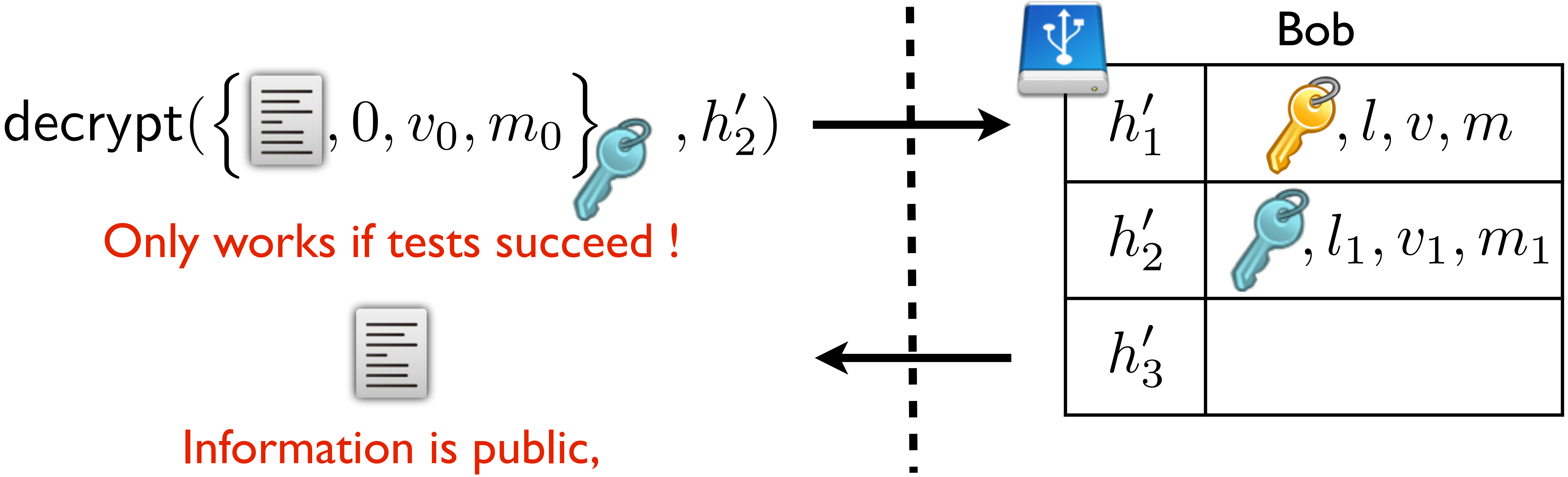

decrypt({📄, $0, v_0, m_0$}🔑, h'_2)

Only works if tests succeed !

	Bob
h'_1	🔑$, l, v, m$
h'_2	🔑$, l_1, v_1, m_1$
h'_3	

📄

Information is public,
no need for handles.

User’s Commands

A set of **basic commands** (summary):

generatePublic(m)

generateSecret(l, m)

Generate a nonce or a key, and store under a handle the information.

decrypt(C, h)

Decrypt C with the key stored under h and return a message or a handle.

encrypt$(\langle X_1, \ldots, X_n \rangle, h)$

Encrypt the input under the key stored in handle h.

Lower Level Keys Management

We also have **admin commands**:

- Allow to **administrate lower level keys** (i.e. level < Max).
- Need **revocation keys,** i.e. keys of level Max.
- Each device has its own set of admin keys.

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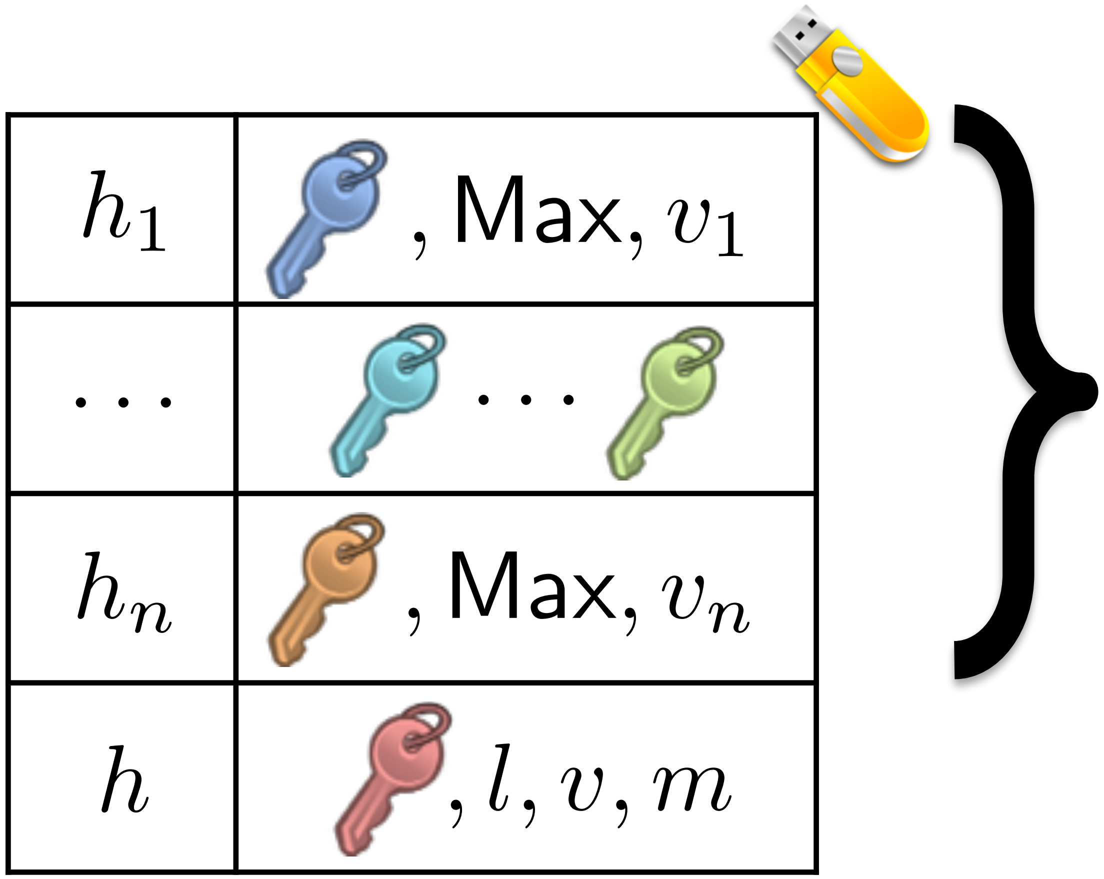

h_1	🔑 $, \mathrm{Max}, v_1$
$\ldots$	🔑 $\ldots$ 🔑
h_n	🔑 $, \mathrm{Max}, v_n$
h	🔑 $, l, v, m$

Revocation keys of the device.

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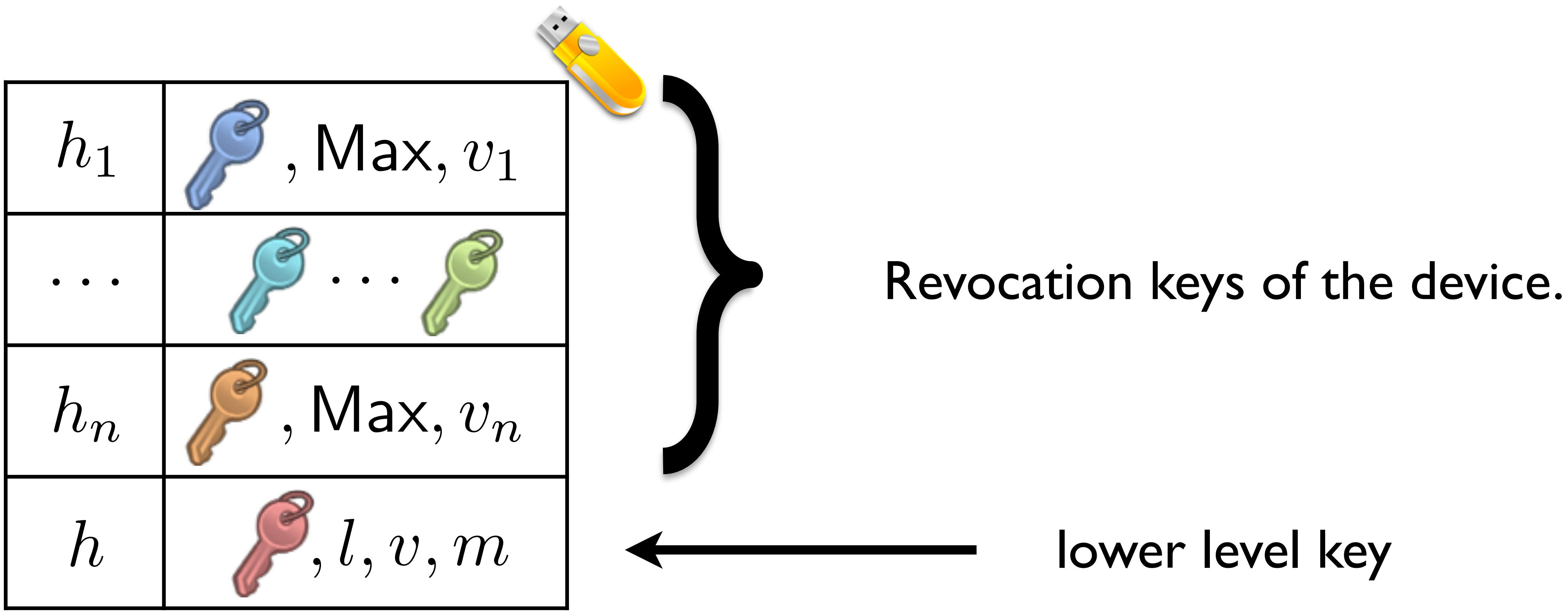


h_1	🔑, Max, v_1
$\dots$	🔑 $\dots$ 🔑
h_n	🔑, Max, v_n
h	🔑, l, v, m

Revocation keys of the device.

lower level key

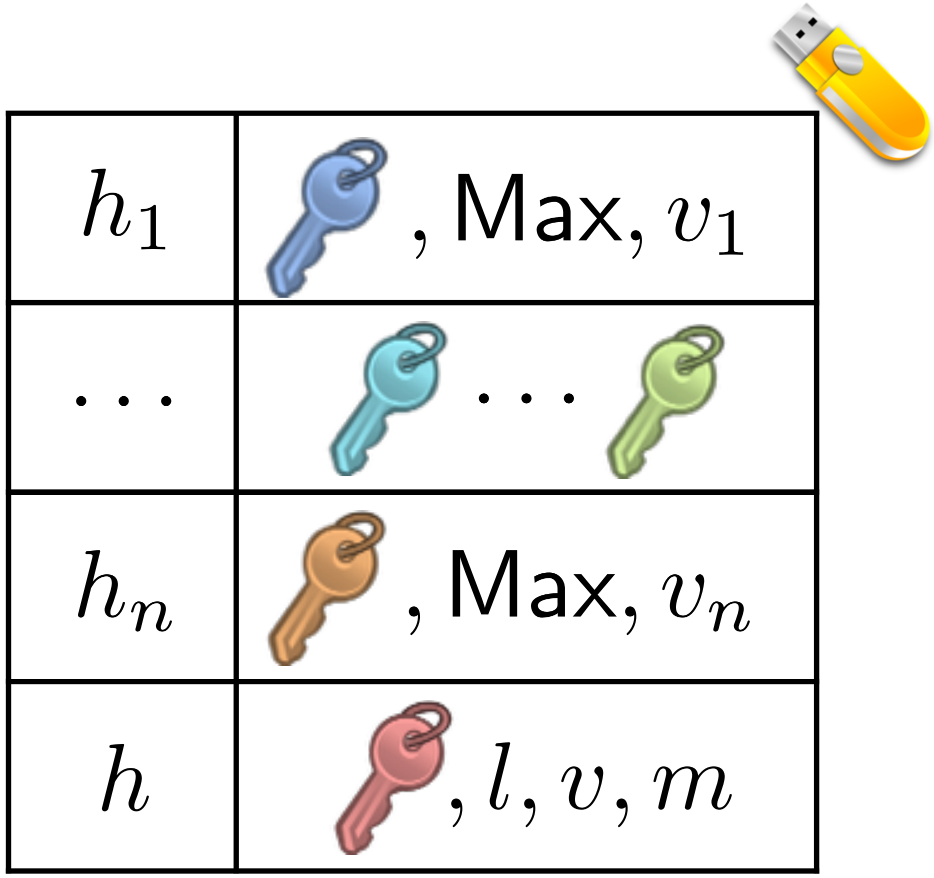
Lower Level Keys Management

h_1	🔑, Max, v_1
$\dots$	🔑 $\dots$ 🔑
h_n	🔑, Max, v_n
h	🔑, l, v, m

update$(C, h_1, \dots, h_n)$

Update value and attributes of keys that are not admin (level Max) keys.

Lower Level Keys Management



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2. Decryption of C.

   > Obtaining old/new value and new attributes.

Lower Level Keys Management

How does it work ?

3. Verify that the old key (🔑) is in the device.

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Lower Level Keys Management

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4. Tests on the new attributes l', v' of new key (🔑).

> Are the new level and validity date correct ?

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The same scheme applies for **revoking revocation keys**.

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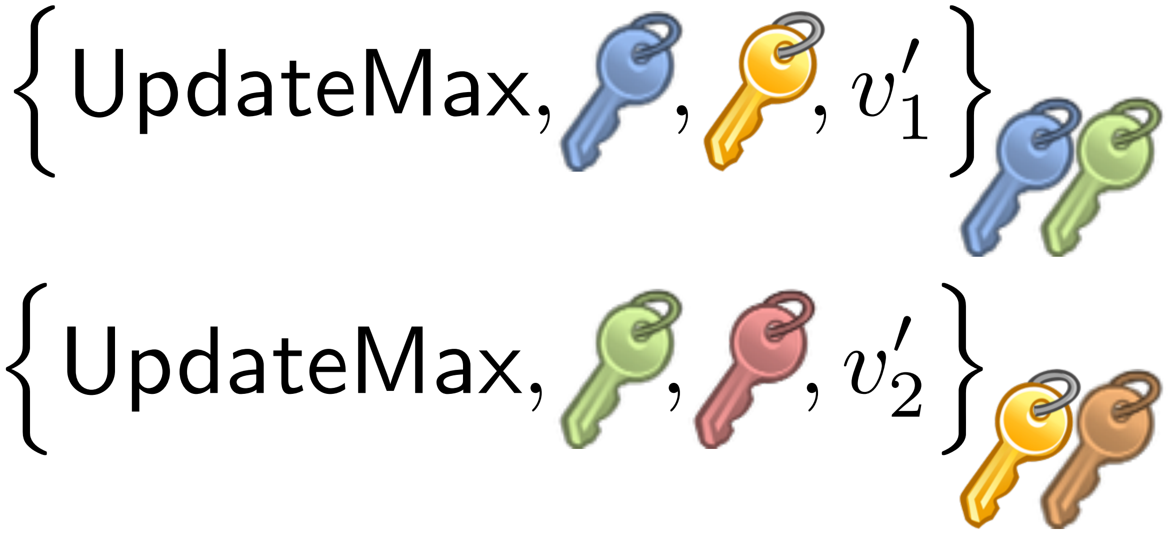

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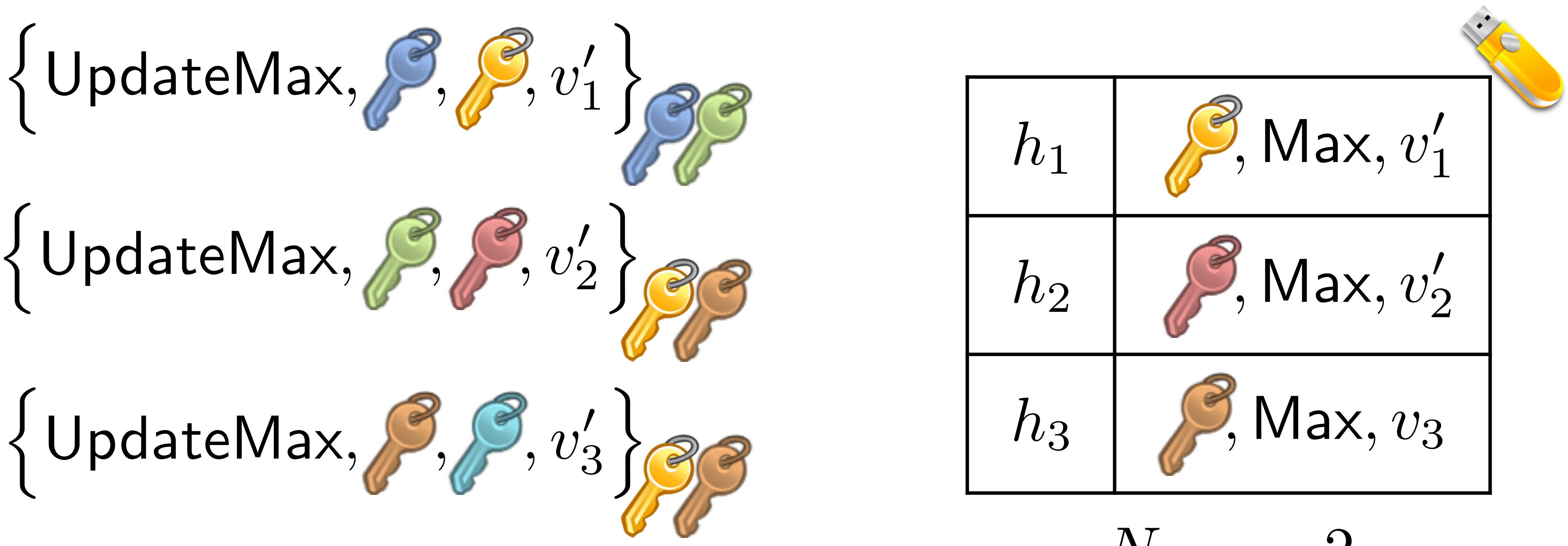

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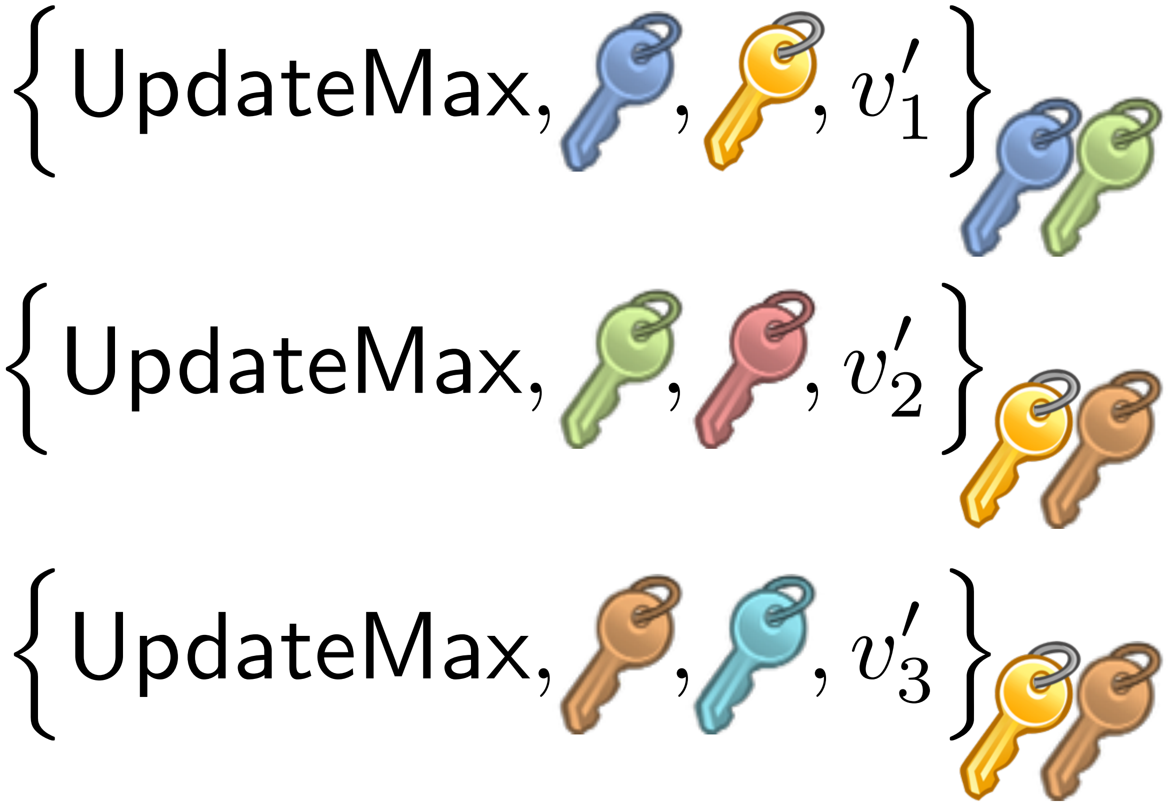

