Achieving Security Despite Compromise Using Zero-knowledge

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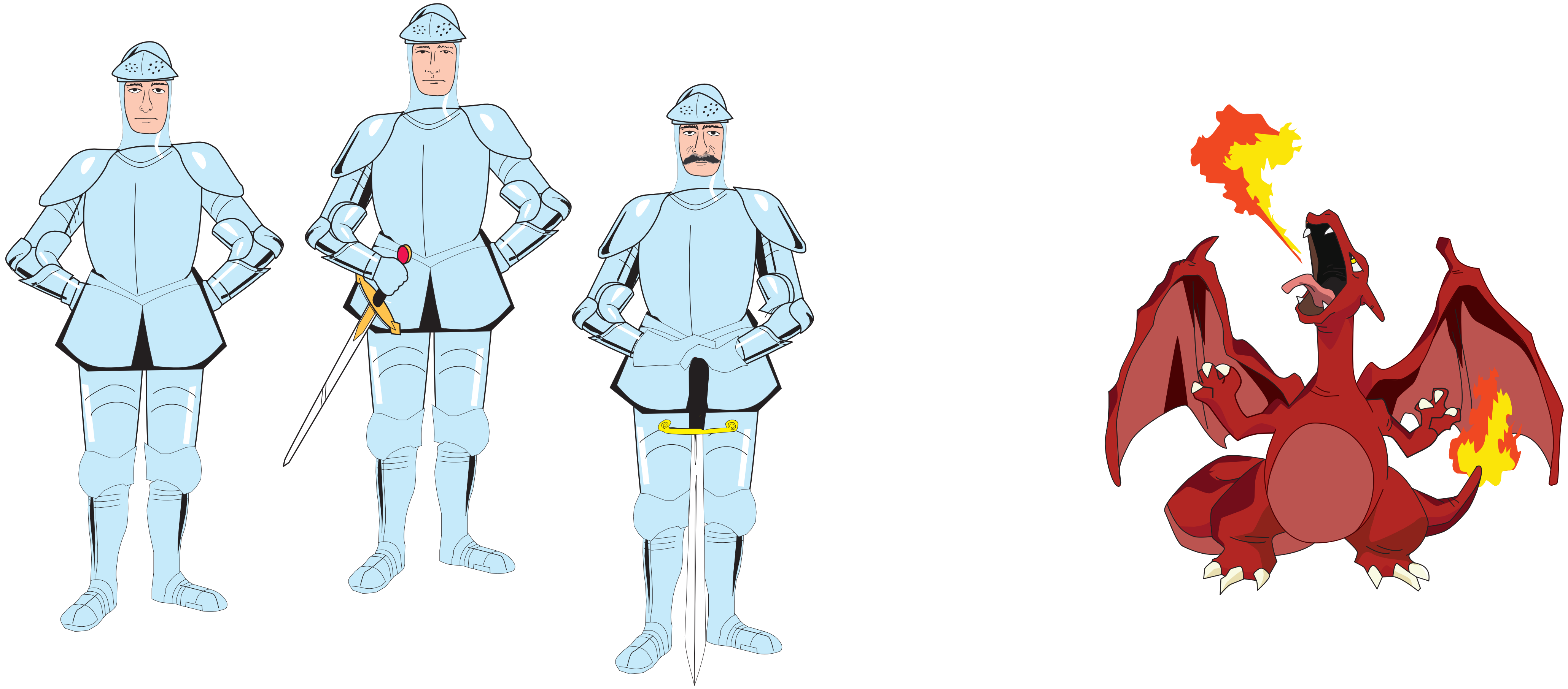
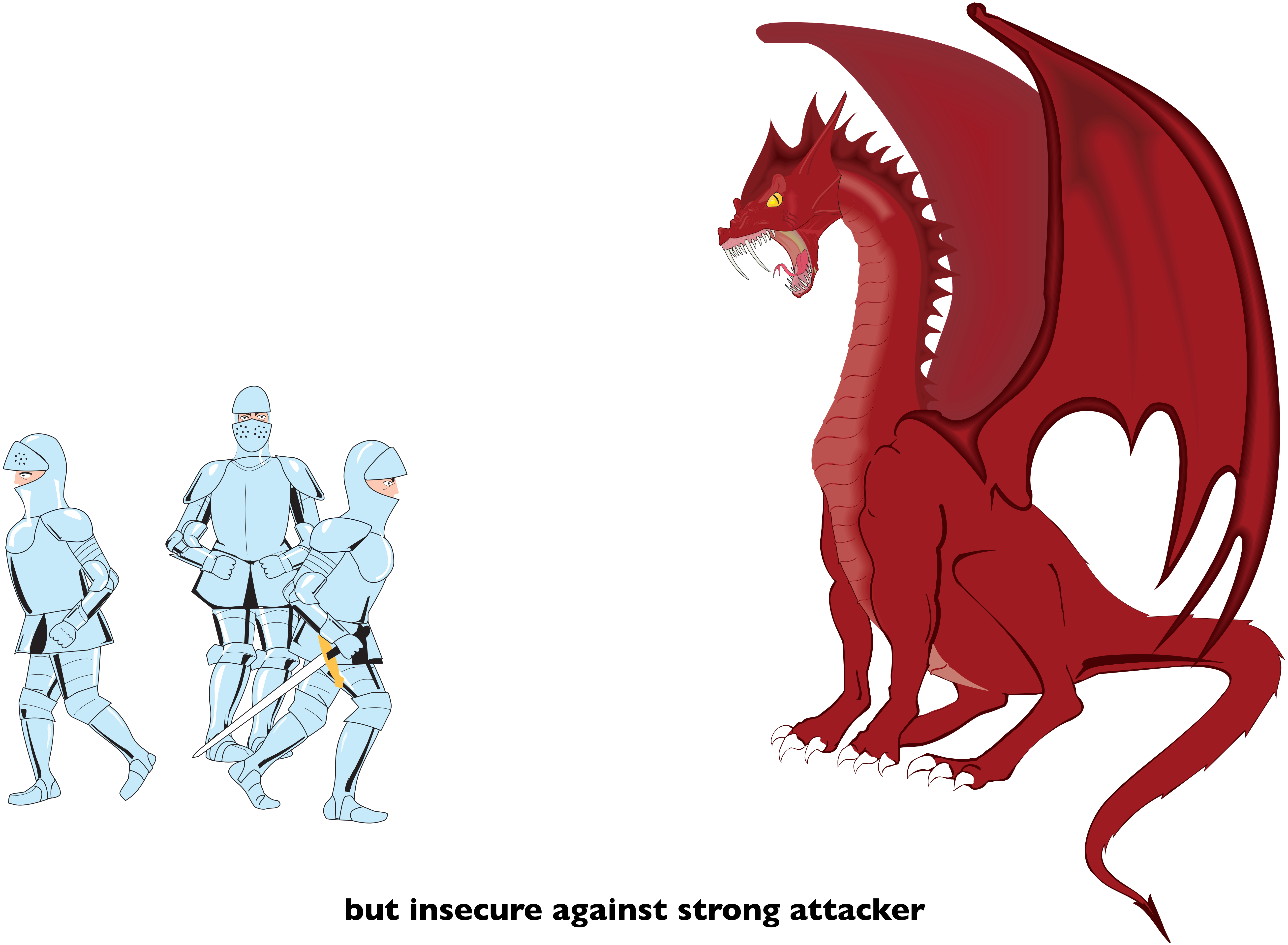
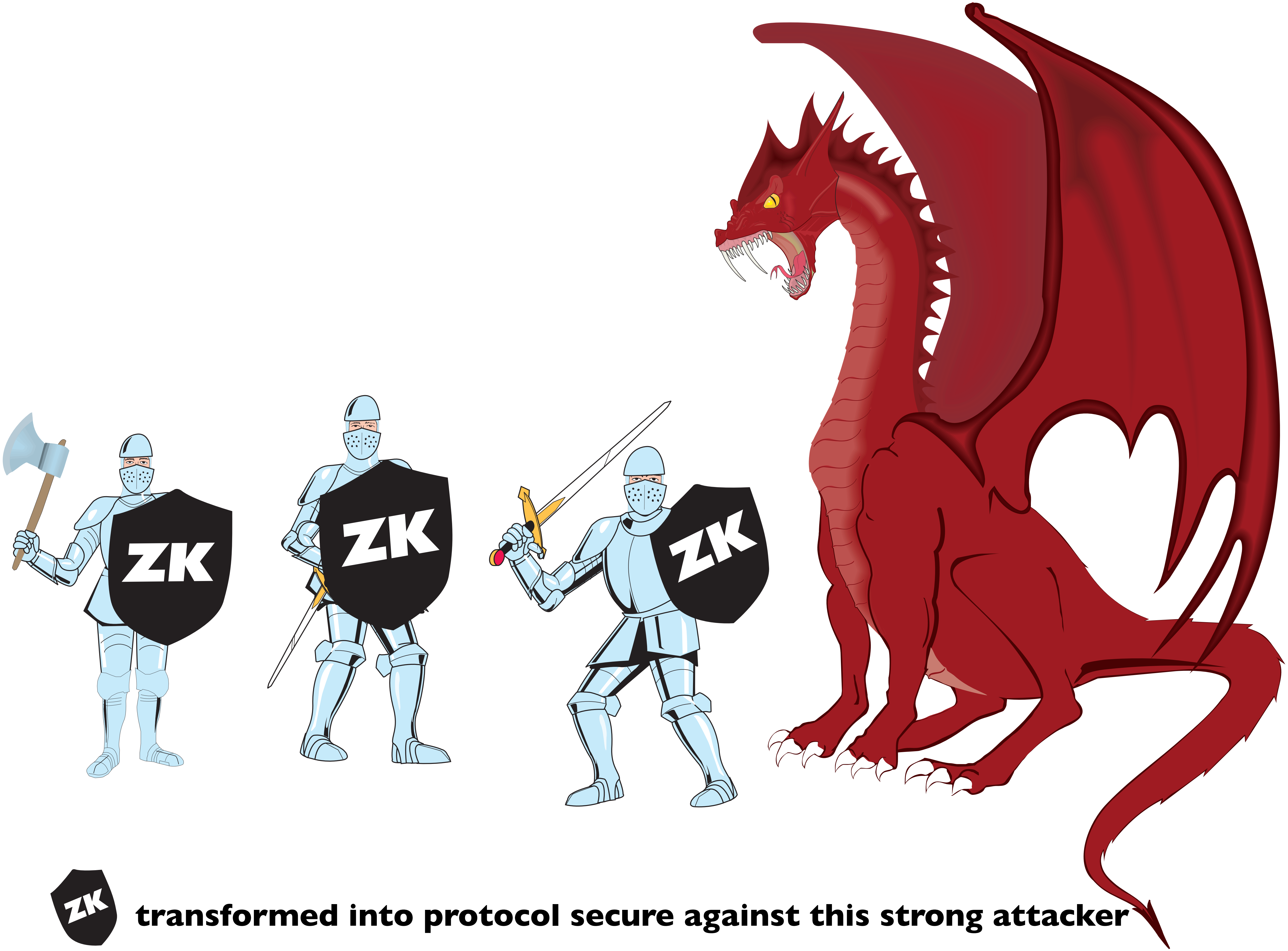
Joint work with: Michael Backes, Martin Grochulla and Matteo Maffei



protocol secure against a weak attacker



but insecure against strong attacker



ZK transformed into protocol secure against this strong attacker

- **General goal:** to aid secure protocol design
    - designer only needs to consider restricted security threats:

What we do and why

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  - designer only needs to consider restricted security threats:
- Automated protocol transformation adding ZK proofs

  - Enforce authorization policy even if some participants are compromised (security despite compromise)
  - Preserve secrecy if everybody is honest

What we do and why

- **General goal:** to aid secure protocol design
  - designer only needs to consider restricted security threats: all participants are honest
- Automated protocol transformation adding ZK proofs

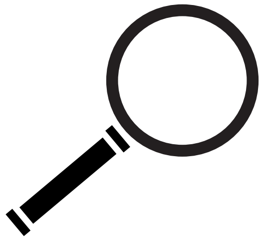
  - Enforce authorization policy even if some participants are compromised (security despite compromise)

  - Preserve secrecy if everybody is honest

What we do and why

- **General goal:** to aid secure protocol design
  - designer only needs to consider restricted security threats: all participants are honest
- Automated protocol transformation adding ZK proofs

  - Enforce authorization policy even if some participants are compromised (security despite compromise)
  - Preserve secrecy if everybody is honest
- Automated verification of the generated protocols (translation validation)



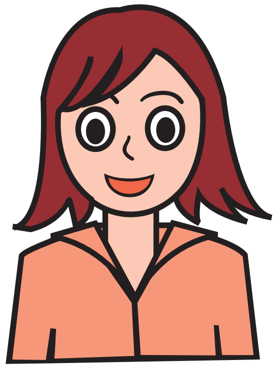
  - Use type system for zero-knowledge [Backes et al., CCS ’08]
    - Now extended to handle security despite compromise

Example

Adapted from [Fournet, Gordon & Maffeis, CSF ’07]

A simple protocol

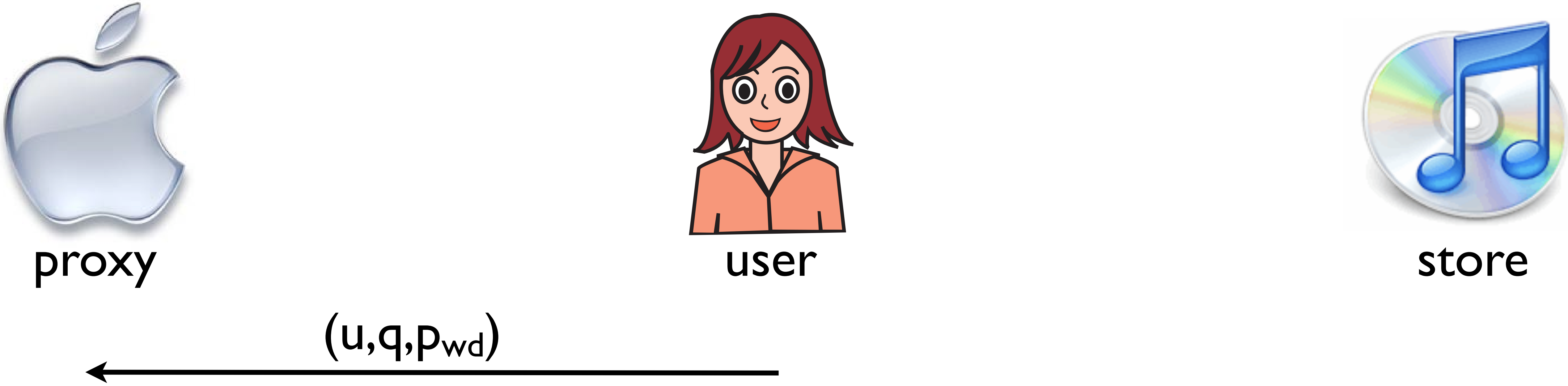
proxy



user

store

A simple protocol



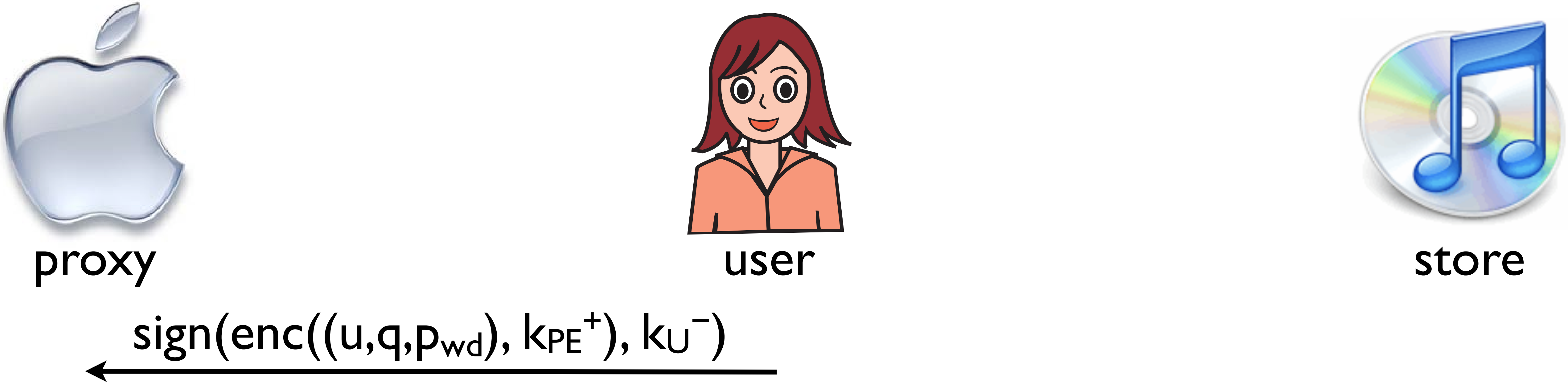
proxy

user

store

(u,q,p_{wd})

A simple protocol



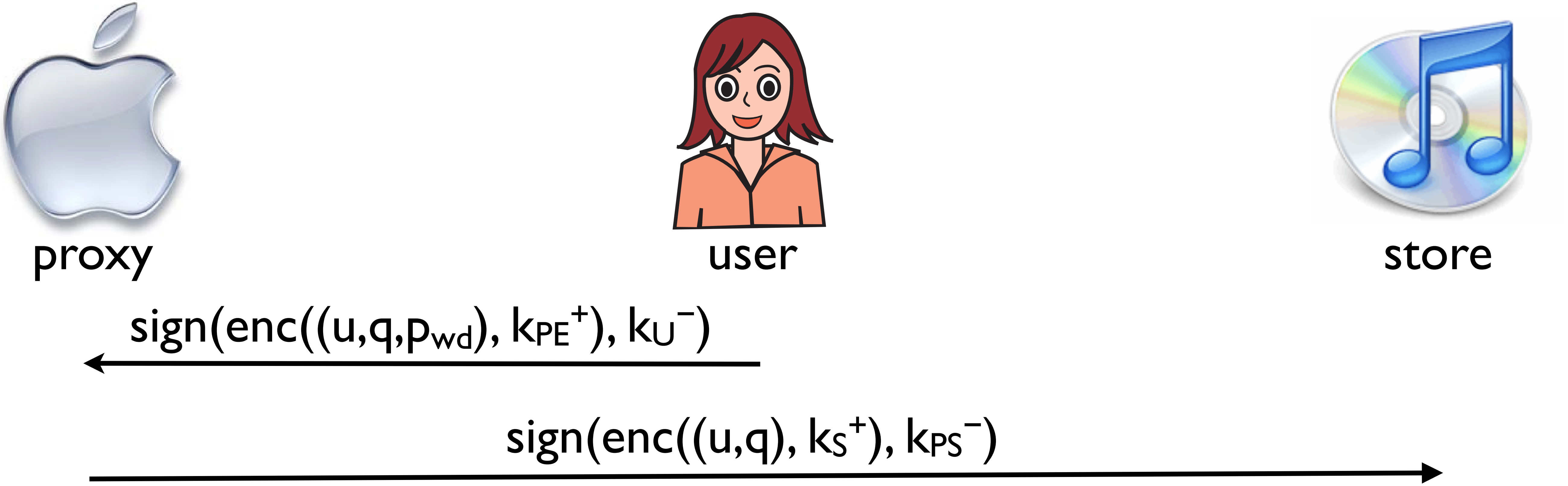
proxy

user

store

$\mathrm{sign}(\mathrm{enc}((u,q,p_{wd}), k_{PE}^{+}), k_{U}^{-})$

A simple protocol



proxy

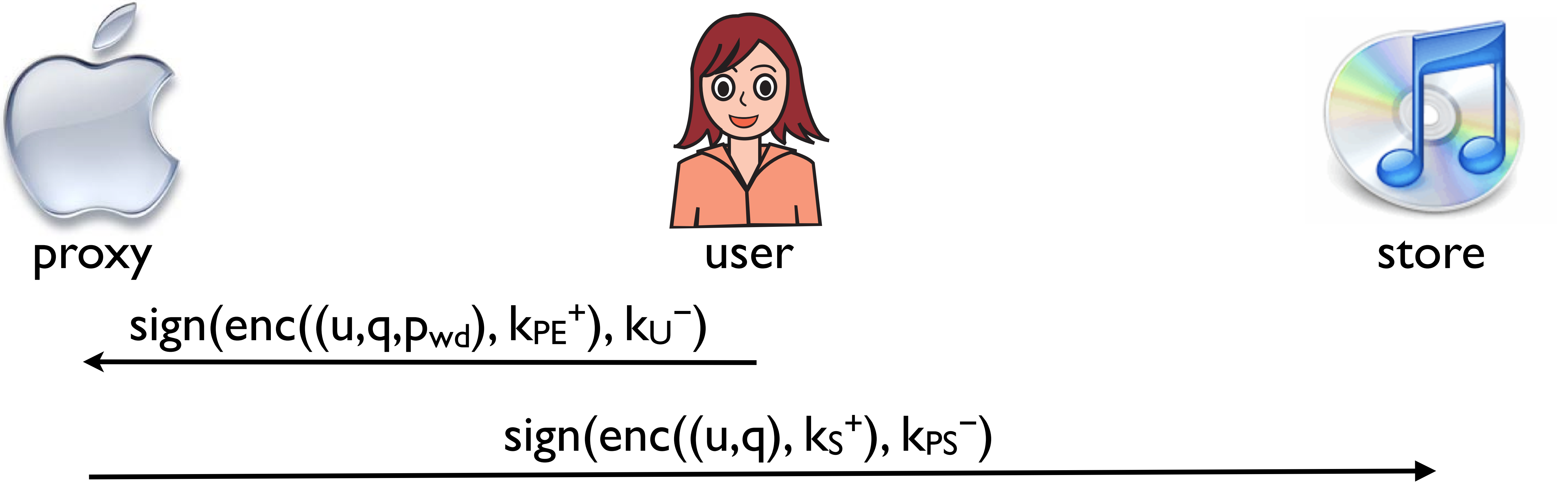
user

store

$\mathrm{sign}(\mathrm{enc}((u,q,p_{wd}), k_{PE}^{+}), k_{U}^{-})$ ←

$\mathrm{sign}(\mathrm{enc}((u,q), k_{S}^{+}), k_{PS}^{-})$ →

A simple protocol



proxy

user

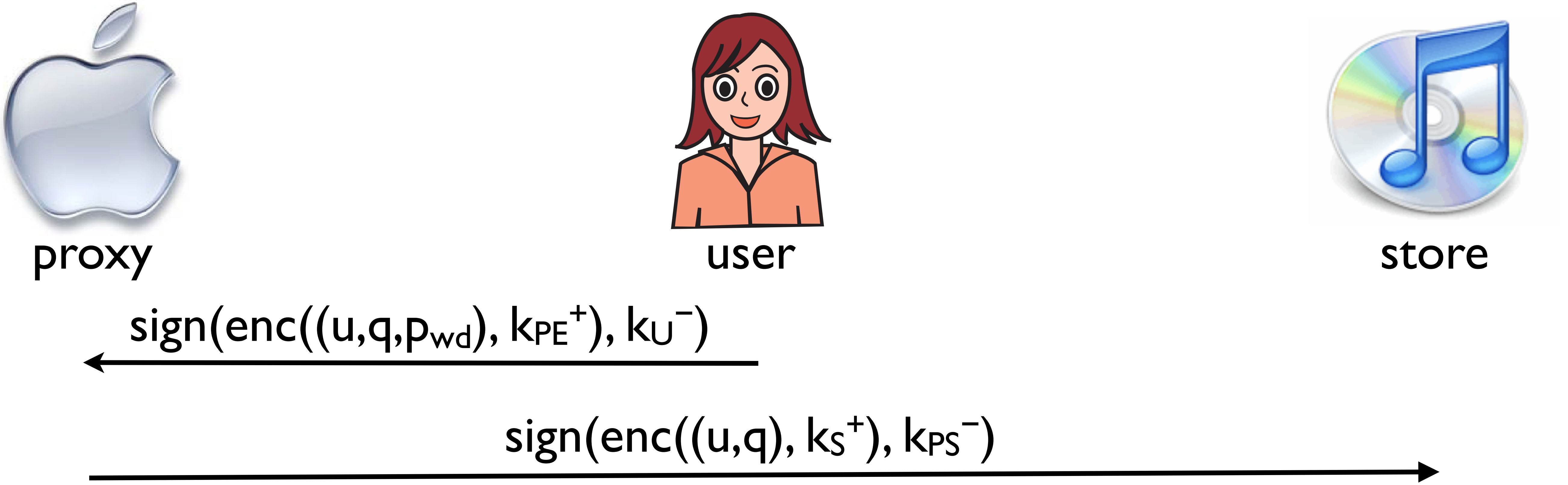
store

$\mathrm{sign}(\mathrm{enc}((u,q,p_{wd}), k_{PE}^{+}), k_{U}^{-})$

$\mathrm{sign}(\mathrm{enc}((u,q), k_{S}^{+}), k_{PS}^{-})$

- This protocol is secure if all participants are honest (q is secret and authentic)