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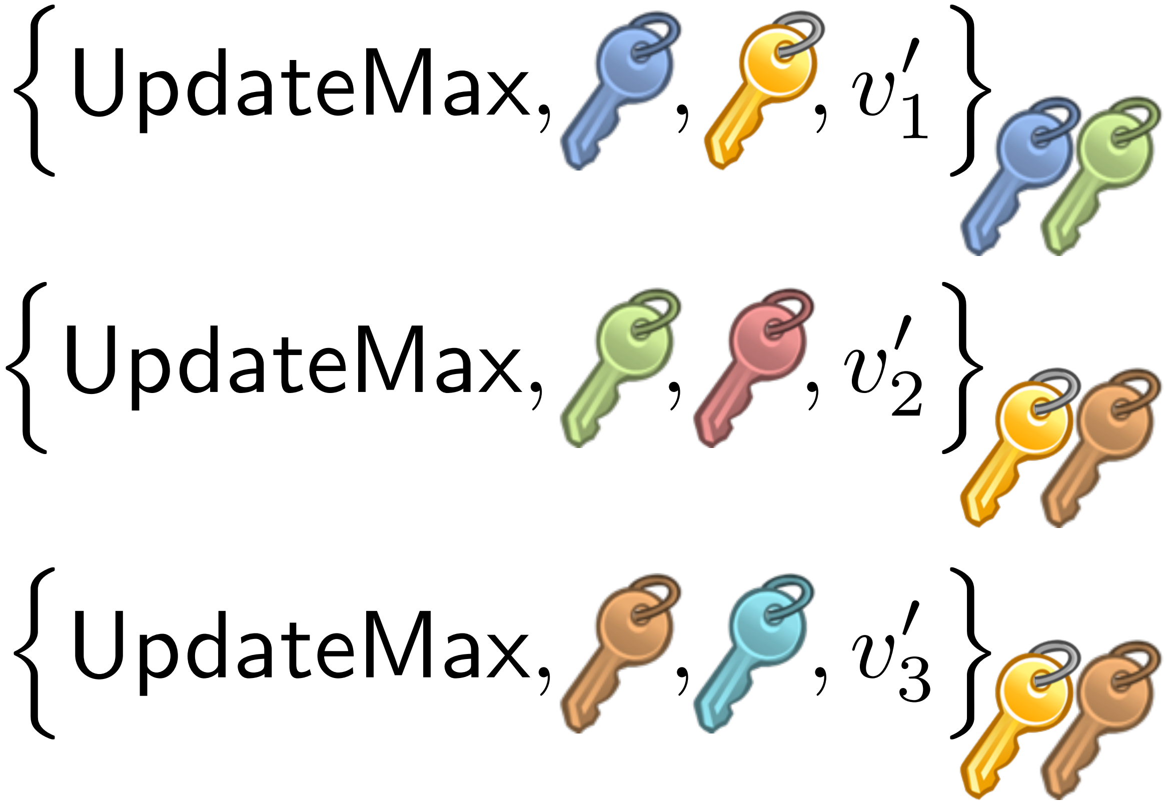

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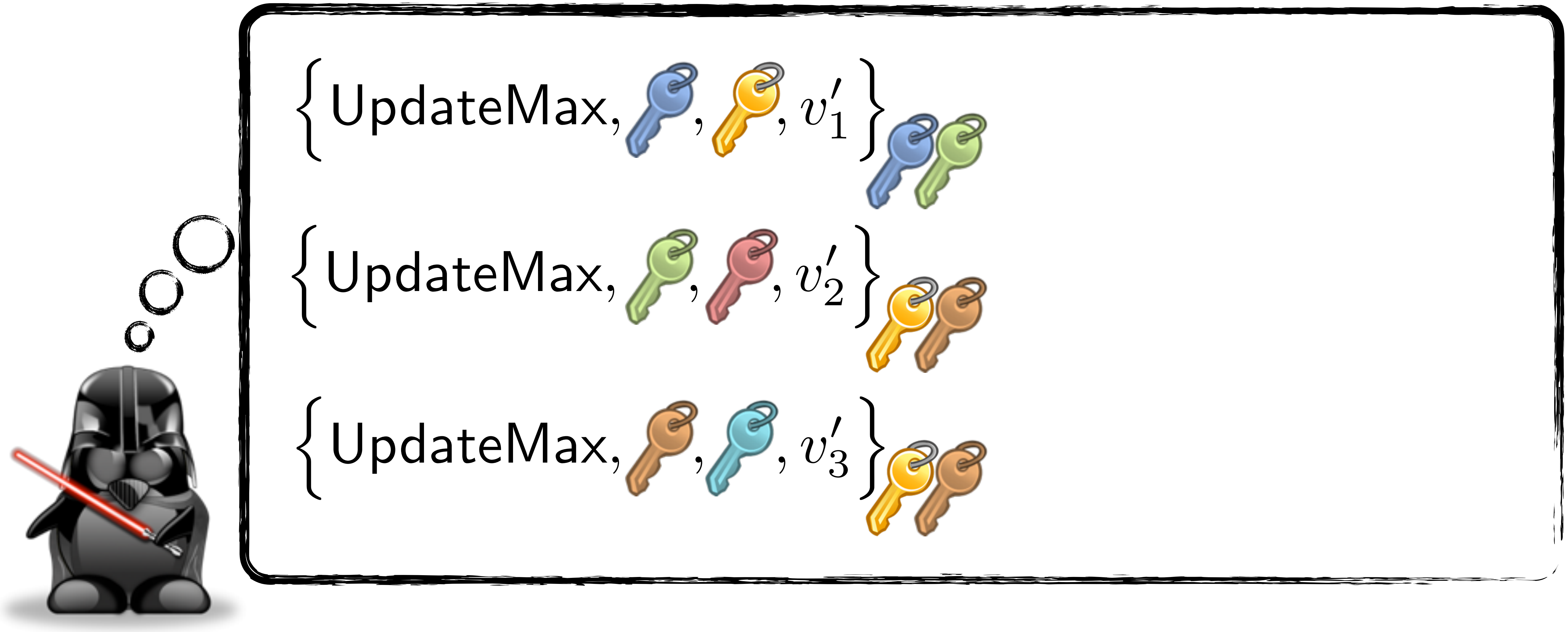

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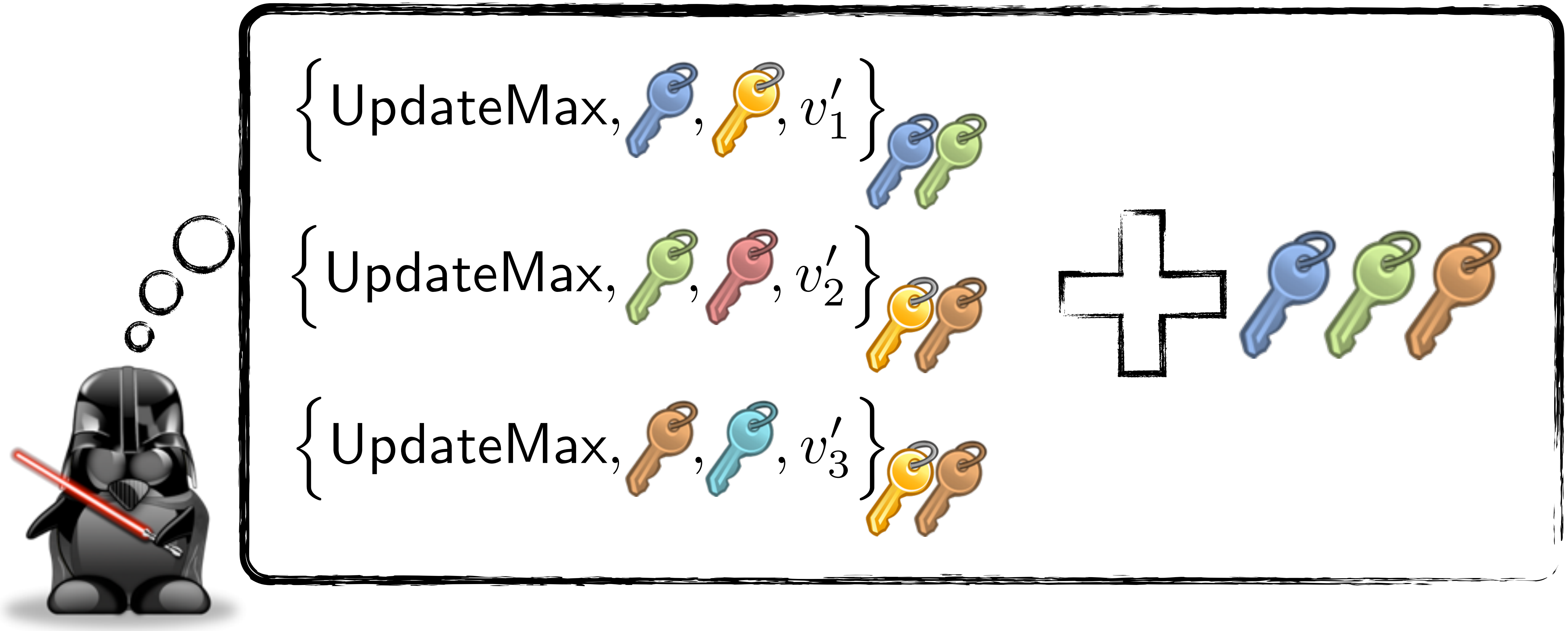
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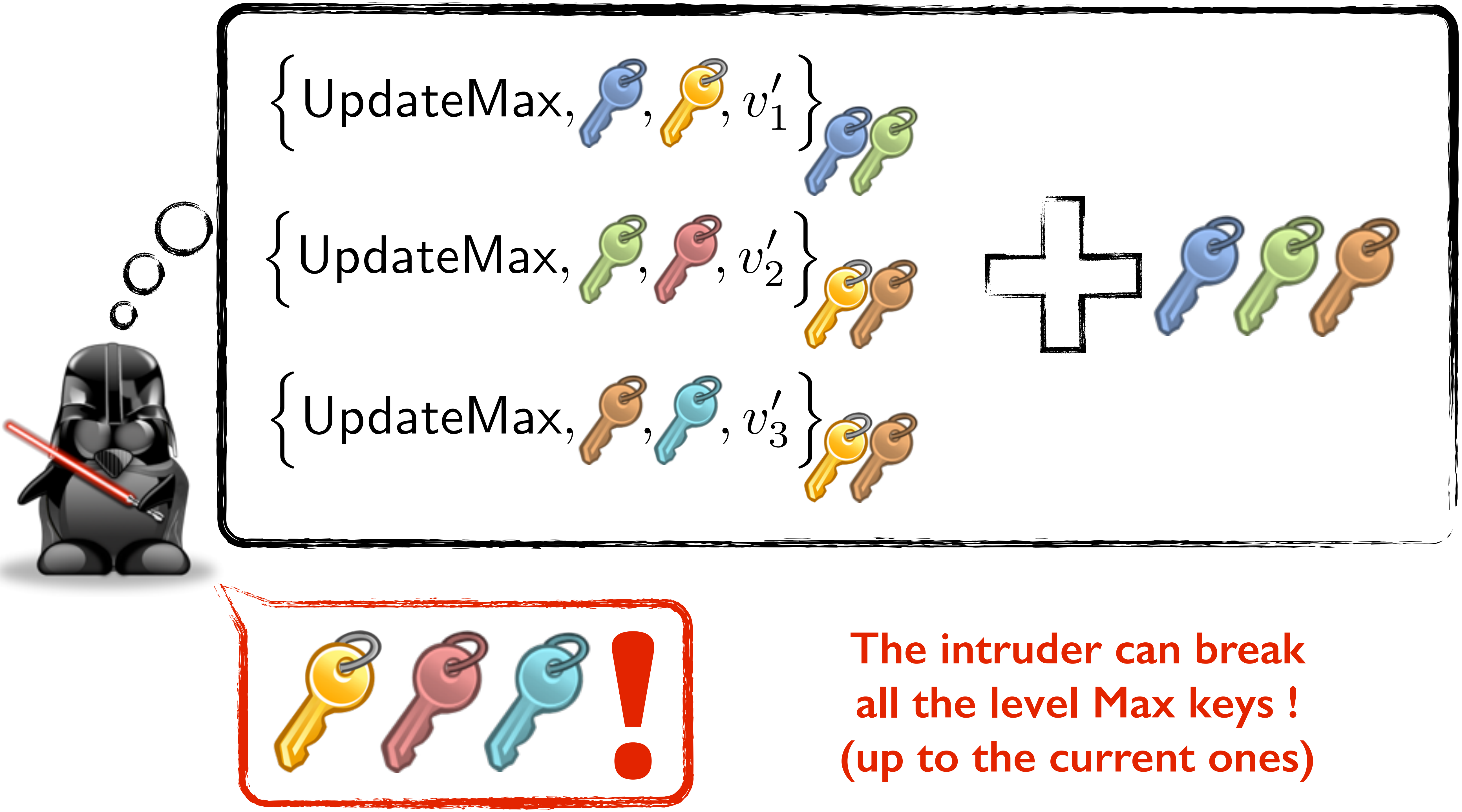
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!

The intruder can break all the level Max keys ! (up to the current ones)

Revocation Keys Management

Hypothesis :

Level Max commands are sent over a secure channel.

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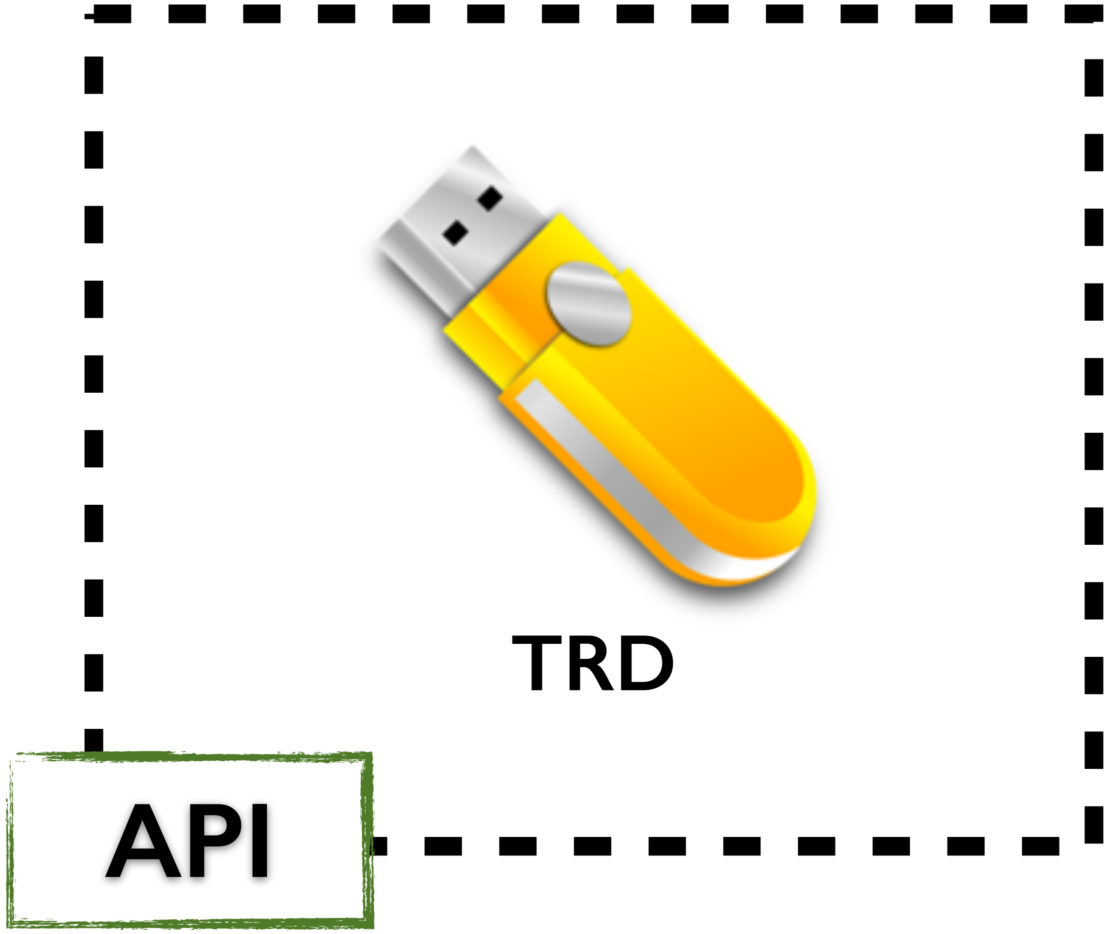
This can be achieved by several means :

- The administrator has a physical access to the TRD that needs to be updated,
- The user would connect his/her TRD to a trusted machine, on which a secure channel (e.g. via TLS) is established with the key administrator.

And now, what about Security ?



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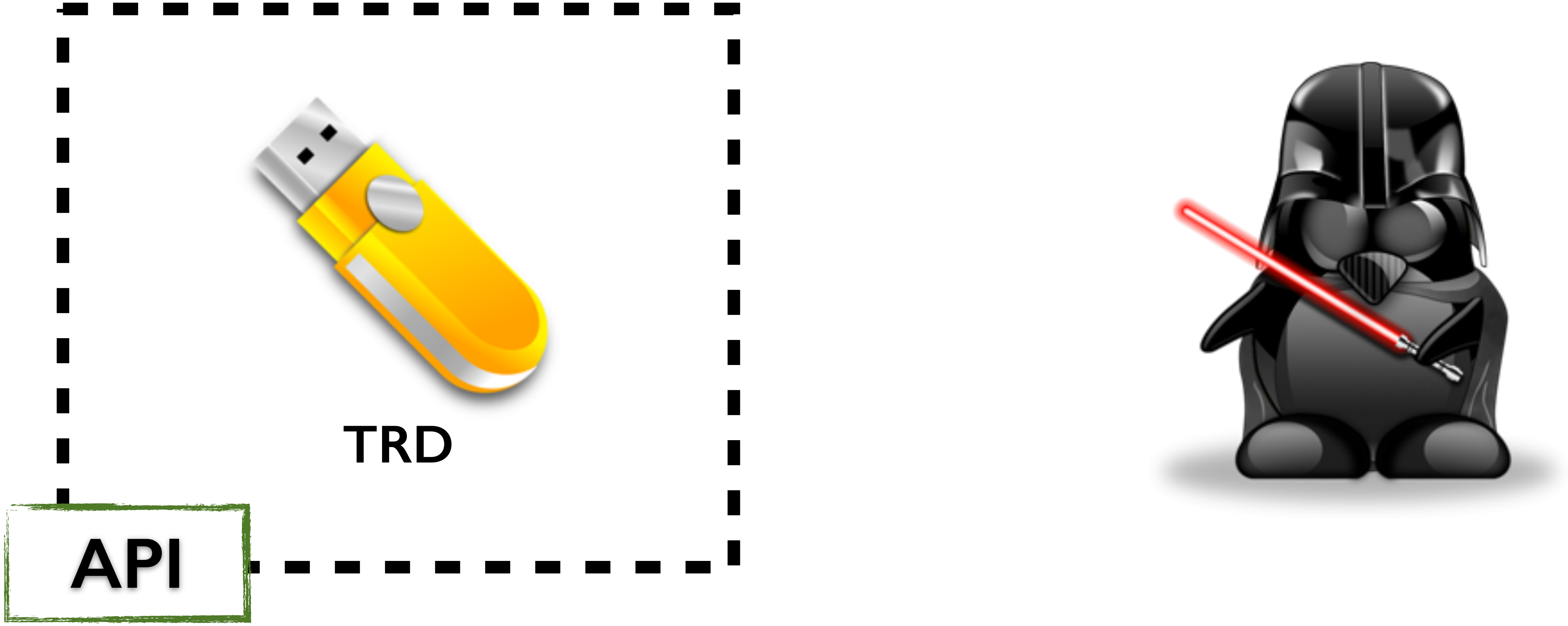