A simple protocol



proxy

user

store

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- .... but insecure if the proxy is compromised

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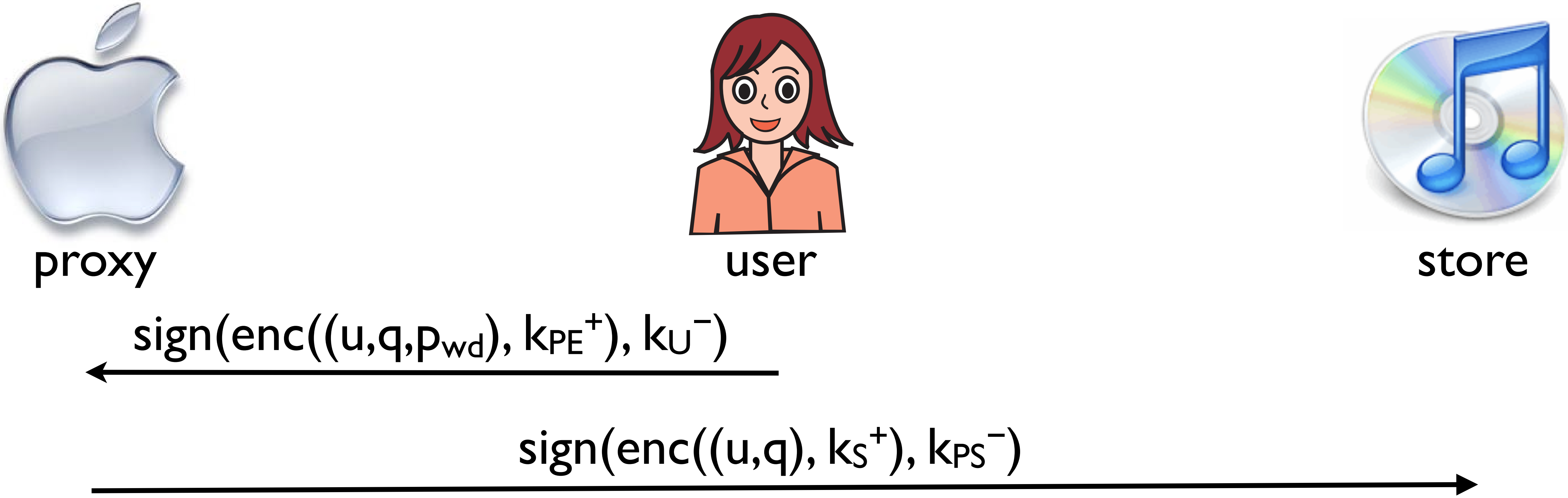


proxy

user

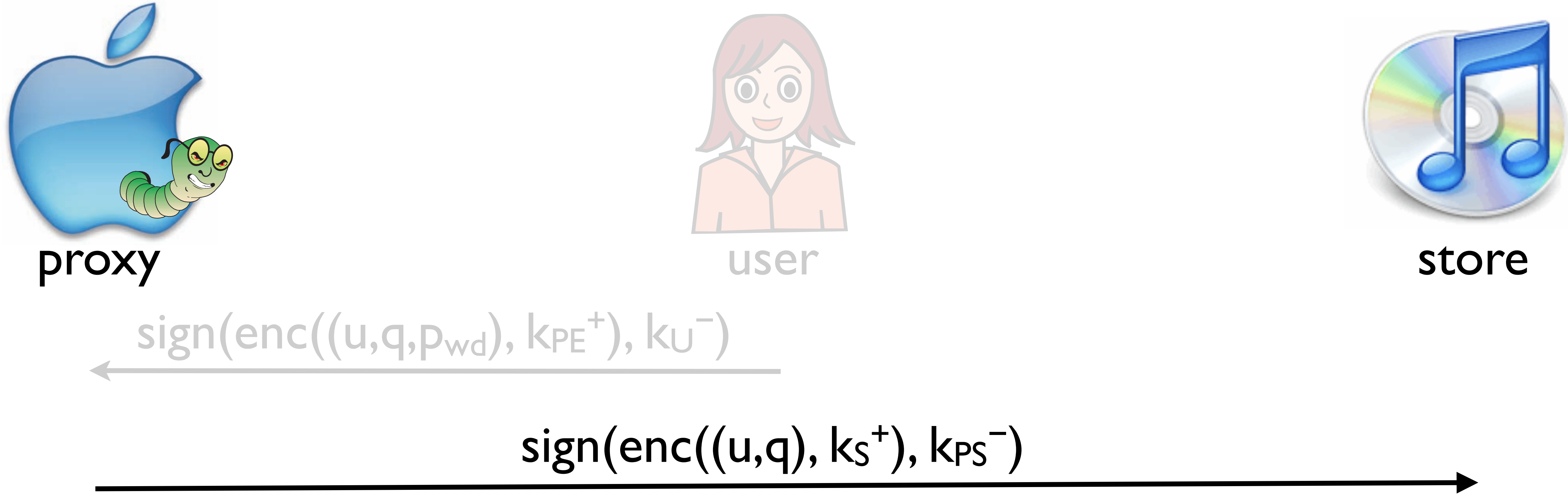
store

$\mathrm{sign}(\mathrm{enc}((u,q,p_{wd}), k_{PE}^{+}), k_{U}^{-})$

$\mathrm{sign}(\mathrm{enc}((u,q), k_{S}^{+}), k_{PS}^{-})$

- This protocol is secure if all participants are honest (q is secret and authentic)
- .... but insecure if the proxy is compromised
  - compromised proxy can leak q or p_{wd} (unavoidable)

A simple protocol



proxy

user

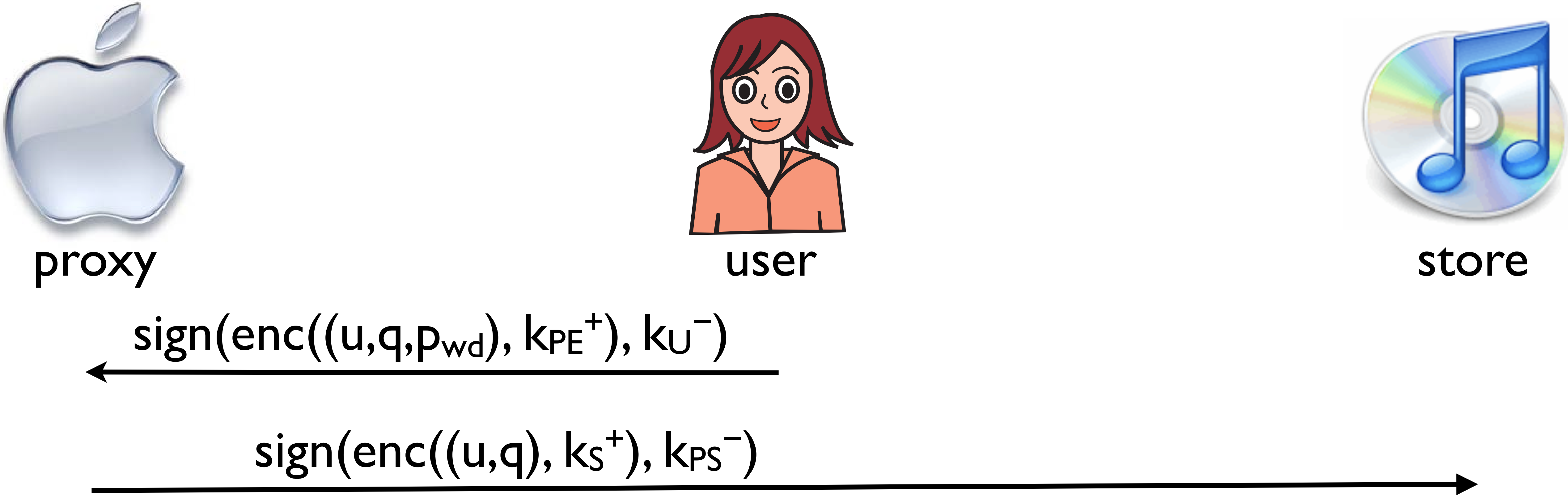
store

$\mathrm{sign}(\mathrm{enc}((u,q,p_{wd}), k_{PE}^{+}), k_{U}^{-})$

$\mathrm{sign}(\mathrm{enc}((u,q), k_{S}^{+}), k_{PS}^{-})$

- This protocol is secure if all participants are honest (q is secret and authentic)
- .... but insecure if the proxy is compromised
  - compromised proxy can leak q or p_{wd} (unavoidable)
  - **compromised proxy can fake request from the user (break authenticity)**

Trying to strengthen the protocol



proxy

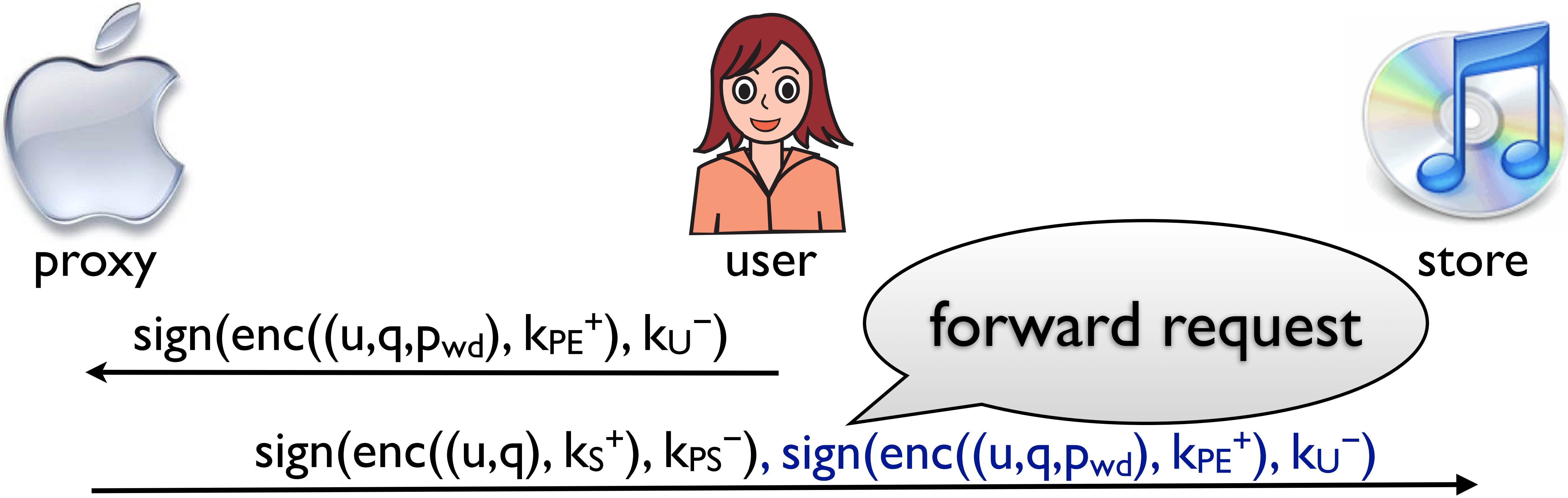
user

store

$\mathrm{sign}(\mathrm{enc}((u,q,p_{wd}), k_{PE}^{+}), k_{U}^{-})$

$\mathrm{sign}(\mathrm{enc}((u,q), k_{S}^{+}), k_{PS}^{-})$

Trying to strengthen the protocol

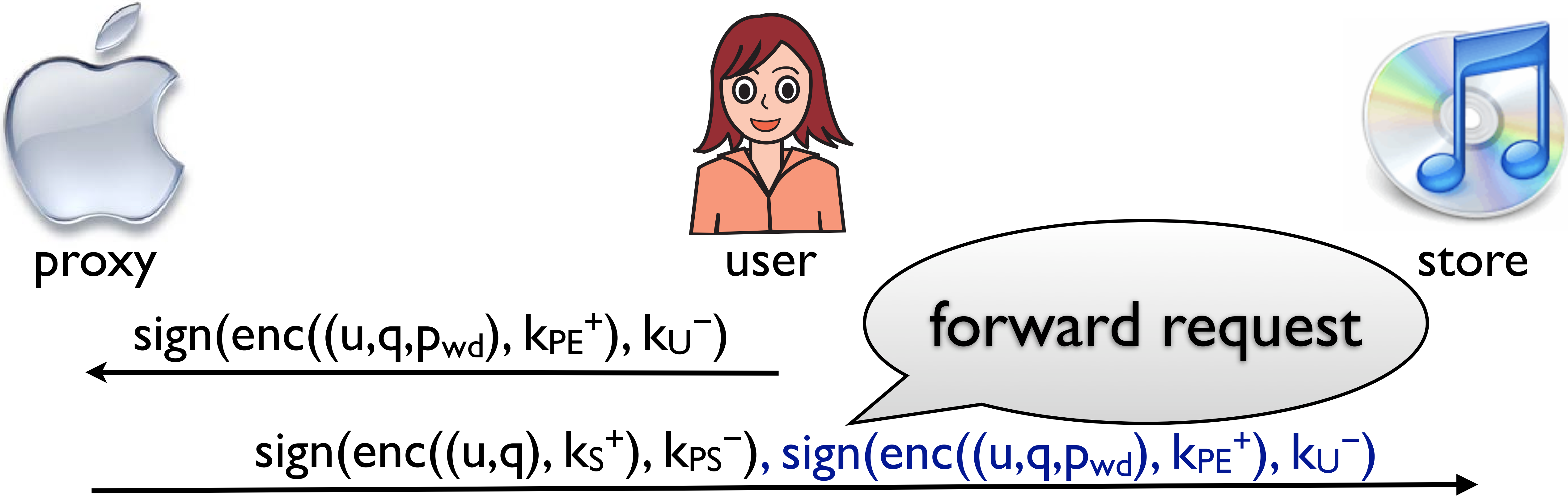


$\text{sign}(\text{enc}((u,q,p_{wd}), k_{PE}^{+}), k_{U}^{-})$

$\text{sign}(\text{enc}((u,q), k_{S}^{+}), k_{PS}^{-}), \text{sign}(\text{enc}((u,q,p_{wd}), k_{PE}^{+}), k_{U}^{-})$

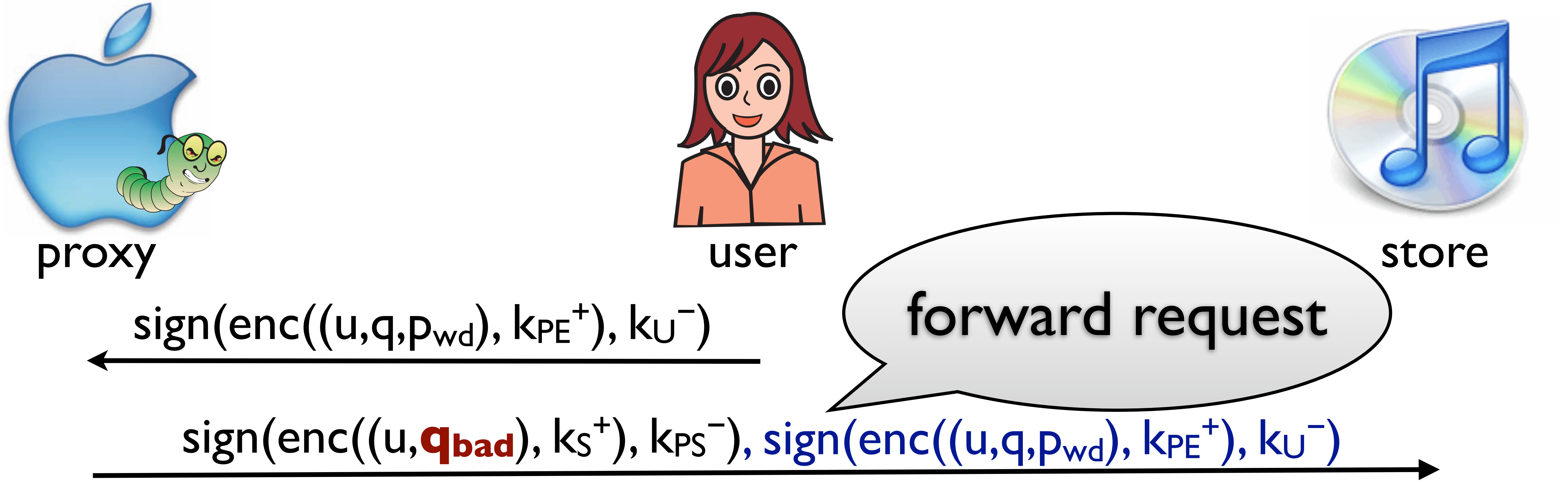
- Store can check user’s signature on “$\text{enc}((q,p_{wd}),k_{PE}^{+})$”

Trying to strengthen the protocol



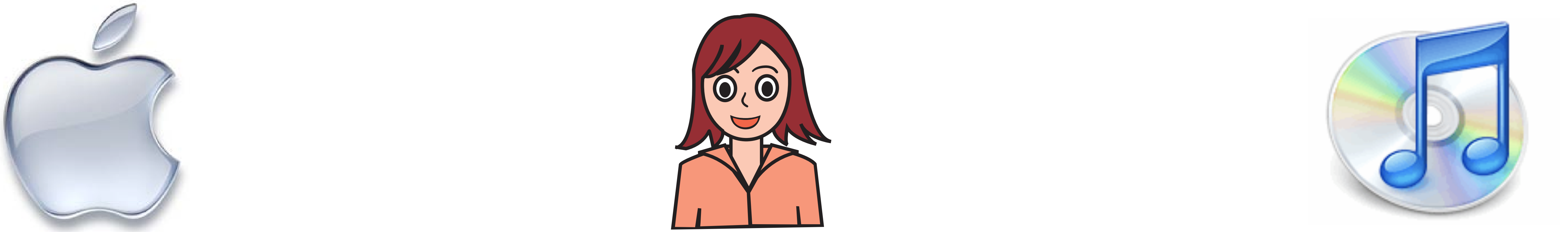
- Store can check user’s signature on “enc((q,p_{wd}),k_{PE}^{+})”
- Store cannot decrypt “enc((u,q,p_{wd}),k_{PE}^{+})” in order to check q

Trying to strengthen the protocol



- Store can check user’s signature on “$\mathrm{enc}((q,p_{wd}),k_{PE}^{+})$”
- Store cannot decrypt “$\mathrm{enc}((u,q,p_{wd}),k_{PE}^{+})$” in order to check q
- **… still insecure if proxy comprised (message substitution attack)**

Using non-interactive ZK



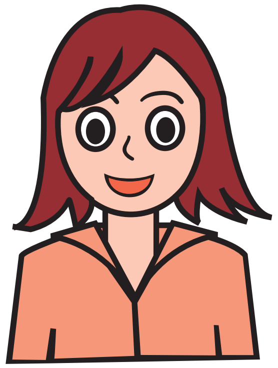
proxy user store

$\text{sign}(\text{enc}((q,p_{wd}), k_{PE}^{+}), k_{U}^{-})$ ←

$\text{sign}(\text{enc}((u,q), k_{S}^{+}), k_{PS}^{-}), \text{sign}(\text{enc}((u,q, p_{wd}), k_{PE}^{+}), k_{U}^{-})$ →

Using non-interactive ZK

proxy



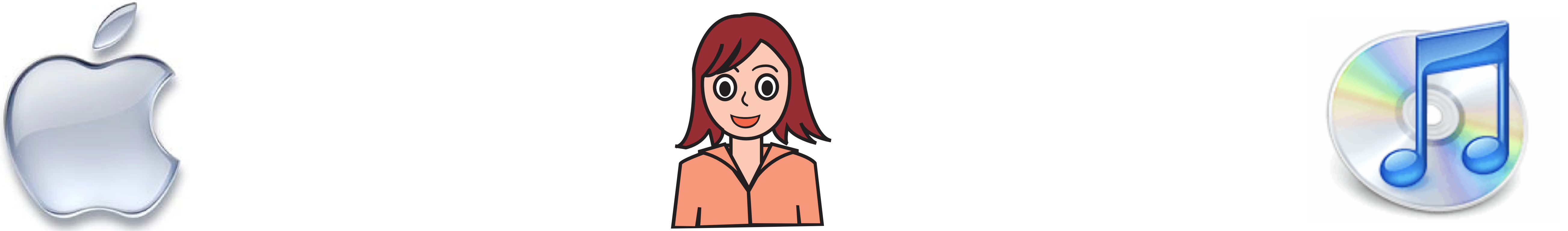
user

store

$\xleftarrow{\text{sign}(\text{enc}((q,p_{wd}), k_{PE}^{+}), k_{U}^{-})}$

$\xrightarrow{\text{zk}_{S}(k_{PE}^{-}, q, p_{wd};\ \text{sign}(\text{enc}((u,q), k_{S}^{+}), k_{PS}^{-}), \text{sign}(\text{enc}((u,q, p_{wd}), k_{PE}^{+}), k_{U}^{-}), u)}$

Using non-interactive ZK



proxy

user

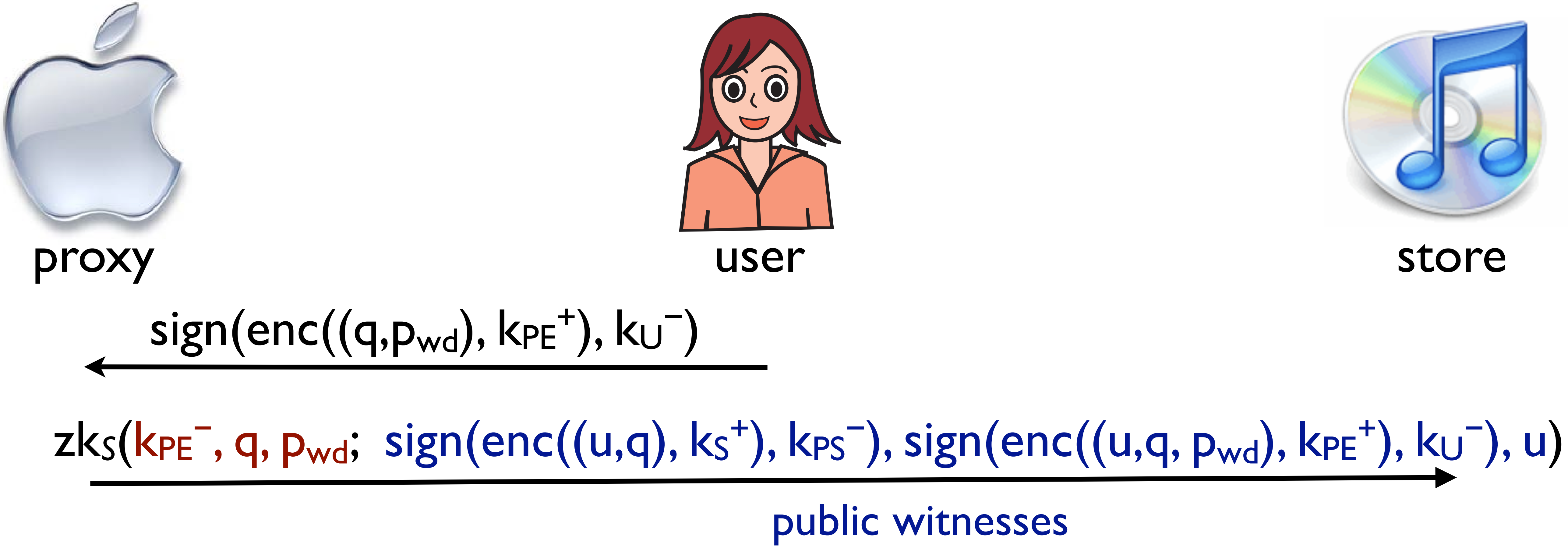
store

$\text{sign}(\text{enc}((q, p_{wd}), k_{PE}^{+}), k_{U}^{-})$ ←

$\text{zk}_S(k_{PE}^{-}, q, p_{wd};\ \text{sign}(\text{enc}((u,q), k_S^{+}), k_{PS}^{-}), \text{sign}(\text{enc}((u,q,p_{wd}), k_{PE}^{+}), k_U^{-}), u)$ →

secret
witnesses

Using non-interactive ZK



proxy

user

store

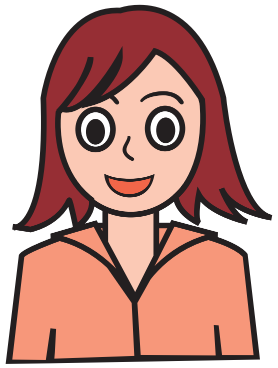
$\mathrm{sign}(\mathrm{enc}((q,p_{wd}), k_{PE}^{+}), k_{U}^{-})$ ←