TRD

API

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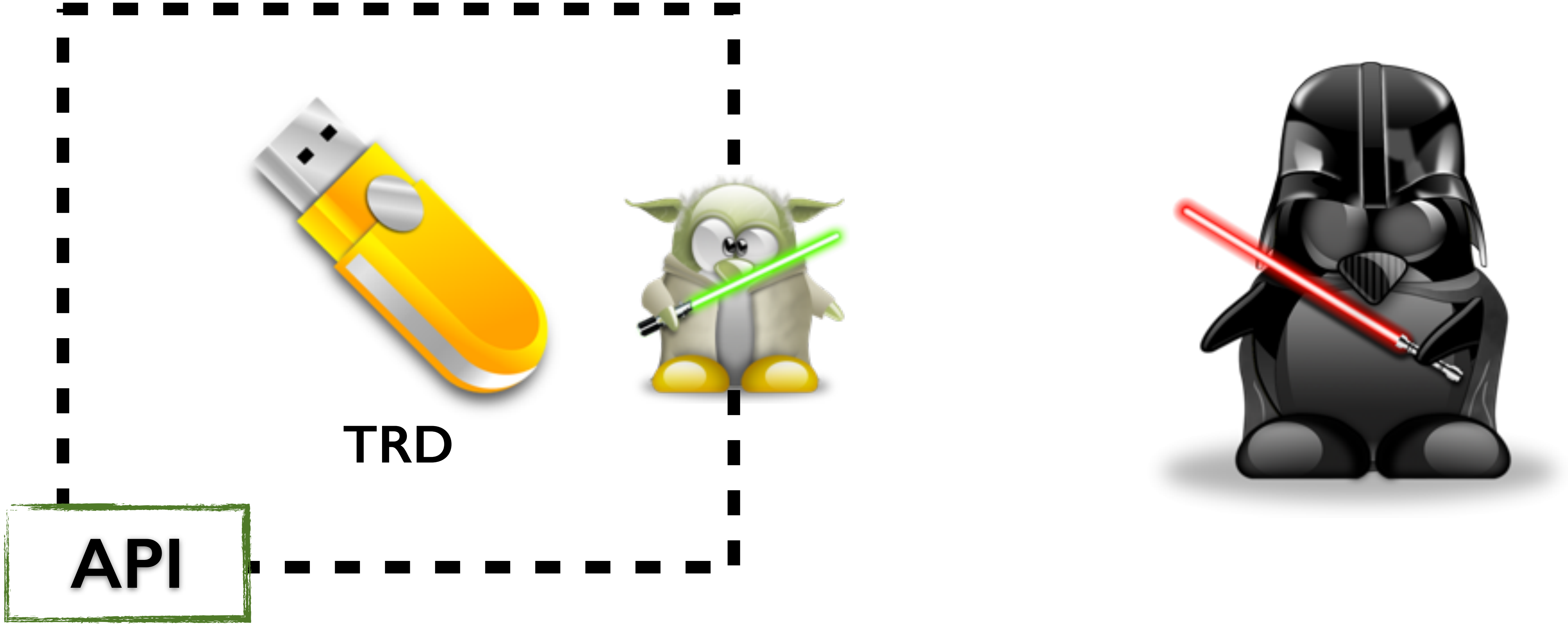
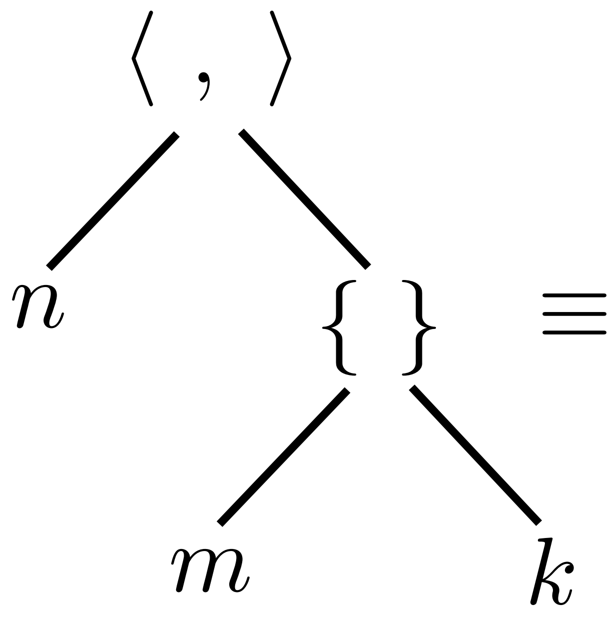


Abstraction

Messages are represented by **terms**

Nonces, keys :

$$n, m, \ldots, k_1, k_2, \ldots$$



$$\equiv \langle n, \{m\}_k \rangle$$

Primitives :

$$\{m\}_k, \langle m_1, m_2 \rangle$$

Modeling deduction rules :

$$\frac{x \quad y}{\langle x, y \rangle} \qquad \frac{\langle x, y \rangle}{x} \qquad \frac{\langle x, y \rangle}{y} \qquad \frac{x \quad y}{\{x\}_y} \qquad \frac{\{x\}_y \quad y}{x}$$

Formal Model

We model the system using **global states**:

$$(\mathcal{P}, \mathcal{I}, \mathfrak{M}, N, K, t)$$

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t, represents the **current time**.

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$$\mathcal{I} : a \mapsto (\Theta_a, H_a, \mathfrak{B}_a, t, N_a, K_a)$$

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Θ_a , a function representing the **memory** of the TRD.

Handle	Value	Level	Validity	Misc.
h_1	🔑	l_1	v_1	m_1
h_2	🔑	l_2	v_2	-
...	...	...	...	...

Formal Model

Semantics

consists in several **transitions** modifying the global state.

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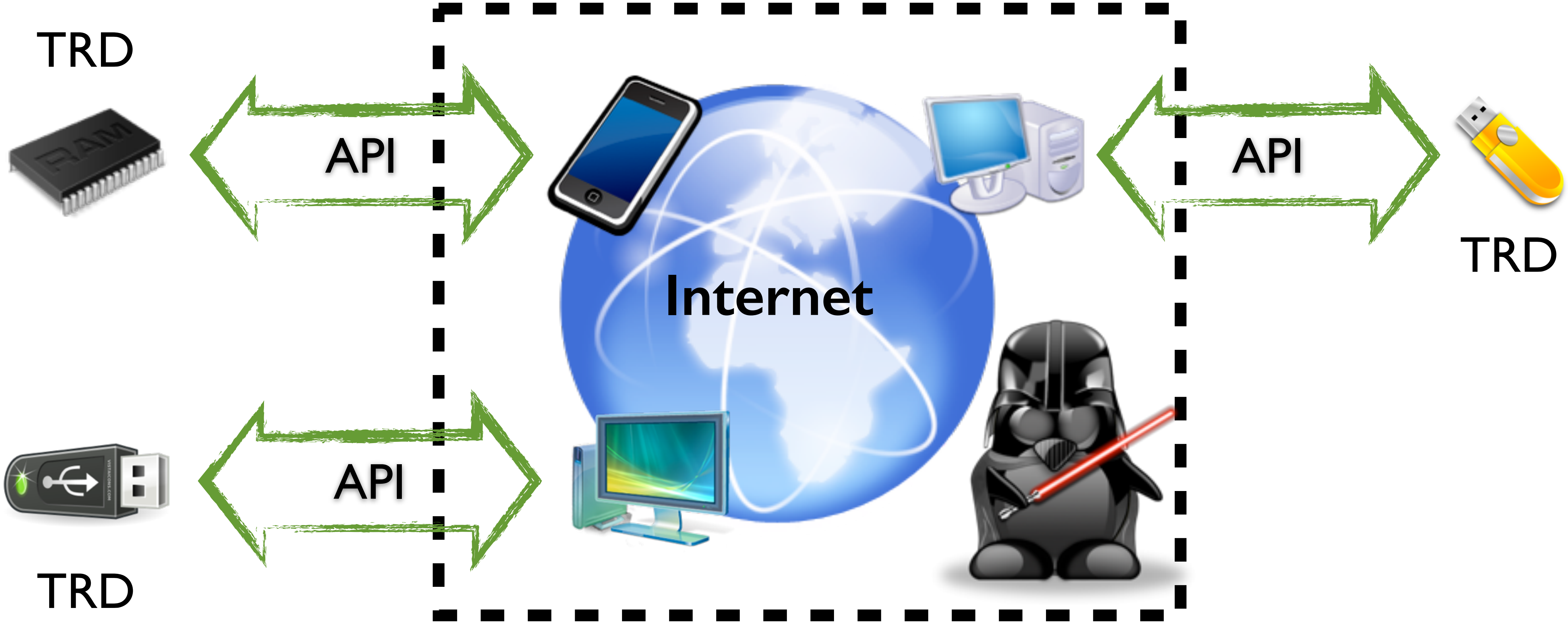
$$\text{(UPD)} \quad (\mathcal{P}, \mathcal{I}, \mathfrak{M}, N, K, t) \longrightarrow (\mathcal{P}, \mathcal{I}', \mathfrak{M} \cup \{m\}, N', K', t)$$

models changes when an update command is performed.

$$m = \Big\{\mathsf{update}, k, k', l', v', m'\Big\}_{k_1 \cdots k_n}$$

Knowledge of the Intruder



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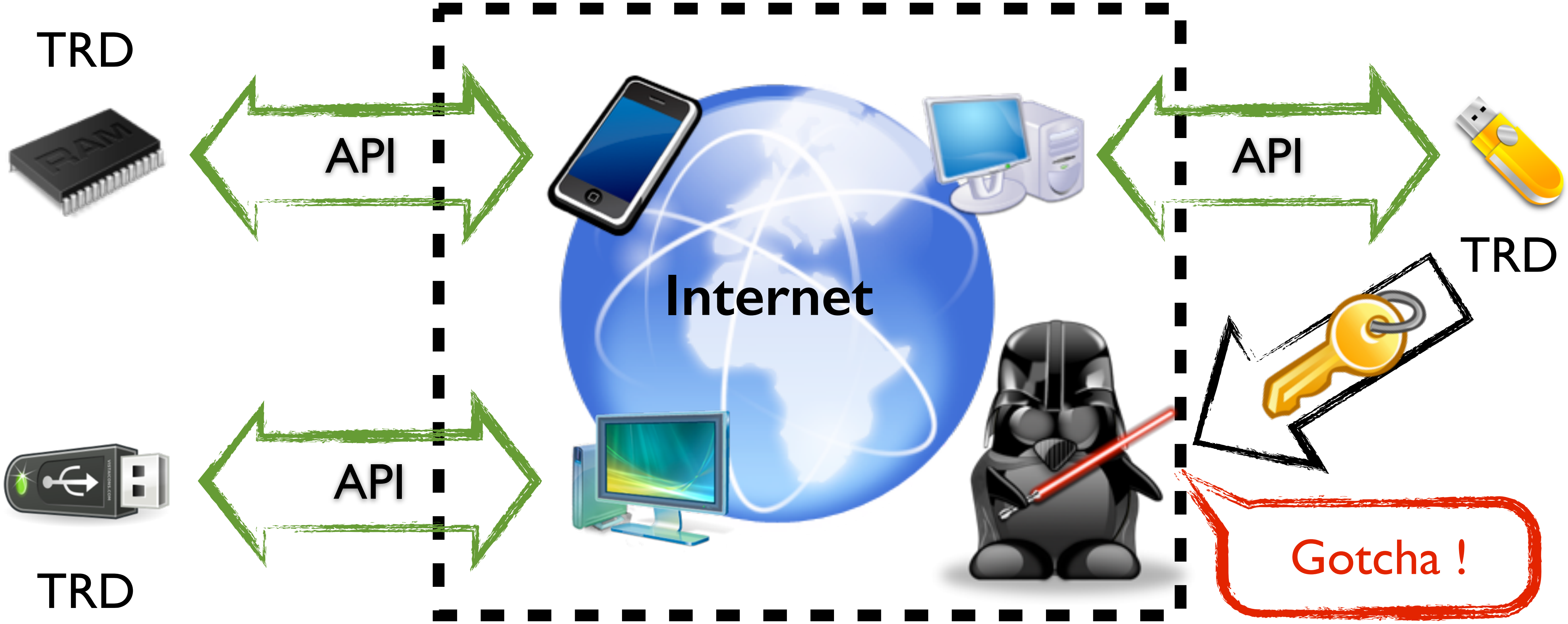

A key in a TRD may be lost and known by the intruder

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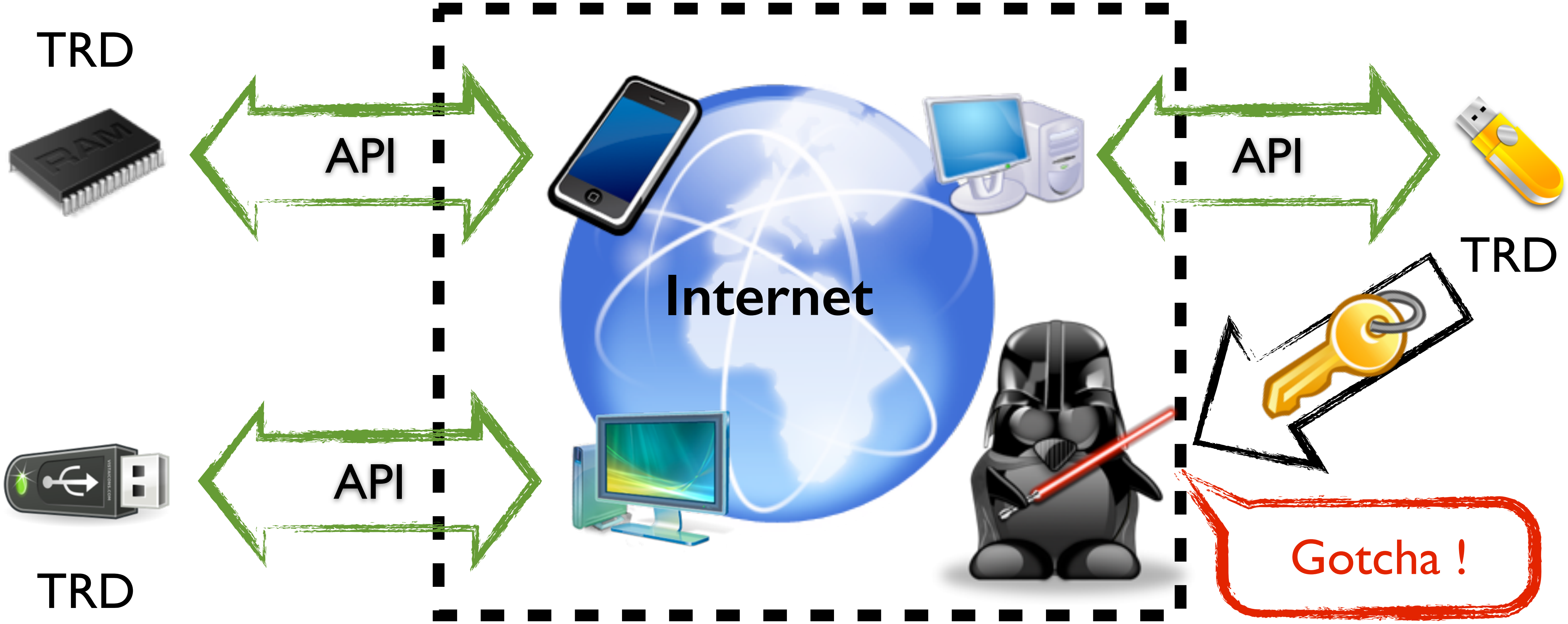
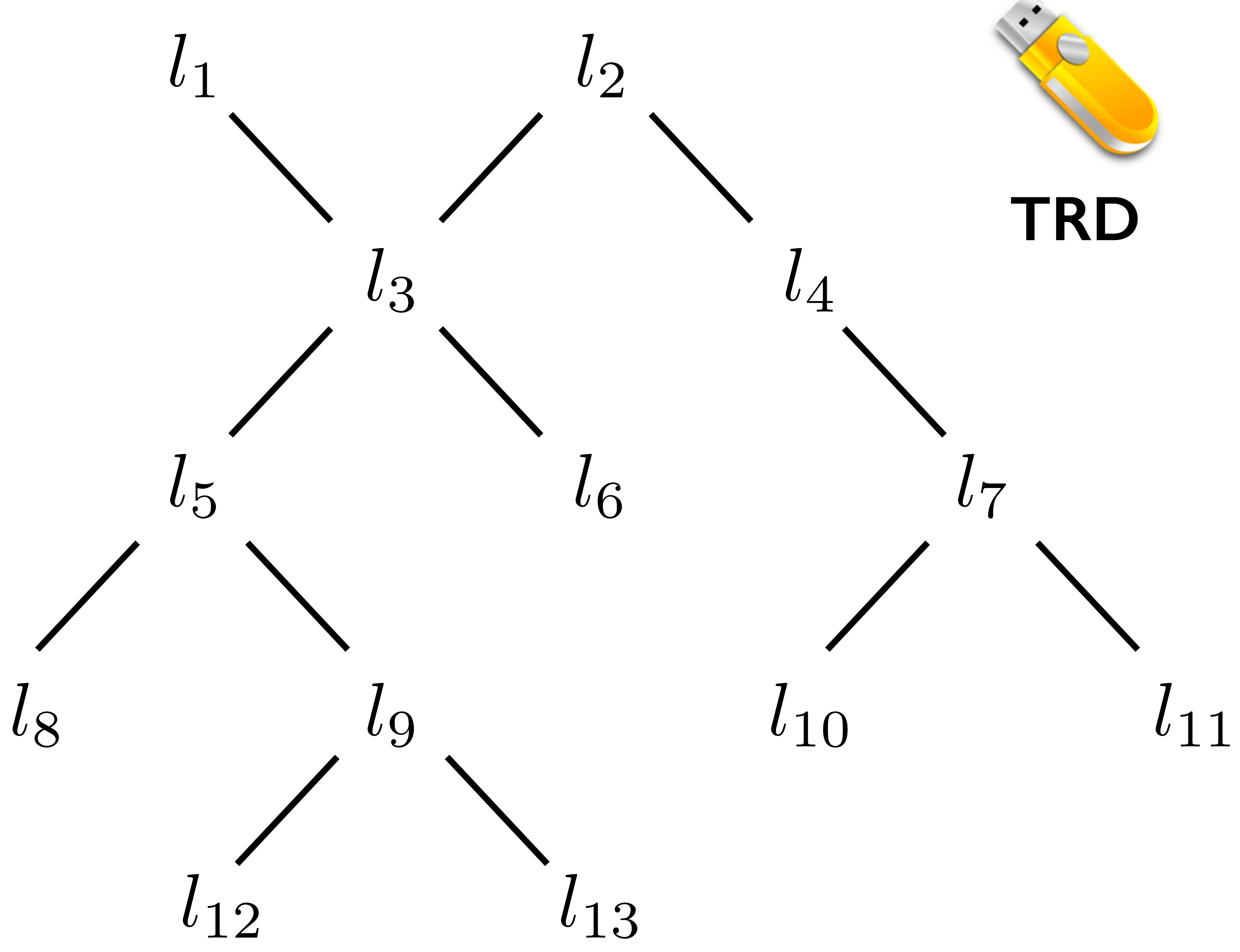


A key in a TRD may be lost and known by the intruder

Hypothesis :

At most a total of $N_{\text{Max}} - 1$ different « current » level Max keys for one TRD can be lost.

What about lost keys ?



TRD

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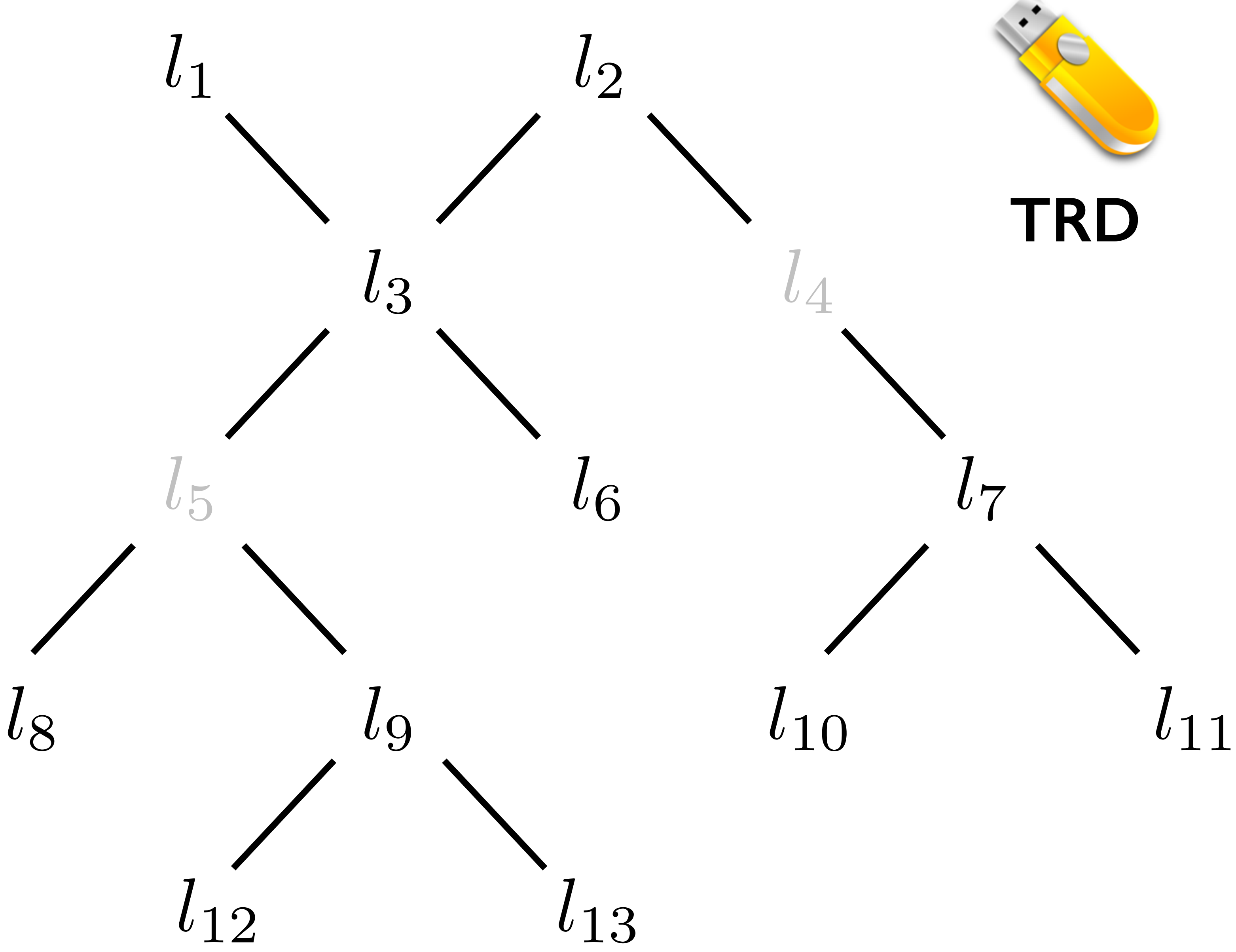

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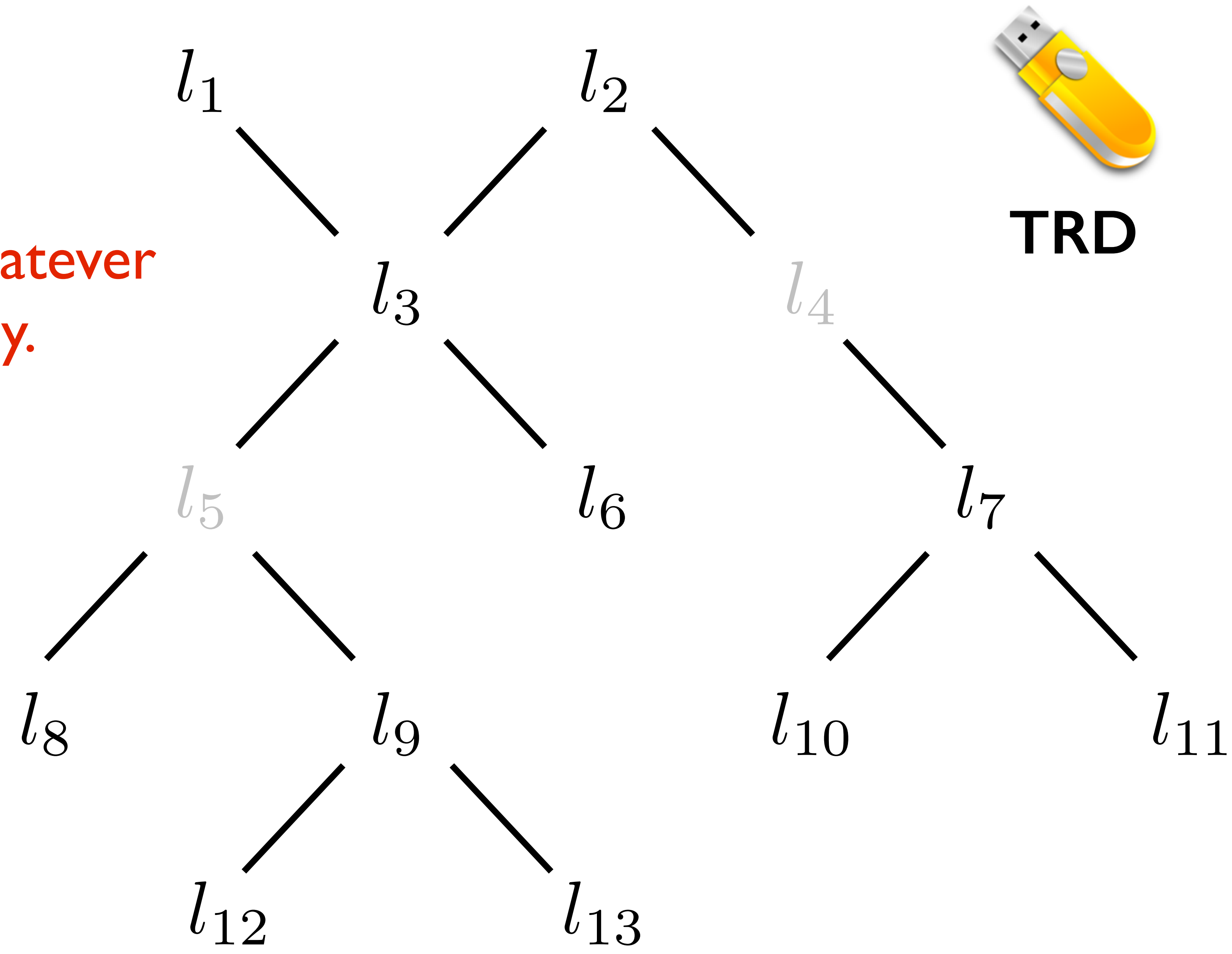

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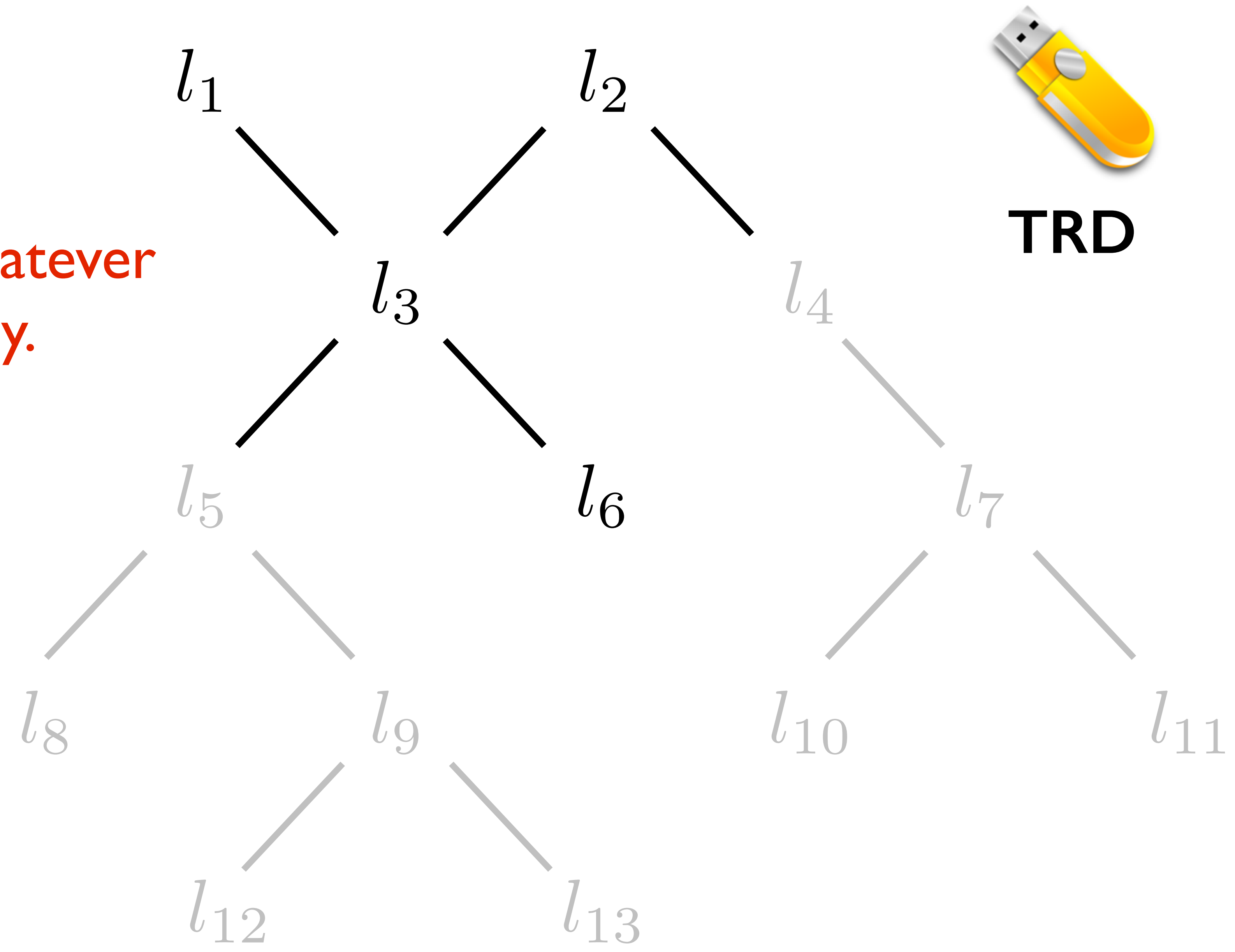

The intruder has control over whatever is under a level with a lost key.

She may use an encrypt command to **get a key** with a lower level in a TRD containing a lost key.

Ex : Receive $\{\langle$ 🔑 $, l_9, v, m\rangle\}_{🔑}$ with 🔑 lost and of level l_5 .

Secrecy Result

«I keep my secrets secret !»

Even if the **intruder** may :

- **control the network** and host machines,
- **break some keys** (but not too many revocation keys),

Secrecy Result

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Even if the intruder may :

- control the network and host machines,
- break some keys (but not too many revocation keys),

We have :

Theorem 1

Keys remain **secret** (not deducible) provided :

A valid expiration date & not « under a lost »

Secrecy Result

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Formally speaking...

Theorem 1

Let $E = (\mathcal{P}, \mathcal{I}, \mathfrak{M}, N, K, t)$ be a global state, $\mathrm{L_V}$ a set of (broken) levels and $k \in K$.

$$\forall k \text{ s.t. } \mathsf{Level}(k) \not\leq \mathrm{L_V}, \quad \mathfrak{M} \not\vdash k$$

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Proof (sketch of):

> **Find invariant properties** of the system.

> **Prove** them !

Self Repair Property

«It’s just a flesh wound !»

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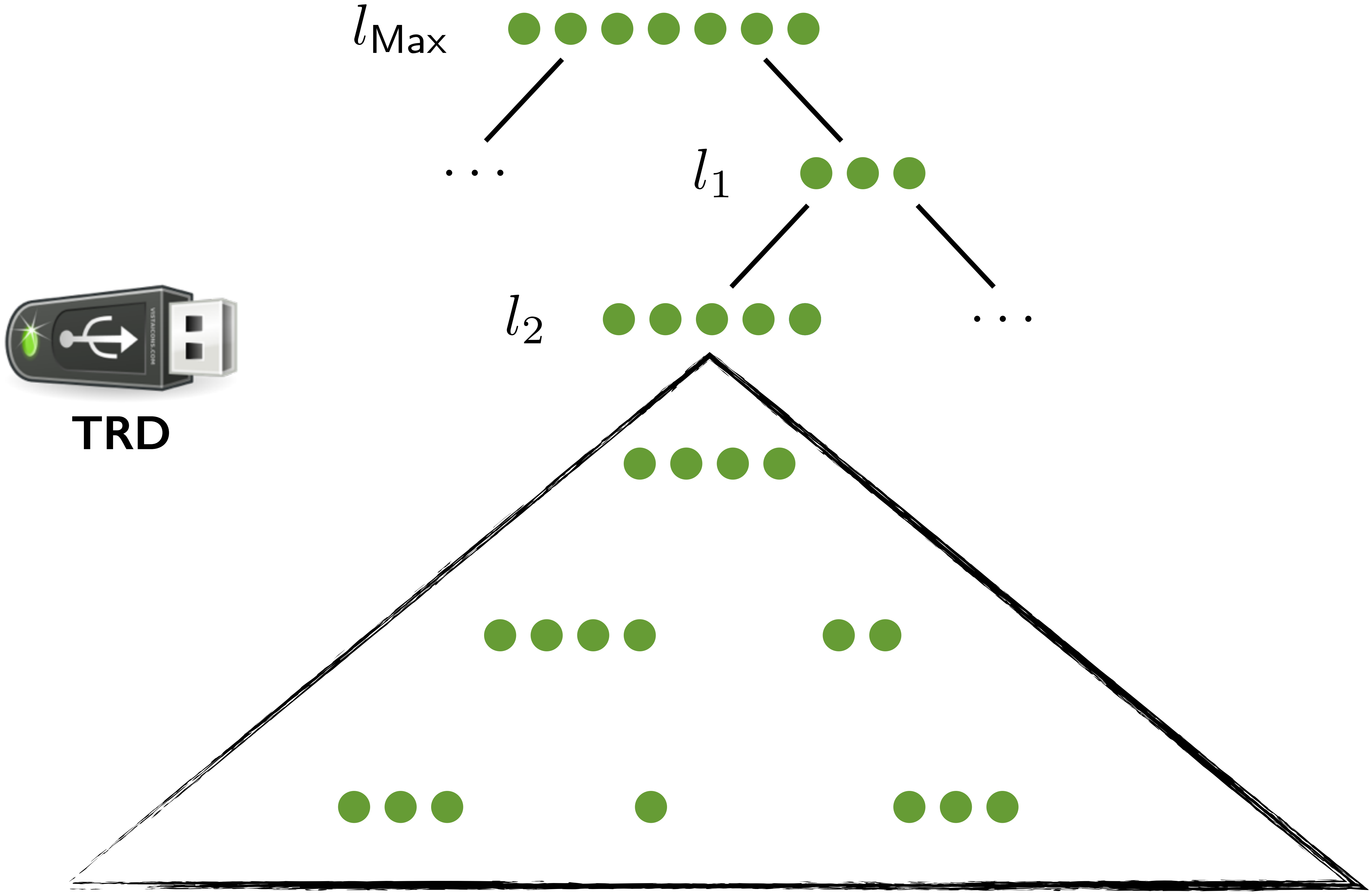

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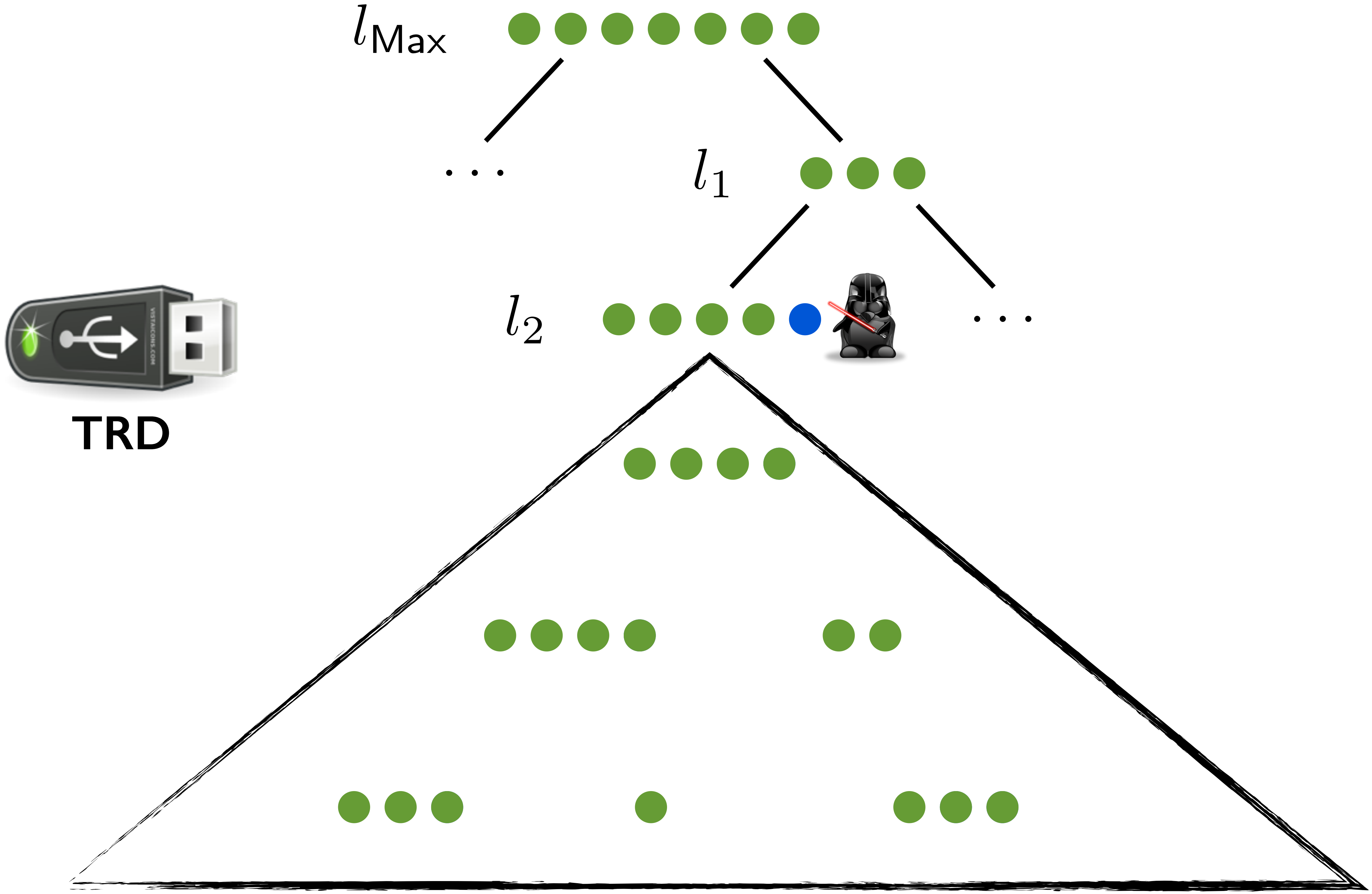

l_{Max}

$\dots$ l_1

l_2 $\dots$

TRD

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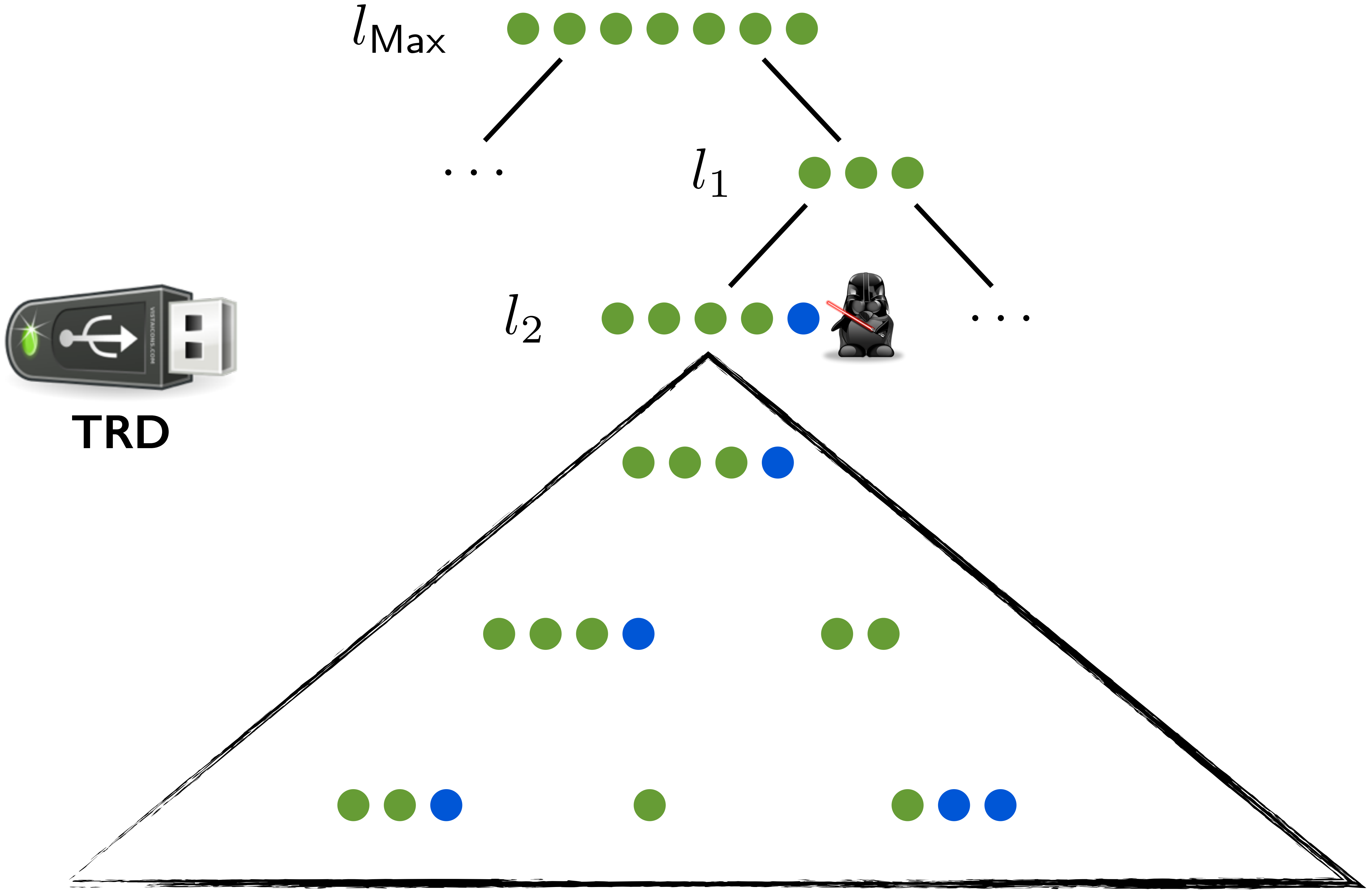