$zk_{S}(k_{PE}^{-}, q, p_{wd};\ \mathrm{sign}(\mathrm{enc}((u,q), k_{S}^{+}), k_{PS}^{-}), \mathrm{sign}(\mathrm{enc}((u,q,p_{wd}), k_{PE}^{+}), k_{U}^{-}), u)$ →

public witnesses

Using non-interactive ZK

proxy



user

store

$\text{sign}(\text{enc}((q,p_{wd}), k_{PE}^{+}), k_{U}^{-})$ ←

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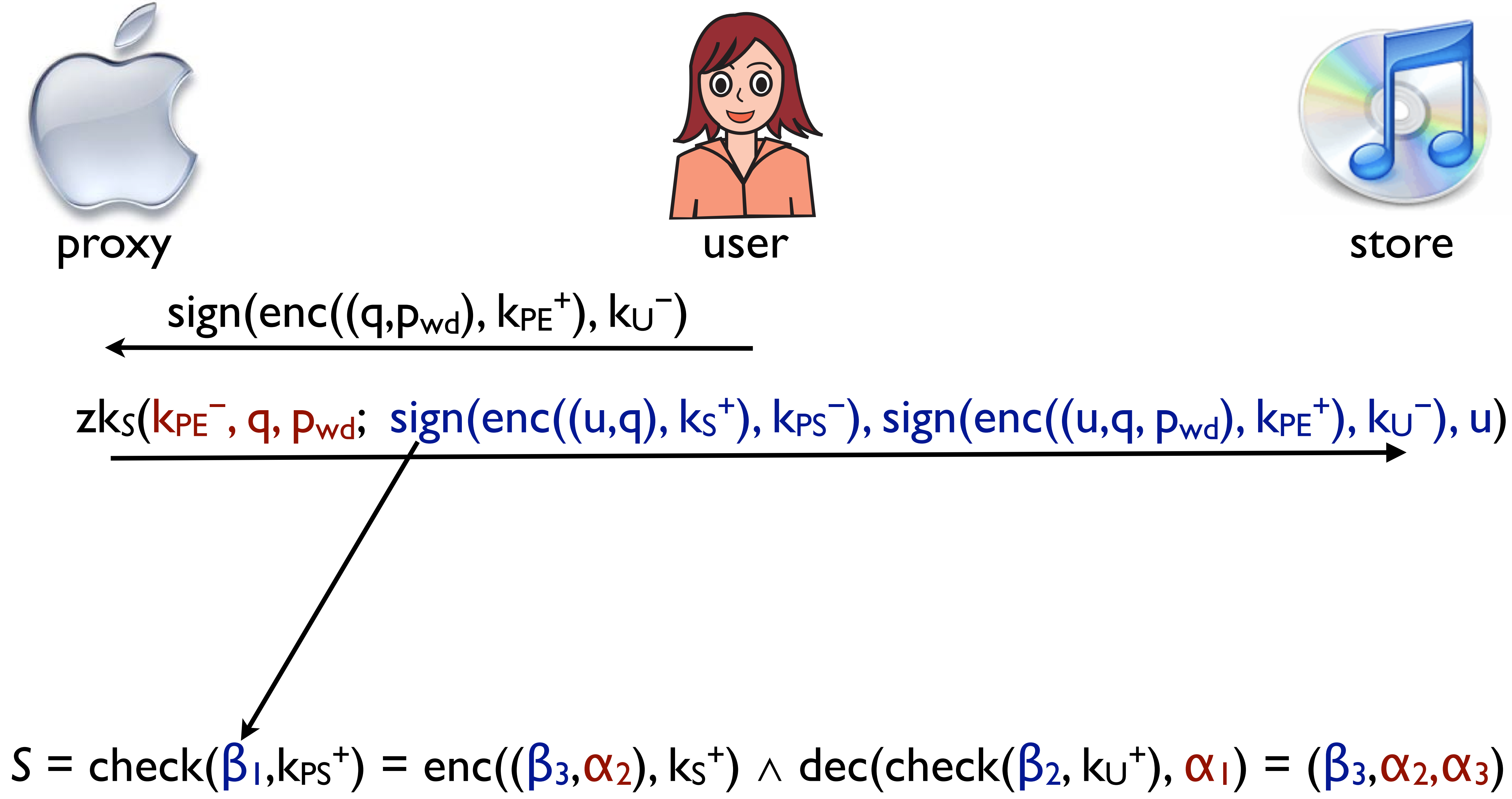
statement (= Boolean formula over equalities between terms with placeholders)

$$S = \text{check}(\beta_1,k_{PS}^{+}) = \text{enc}((\beta_3,\alpha_2), k_{S}^{+}) \wedge \text{dec}(\text{check}(\beta_2, k_{U}^{+}), \alpha_1) = (\beta_3,\alpha_2,\alpha_3)$$

Using non-interactive ZK



$\mathrm{sign}(\mathrm{enc}((q,p_{wd}), k_{PE}^{+}), k_U^{-})$

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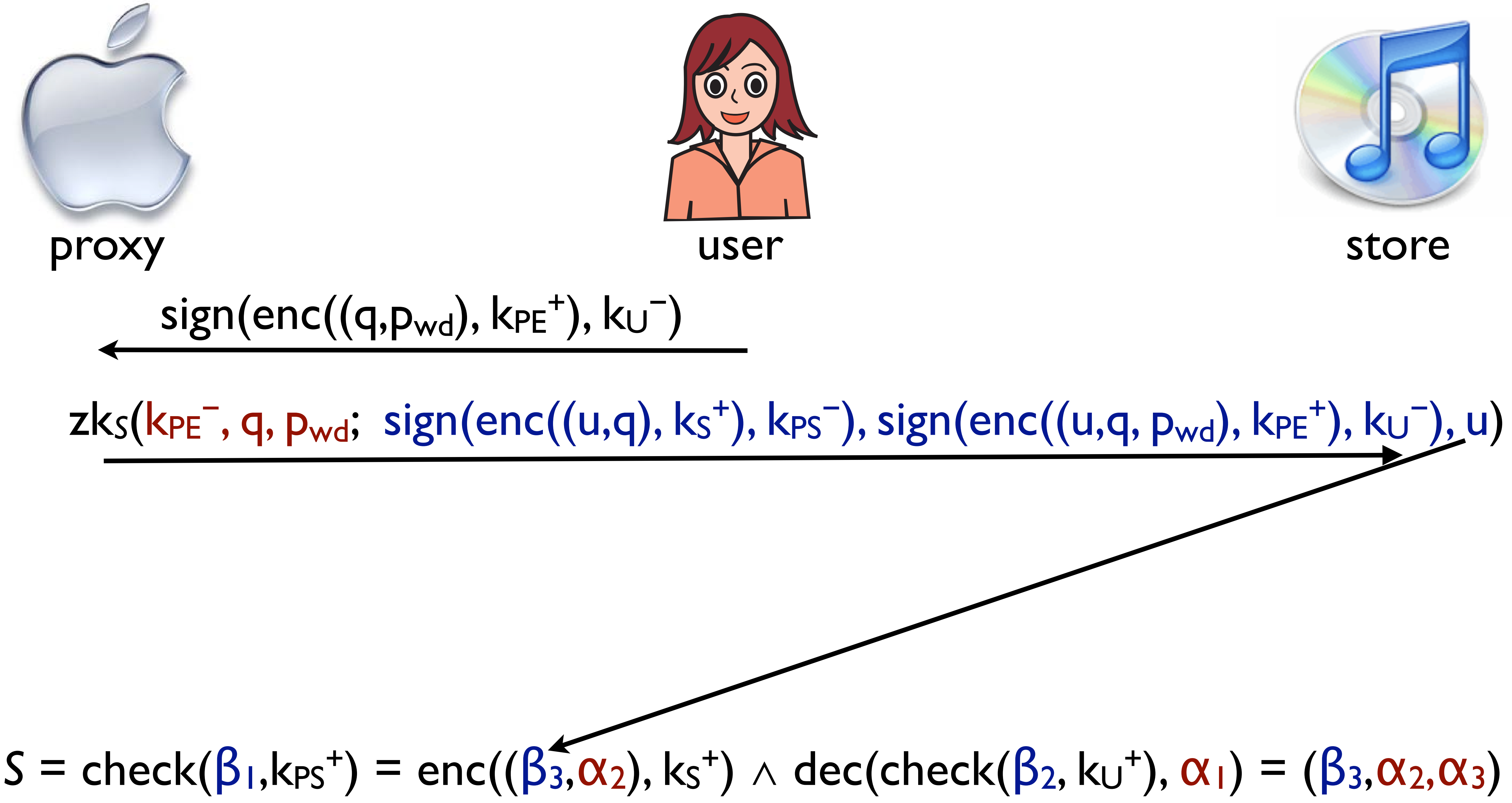

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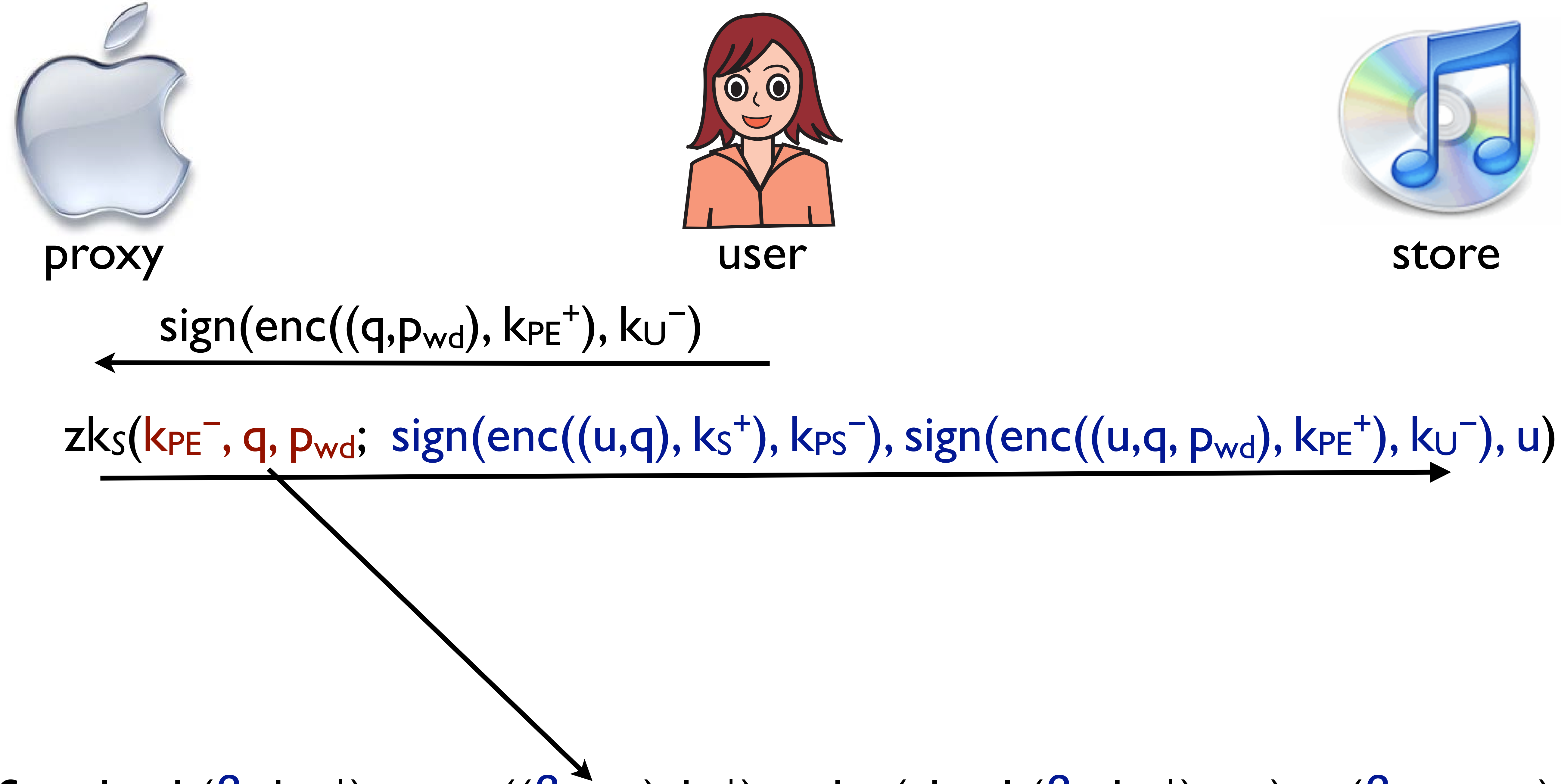

proxy

user

store

$\mathrm{sign}(\mathrm{enc}((q,p_{wd}), k_{PE}^{+}), k_{U}^{-})$

$\mathrm{zk}_{S}(k_{PE}^{-}, q, p_{wd};\ \mathrm{sign}(\mathrm{enc}((u,q), k_{S}^{+}), k_{PS}^{-}), \mathrm{sign}(\mathrm{enc}((u,q,p_{wd}), k_{PE}^{+}), k_{U}^{-}), u)$

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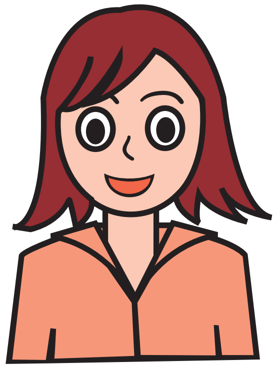
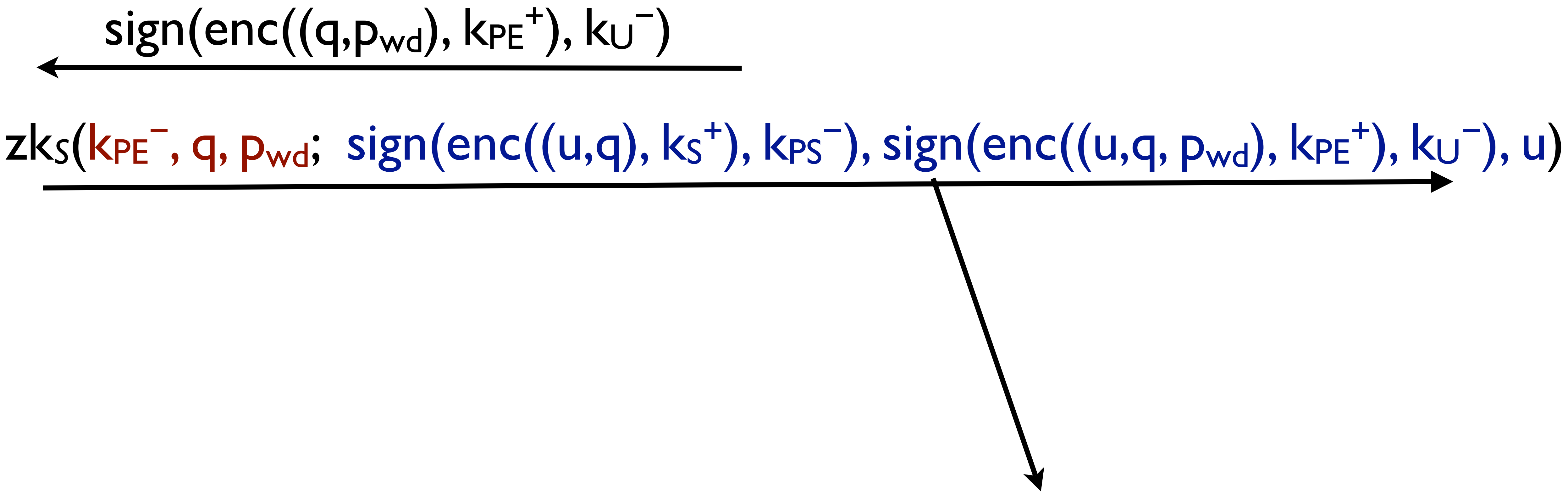
Using non-interactive ZK

proxy



user

store



$\mathrm{sign}(\mathrm{enc}((q,p_{wd}), k_{PE}^{+}), k_{U}^{-})$

$\mathrm{zk}_{S}(k_{PE}^{-}, q, p_{wd};\ \mathrm{sign}(\mathrm{enc}((u,q), k_{S}^{+}), k_{PS}^{-}), \mathrm{sign}(\mathrm{enc}((u,q, p_{wd}), k_{PE}^{+}), k_{U}^{-}), u)$

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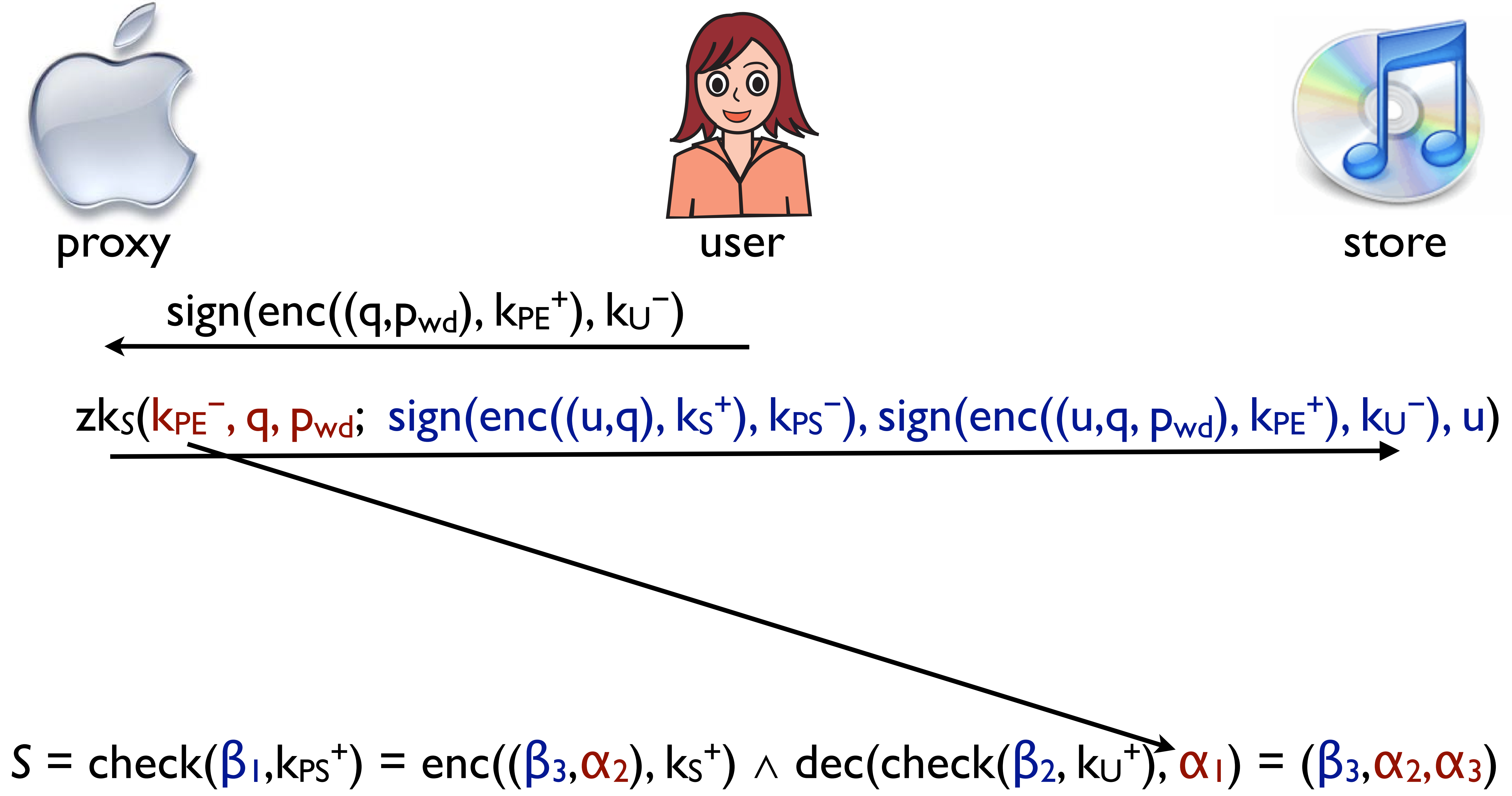
Using non-interactive ZK



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$zk_{S}(k_{PE}^{-}, q, p_{wd};\ \mathrm{sign}(\mathrm{enc}((u,q), k_{S}^{+}), k_{PS}^{-}), \mathrm{sign}(\mathrm{enc}((u,q,p_{wd}), k_{PE}^{+}), k_{U}^{-}), u)$