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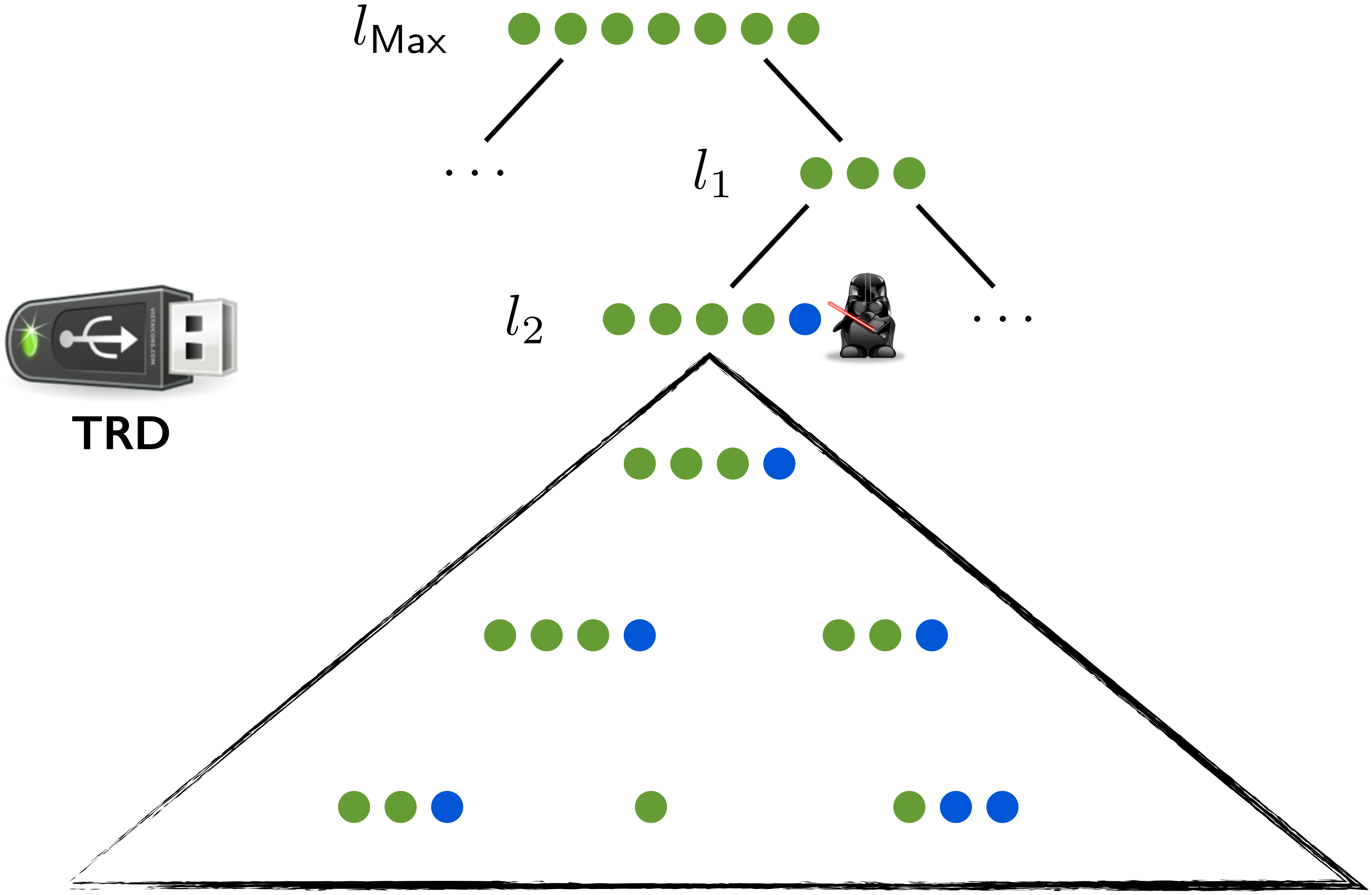

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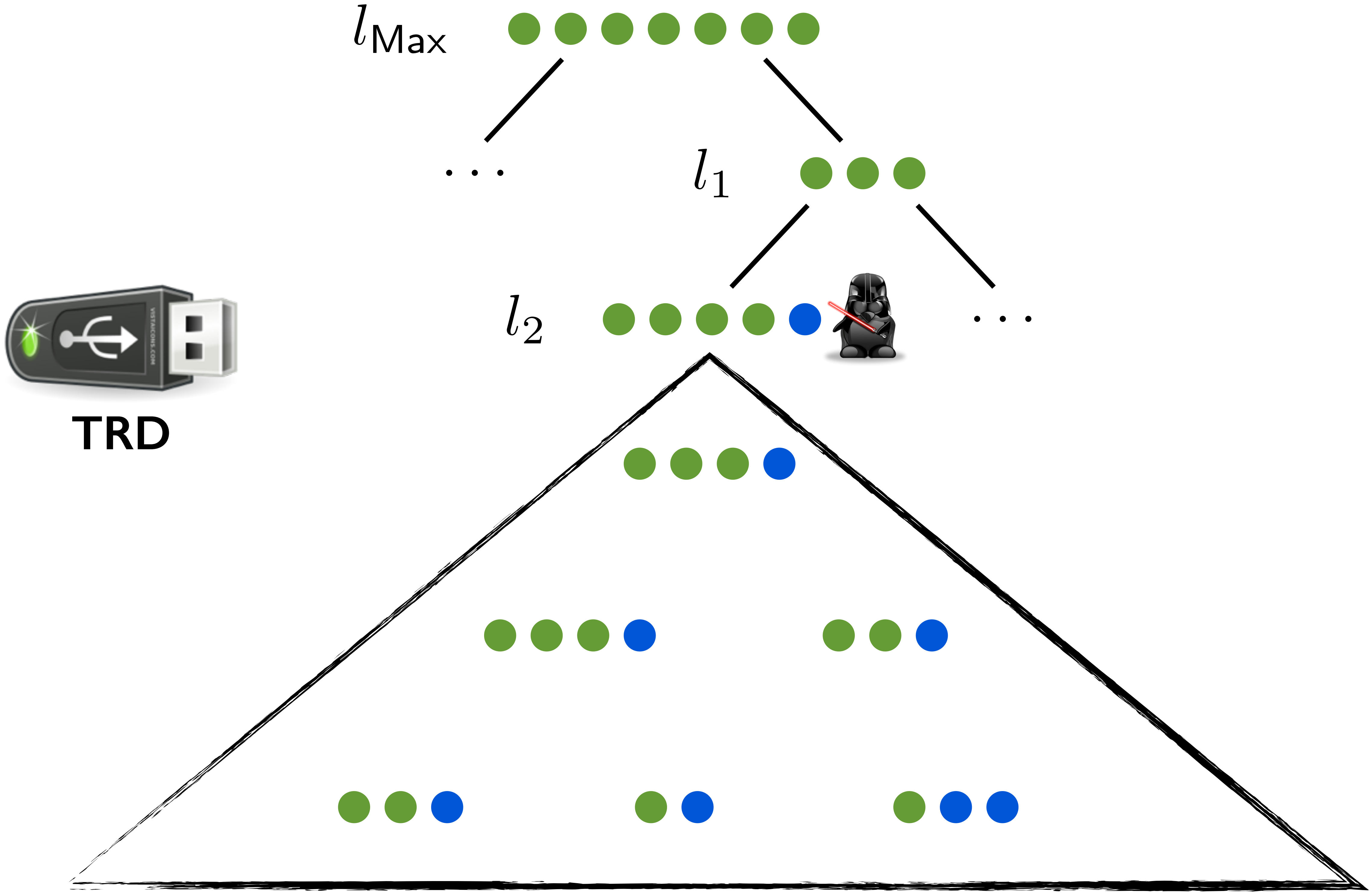

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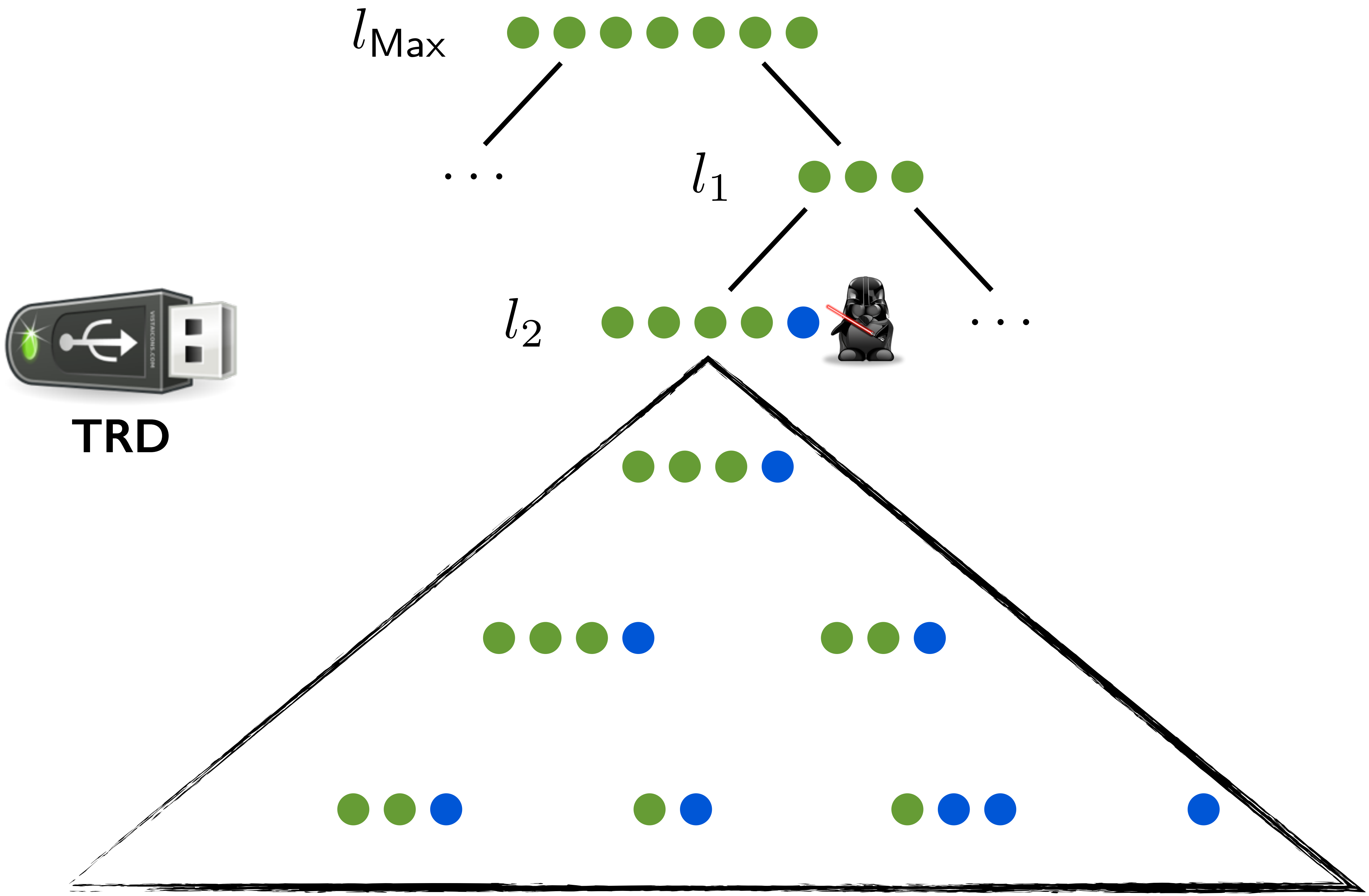

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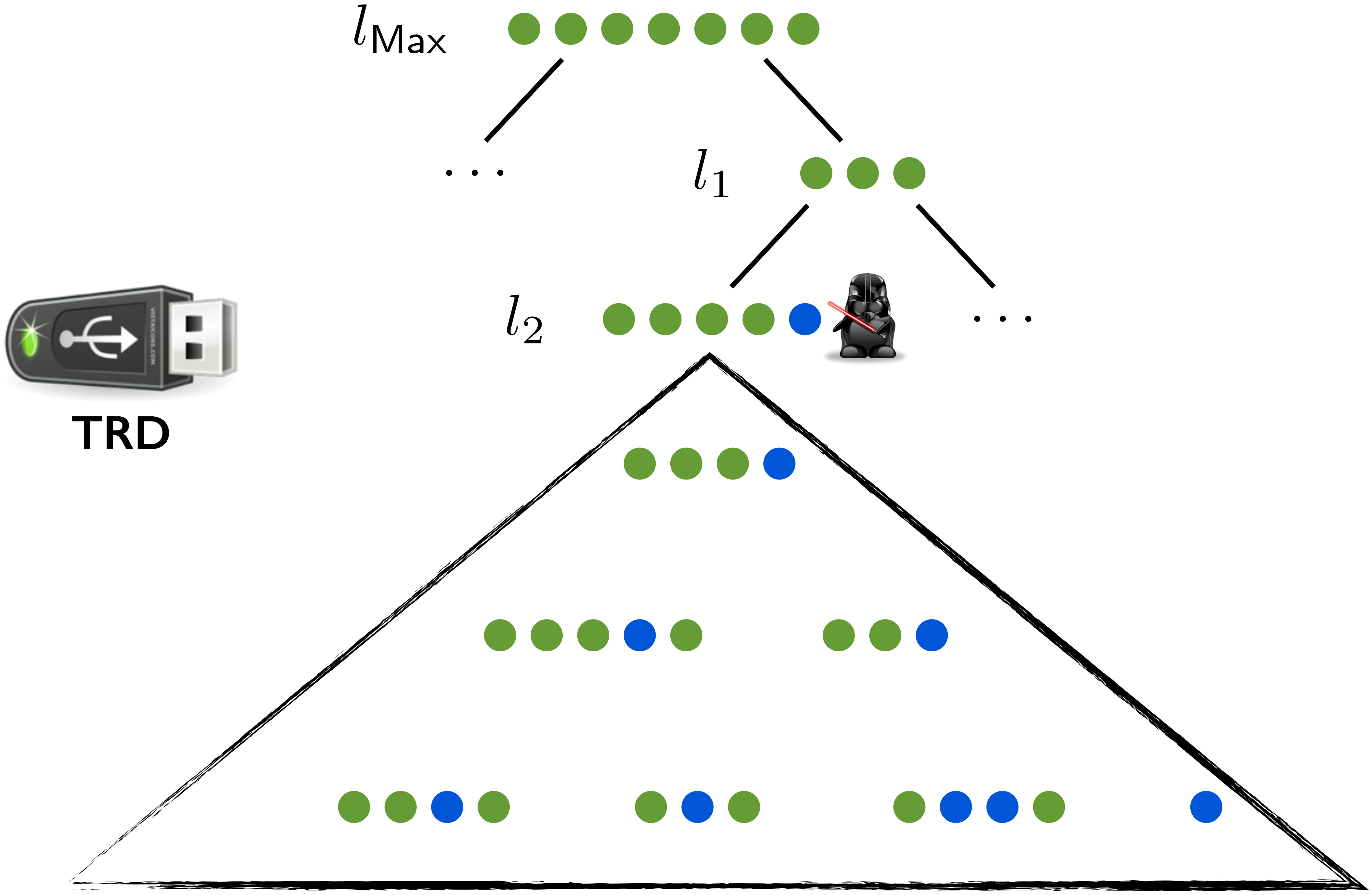

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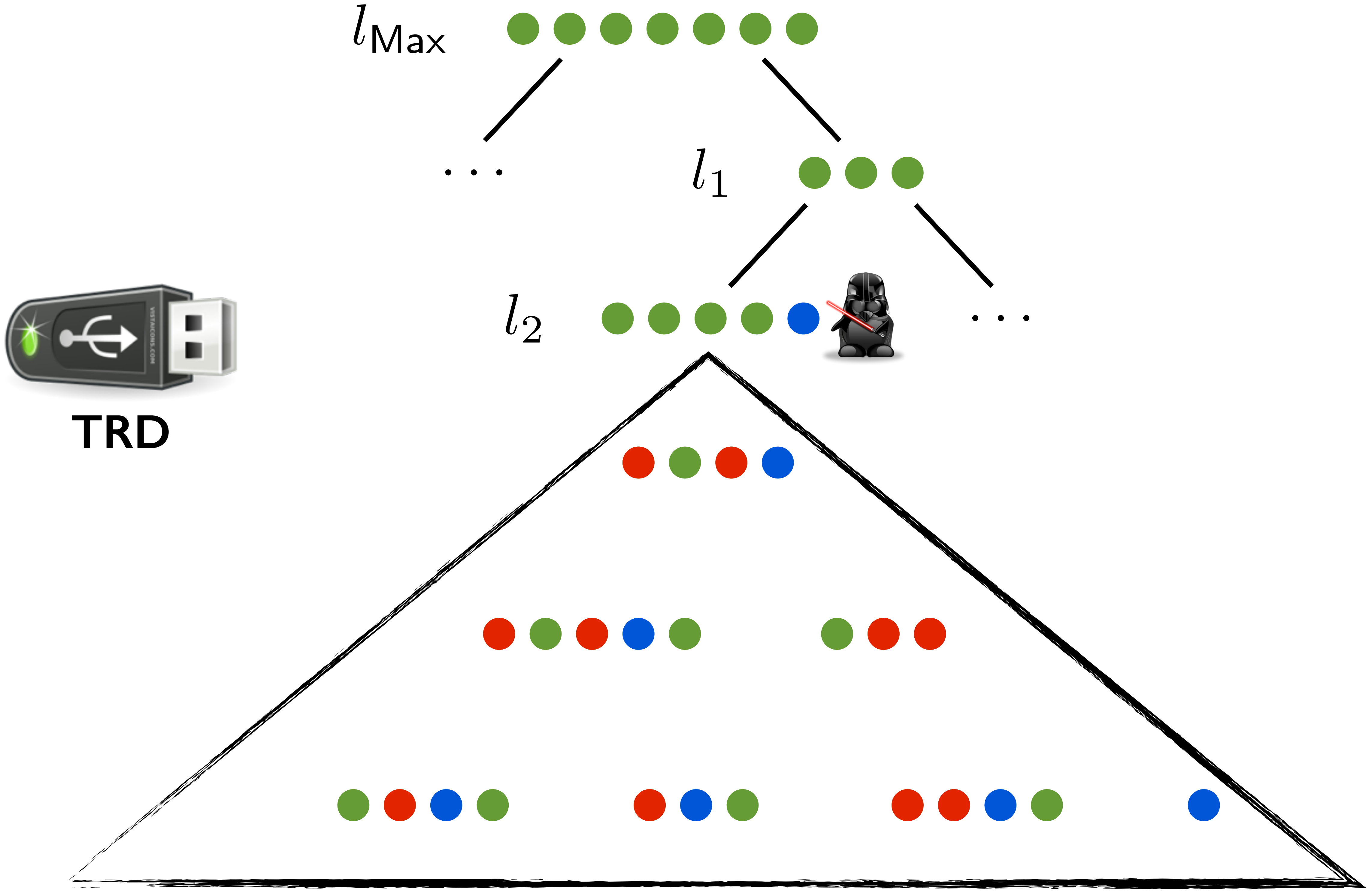