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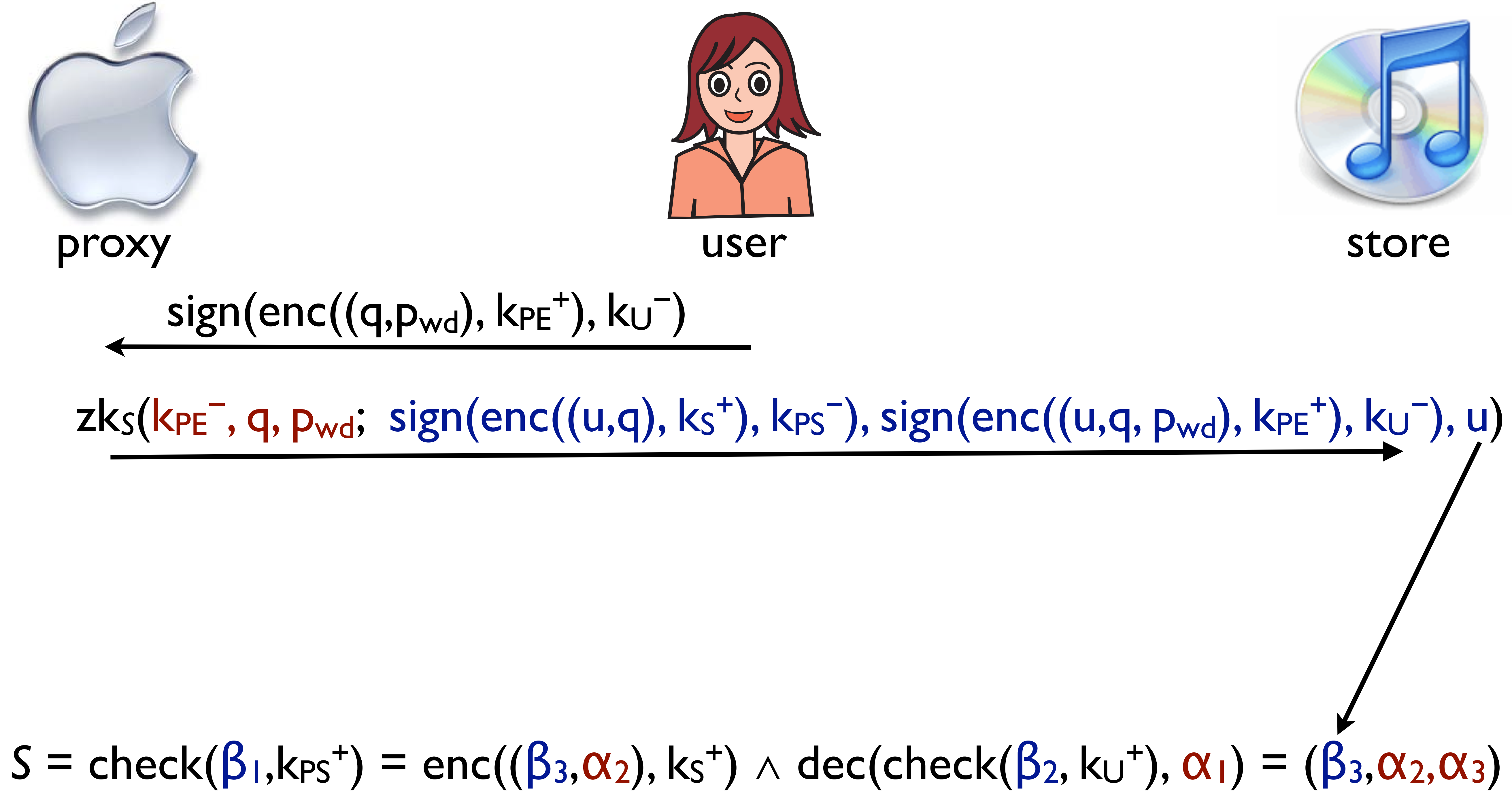
Using non-interactive ZK



proxy

user

store

$\text{sign}(\text{enc}((q,p_{wd}), k_{PE}^{+}), k_U^{-})$

$\text{zk}_S(k_{PE}^{-}, q, p_{wd};\ \text{sign}(\text{enc}((u,q), k_S^{+}), k_{PS}^{-}), \text{sign}(\text{enc}((u,q, p_{wd}), k_{PE}^{+}), k_U^{-}), u)$

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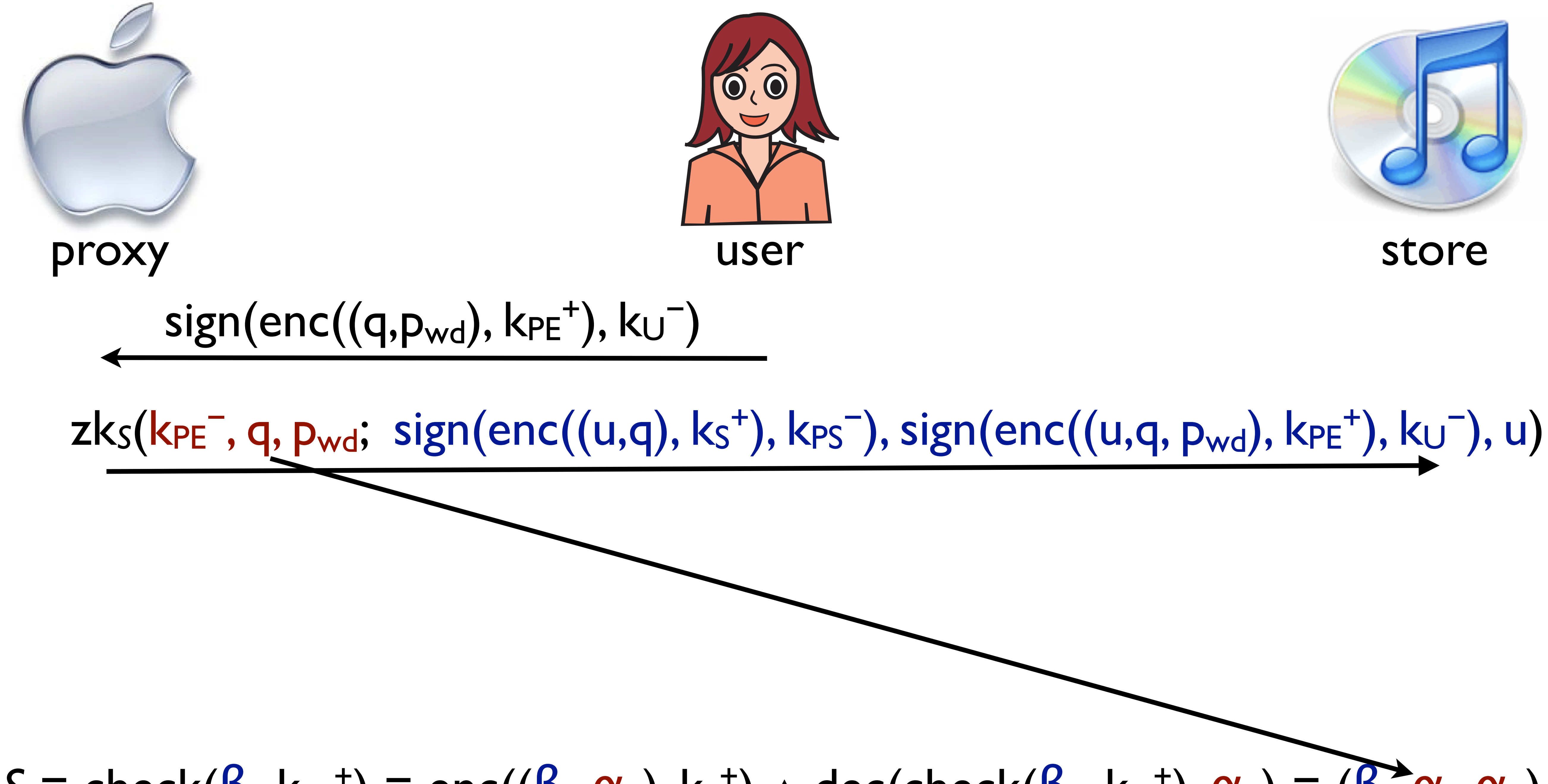

proxy

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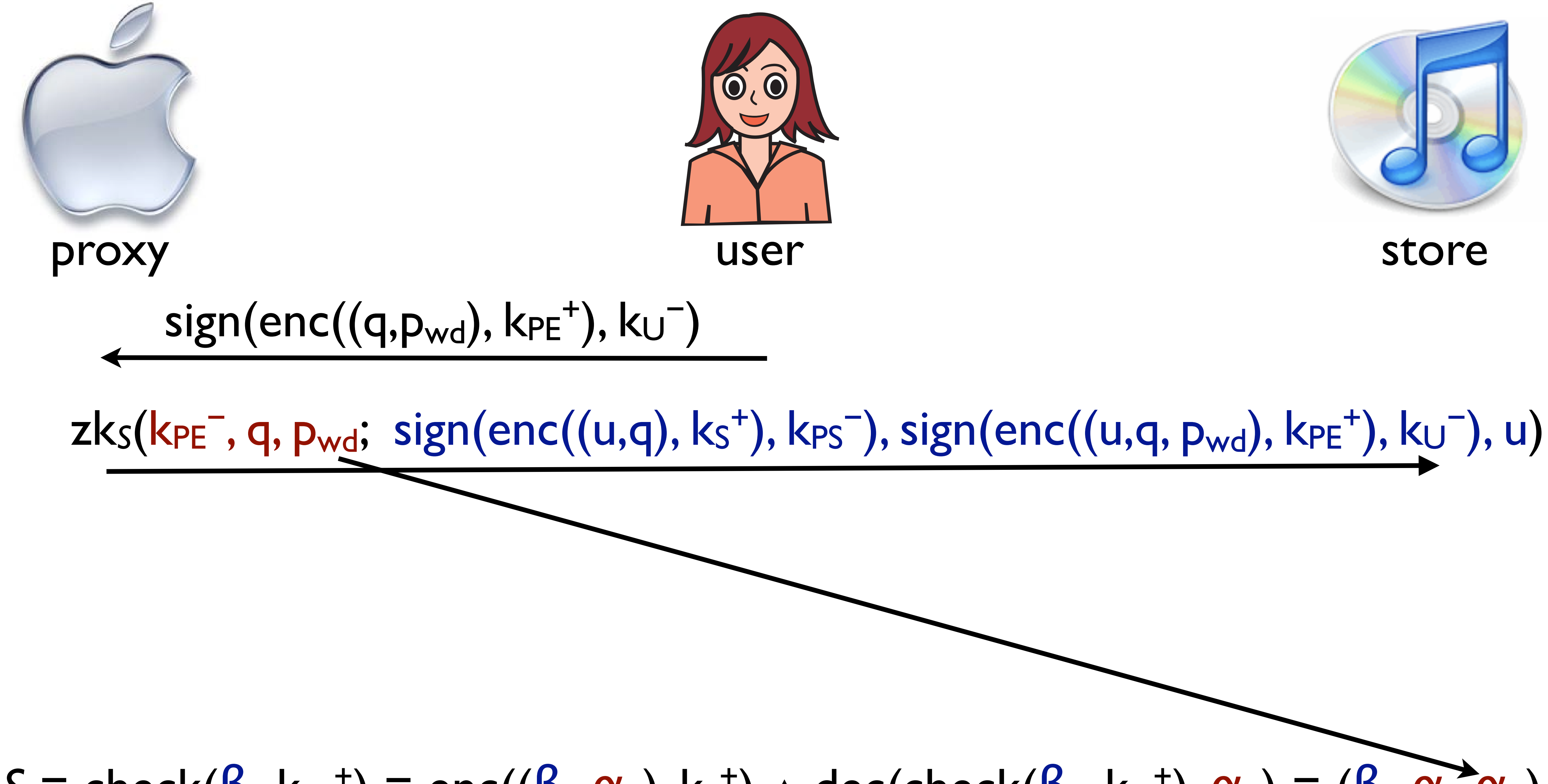

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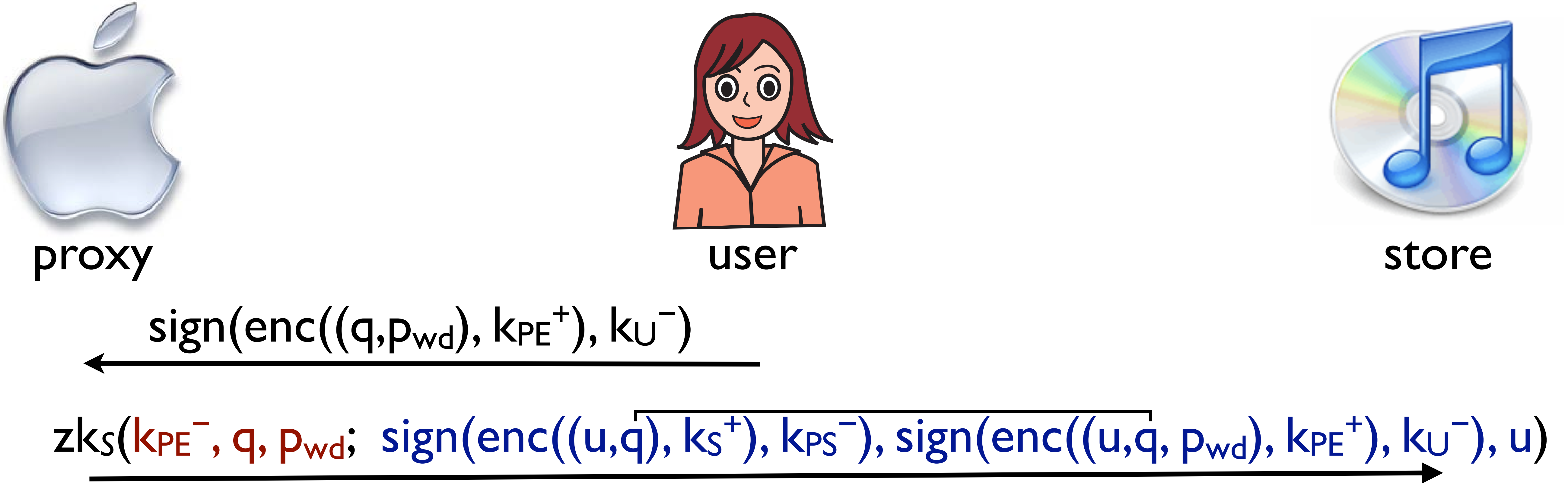
Using non-interactive ZK



proxy

user

store

$\xleftarrow{\mathrm{sign}(\mathrm{enc}((q,p_{wd}),\, k_{PE}^{+}),\, k_U^{-})}$

$$zk_S(k_{PE}^{-},\, q,\, p_{wd};\;\; \mathrm{sign}(\mathrm{enc}((u,\overbrace{q),\, k_S^{+}),\, k_{PS}^{-}),\, \mathrm{sign}(\mathrm{enc}((u,q}, p_{wd}),\, k_{PE}^{+}),\, k_U^{-}),\, u) \longrightarrow$$

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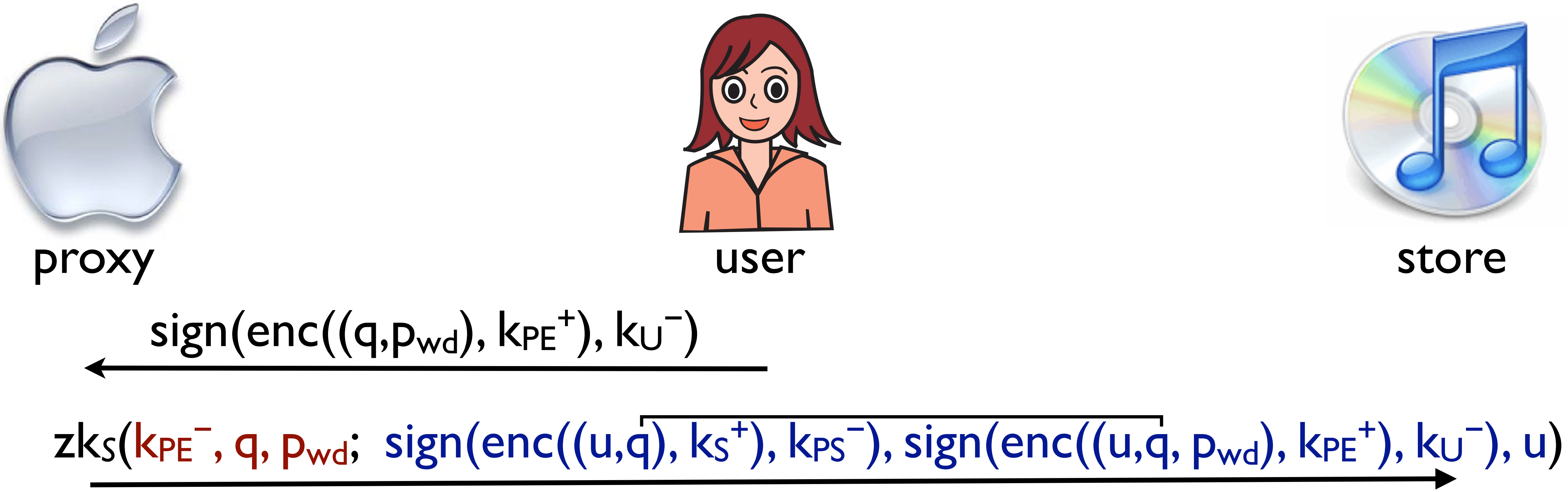
Using non-interactive ZK

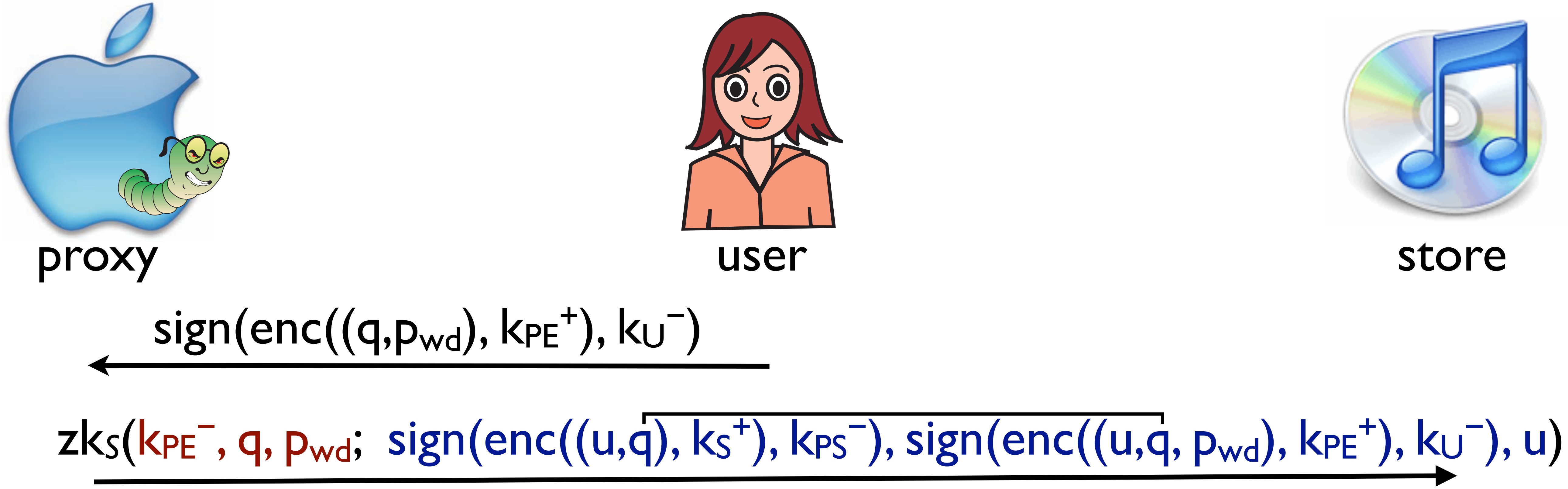


$\mathrm{sign}(\mathrm{enc}((q, p_{wd}), k_{PE}^{+}), k_{U}^{-})$

$\mathrm{zk}_{S}(k_{PE}^{-}, q, p_{wd};\ \mathrm{sign}(\mathrm{enc}((u,\overline{q), k_{S}^{+}), k_{PS}^{-}), \mathrm{sign}(\mathrm{enc}((u,q}, p_{wd}), k_{PE}^{+}), k_{U}^{-}), u)$

- The proxy has to prove that its message is correctly generated from a request he received from the user

Using non-interactive ZK



proxy

user

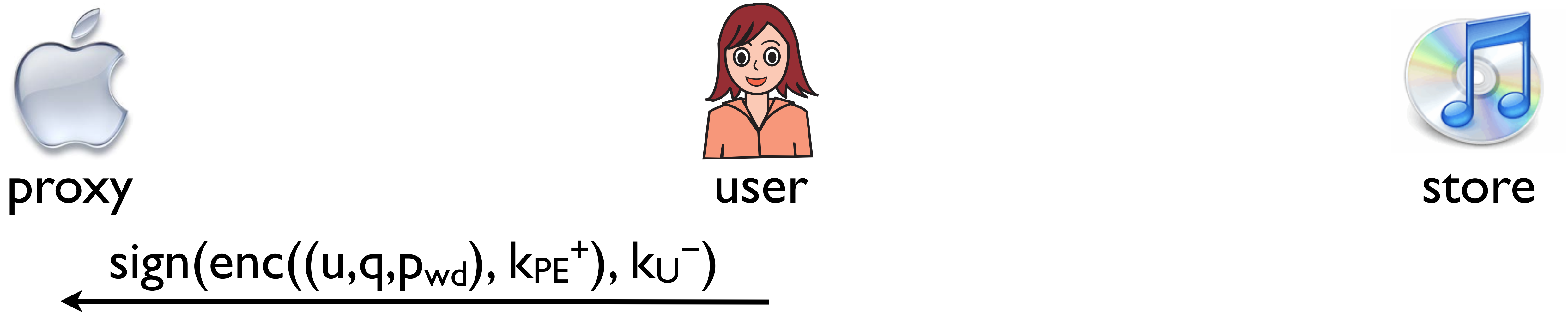
store

$\mathrm{sign}(\mathrm{enc}((q, p_{wd}), k_{PE}^{+}), k_{U}^{-})$

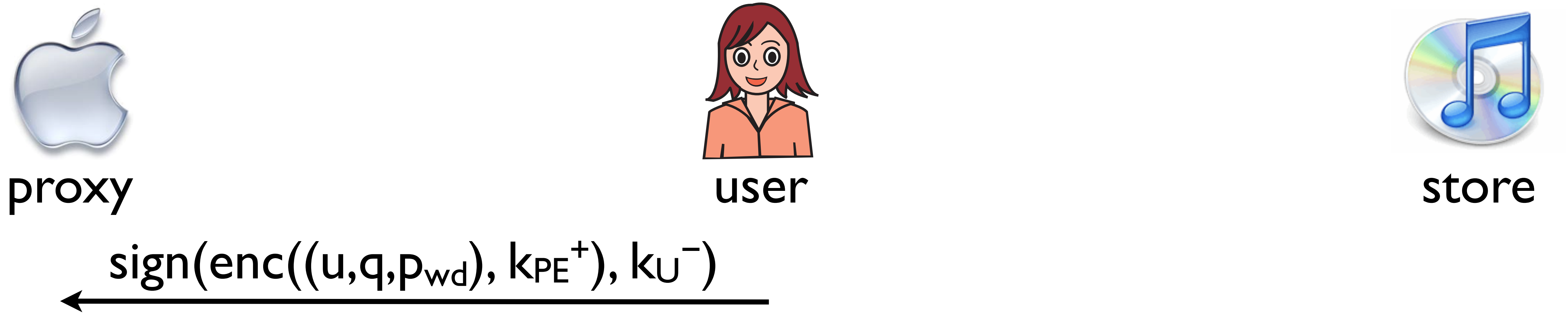
$\mathrm{zk}_{S}(k_{PE}^{-}, q, p_{wd};\ \mathrm{sign}(\mathrm{enc}((u,\overline{q), k_{S}^{+}), k_{PS}^{-}), \mathrm{sign}(\mathrm{enc}((u,q}, p_{wd}), k_{PE}^{+}), k_{U}^{-}), u)$

- The proxy has to prove that its message is correctly generated from a request he received from the user
  - Compromised proxy can no longer cheat

Protocol model and security properties



$\mathrm{sign}(\mathrm{enc}((u,q,p_{wd}), k_{PE}^{+}), k_{U}^{-})$



proxy

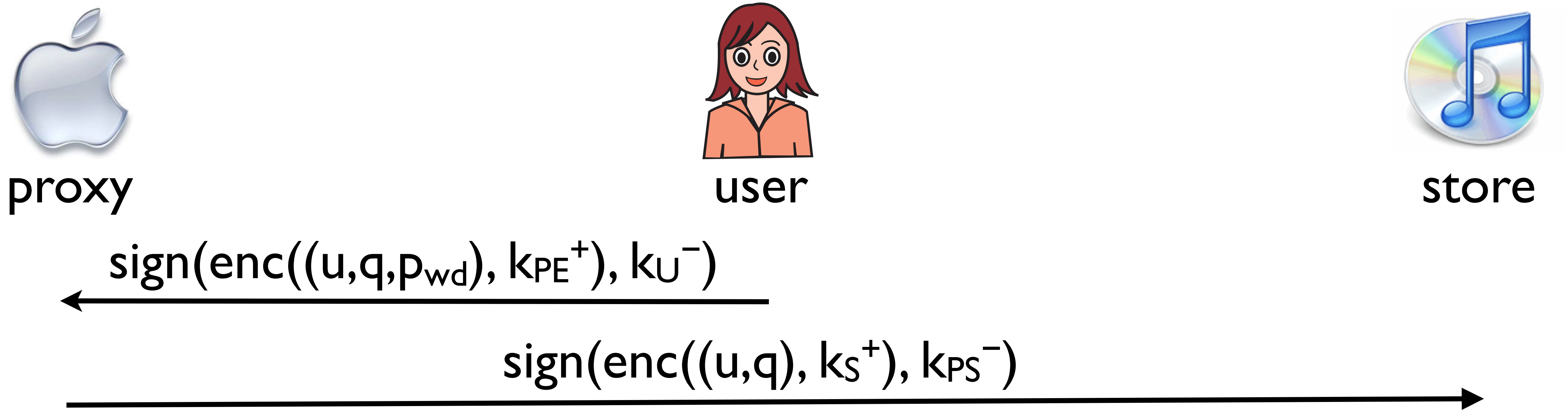
user

store

$\mathrm{sign}(\mathrm{enc}((u,q,p_{wd}), k_{PE}^{+}), k_{U}^{-})$

let user = **new** q;
out(c_1, $\mathrm{sign}(\mathrm{enc}((u,q,p_{wd}), k_{PE}^{+}), k_{U}^{-})$).

let proxy =
in(c_1, x);
let (=u, x_q, =p_{wd}) = $\mathrm{dec}(\mathrm{check}(x, k_{U}^{+}), k_{PE}^{-})$ **in**
...



proxy

user

store

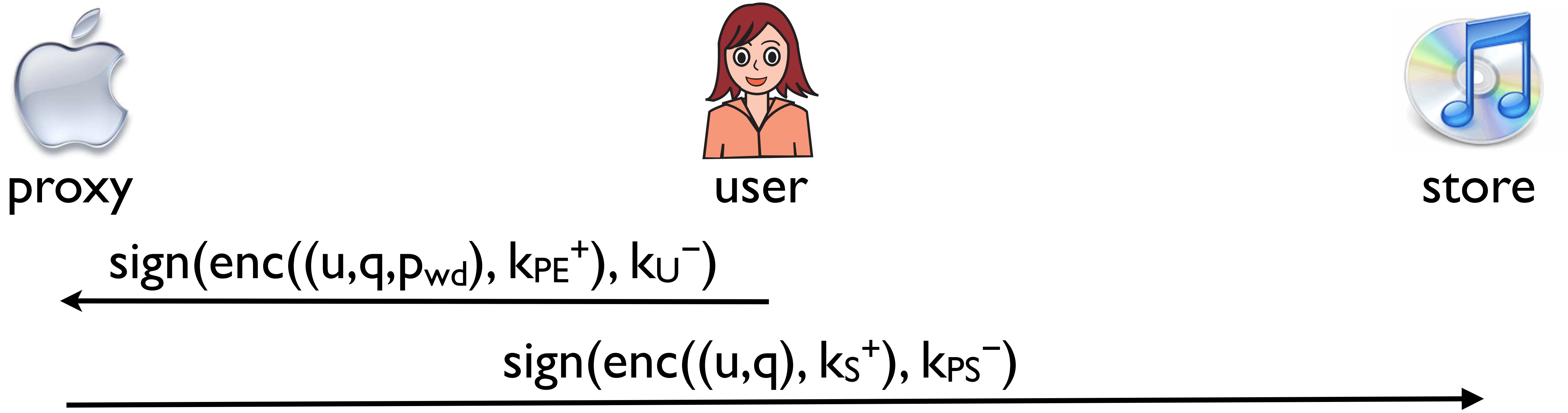
$\mathrm{sign}(\mathrm{enc}((u,q,p_{wd}), k_{PE}^{+}), k_{U}^{-})$

$\mathrm{sign}(\mathrm{enc}((u,q), k_{S}^{+}), k_{PS}^{-})$

```
let user = new q;
           out(c_1, sign(enc((u,q,p_wd), k_PE^+), k_U^-)).

let proxy =
           in(c_1, x);
           let (=u, x_q, =p_wd) = dec(check(x, k_U^+), k_PE^-) in
           out(c_2, sign(enc((u,x_q), k_S^+), k_PS^-)).

let store = in(c_2, z);
           let (x_u,x_q) = dec(check(z, k_PS^+), k_S^-) in
           ...
```



$\mathrm{sign}(\mathrm{enc}((u,q,p_{wd}), k_{PE}^{+}), k_{U}^{-})$

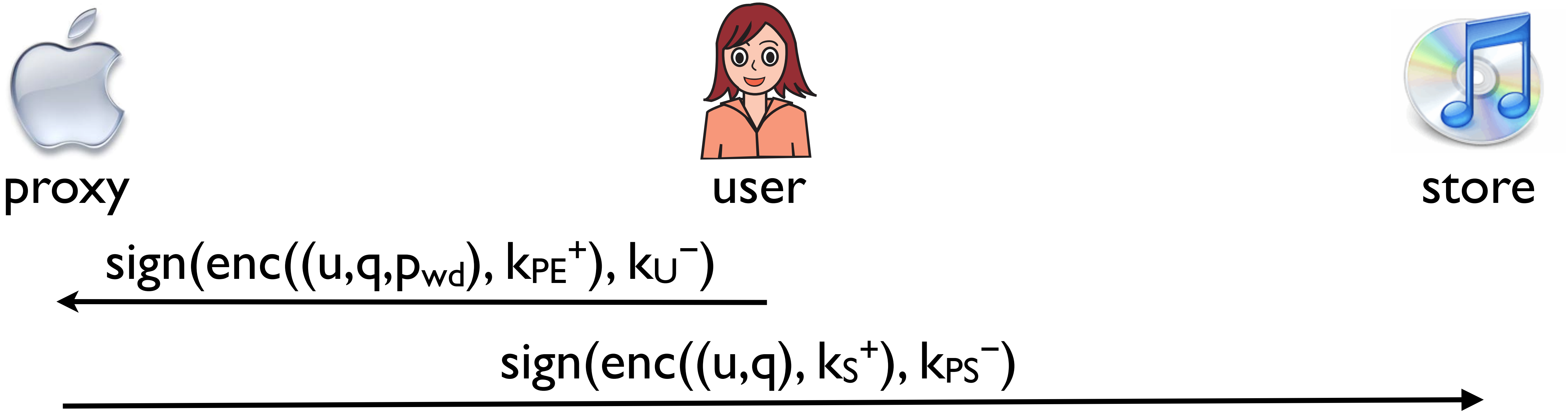
$\mathrm{sign}(\mathrm{enc}((u,q), k_{S}^{+}), k_{PS}^{-})$

let user = **new** q;
    out(c_1, $\mathrm{sign}(\mathrm{enc}((u,q,p_{wd}), k_{PE}^{+}), k_{U}^{-})$).

let proxy =
    in(c_1, x);
    let ($=u, x_q, =p_{wd}$) = $\mathrm{dec}(\mathrm{check}(x, k_{U}^{+}), k_{PE}^{-})$ **in**
    out(c_2, $\mathrm{sign}(\mathrm{enc}((u,x_q), k_{S}^{+}), k_{PS}^{-})$).

let store = **in**(c_2, z);
    let (x_u,x_q) = $\mathrm{dec}(\mathrm{check}(z, k_{PS}^{+}), k_{S}^{-})$ **in**
    …

new k_{U}^{-}, k_{PE}^{-}, k_{PS}^{-}, k_{S}^{-}, p_{wd}; (user | proxy | store)



$sign(enc((u,q,p_{wd}), k_{PE}^{+}), k_{U}^{-})$

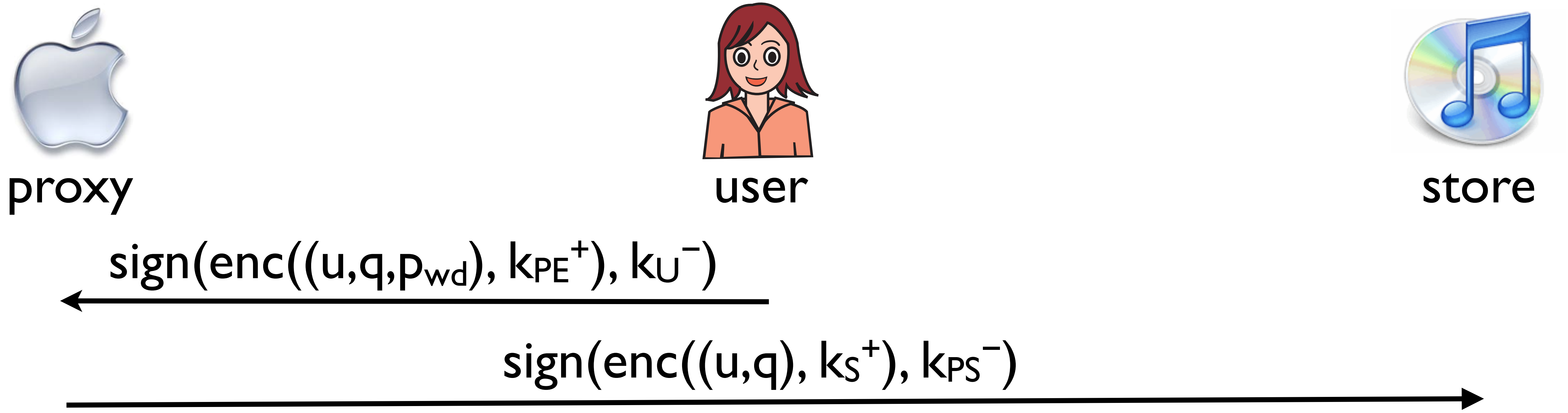
$sign(enc((u,q), k_{S}^{+}), k_{PS}^{-})$

let user = **new** q; **assume** Request(u, q) |
    out(c_1, $sign(enc((u,q,p_{wd}), k_{PE}^{+}), k_{U}^{-})$).

let proxy = **assume** Registered(u) |
    in(c_1, x);
    let (=u, x_q, =p_{wd}) = $dec(check(x, k_{U}^{+}), k_{PE}^{-})$ **in**
    out(c_2, $sign(enc((u,x_q), k_{S}^{+}), k_{PS}^{-})$).

let store = **in**(c_2, z);
    let (x_u,x_q) = $dec(check(z, k_{PS}^{+}), k_{S}^{-})$ **in**
    …

new k_{U}^{-}, k_{PE}^{-}, k_{PS}^{-}, k_{S}^{-}, p_{wd}; (user | proxy | store)



proxy

user

store

$\mathrm{sign}(\mathrm{enc}((u,q,p_{wd}), k_{PE}^{+}), k_{U}^{-})$

$\mathrm{sign}(\mathrm{enc}((u,q), k_{S}^{+}), k_{PS}^{-})$

let user = **new** q; **assume** Request(u, q) |
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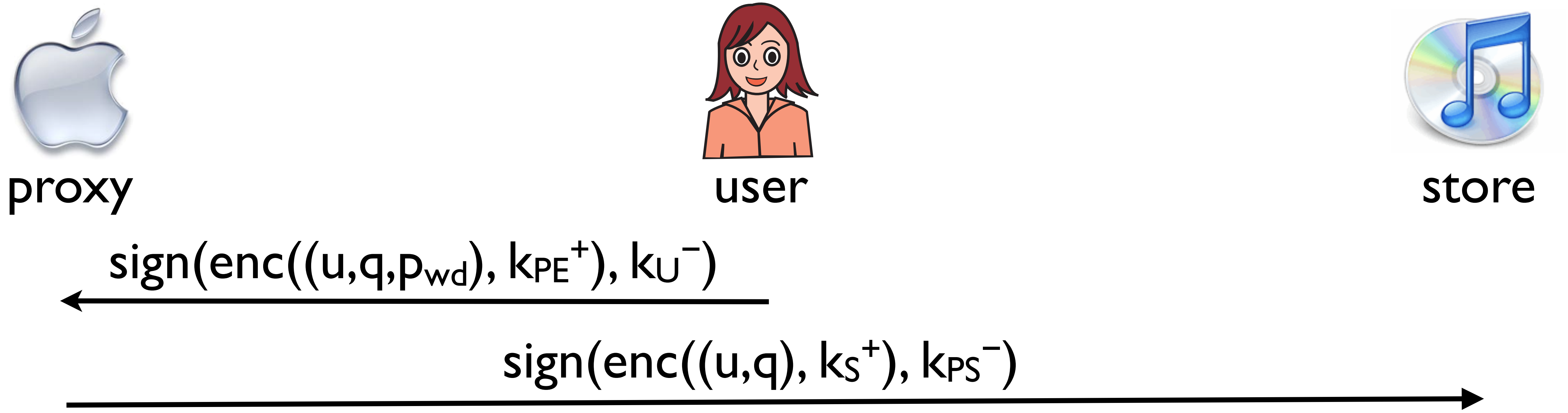
out(c_2, $\mathrm{sign}(\mathrm{enc}((u,x_q), k_{S}^{+}), k_{PS}^{-})$).

let store = **in**(c_2, z);
let (x_u,x_q) = $\mathrm{dec}(\mathrm{check}(z, k_{PS}^{+}), k_{S}^{-})$ **in**
assert Authenticate(x_u,x_q).

new k_{U}^{-}, k_{PE}^{-}, k_{PS}^{-}, k_{S}^{-}, p_{wd}; (user | proxy | store)



let user = **new** q; **assume** Request(u, q) |
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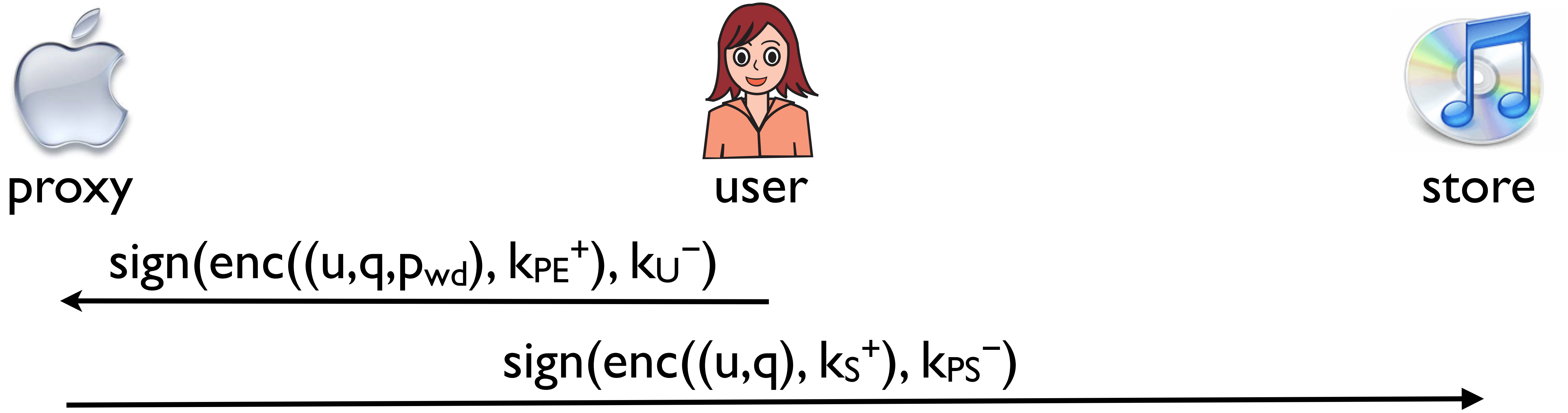
    in(c_1, x);
    let (=u, x_q, =p_{wd}) = dec(check(x, k
    out(c_2, sign(enc((u,x_q), k_S^{+}), k

let store = **in**(c_2, z);
    let (x_u,x_q) = dec(check(z, k_{PS}
    assert Authenticate(x_u,x_q).

assert succeeds only if
Authenticate(x_u,x_q) holds

new k_U^{-}, k_{PE}^{-}, k_{PS}^{-}, k_S^{-}, p_{wd}; (user | proxy | store)



$\mathrm{sign}(\mathrm{enc}((u,q,p_{wd}), k_{PE}^{+}), k_{U}^{-})$

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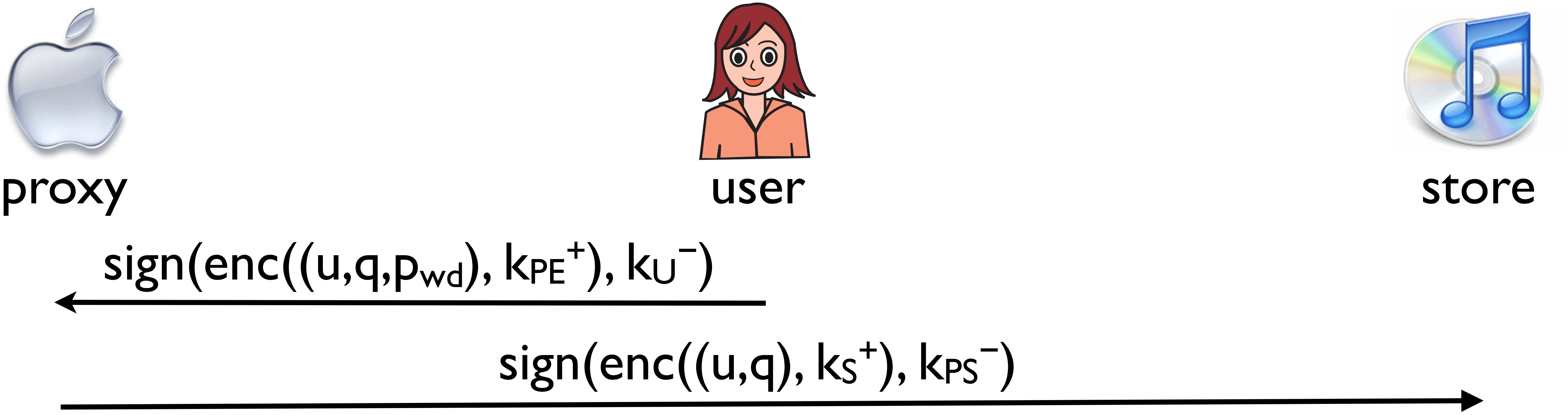
let store = **in**(c_2, z);
let (x_u,x_q) = dec(check(z, k_{PS}^{+}), k_{S}^{-}) **in**
assert Authenticate(x_u,x_q).

formula in some
authorization logic (here FOL)

let policy = **assume** $\forall$ u, q. (Request(u, q) $\wedge$ Registered(u) $\Rightarrow$ Authenticate(u, q))

new k_{U}^{-}, k_{PE}^{-}, k_{PS}^{-}, k_{S}^{-}, p_{wd}; (user | proxy | store | policy)



proxy user store

$\mathrm{sign}(\mathrm{enc}((u,q,p_{wd}), k_{PE}^{+}), k_{U}^{-})$

$\mathrm{sign}(\mathrm{enc}((u,q), k_{S}^{+}), k_{PS}^{-})$

let user = **new** q; **assume** Request(u, q) |
out(c_1, sign(enc((u,q,p_{wd}), k_{PE}^{+}), k_{U}^{-})).

let proxy = **assume** Registered(u) |
in(c_1, x);
let (=u, x_q, =p_{wd}) = dec(check(x, k_{U}^{+}),
out(c_2, sign(enc((u,x_q), k_{S}^{+}), k

let store = **in**(c_2, z);
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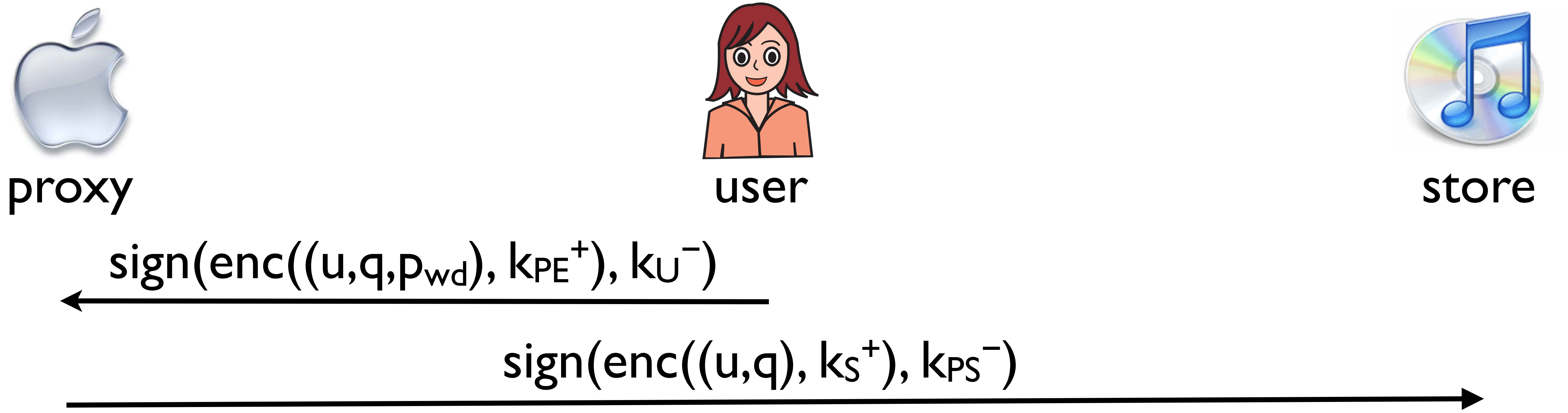
assert succeeds only if
Authenticate(x_u,x_q) holds

let policy = **assume** $\forall$ u, q. (Request(u, q) $\wedge$ Registered(u) $\Rightarrow$ Authenticate(u, q))

new k_{U}^{-}, k_{PE}^{-}, k_{PS}^{-}, k_{S}^{-}, p_{wd}; (user | proxy | store | policy)



proxy   user   store

sign(enc((u,q,p_{wd}), k_{PE}^{+}), k_{U}^{-})

sign(enc((u,q), k_{S}^{+}), k_{PS}^{-})

let user = **new** q; **assume** Request(u, q) |
    out(c_1, sign(enc((u,q,p_{wd}), k_{PE}^{+}), k_{U}^{-})).

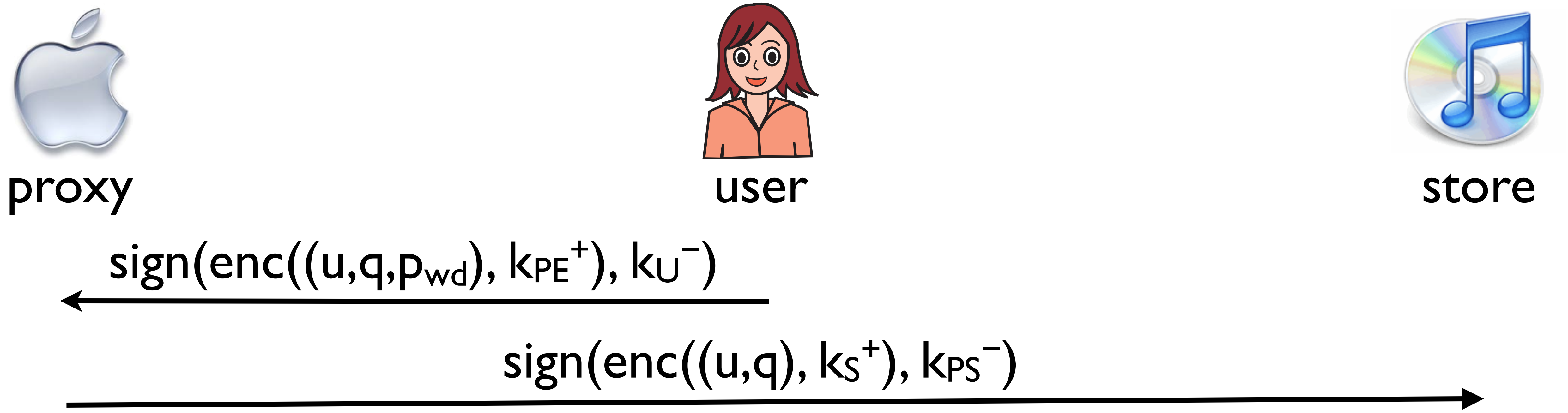
let proxy = **assume** Registered(u) |
    in(c_1, x);
    let (=u, x_q, =p_{wd}) = dec(check(x, k_{U}^{+}), k_{PE}^{-}) **in**
    out(c_2, sign(enc((u,x_q), k_{S}^{+}), k_{PS}^{-})).

let store = **in**(c_2, z);
    let (x_u,x_q) = dec(check(z, k_{PS}^{+}), k_{S}^{-}) **in**
    assert Authenticate(x_u,x_q).