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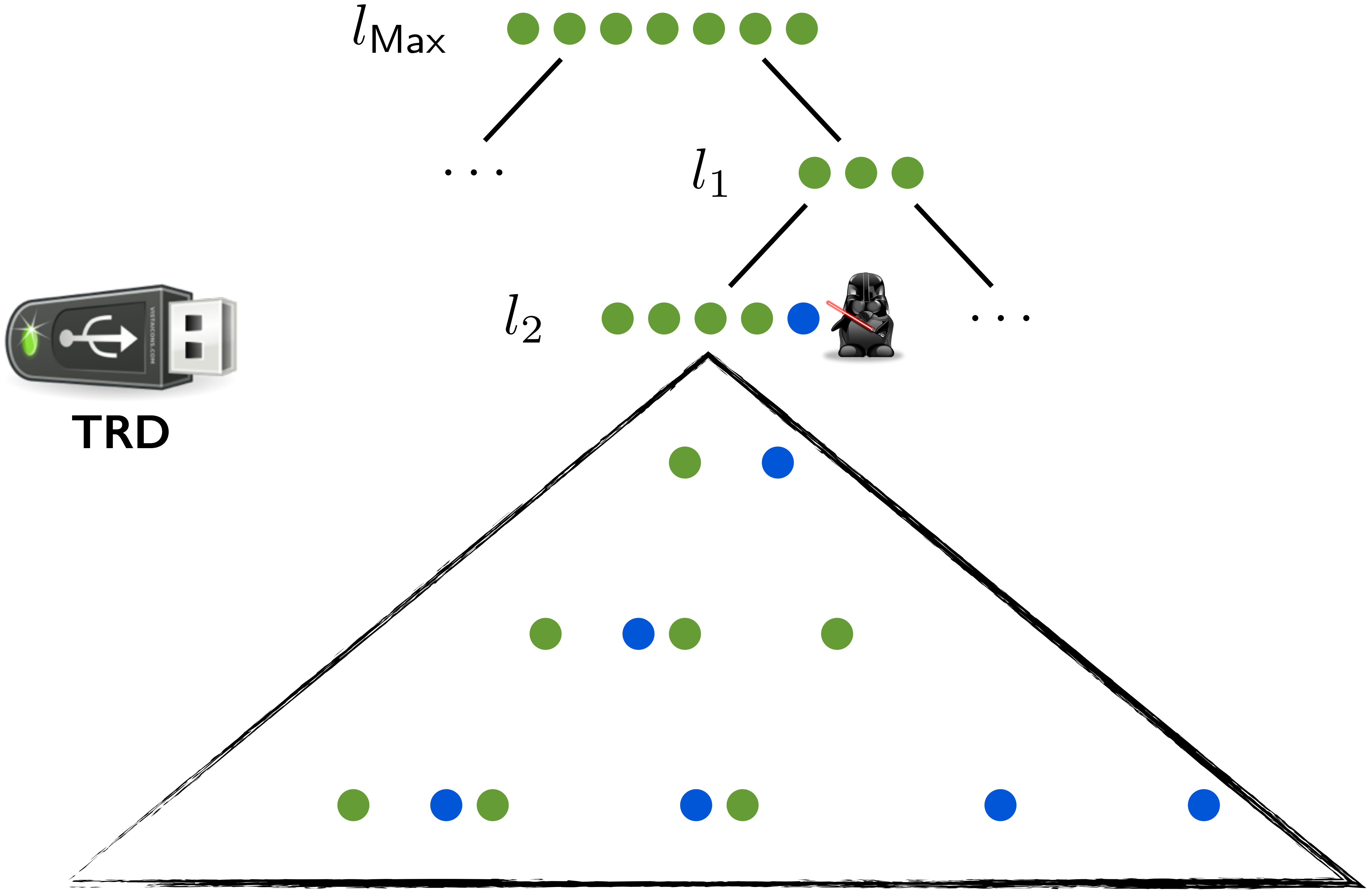

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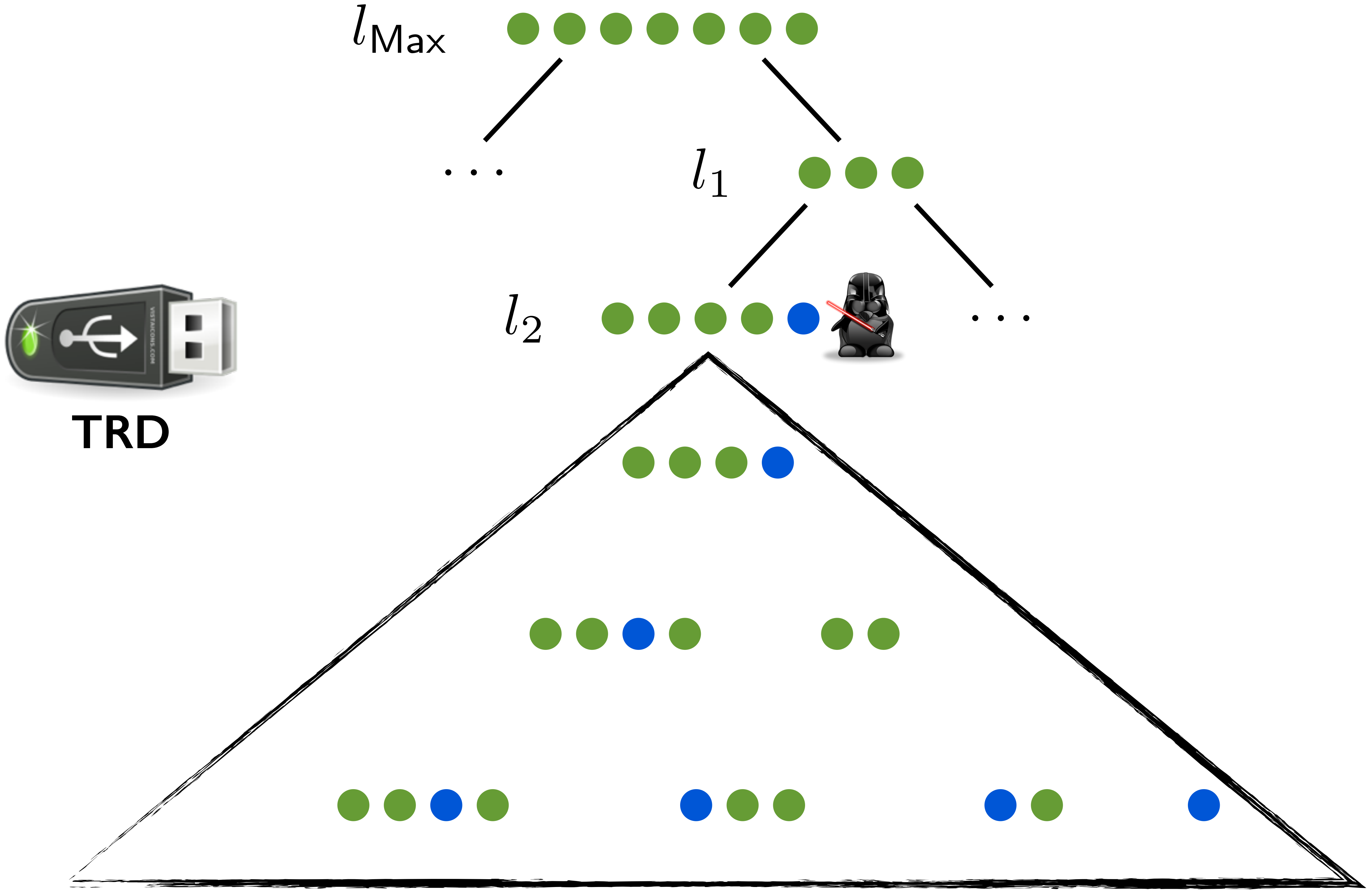

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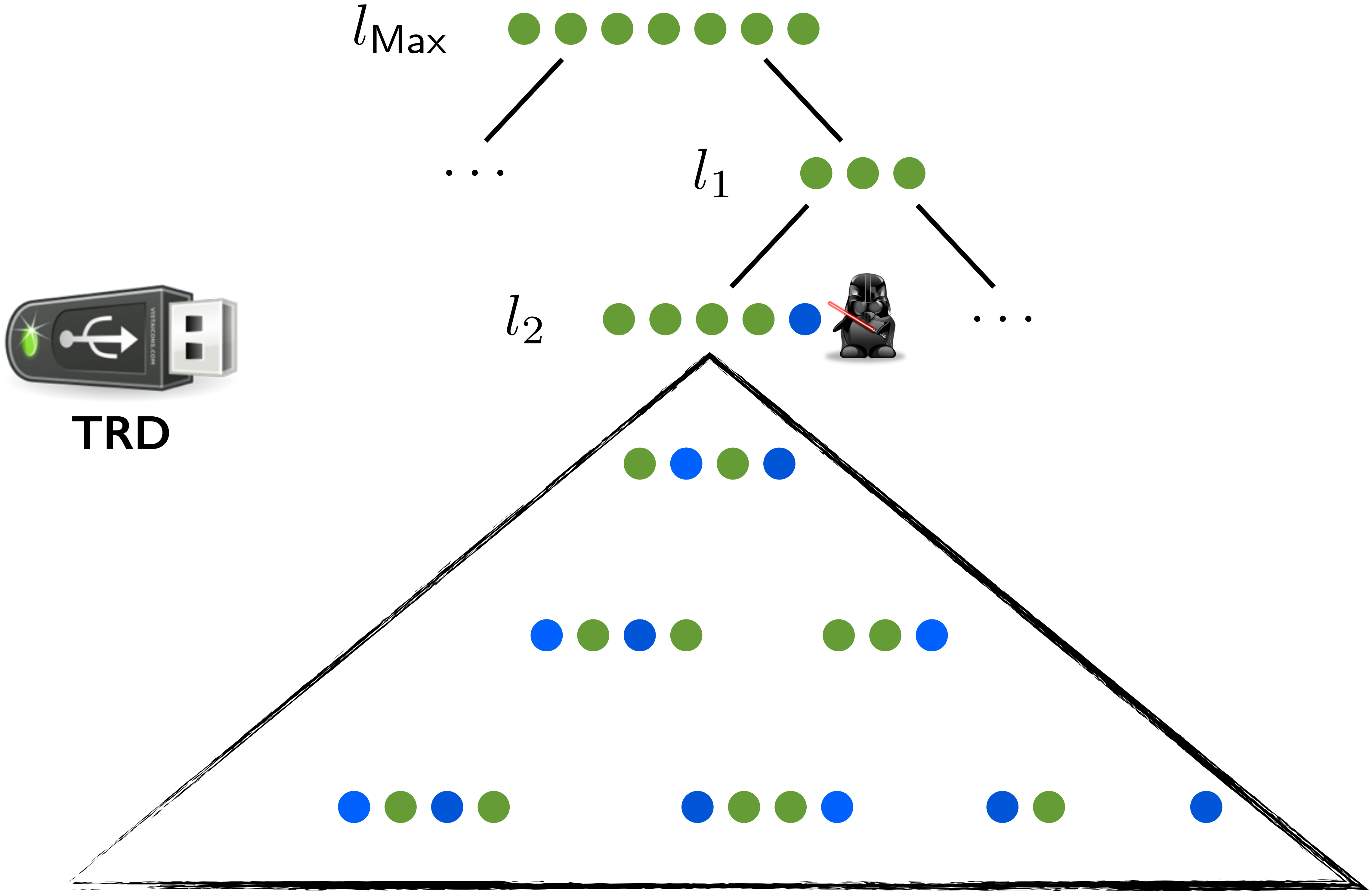

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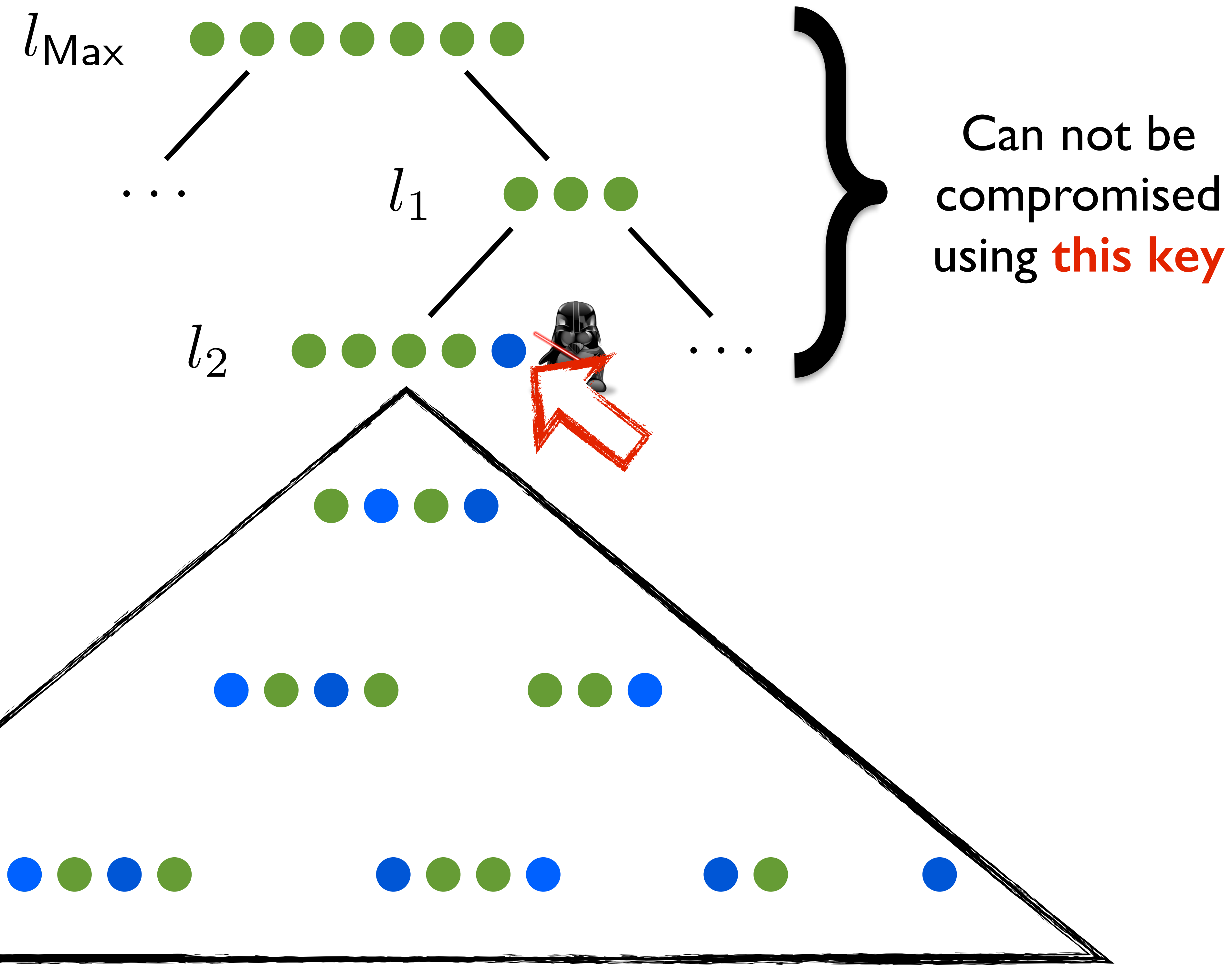

Can not be compromised using **this key**

TRD

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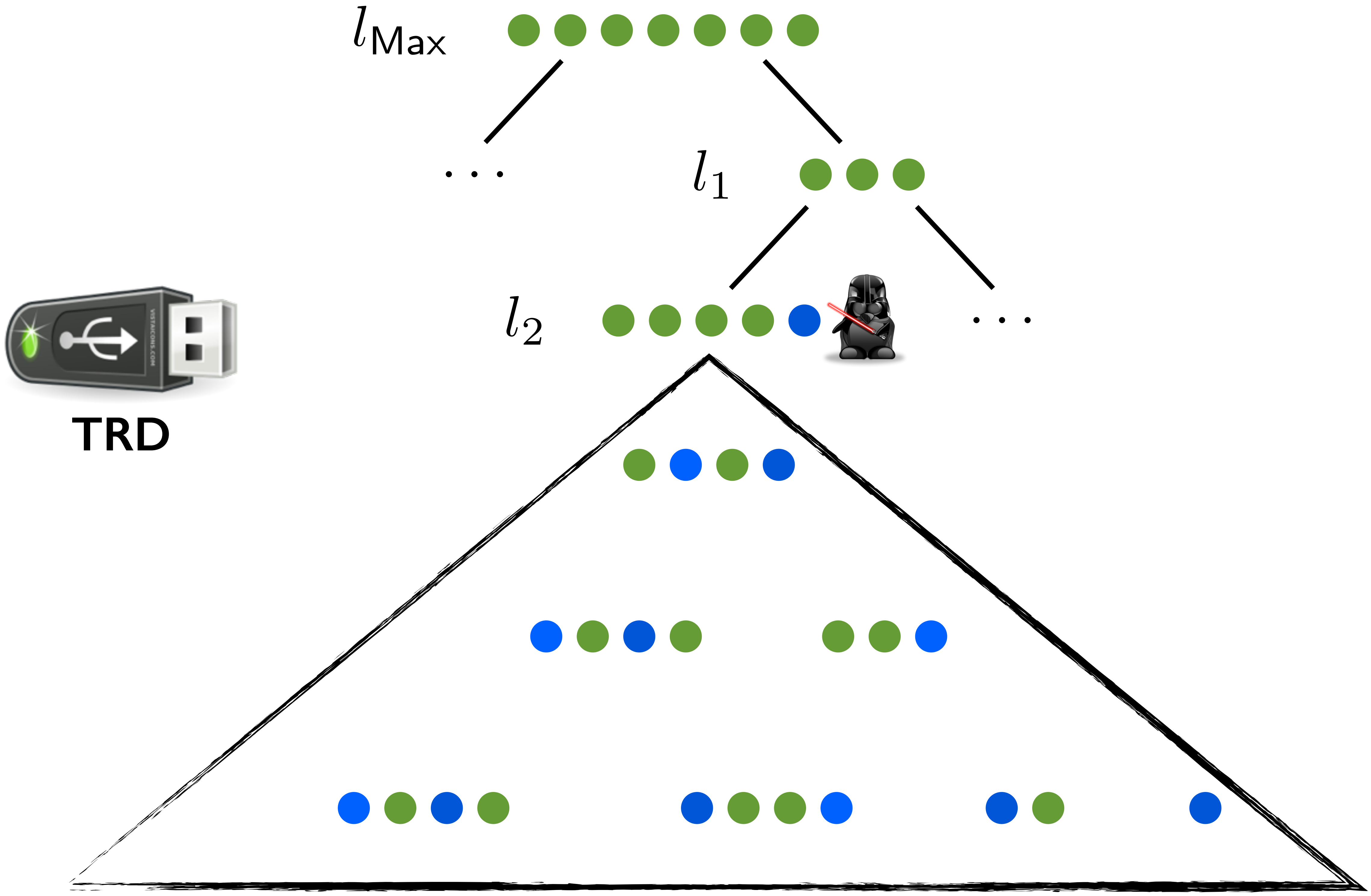