Authenticate(x_u,x_q) holds only if
Request(x_u, x_q) $\wedge$ Registered(x_u) holds
(since Authenticate only appears here)

let policy = **assume** $\forall$ u, q. (Request(u, q) $\wedge$ Registered(u) $\Rightarrow$ Authenticate(u, q))

new k_{U}^{-}, k_{PE}^{-}, k_{PS}^{-}, k_{S}^{-}, p_{wd}; (user | proxy | store | policy)



proxy

user

store

sign(enc((u,q,p_{wd}), k_{PE}^+), k_U^-)

sign(enc((u,q), k_S^+), k_{PS}^-)

let user = **new** q; **assume** Request(u, q) |
out(c_1, sign(enc((u,q,p_{wd}), k_{PE}^+), k_U^-)).

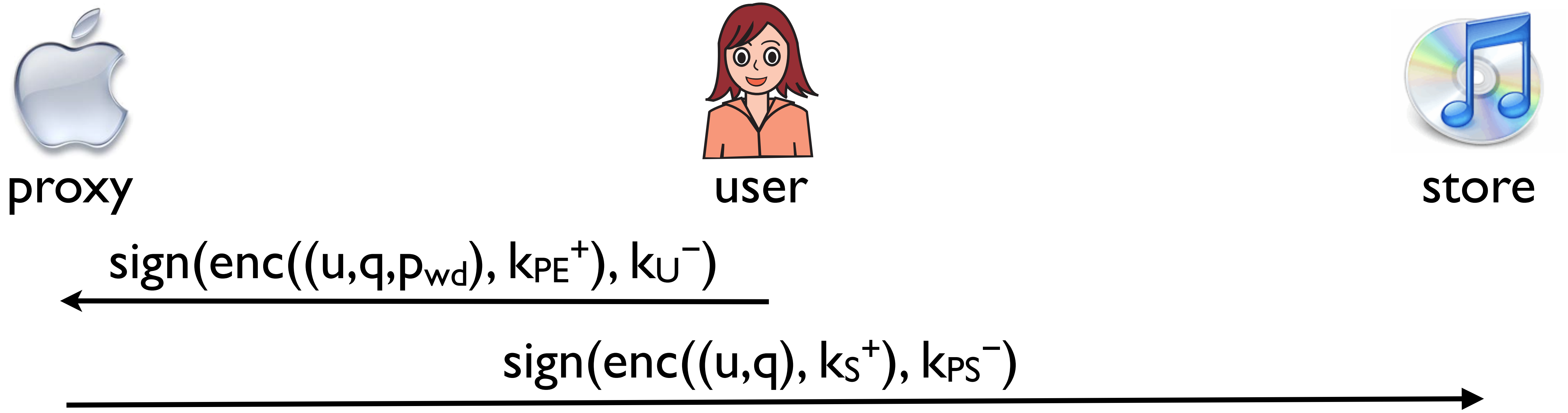
Request(x_u, x_q) holds only if the user has indeed issued a request

let proxy = **assume** Registered(u) |
in(c_1, x);
let (=u, x_q, =p_{wd}) = dec(check(x, k_U^+), k_{PE}^-) **in**
out(c_2, sign(enc((u,x_q), k_S^+), k_{PS}^-)).

let store = **in**(c_2, z);
let (x_u,x_q) = dec(check(z, k_{PS}^+), k_S^-) **in**
assert Authenticate(x_u,x_q).

let policy = **assume** $\forall$ u, q. (Request(u, q) $\wedge$ Registered(u) $\Rightarrow$ Authenticate(u, q))

new k_U^-, k_{PE}^-, k_{PS}^-, k_S^-, p_{wd}; (user | proxy | store | policy)



proxy

user

store

sign(enc((u,q,p_{wd}), k_{PE}^+), k_U^-)

sign(enc((u,q), k_S^+), k_{PS}^-)

let user = **new** q; **assume** Request(u, q) |
out(c_1, sign(enc((u,q,p_{wd}), k_{PE}^+), k_U^-)).

let proxy = **assume** Registered(u) |
in(c_1, x);
let (=u, x_q, =p_{wd}) = dec(check(x, k
out(c_2, sign(enc((u,x_q), k_S^+), k_{PS}

let store = **in**(c_2, z);
let (x_u,x_q) = dec(check(z, k_{PS}^+), k_S
assert Authenticate(x_u,x_q).

This policy enforces that the store authenticates the user only if a registered user has indeed issued a request

let policy = **assume** $\forall$ u, q. (Request(u, q) $\wedge$ Registered(u) $\Rightarrow$ Authenticate(u, q))

new k_U^-, k_{PE}^-, k_{PS}^-, k_S^-, p_{wd}; (user | proxy | store | policy)

Safety and robust safety

- **Safety:** in all executions all asserts succeed (i.e. asserts are logically entailed by the active assumes)

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Safety and robust safety

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- **Robust safety:**
  safety in the presence of <u>arbitrary DY attacker</u>

- If all participants are honest our example protocol is robustly safe (we can show it using the type system)

  - but this is no longer true if the proxy is compromised

Security despite compromise

[Fournet, Gordon & Maffeis, CSF ’07]

- **Informal principle:**

  “An invalid authorization decision [...] should only arise if participants on which the decision logically depends are compromised.”

  “Hence, the impact of partial compromise should be apparent from the policy, without study of the code”

let user = **new** q; **assume** Request(u, q) |
out(c_1, sign(enc((u,q,p_{wd}), k_{PE}^{+}), k_U^{-})).

let proxy = **assume** Registered(u) | …

let store = …

let policy = **assume** $\forall$ u, q. (Request(u, q) $\wedge$ Registered(u) $\Rightarrow$ Authenticate(u, q))

let user = **new** q; **assume** Request(u, q) |
out(c_1, sign(enc((u,q,p_{wd}), k_{PE}^{+}), k_U^{-})).

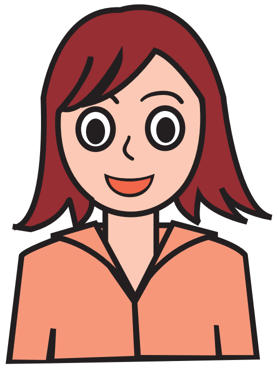
let proxy = **assume** Registered(u) | ...

let store = ...

let policy = **assume** $\forall$ u, q. (Request(u, q) $\wedge$ Registered(u) $\Rightarrow$ Authenticate(u, q)) |
assume Compromised(u) $\Rightarrow$ $\forall$ q. Request(u, q) |
assume Compromised(p) $\Rightarrow$ $\forall$ u. Registered(u)

security
despite compromise

Compromising the user



user

let user = **new** q; **assume** Request(u, q) |
out(c_1, sign(enc((u,q,p_{wd}), k_{PE}^{+}), k_{U}^{-})).

let proxy = **assume** Registered(u) | ...

let store = ...

let policy = **assume** ∀ u, q. (Request(u, q) ∧ Registered(u) ⇒ Authenticate(u, q)) |
assume Compromised(u) ⇒ ∀ q. Request(u, q) |
assume Compromised(p) ⇒ ∀ u. Registered(u)

Compromising the user

user

let user = **new** q; **assume** Request(u, q) |
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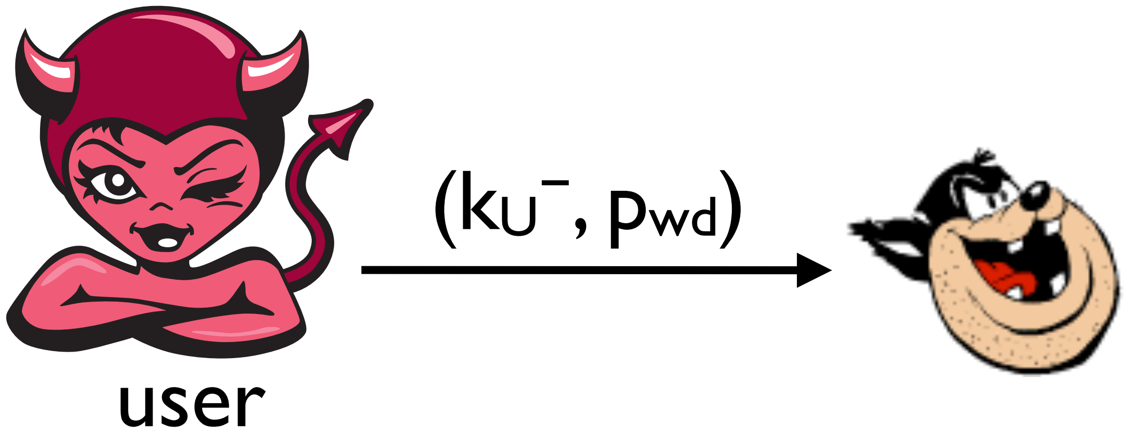
let proxy = **assume** Registered(u) | ...

let store = ...

let policy = **assume** ∀ u, q. (Request(u, q) ∧ Registered(u) ⇒ Authenticate(u, q)) |
assume Compromised(u) ⇒ ∀ q. Request(u, q) |
assume Compromised(p) ⇒ ∀ u. Registered(u)
assume Compromised(u) ∧ ¬Compromised(p) ∧ ¬Compromised(s)

Compromising the user



let bad_user = **out**(c_{pub}, (k_U^-,p_{wd})).

let proxy = **assume** Registered(u) | …

let store = …

let policy = **assume** ∀ u, q. (Request(u, q) ∧ Registered(u) ⇒ Authenticate(u, q)) |
assume Compromised(u) ⇒ ∀ q. Request(u, q) |
assume Compromised(p) ⇒ ∀ u. Registered(u)
assume Compromised(u) ∧ ¬Compromised(p) ∧ ¬Compromised(s)

Compromising the user

user

$(k_U^-, p_{wd}) \longrightarrow$

$\mathrm{sign}(\mathrm{enc}((u,q_{bad}), k_S^+), k_{PS}^-) \longrightarrow$

proxy

store

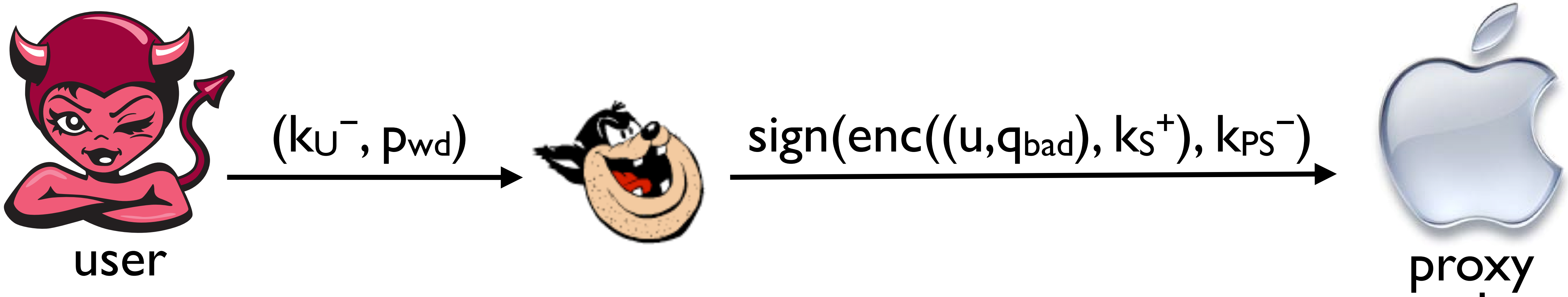
let bad_user = **out**(c_{pub}, (k_U^-,p_{wd})).

let proxy = **assume** Registered(u) | ...

let store = ...

let policy = **assume** ∀ u, q. (Request(u, q) ∧ Registered(u) ⇒ Authenticate(u, q)) |
assume Compromised(u) ⇒ ∀ q. Request(u, q) |
assume Compromised(p) ⇒ ∀ u. Registered(u)
assume Compromised(u) ∧ ¬Compromised(p) ∧ ¬Compromised(s)

Compromising the user



let bad_user = **out**(c_{pub}, (k_U^-,p_{wd})).

let proxy = **assume** Registered(u) | …

let store = **in**(c_2, z);
    let (x_u,x_q) = dec(check(z, k_{PS}^+), k_S^-) **in**
    assert Authenticate(x_u,x_q).

let policy = **assume** $\forall$ u, q. (Request(u, q) $\wedge$ Registered(u) $\Rightarrow$ Authenticate(u, q)) |
    assume Compromised(u) $\Rightarrow$ $\forall$ q. Request(u, q) |
    assume Compromised(p) $\Rightarrow$ $\forall$ u. Registered(u)
    assume Compromised(u) $\wedge$ $\neg$Compromised(p) $\wedge$ $\neg$Compromised(s)

Compromising the user

user

(k_U^-, p_{wd}) →

$\text{sign}(\text{enc}((u,q_{bad}), k_S^+), k_{PS}^-)$ →

proxy

store

let bad_user = **out**(c_{pub}, (k_U^-,p_{wd})).

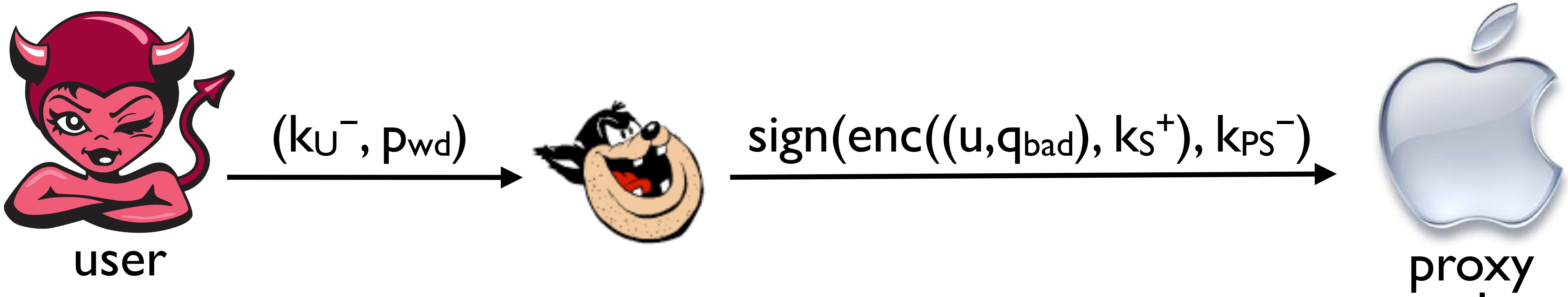
let proxy = **assume** Registered(u) | …

let store = **in**(c_2, z);
    let (x_u,x_q) = dec(check(z, k_{PS}^-), k_S^-) **in**
    assert Authenticate(x_u,x_q).

Authenticate(u, q_{bad}) is entailed since ∀q. Request(u, q)

let policy = **assume** ∀ u, q. (Request(u, q) ∧ Registered(u) ⇒ Authenticate(u, q)) |
    assume Compromised(u) ⇒ ∀ q. Request(u, q) |
    assume Compromised(p) ⇒ ∀ u. Registered(u)
    assume Compromised(u) ∧ ¬Compromised(p) ∧ ¬Compromised(s)

Compromising the user



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assume Compromised(u) ∧ ¬Compromised(p) ∧ ¬Compromised(s)

Compromising the user

user

(k_U^-, p_{wd}) →

$\text{sign}(\text{enc}((u, q_{bad}), k_S^+), k_{PS}^-)$ →

proxy

↓

store

let bad_user = **out**(c_{pub}, (k_U^-, p_{wd})).

let proxy = **assume** Registered(u) | ...

let store = **in**(c_2, z);
let (x_u, x_q) = dec(check(z, k_{PS}^+))
assert Authenticate(x_u, x_q).

assert succeeds, so protocol is secure (robustly safe) despite the user's compromise

let policy = **assume** ∀ u, q. (~~Request(u, q) ∧~~ Registered(u) ⇒ Authenticate(u, q)) |
assume Compromised(u) ⇒ ∀ q. Request(u, q) |
assume Compromised(p) ⇒ ∀ u. Registered(u)
assume Compromised(u) ∧ ¬Compromised(p) ∧ ¬Compromised(s)

Compromising the proxy

```
**let** user = …

**let** proxy = **assume** Registered(u) |
            **in**($c_1$, x);
            **let** (=u, $x_q$, =$p_{wd}$) = dec(check(x, $k_U^+$), $k_{PE}^-$) **in**
            **out**($c_2$, sign(enc((u,$x_q$), $k_S^+$), $k_{PS}^-$)).
**let** store = …


**let** policy = **assume** $\forall$ u, q. (Request(u, q) $\wedge$ Registered(u) $\Rightarrow$ Authenticate(u, q)) |
                 **assume** Compromised(u) $\Rightarrow$ $\forall$ q. Request(u, q) |
                 **assume** Compromised(p) $\Rightarrow$ $\forall$ u. Registered(u)
```

Compromising the proxy

proxy

let user = ...

let proxy = **assume** Registered(u) |
in(c_1, x);
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out(c_2, sign(enc((u,x_q), k_S^+), k_{PS}^-)).

let store = ...

let policy = **assume** $\forall$ u, q. (Request(u, q) $\wedge$ Registered(u) $\Rightarrow$ Authenticate(u, q)) |

assume Compromised(u) $\Rightarrow$ $\forall$ q. Request(u, q) |

assume Compromised(p) $\Rightarrow$ $\forall$ u. Registered(u)

assume $\neg$Compromised(u) $\wedge$ Compromised(p) $\wedge$ $\neg$Compromised(s)

Compromising the proxy

proxy

let user = …

let proxy = **assume** Registered(u) |
    in(c_1, x);
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    out(c_2, sign(enc((u,x_q), k_S^+), k_{PS}^-)).

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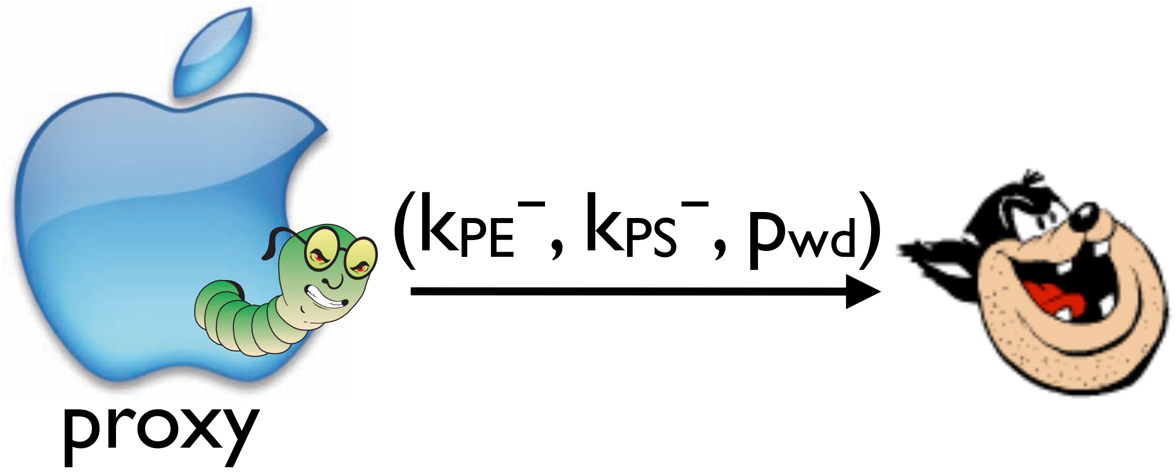
Compromising the proxy



let user = ...

let bad_proxy = **out**(c_{pub}, (k_{PE}^-, k_{PS}^-, p_{wd})).

let store = ...

let policy = **assume** ∀ u, q. (Request(u, q) ~~∧ Registered(u)~~ ⇒ Authenticate(u, q)) |
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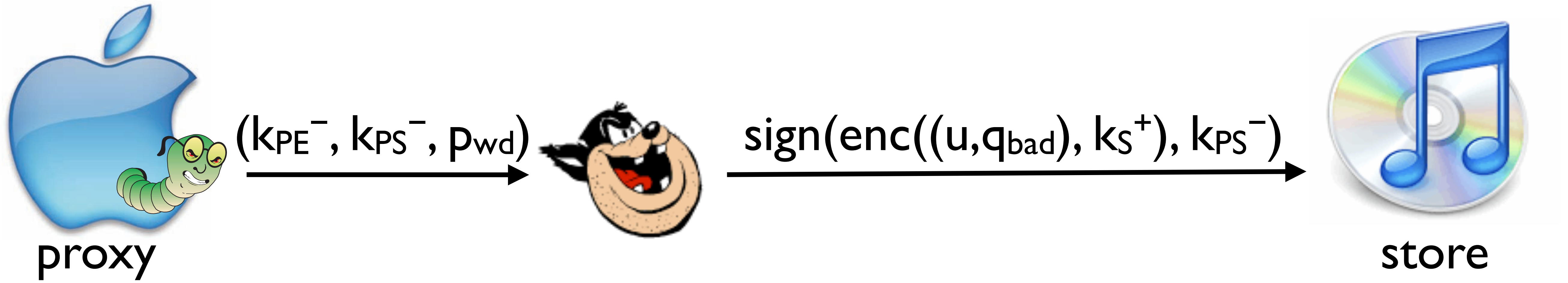
Compromising the proxy



(k_{PE}^-, k_{PS}^-, p_{wd})

sign(enc((u,q_{bad}), k_S^+), k_{PS}^-)

proxy

store

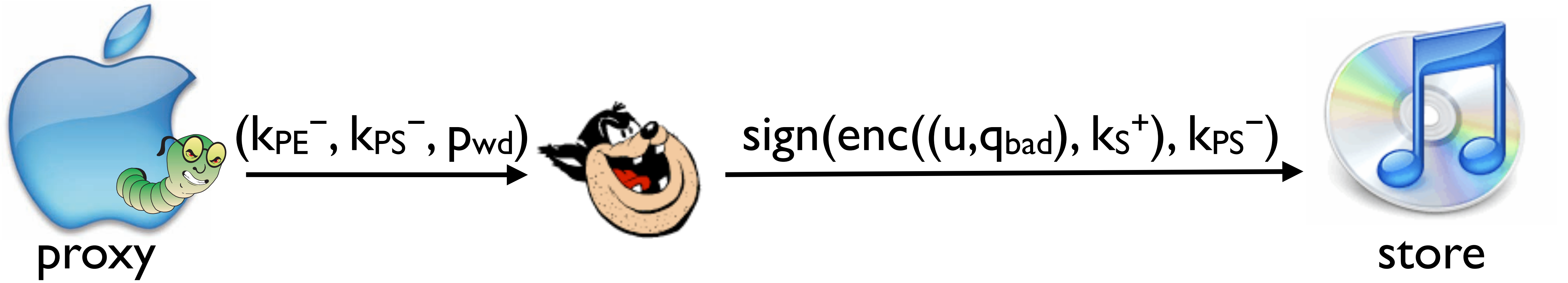
let user = ...

let bad_proxy = **out**(c_{pub}, (k_{PE}^-, k_{PS}^-, p_{wd})).

let store = ...

let policy = **assume** ∀ u, q. (Request(u, q) ~~∧ Registered(u)~~ ⇒ Authenticate(u, q)) |
assume Compromised(u) ⇒ ∀ q. Request(u, q) |
assume Compromised(p) ⇒ ∀ u. Registered(u)
assume ¬Compromised(u) ∧ Compromised(p) ∧ ¬Compromised(s)

Compromising the proxy



$(k_{PE}^{-}, k_{PS}^{-}, p_{wd})$

$\mathrm{sign}(\mathrm{enc}((u,q_{bad}), k_S^{+}), k_{PS}^{-})$

proxy

store

let user = ...

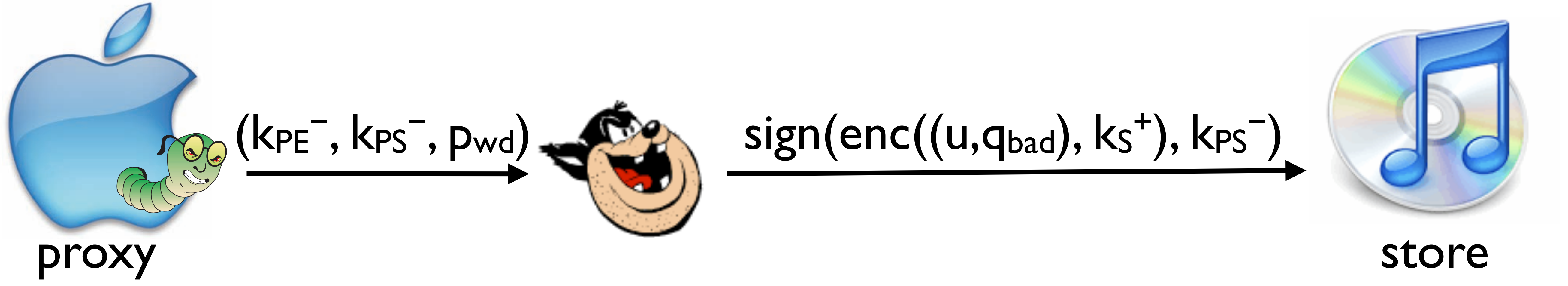
let bad_proxy = **out**(c_{pub}, (k_{PE}^{-}, k_{PS}^{-}, p_{wd})).

let store = **in**(c_2, z);
    let (x_u,x_q) = dec(check(z, k_{PS}^{+}), k_S^{-}) **in**
    assert Authenticate(x_u,x_q).

let policy = **assume** ∀ u, q. (Request(u, q) ~~∧ Registered(u)~~ ⇒ Authenticate(u, q)) |
    assume Compromised(u) ⇒ ∀ q. Request(u, q) |
    assume Compromised(p) ⇒ ∀ u. Registered(u)

assume ¬Compromised(u) ∧ Compromised(p) ∧ ¬Compromised(s)

Compromising the proxy



let user = ...

let bad_proxy = **out**(c_{pub}, (k_{PE}^-, k_{PS}^-, p_{wd})).

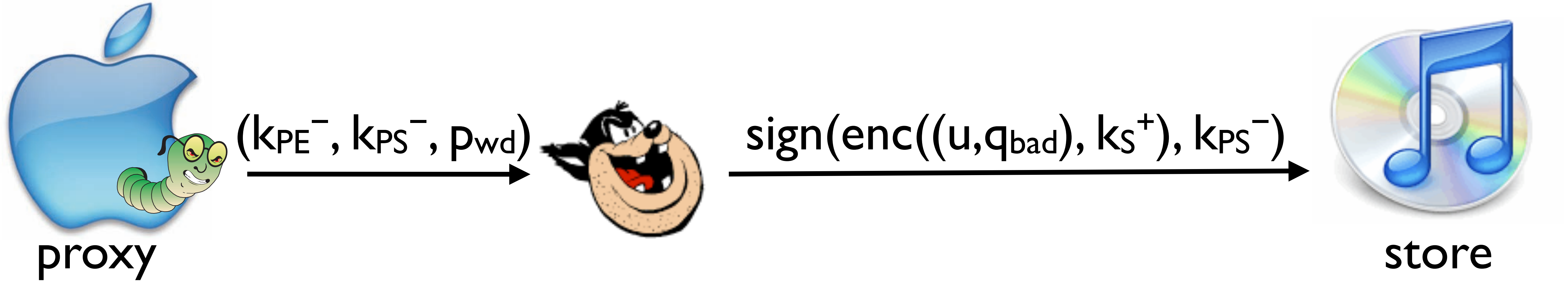
let store = **in**(c_2, z);
let (x_u,x_q) = dec(check(z, k_{PS}^+));
assert Authenticate(x_u,x_q).

Authenticate(u, q_{bad}) is not entailed since user never requested anything

let policy = **assume** ∀ u, q. (Request(u, q) ~~∧ Registered(u)~~ ⇒ Authenticate(u, q)) |
assume Compromised(u) ⇒ ∀ q. Request(u, q) |
assume Compromised(p) ⇒ ∀ u. Registered(u)

assume ¬Compromised(u) ∧ Compromised(p) ∧ ¬Compromised(s)

Compromising the proxy



$(k_{PE}^{-}, k_{PS}^{-}, p_{wd})$

sign(enc((u,q_{bad}), k_S^{+}), k_{PS}^{-})

proxy

store

let user = ...

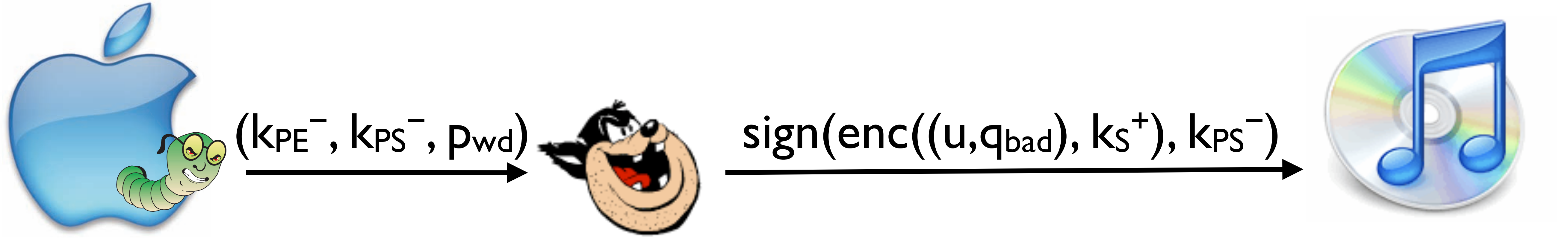
let bad_proxy = **out**(c_{pub}, $(k_{PE}^{-}, k_{PS}^{-}, p_{wd})$).

assert fails, so protocol is not secure (robustly safe) if the proxy is compromised

let store = **in**(c_2, z);
    let (x_u,x_q) = dec(check(z, k_{PS}^{+}
    assert Authenticate(x_u,x_q).

let policy = **assume** ∀ u, q. (Request(u, q) ~~∧ Registered(u)~~ ⇒ Authenticate(u, q)) |
    assume Compromised(u) ⇒ ∀ q. Request(u, q) |
    assume Compromised(p) ⇒ ∀ u. Registered(u)
    assume ¬Compromised(u) ∧ Compromised(p) ∧ ¬Compromised(s)

Compromising the proxy



$(k_{PE}^-, k_{PS}^-, p_{wd})$

sign(enc((u,q_{bad}), k_S^+), k_{PS}^-)

proxy

store

let user = ...

let bad_proxy = **out**(c_{pub}, (k_{PE}^-, k_{PS}^-, p_{wd})).

Our transformation fixes this

assert fails, so protocol is not secure (robustly safe) if the proxy is compromised

let store = **in**(c_2, z);
let (x_u,x_q) = dec(check(z, k_{PS}^+
assert Authenticate(x_u,x_q).

let policy = **assume** ∀ u, q. (Request(u, q) ~~∧ Registered(u)~~ ⇒ Authenticate(u, q)) |
assume Compromised(u) ⇒ ∀ q. Request(u, q) |
assume Compromised(p) ⇒ ∀ u. Registered(u)

assume ¬Compromised(u) ∧ Compromised(p) ∧ ¬Compromised(s)

Transformation
(on the example)

Transformation

1. **Static analysis**
2. **Process translation**

Transformation

1. **Static analysis**
2. **Process translation**

let user = …

let proxy = **assume** Registered(u) |
in(c_1, x);
let (=u, x_q, =p_{wd}) = dec(check(x, k_U^{+}), k_{PE}^{-}) **in**
out(c_2, sign(enc((u,x_q), k_S^{+}), k_{PS}^{-})).

let store = …

let policy = …

new k_U^{-}, k_{PE}^{-}, k_{PS}^{-}, k_S^{-}, p_{wd}; (user | proxy | store | policy)

Transformation

1. **Static analysis**
2. **Process translation**

public values: c_1, c_2, u, z, k_{PS}^+, k_S^+, k_U^+

secret values: x_q, k_{PE}^-, k_{PS}^-

let user = ...

let proxy = **assume** Registered(u) |
    in(c_1, x);
    let (=u, x_q, =p_{wd}) = dec(check(x, k_U^+), k_{PE}^-) **in**
    out(c_2, sign(enc((u,x_q), k_S^+), k_{PS}^-)).

let store = ...

let policy = ...

new k_U^-, k_{PE}^-, k_{PS}^-, k_S^-, p_{wd}; (user | proxy | store | policy)

Transformation

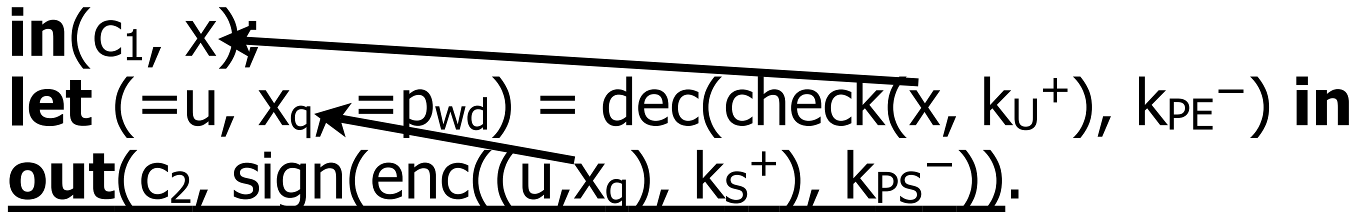
1. **Static analysis**
2. **Process translation**

public values: c_1, c_2, u, z, k_{PS}^+, k_S^+, k_U^+

secret values: x_q, k_{PE}^-, k_{PS}^-

output-input data dependency:

let user = …



let proxy = **assume** Registered(u) |
  in(c_1, x);
  let (=u, x_q, =p_{wd}) = dec(check(x, k_U^+), k_{PE}^-) **in**
  out(c_2, sign(enc((u,x_q), k_S^+), k_{PS}^-)).

let store = …

let policy = …

new k_U^-, k_{PE}^-, k_{PS}^-, k_S^-, p_{wd}; (user | proxy | store | policy)

Transformation

1. **Static analysis**
2. **Process translation**

public values: $c_1, c_2, u, z, k_{PS}^+, k_S^+, k_U^+$

secret values: x_q, k_{PE}^-, k_{PS}^-

output-input data dependency:
$dec(check(x, k_U^+), k_{PE}^-) = (u, x_q, p_{wd})$

let user = ...

let proxy = **assume** Registered(u) |
    in(c_1, x);
    let (=u, x_q, =p_{wd}) = dec(check(x, k_U^+), k_{PE}^-) **in**
    out(c_2, sign(enc((u,x_q), k_S^+), k_{PS}^-)).

let store = ...

let policy = ...

new k_U^-, k_{PE}^-, k_{PS}^-, k_S^-, p_{wd}; (user | proxy | store | policy)

Transformation

1. **Static analysis**
2. **Process translation**
   (incl. zk statement generation)

public values: $c_1, c_2, u, z, k_{PS}^{+}, k_S^{+}, k_U^{+}$

secret values: $x_q, k_{PE}^{-}, k_{PS}^{-}$

output-input data dependency:
$dec(check(x, k_U^{+}), k_{PE}^{-}) = (u, x_q, p_{wd})$

let user = ...

let proxy′= **assume** Registered(u) |
    in(c_1, x);
    let (=u, x_q, =p_{wd}) = dec(check(x, k_U^{+}), k_{PE}^{-}) **in**
    out(c_2, sign(enc((u,x_q), k_S^{+}), k_{PS}^{-})).

let store = ...

let policy = ...

new k_U^{-}, k_{PE}^{-}, k_{PS}^{-}, k_S^{-}, p_{wd}; (user | proxy′| store | policy)

Transformation

1. **Static analysis**
2. **Process translation**
   (incl. zk statement generation)

public values: c_1, c_2, u, z, k_{PS}^+, k_S^+, k_U^+

secret values: x_q, k_{PE}^-, k_{PS}^-

output-input data dependency:
$dec(check(x, k_U^+), k_{PE}^-) = (u, x_q, p_{wd})$

let user = ...

let proxy′= **assume** Registered(u) |
  in(c_1, x);
  let (=u, x_q, =p_{wd}) = dec(check(x, k_U^+), k_{PE}^-) **in**
  out(c_2, zk_S(, , ; sign(enc((u,x_q), k_S^+), k_{PS}^-), x,).

let store = ...

let policy = ...

new k_U^-, k_{PE}^-, k_{PS}^-, k_S^-, p_{wd}; (user | proxy′| store | policy)

Transformation

1. **Static analysis**
2. **Process translation**
   (incl. zk statement generation)

public values: c_1, c_2, u, z, k_{PS}^+, k_S^+, k_U^+

secret values: x_q, k_{PE}^-, k_{PS}^-

output-input data dependency:
dec(check(x, k_U^+), k_{PE}^-) = (u, x_q, p_{wd})

stmt *S* = true

let user = ...

let proxy′= **assume** Registered(u) |
    in(c_1, x);
    let (=u, x_q, =p_{wd}) = dec(check(x, k_U^+), k_{PE}^-) **in**
    out(c_2, zk$_S$(,   ,   ; sign(enc((u,x_q), k_S^+), k_{PS}^-), x,   ).

let store = ...

let policy = ...

new k_U^-, k_{PE}^-, k_{PS}^-, k_S^-, p_{wd}; (user | proxy′| store | policy)

Transformation

1. **Static analysis**
2. **Process translation**
   (incl. zk statement generation)

public values: c_1, c_2, u, z, k_{PS}^+, k_S^+, k_U^+

secret values: x_q, k_{PE}^-, k_{PS}^-

output-input data dependency:
$\mathrm{dec}(\mathrm{check}(x, k_U^+), k_{PE}^-) = (u, x_q, p_{wd})$

stmt *S* = true

let user = ...

let proxy′= **assume** Registered(u) |
in(c_1, x);
let (=u, x_q, =p_{wd}) = dec(check(x, k_U^+), k_{PE}^-) **in**
out(c_2, zk_S(,   ,   ; $\underline{\mathrm{sign}(\mathrm{enc}((u,x_q), k_S^+), k_{PS}^-)}$, x,   ).

let store = ...

let policy = ...

new k_U^-, k_{PE}^-, k_{PS}^-, k_S^-, p_{wd}; (user | proxy′| store | policy)

Transformation

1. **Static analysis**
2. **Process translation**
   (incl. zk statement generation)

public values: $c_1, c_2, u, z, k_{PS}^+, k_S^+, k_U^+$

secret values: x_q, k_{PE}^-, k_{PS}^-

output-input data dependency:
$dec(check(x, k_U^+), k_{PE}^-) = (u, x_q, p_{wd})$

stmt S = $check(\beta_1, k_{PS}^+) = enc((\beta_3, \alpha_2), k_S^+)$

let user = ...

let proxy′= **assume** Registered(u) |
    in(c_1, x);
    let (=u, x_q, =p_{wd}) = $dec(check(x, k_U^+), k_{PE}^-)$ **in**
    out(c_2, $zk_S($ $\quad , \quad , \quad ;$ $\underline{sign(enc((u,x_q), k_S^+), k_{PS}^-)}$, x, $\quad$).

let store = ...

let policy = ...

new $k_U^-, k_{PE}^-, k_{PS}^-, k_S^-, p_{wd}$; (user | proxy′| store | policy)

Transformation

1. **Static analysis**
2. **Process translation**
   (incl. zk statement generation)

public values: c_1, c_2, u, z, k_{PS}^+, k_S^+, k_U^+

secret values: x_q, k_{PE}^-, k_{PS}^-

output-input data dependency:
$dec(check(x, k_U^+), k_{PE}^-) = (u, x_q, p_{wd})$

stmt *S* = $check(\beta_1,k_{PS}^+) = enc((\beta_3,\alpha_2), k_S^+)$

let user = ...

let proxy′= **assume** Registered(u) |
  in(c_1, x);
  let (=u, x_q, =p_{wd}) = dec(check(x, k_U^+), k_{PE}^-) **in**
  out(c_2, zk_S(,   ,   ; $\underline{sign(enc((u,x_q), k_S^+), k_{PS}^-)}$, x,   ).

let store = ...

let policy = ...

new k_U^-, k_{PE}^-, k_{PS}^-, k_S^-, p_{wd}; (user | proxy′| store | policy)

Transformation

1. **Static analysis**
2. **Process translation**
   (incl. zk statement generation)

public values: c_1, c_2, u, z, k_{PS}^+, k_S^+, k_U^+

secret values: x_q, k_{PE}^-, k_{PS}^-

output-input data dependency:
$dec(check(x, k_U^+), k_{PE}^-) = (u, x_q, p_{wd})$

stmt S = $check(\beta_1,k_{PS}^+) = enc((\beta_3,\alpha_2), k_S^+)$

let user = ...

let proxy′= **assume** Registered(u) |
    in(c_1, x);
    let (=u, x_q, =p_{wd}) = $dec(check(x, k_U^+), k_{PE}^-)$ **in**
    out(c_2, $zk_S($, , ; $\underline{sign(enc((u,x_q), k_S^+), k_{PS}^-)}$, x, u).

let store = ...

let policy = ...

new k_U^-, k_{PE}^-, k_{PS}^-, k_S^-, p_{wd}; (user | proxy′| store | policy)

Transformation

1. **Static analysis**
2. **Process translation**
   (incl. zk statement generation)

public values: c_1, c_2, u, z, k_{PS}^+, k_S^+, k_U^+

secret values: x_q, k_{PE}^-, k_{PS}^-

output-input data dependency:
$dec(check(x, k_U^+), k_{PE}^-) = (u, x_q, p_{wd})$

stmt S = $check(\beta_1, k_{PS}^+) = enc((\beta_3, \alpha_2), k_S^+)$

let user = ...

let proxy′= **assume** Registered(u) |
  in(c_1, x);
  let (=u, x_q, =p_{wd}) = dec(check(x, k_U^+), k_{PE}^-) **in**
  out(c_2, $zk_S($, x_q, ; $\underline{sign(enc((u,x_q), k_S^+), k_{PS}^-)}$, x, u).

let store = ...

let policy = ...

new k_U^-, k_{PE}^-, k_{PS}^-, k_S^-, p_{wd}; (user | proxy′| store | policy)

Transformation

1. **Static analysis**
2. **Process translation**
   (incl. zk statement generation)

public values: c_1, c_2, u, z, k_{PS}^+, k_S^+, k_U^+

secret values: x_q, k_{PE}^-, k_{PS}^-

output-input data dependency:
$\mathrm{dec}(\mathrm{check}(x, k_U^+), k_{PE}^-) = (u, x_q, p_{wd})$

stmt $S = \mathrm{check}(\beta_1, k_{PS}^+) = \mathrm{enc}((\beta_3, \alpha_2), k_S^+)$

let user = ...

let proxy′= **assume** Registered(u) |
in(c_1, x);
let $(=u, x_q, =p_{wd}) = \mathrm{dec}(\mathrm{check}(x, k_U^+), k_{PE}^-)$ **in**
out(c_2, $zk_S($, x_q, ; $\mathrm{sign}(\mathrm{enc}((u,x_q), k_S^+), k_{PS}^-)$, $\underline{x,}$ u).

let store = ...

let policy = ...

new k_U^-, k_{PE}^-, k_{PS}^-, k_S^-, p_{wd}; (user | proxy′| store | policy)

Transformation

1. **Static analysis**
2. **Process translation**
   (incl. zk statement generation)

public values: $c_1, c_2, u, z, k_{PS}^+, k_S^+, k_U^+$

secret values: x_q, k_{PE}^-, k_{PS}^-

output-input data dependency:
$\underline{\mathrm{dec}(\mathrm{check}(x, k_U^+), k_{PE}^-) = (u, x_q, p_{wd})}$

stmt S = $\mathrm{check}(\beta_1, k_{PS}^+) = \mathrm{enc}((\beta_3, \alpha_2), k_S^+)$

let user = ...

let proxy′= **assume** Registered(u) |
    in(c_1, x);
    let (=u, x_q, =p_{wd}) = dec(check(x, k_U^+), k_{PE}^-) **in**
    out(c_2, zk_S(, x_q,   ; sign(enc((u,x_q), k_S^+), k_{PS}^-)$\underline{, x,}$ u).

let store = ...

let policy = ...

new k_U^-, k_{PE}^-, k_{PS}^-, k_S^-, p_{wd}; (user | proxy′| store | policy)

Transformation

1. **Static analysis**
2. **Process translation**
   (incl. zk statement generation)

public values: $c_1, c_2, u, z, k_{PS}^+, k_S^+, k_U^+$

secret values: x_q, k_{PE}^-, k_{PS}^-

output-input data dependency:
$\underline{dec(check(x, k_U^+), k_{PE}^-) = (u, x_q, p_{wd})}$

stmt $S = check(\beta_1, k_{PS}^+) = enc((\beta_3, \alpha_2), k_S^+) \wedge dec(check(\beta_2, k_U^+), \alpha_1) = (\beta_3, \alpha_2, \alpha_3)$

let user = ...

let proxy′= **assume** Registered(u) |
    in(c_1, x);
    let $(=u, x_q, =p_{wd}) = dec(check(x, k_U^+), k_{PE}^-)$ **in**
    out(c_2, $zk_S(\quad\quad, x_q, \quad\quad; sign(enc((u, x_q), k_S^+), k_{PS}^-), \underline{x,}\ u)$.

let store = ...

let policy = ...

new $k_U^-, k_{PE}^-, k_{PS}^-, k_S^-, p_{wd}$; (user | proxy′| store | policy)

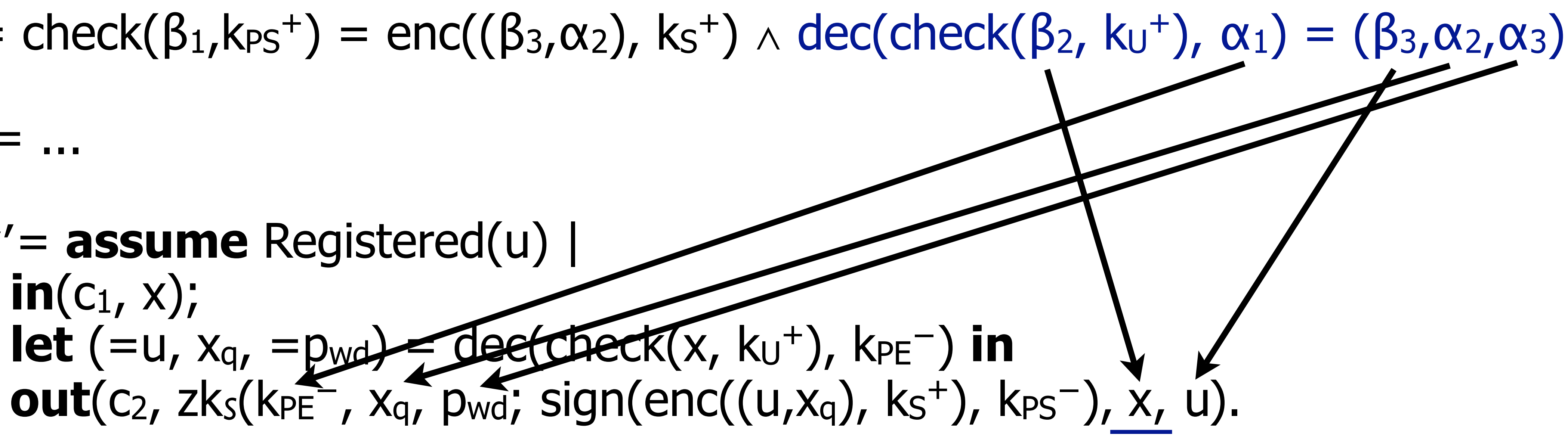
Transformation

1. **Static analysis**
2. **Process translation**
   (incl. zk statement generation)

public values: $c_1, c_2, u, z, k_{PS}^+, k_S^+, k_U^+$

secret values: x_q, k_{PE}^-, k_{PS}^-

output-input data dependency:
$\underline{\text{dec}(\text{check}(x, k_U^+), k_{PE}^-) = (u, x_q, p_{wd})}$



stmt $S = \text{check}(\beta_1, k_{PS}^+) = \text{enc}((\beta_3, \alpha_2), k_S^+) \wedge \text{dec}(\text{check}(\beta_2, k_U^+), \alpha_1) = (\beta_3, \alpha_2, \alpha_3)$

let user = ...