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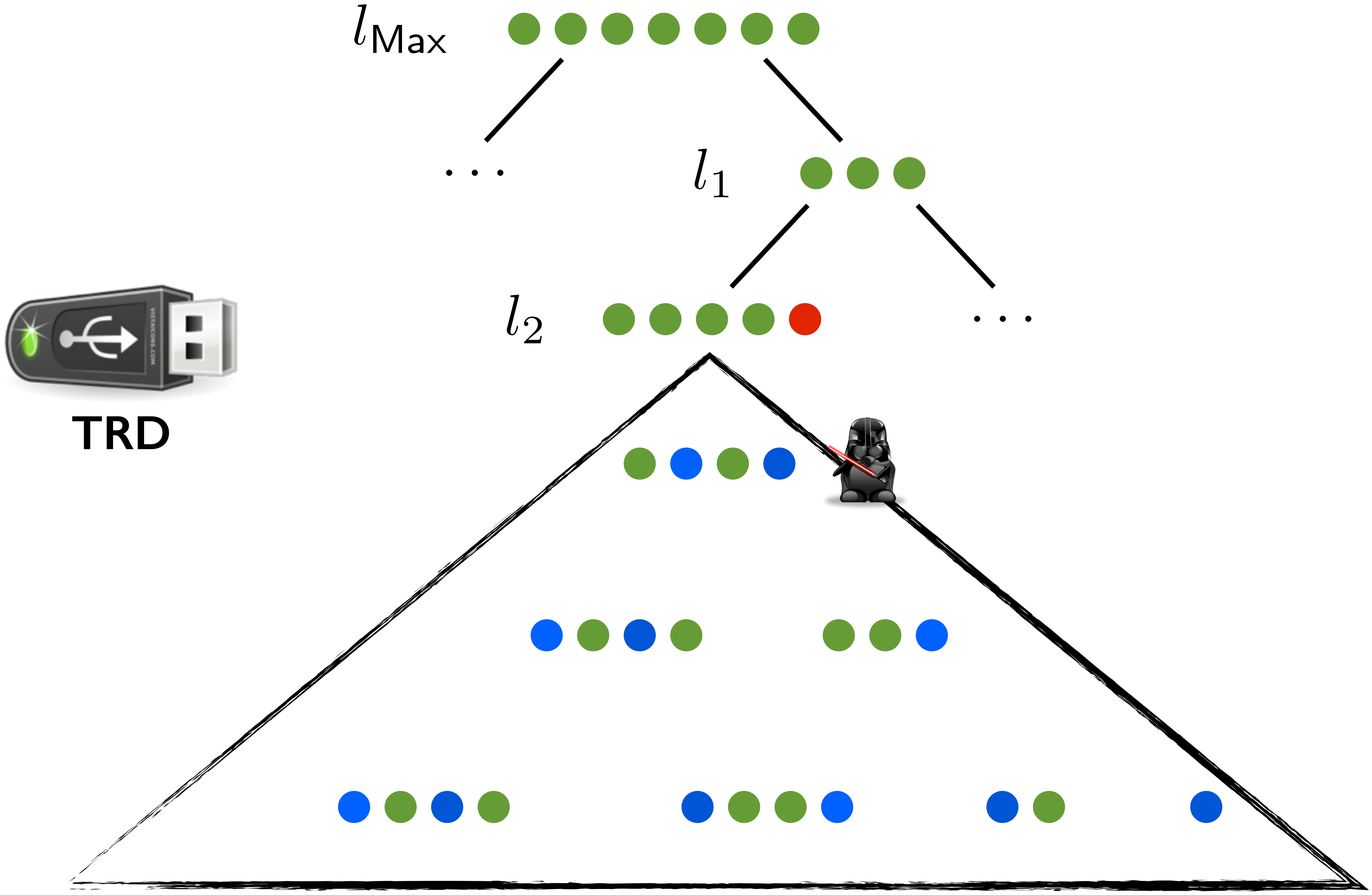

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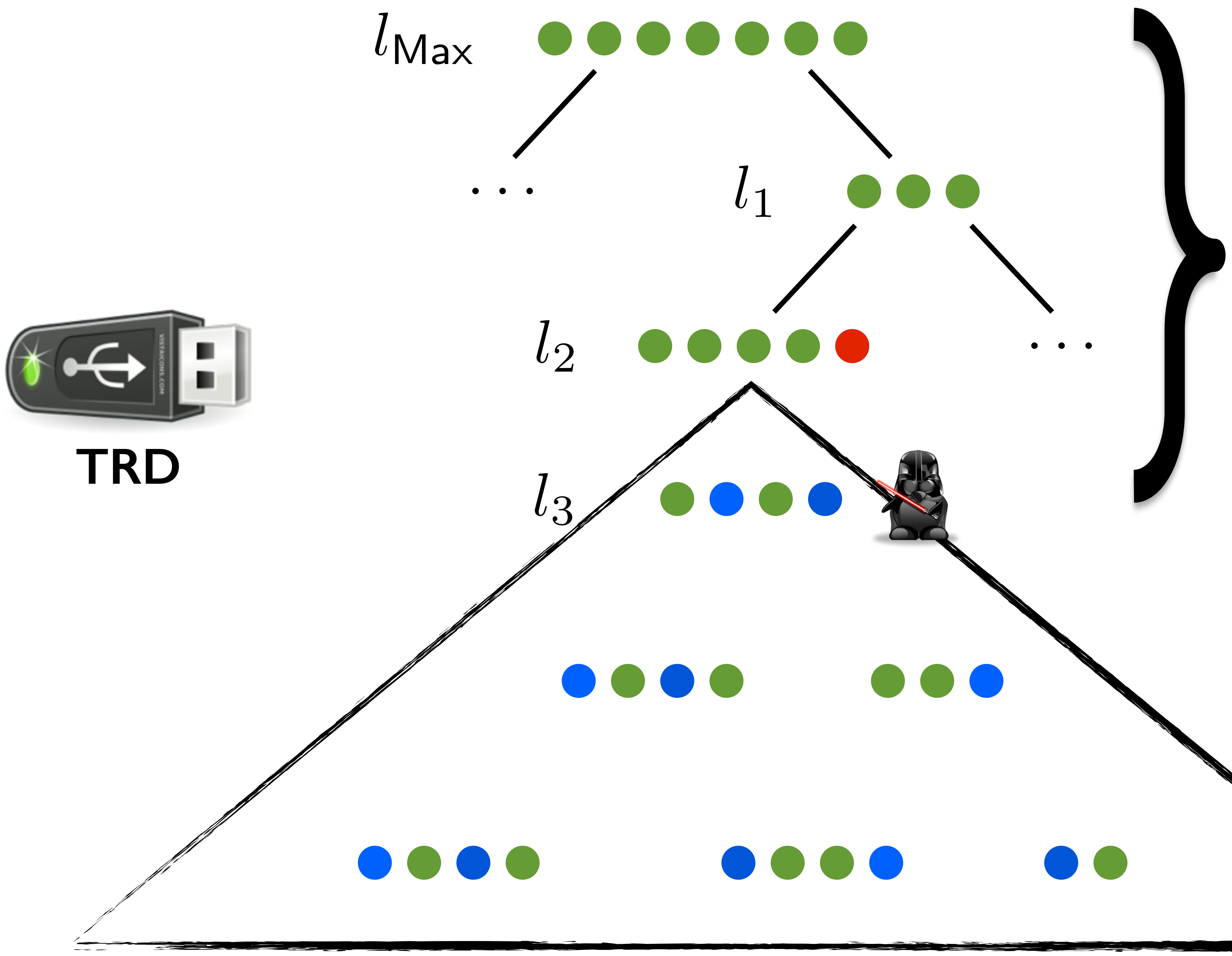

Can not be compromised using remaining corrupted keys.

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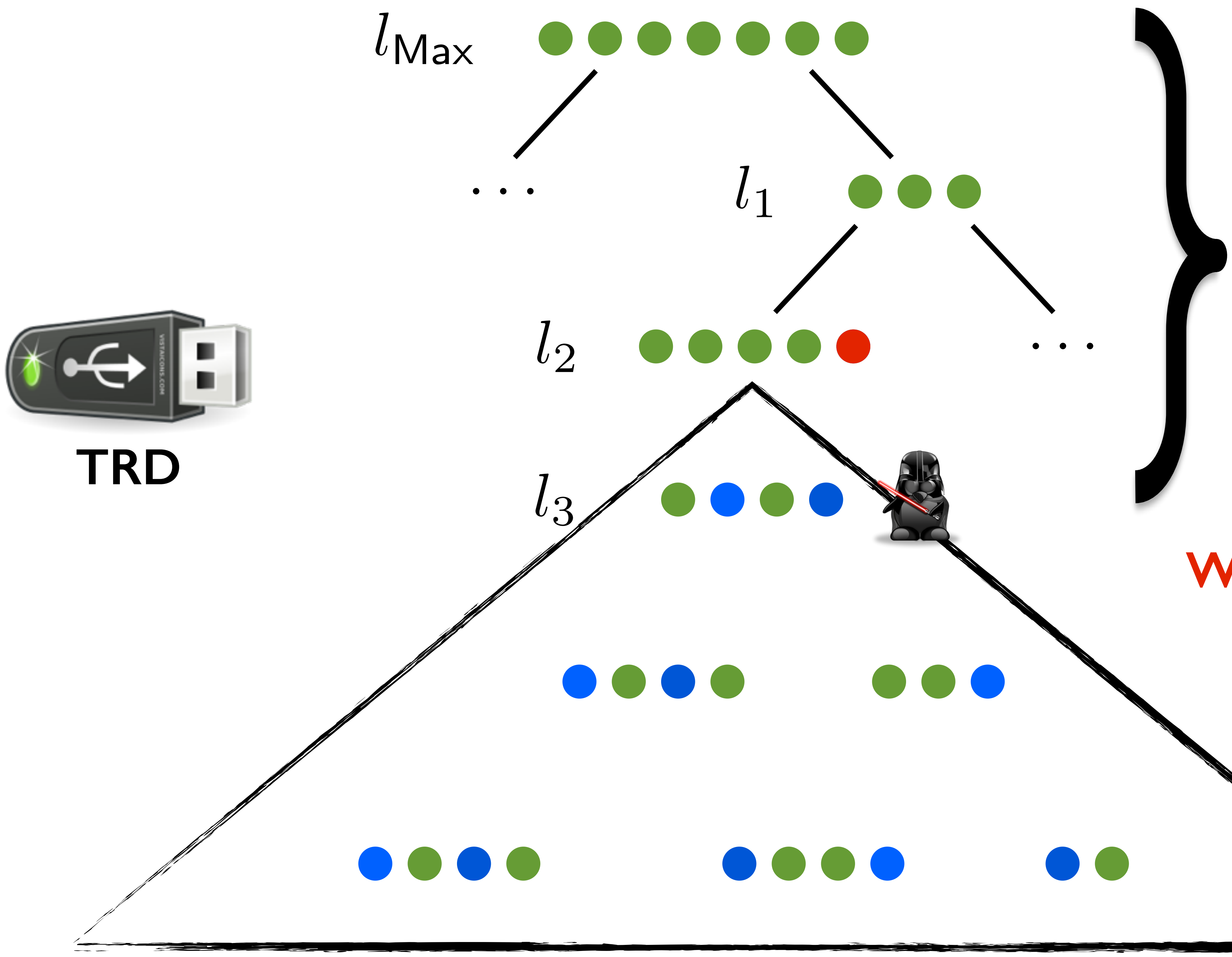

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We gain a level !

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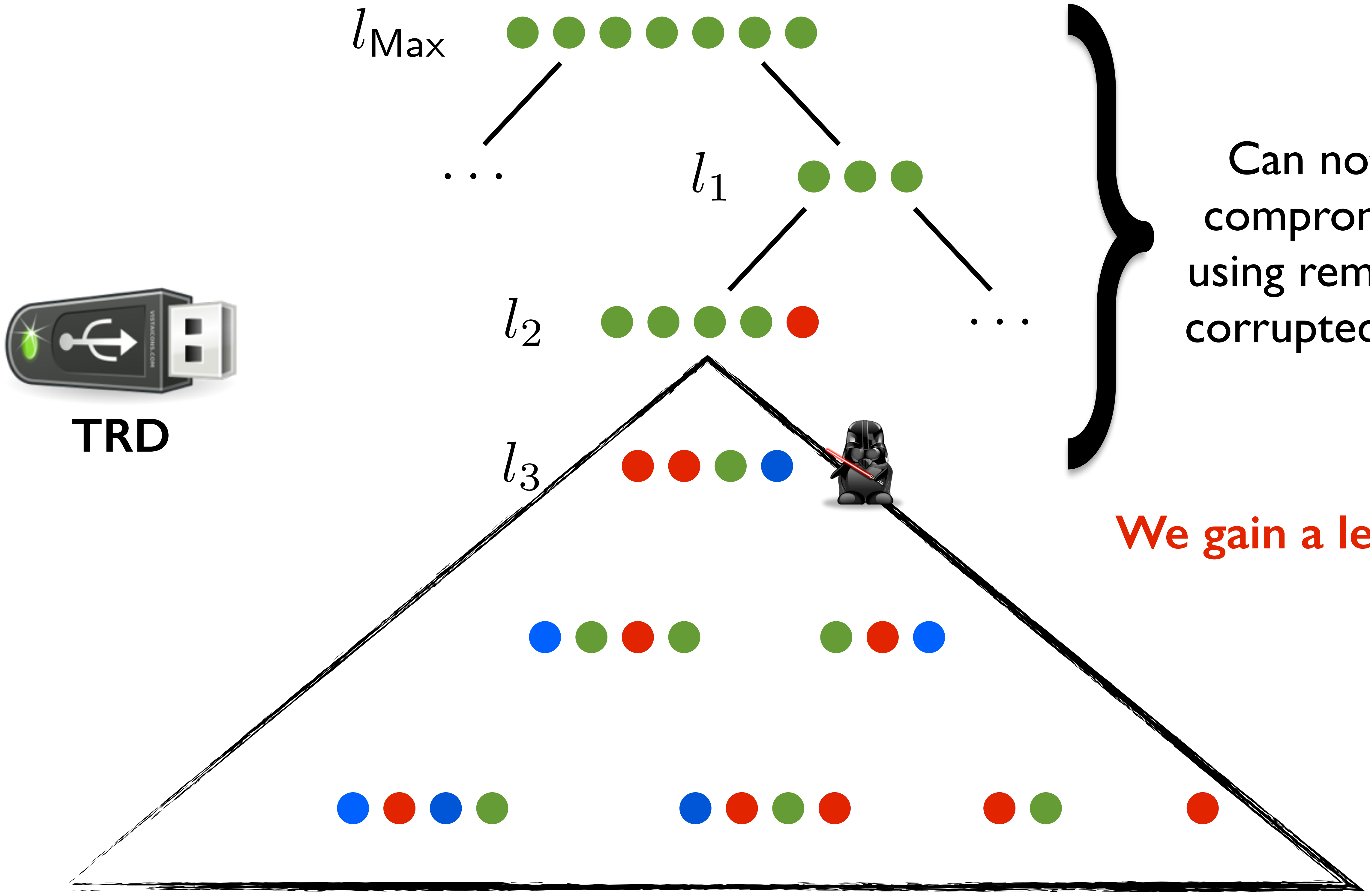

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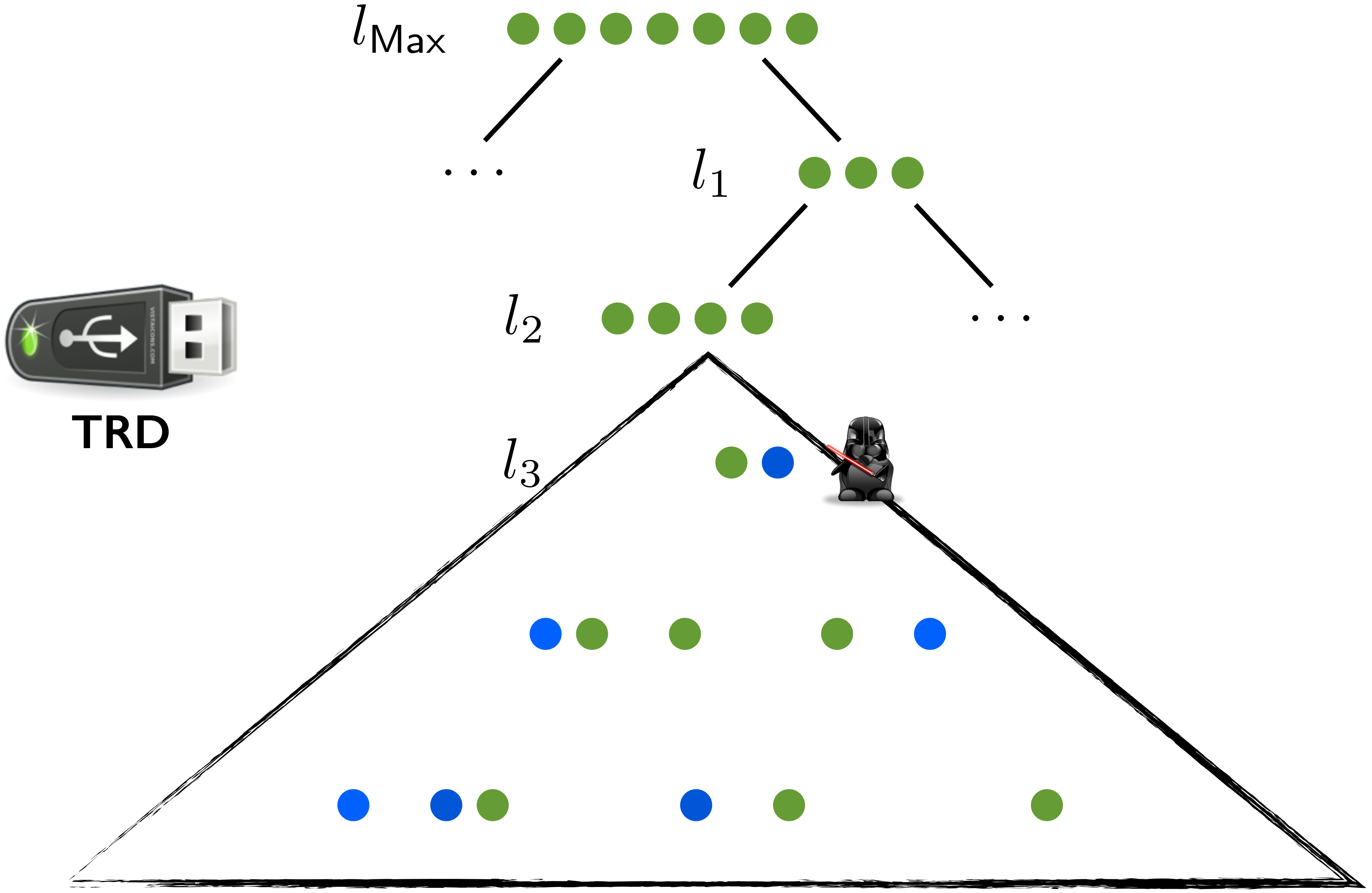

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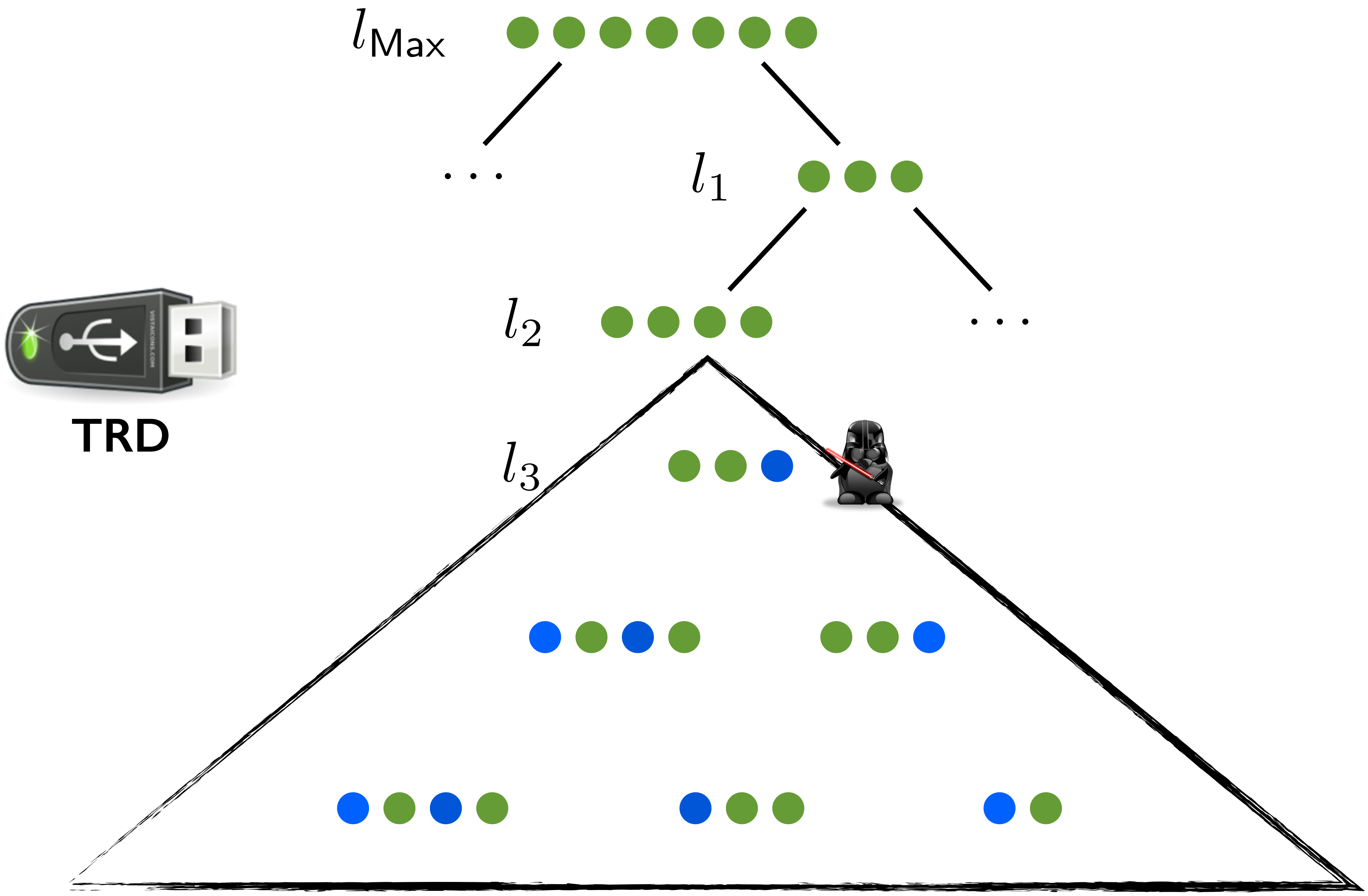

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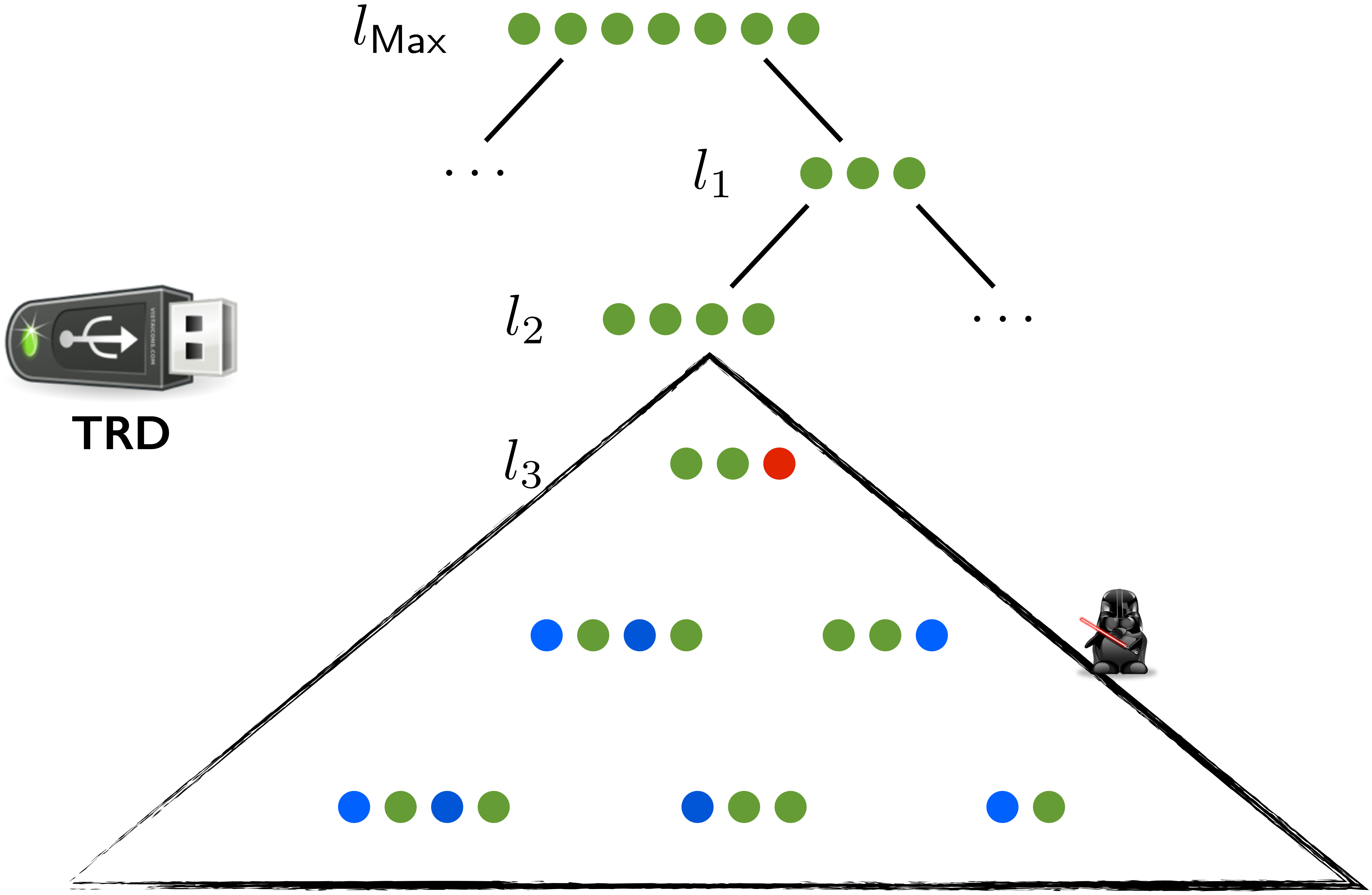

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Then at time $t + \Delta(l)$, all keys are secret except those under levels $l_1, \ldots, l_n$ such that $l_i < l$.

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Blacklist Option

«For those who are in a hurry...»

$\mathsf{blacklist}(C, h_1, \ldots, h_n)$

Ex : $C = \left\{ \langle \mathsf{blacklist}, \langle l_3, t \rangle \rangle \right\}$ 🔑 $\ldots$ 🔑

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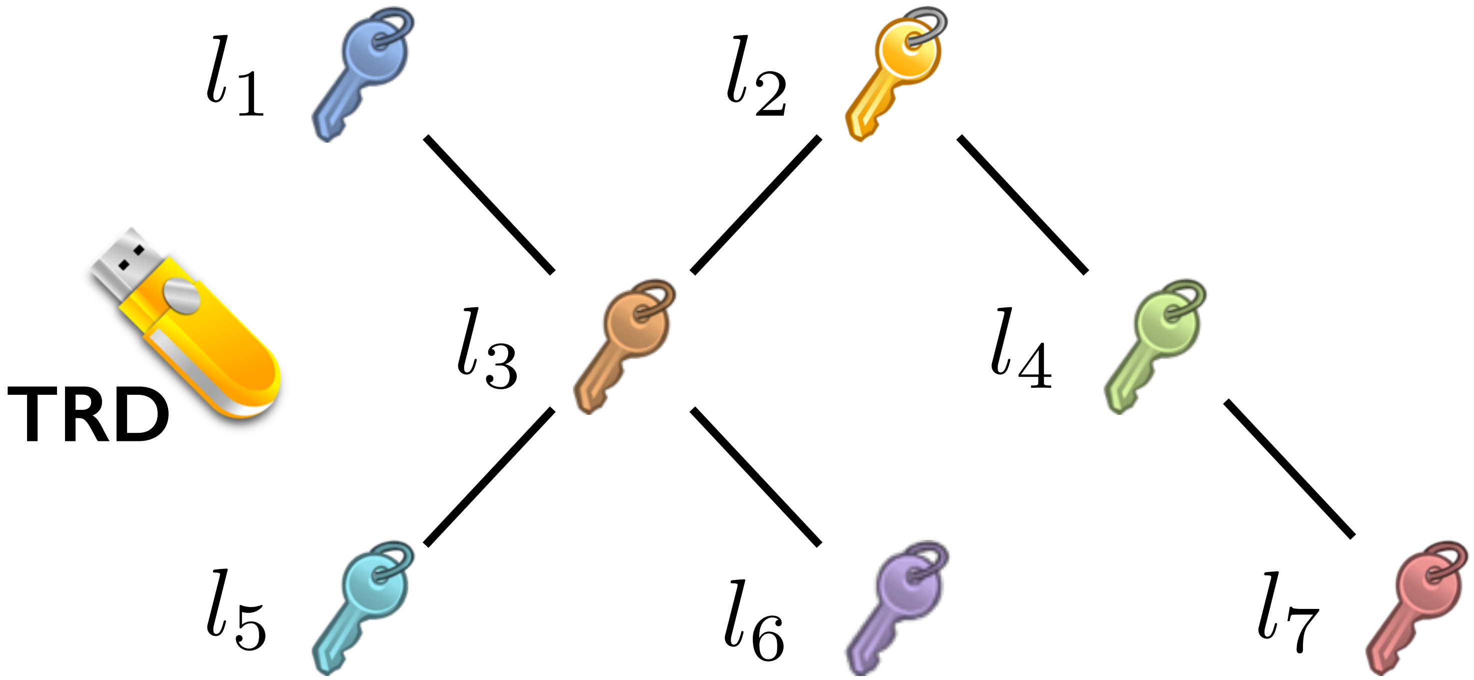

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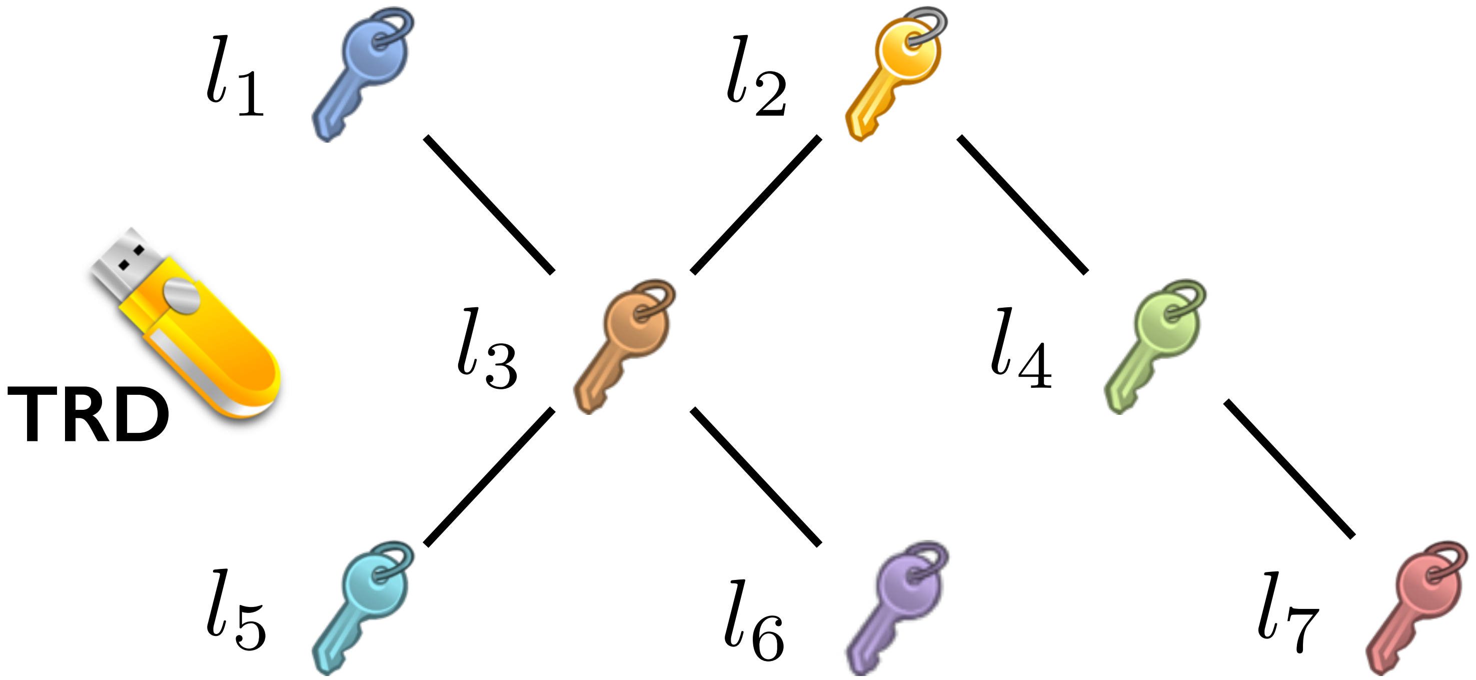

$(l_3, t_3) \longrightarrow$

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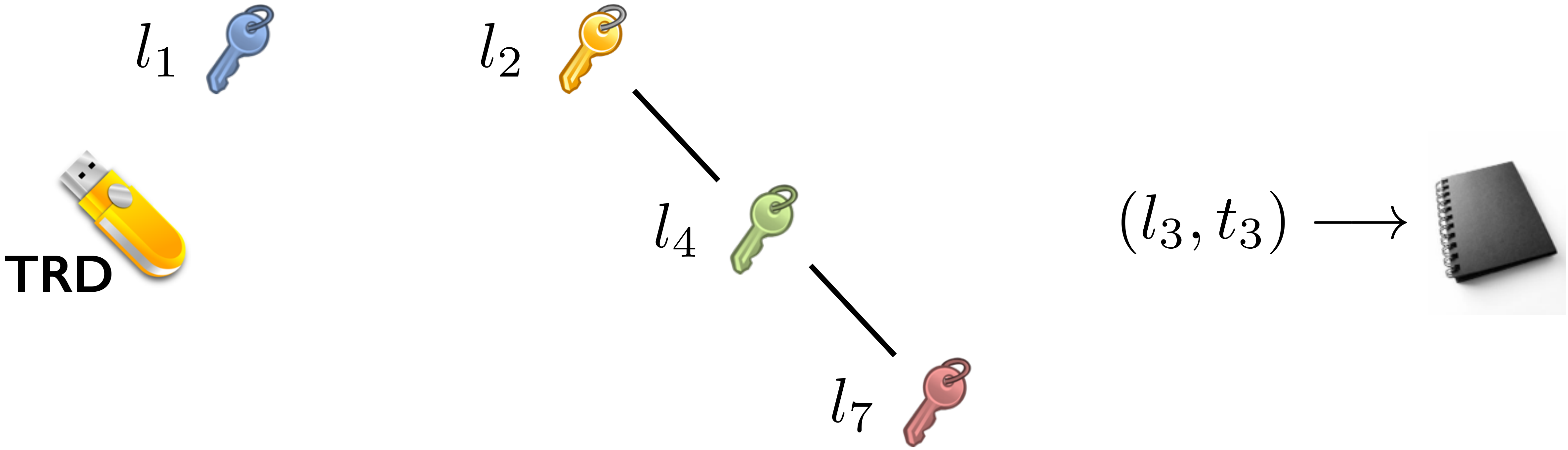

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Theorem 3 (Stated for one level)

Assume that all keys are secret at time t except those under a level l.

If we blacklist level l on a TRD , then, **immediately**, all keys are secret.

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Theorem 3 (Stated for one level)

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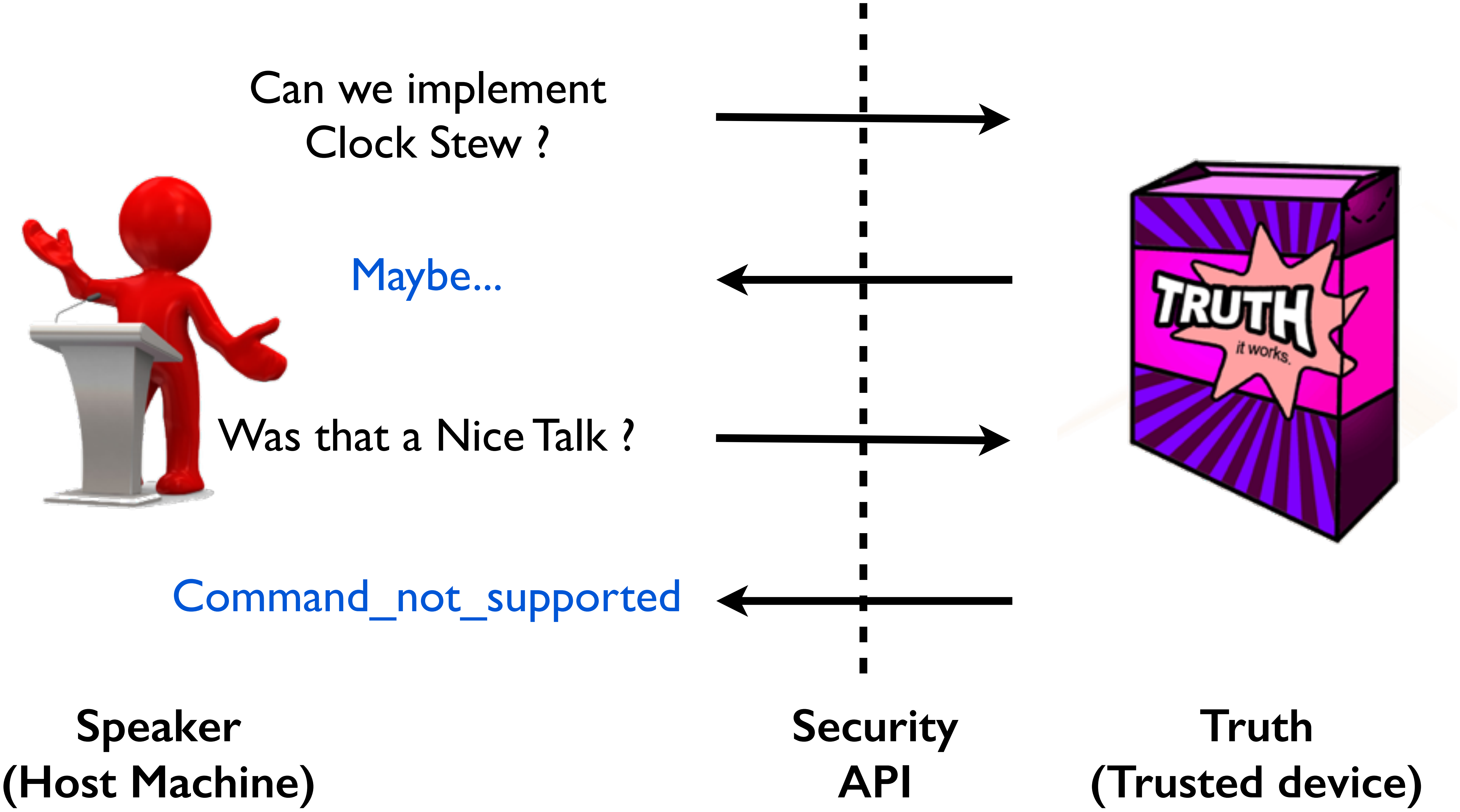
If we blacklist level l on a TRD , then, **immediately**, all keys are secret.

- It **only works** for the blacklisted TRD.
- The time of the blacklist should be long enough.
- It **prevents the attacker** to operate on the TRD.

Future Work

- **Weaken assumptions**, especially on hidden level Max messages (maybe requiring more cryptographic primitives),
- **Extend** revocation to **asymmetric encryption**,
- **Adapt** the result taking account of possible **clock skew**, or replacing the clock by some sort of nonce based freshness test,
- **Implement** the API in order to carry out some performance tests. [Ongoing work in JavaCard]

Thank you for your attention !



Can we implement Clock Stew ?

Maybe...

Was that a Nice Talk ?

Command_not_supported

Speaker
(Host Machine)

Security
API

Truth
(Trusted device)