let proxy′= **assume** Registered(u) |
in(c_1, x);
let (=u, x_q, =p_{wd}) = dec(check(x, k_U^+), k_{PE}^-) **in**
out(c_2, $zk_S(k_{PE}^-, x_q, p_{wd}; \text{sign}(\text{enc}((u,x_q), k_S^+), k_{PS}^-), \underline{x,}\ u)$.

let store = ...

let policy = ...

new $k_U^-, k_{PE}^-, k_{PS}^-, k_S^-, p_{wd}$; (user | proxy′| store | policy)

Transformation

1. **Static analysis**
2. **Process translation**
   (incl. zk statement generation)

public values: $c_1, c_2, u, z, k_{PS}^+, k_S^+, k_U^+$

secret values: x_q, k_{PE}^-, k_{PS}^-

output-input data dependency:
$\underline{\mathrm{dec}(\mathrm{check}(x, k_U^+), k_{PE}^-) = (u, x_q, p_{wd})}$

stmt S = check(β_1,k_{PS}^+) = enc((β_3,α_2), k_S^+) $\wedge$ dec(check(β_2, k_U^+), α_1) = (β_3,α_2,α_3)

Asymmetry caused by k_S^+ being unknown to the proxy

let user = ...

let proxy′= **assume** Registered(u) |
    in(c_1, x);
    let (=u, x_q, =p_{wd}) = dec(check(x, k_U^+), k_{PE}^-) **in**
    out(c_2, zk_S(k_{PE}^-, x_q, p_{wd}; sign(enc((u,x_q), k_S^+), k_{PS}^-), $\underline{x,}$ u).

let store = ...

let policy = ...

new k_U^-, k_{PE}^-, k_{PS}^-, k_S^-, p_{wd}; (user | proxy′| store | policy)

Transformation

1. **Static analysis**
2. **Process translation**
   (incl. zk statement generation)

public values: $c_1, c_2, u, z, k_{PS}^+, k_S^+, k_U^+$

secret values: x_q, k_{PE}^-, k_{PS}^-

output-input data dependency:
$dec(check(x, k_U^+), k_{PE}^-) = (u, x_q, p_{wd})$

stmt $S = check(\beta_1, k_{PS}^+) = enc((\beta_3, \alpha_2), k_S^+) \wedge dec(check(\beta_2, k_U^+), \alpha_1) = (\beta_3, \alpha_2, \alpha_3)$

let user = ...

let proxy′= **assume** Registered(u) |
    in(c_1, x);
    let $(=u, x_q, =p_{wd}) = dec(check(x, k_U^+), k_{PE}^-)$ **in**
    out(c_2, $zk_S(k_{PE}^-, x_q, p_{wd}; sign(enc((u,x_q), k_S^+), k_{PS}^-), x, u)$).

let store′= **in**(c_2, z);

    let $(x_u, x_q) = dec(check(z , k_{PS}^+), k_S^-)$ **in**
    assert Authenticate(x_u, x_q).

let policy = ...

new $k_U^-, k_{PE}^-, k_{PS}^-, k_S^-, p_{wd}$; (user | proxy′| store′| policy)

Transformation

1. **Static analysis**
2. **Process translation**
   (incl. zk statement generation)

public values: $c_1, c_2, u, z, k_{PS}^+, k_S^+, k_U^+$

secret values: x_q, k_{PE}^-, k_{PS}^-

output-input data dependency:
$\mathrm{dec}(\mathrm{check}(x, k_U^+), k_{PE}^-) = (u, x_q, p_{wd})$

stmt $S = \mathrm{check}(\beta_1, k_{PS}^+) = \mathrm{enc}((\beta_3, \alpha_2), k_S^+) \wedge \mathrm{dec}(\mathrm{check}(\beta_2, k_U^+), \alpha_1) = (\beta_3, \alpha_2, \alpha_3)$

let user = ...

let proxy′= **assume** Registered(u) |
    in(c_1, x);
    let $(=u, x_q, =p_{wd}) = \mathrm{dec}(\mathrm{check}(x, k_U^+), k_{PE}^-)$ **in**
    out(c_2, $\mathrm{zk}_S(k_{PE}^-, x_q, p_{wd}; \mathrm{sign}(\mathrm{enc}((u, x_q), k_S^+), k_{PS}^-), x, u)$).

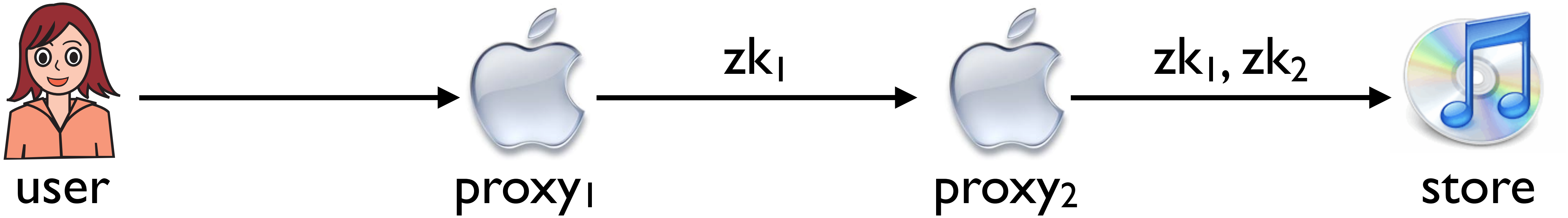
let store′= **in**(c_2, z);
    let $(\beta_1, \beta_2, \beta_3) = \mathrm{ver}_S(z)$ **in**
    let $(x_u, x_q) = \mathrm{dec}(\mathrm{check}(\beta_1, k_{PS}^+), k_S^-)$ **in**
    assert Authenticate(x_u, x_q).

let policy = ...

new $k_U^-, k_{PE}^-, k_{PS}^-, k_S^-, p_{wd}$; (user | proxy′| store′| policy)

Further complications

- Forwarding zero-knowledge proofs
  - Ensure correct behavior of all protocol participants



- Symmetric encryption
- Transforming types

Enhanced type system for zero-knowledge

Translation validation

[Pnueli et al., TACAS ’98]

- Accepted technique for increasing user’s confidence in complex transformations (e.g. compiler)
  - + prevents incorrect code from being run
  - + strong guarantees if validation succeeds
  - + without the need to prove transformation is always correct
  - + changing transformation is very easy (e.g. optimizing)

Translation validation

[Pnueli et al., TACAS '98]

- Accepted technique for increasing user's confidence in complex transformations (e.g. compiler)
  - \+ prevents incorrect code from being run
  - \+ strong guarantees if validation succeeds
  - \+ without the need to prove transformation is always correct
  - \+ changing transformation is very easy (e.g. optimizing)
  - – disadvantage: no guarantees if validation fails

Translation validation

[Pnueli et al., TACAS '98]

- Accepted technique for increasing user's confidence in complex transformations (e.g. compiler)
  - \+ prevents incorrect code from being run
  - \+ strong guarantees if validation succeeds
  - \+ without the need to prove transformation is always correct
  - \+ changing transformation is very easy (e.g. optimizing)
  - – disadvantage: no guarantees if validation fails
- We use type system for validation [Backes, Hriţcu & Maffei, CCS '08] [Fournet, Gordon & Maffeis, CSF '07]
  - Now extended to handle security despite compromise:
    - added union and intersection types
    - new logical characterization of kinding

```
let user = new q          ; assume Request(u, q) |
           out($c_1$, sign(enc((u,q,$p_{wd}$), $k_{PE}^+$), $k_U^-$)).

let proxy' = assume Registered(u) |
           in($c_1$, x);
           let (=u, $x_q$, =$p_{wd}$) = dec(check(x, $k_U^+$), $k_{PE}^-$) in
           out($c_2$, $zk_S$($k_{PE}^-$, $x_q$, $p_{wd}$; sign(enc((u,$x_q$), $k_S^+$), $k_{PS}^-$), x, u).

let store' = in($c_2$, z);
           let ($\beta_1$,$\beta_2$,$\beta_3$) = $ver_S$(z) in
           let ($x_u$,$x_q$) = dec(check($\beta_1$, $k_{PS}^+$), $k_S^-$) in
           assert Authenticate($x_u$,$x_q$).

let policy = assume $\forall$ u, q. (Request(u, q) $\wedge$ Registered(u) $\Rightarrow$ Authenticate(u, q)) ...


new $k_U^-$                        ;        new $k_{PS}^-$                              ;
new $k_{PE}^-$                   ;          new $k_S^-$                              ;
new $p_{wd}$                       ;
(user | proxy'       | store' | policy)
```

let user = **new** q ; **assume** Request(u, q) |
out(c_1, sign(enc($\underline{(u,q,p_{wd})}$, k_{PE}^{+}), k_U^{-})).

let proxy′ = **assume** Registered(u) |
in(c_1, x);
let (=u, x_q, =p_{wd}) = dec(check(x, k_U^{+}), k_{PE}^{-}) **in**
out(c_2, zk_S(k_{PE}^{-}, x_q, p_{wd}; sign(enc((u,x_q), k_S^{+}), k_{PS}^{-}), x, u).

let store′ = **in**(c_2, z);
let (β_1,β_2,β_3) = ver_S(z) **in**
let (x_u,x_q) = dec(check(β_1, k_{PS}^{+}), k_S^{-}) **in**
assert Authenticate(x_u,x_q).

let policy = **assume** ∀ u, q. (Request(u, q) ∧ Registered(u) ⇒ Authenticate(u, q)) ...

new k_U^{-} ; **new** k_{PS}^{-} ;
new k_{PE}^{-} ; **new** k_S^{-} ;
new p_{wd} ;
(user | proxy′ | store′ | policy)

let user = **new** q : Un; **assume** Request(u, q) |
out(c_1, sign(enc($\underline{(u,q,p_{wd})}$, k_{PE}^{+}), k_U^{-})).

let proxy′ = **assume** Registered(u) |
in(c_1, x);
let (=u, x_q, =p_{wd}) = dec(check(x, k_U^{+}), k_{PE}^{-}) **in**
out(c_2, zk_S(k_{PE}^{-}, x_q, p_{wd}; sign(enc((u,x_q), k_S^{+}), k_{PS}^{-}), x, u).

let store′ = **in**(c_2, z);
let (β_1,β_2,β_3) = ver_S(z) **in**
let (x_u,x_q) = dec(check(β_1, k_{PS}^{+}), k_S^{-}) **in**
assert Authenticate(x_u,x_q).

let policy = **assume** $\forall$ u, q. (Request(u, q) $\wedge$ Registered(u) $\Rightarrow$ Authenticate(u, q)) ...

new k_U^{-} ; **new** k_{PS}^{-} ;
new k_{PE}^{-} ; **new** k_S^{-} ;
new p_{wd} ;
(user | proxy′ | store′ | policy)

let user = **new** q : Un; **assume** Request(u, q) |
out(c_1, sign(enc($\underline{(u,q,p_{wd})}$, k_{PE}^+), k_U^-)).

let proxy′ = **assume** Registered(u) |
in(c_1, x);
let (=u, x_q, =p_{wd}) = dec(check(x, k_U^+), k_{PE}^-) **in**
out(c_2, zk_S(k_{PE}^-, x_q, p_{wd}; sign(enc((u,x_q), k_S^+), k_{PS}^-), x, u).

let store′ = **in**(c_2, z);
let (β_1,β_2,β_3) = ver_S(z) **in**
let (x_u,x_q) = dec(check(β_1, k_{PS}^+), k_S^-) **in**
assert Authenticate(x_u,x_q).

let policy = **assume** ∀ u, q. (Request(u, q) ∧ Registered(u) ⇒ Authenticate(u, q)) ...

new k_U^- ; **new** k_{PS}^- ;
new k_{PE}^- ; **new** k_S^- ;
new p_{wd} : Private ;
(user | proxy′ | store′ | policy)

typedef T_1 = Triple(x_u : Un, {x_q : Un | Request(x_u, x_q)}, x_p : Private)

let user = **new** q : Un; **assume** Request(u, q) |
  out(c_1, sign(enc($\underline{(u,q,p_{wd})}$, $k_{PE}{}^{+}$), $k_U{}^{-}$)).

let proxy′ = **assume** Registered(u) |
  in(c_1, x);
  let (=u, x_q, =p_{wd}) = dec(check(x, $k_U{}^{+}$), $k_{PE}{}^{-}$) **in**
  out(c_2, zk_S($k_{PE}{}^{-}$, x_q, p_{wd}; sign(enc((u,x_q), $k_S{}^{+}$), $k_{PS}{}^{-}$), x, u).

let store′ = **in**(c_2, z);
  let (β_1,β_2,β_3) = ver_S(z) **in**
  let (x_u,x_q) = dec(check(β_1, $k_{PS}{}^{+}$), $k_S{}^{-}$) **in**
  assert Authenticate(x_u,x_q).

let policy = **assume** $\forall$ u, q. (Request(u, q) $\wedge$ Registered(u) $\Rightarrow$ Authenticate(u, q)) ...

new $k_U{}^{-}$;   **new** $k_{PS}{}^{-}$;
new $k_{PE}{}^{-}$;   **new** $k_S{}^{-}$;
new p_{wd} : Private ;
(user | proxy′ | store′ | policy)

typedef T_1 = Triple(x_u : Un, $\underline{\{x_q : \text{Un} \mid \text{Request}(x_u, x_q)\}}$, x_p : Private)

let user = **new** q : Un; **assume** Request(u, q) |
  out(c_1, sign(enc($\underline{(u,q,p_{wd})}$, k_{PE}^{+}), k_U^{-})).

let proxy′ = **assume** Registered(u) |
  in(c_1, x);
  let (=u, x_q, =p_{wd}) = dec(check(x, k_U^{+}), k_{PE}^{-}) **in**
  out(c_2, zk_S(k_{PE}^{-}, x_q, p_{wd}; sign(enc((u,x_q), k_S^{+}), k_{PS}^{-}), x, u).

let store′ = **in**(c_2, z);
  let (β_1,β_2,β_3) = ver_S(z) **in**
  let (x_u,x_q) = dec(check(β_1, k_{PS}^{+}), k_S^{-}) **in**
  assert Authenticate(x_u,x_q).

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new k_U^{-} ; **new** k_{PS}^{-} ;
new k_{PE}^{-} ; **new** k_S^{-} ;
new p_{wd} : Private ;
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out(c_1, sign(enc((u,q,p_{wd}), $\underline{k_{PE}^{+}}$), k_U^{-})).

let proxy′ = **assume** Registered(u) |
in(c_1, x);
let (=u, x_q, =p_{wd}) = dec(check(x, k_U^{+}), k_{PE}^{-}) **in**
out(c_2, zk_S(k_{PE}^{-}, x_q, p_{wd}; sign(enc((u,x_q), k_S^{+}), k_{PS}^{-}), x, u).

let store′ = **in**(c_2, z);
let (β_1,β_2,β_3) = ver_S(z) **in**
let (x_u,x_q) = dec(check(β_1, k_{PS}^{+}), k_S^{-}) **in**
assert Authenticate(x_u,x_q).

let policy = **assume** $\forall$ u, q. (Request(u, q) $\wedge$ Registered(u) $\Rightarrow$ Authenticate(u, q)) ...

new k_U^{-} ; **new** k_{PS}^{-} ;
new k_{PE}^{-} : DecKey(T_1); **new** k_S^{-} ;
new p_{wd} : Private ;
(user | proxy′ | store′ | policy)

typedef T_1 = Triple(x_u : Un, {x_q : Un | Request(x_u, x_q)}, x_p : Private)

let user = **new** q : Un; **assume** Request(u, q) |
    out(c_1, sign(enc((u,q,p_{wd}), k_{PE}^{+}), $\underline{k_U^{-}}$)).

let proxy' = **assume** Registered(u) |
    in(c_1, x);
    let (=u, x_q, =p_{wd}) = dec(check(x, k_U^{+}), k_{PE}^{-}) **in**
    out(c_2, zk_S(k_{PE}^{-}, x_q, p_{wd}; sign(enc((u,x_q), k_S^{+}), k_{PS}^{-}), x, u).

let store' = **in**(c_2, z);
    let (β_1,β_2,β_3) = ver_S(z) **in**
    let (x_u,x_q) = dec(check(β_1, k_{PS}^{+}), k_S^{-}) **in**
    assert Authenticate(x_u,x_q).

let policy = **assume** $\forall$ u, q. (Request(u, q) $\wedge$ Registered(u) $\Rightarrow$ Authenticate(u, q)) ...

new k_U^{-} : SigKey(PubEnc(T_1));
new k_{PE}^{-} : DecKey(T_1);
new p_{wd} : Private ;
new k_{PS}^{-} ;
new k_S^{-} ;
(user | proxy' | store' | policy)

typedef T_1 = Triple(x_u : Un, {x_q : Un | Request(x_u, x_q)}, x_p : Private)

let user = **new** q : Un; **assume** Request(u, q) |
    out(c_1, sign(enc((u,q,p_{wd}), k_{PE}^{+}), k_{U}^{-})).

let proxy' = **assume** Registered(u) |
    in(c_1, x);
    let (=u, x_q, =p_{wd}) = dec(check(x, k_U^{+}), k_{PE}^{-}) **in**
    out(c_2, zk_S(k_{PE}^{-}, x_q, p_{wd}; sign(enc($\underline{(u,x_q)}$, k_S^{+}), k_{PS}^{-}), x, u).

let store' = **in**(c_2, z);
    let (β_1,β_2,β_3) = ver_S(z) **in**
    let (x_u,x_q) = dec(check(β_1, k_{PS}^{+}), k_S^{-}) **in**
    assert Authenticate(x_u,x_q).

let policy = **assume** ∀ u, q. (Request(u, q) ∧ Registered(u) ⇒ Authenticate(u, q)) ...

new k_U^{-} : SigKey(PubEnc(T_1));
new k_{PE}^{-} : DecKey(T_1);
new p_{wd} : Private ;
new k_{PS}^{-} ;
new k_S^{-} ;
(user | proxy' | store' | policy)

typedef T_1 = Triple(x_u : Un, {x_q : Un | Request(x_u, x_q)}, x_p : Private)
typedef T_2 = Pair(x_u : Un, {x_q : Un | Request(x_u, x_q) $\wedge$ Registered(x_u)})

let user = **new** q : Un; **assume** Request(u, q) |
out(c_1, sign(enc((u,q,p_{wd}), k_{PE}^{+}), k_U^{-})).

let proxy′ = **assume** Registered(u) |
in(c_1, x);
let (=u, x_q, =p_{wd}) = dec(check(x, k_U^{+}), k_{PE}^{-}) **in**
out(c_2, zk_S(k_{PE}^{-}, x_q, p_{wd}; sign(enc($\underline{(u,x_q)}$, k_S^{+}), k_{PS}^{-}), x, u).

let store′ = **in**(c_2, z);
let (β_1,β_2,β_3) = ver_S(z) **in**
let (x_u,x_q) = dec(check(β_1, k_{PS}^{+}), k_S^{-}) **in**
assert Authenticate(x_u,x_q).

let policy = **assume** $\forall$ u, q. (Request(u, q) $\wedge$ Registered(u) $\Rightarrow$ Authenticate(u, q)) ...

new k_U^{-} : SigKey(PubEnc(T_1)); **new** k_{PS}^{-} ;
new k_{PE}^{-} : DecKey(T_1); **new** k_S^{-} ;
new p_{wd} : Private ;
(user | proxy′ | store′ | policy)

typedef T_1 = Triple(x_u : Un, {x_q : Un | Request(x_u, x_q)}, x_p : Private)
typedef T_2 = Pair(x_u : Un, {x_q : Un | Request(x_u, x_q) $\wedge$ Registered(x_u)})

let user = **new** q : Un; **assume** Request(u, q) |
out(c_1, sign(enc((u,q,p_{wd}), k_{PE}^{+}), k_U^{-})).

let proxy′ = **assume** Registered(u) |
in(c_1, x);
let (=u, x_q, =p_{wd}) = dec(check(x, k_U^{+}), k_{PE}^{-}) **in**
out(c_2, zk_S(k_{PE}^{-}, x_q, p_{wd}; sign(enc((u,x_q), k_S^{+}), k_{PS}^{-}), x, u).

let store′ = **in**(c_2, z);
let (β_1,β_2,β_3) = ver_S(z) **in**
let (x_u,x_q) = dec(check(β_1, k_{PS}^{+}), k_S^{-}) **in**
assert Authenticate(x_u,x_q).

let policy = **assume** $\forall$ u, q. (Request(u, q) $\wedge$ Registered(u) $\Rightarrow$ Authenticate(u, q)) ...

new k_U^{-} : SigKey(PubEnc(T_1));
new k_{PE}^{-} : DecKey(T_1);
new p_{wd} : Private ;
new k_{PS}^{-} : SigKey(PubEnc(T_2)) ;
new k_S^{-} : DecKey(T_2) ;
(user | proxy′ | store′ | policy)

typedef T_1 = Triple(x_u : Un, {x_q : Un | Request(x_u, x_q)}, x_p : Private)
typedef T_2 = Pair(x_u : Un, {x_q : Un | Request(x_u, x_q) ∧ Registered(x_u)})

let user = **new** q : Un; **assume** Request(u, q) |
out(c_1, sign(enc((u,q,p_{wd}), k_{PE}^+), k_U^-)).

✓ Transformed protocol
type-checks when all
participants are honest

let proxy′ = **assume** Registered(u) |
in(c_1, x);
let (=u, x_q, =p_{wd}) = dec(check(x, k_U^+), k_{PE}^-) **in**
out(c_2, zk_S(k_{PE}^-, x_q, p_{wd}; sign(enc((u,x_q), k_S^+), k_{PS}^-), x, u).

let store′ = **in**(c_2, z);
let (β_1,β_2,β_3) = ver_S(z) **in**
let (x_u,x_q) = dec(check(β_1, k_{PS}^+), k_S^-) **in**
assert Authenticate(x_u,x_q).

let policy = **assume** ∀ u, q. (Request(u, q) ∧ Registered(u) ⇒ Authenticate(u, q)) ...

new k_U^- : SigKey(PubEnc(T_1));
new k_{PE}^- : DecKey(T_1);
new p_{wd} : Private ;
(user | proxy′ | store′ | policy)

new k_{PS}^- : SigKey(PubEnc(T_2)) ;
new k_S^- : DecKey(T_2) ;

typedef T_1 = Triple(x_u : Un, {x_q : Un | Request(x_u, x_q)}, x_p : Private)
typedef T_2 = Pair(x_u : Un, {x_q : Un | Request(x_u, x_q) $\wedge$ Registered(x_u)})

let user = **new** q : Un; **assume** Request(u, q) |
out(c_1, sign(enc((u,q,p_{wd}), k_{PE}^{+}), k_U^{-})).

let proxy′ = **assume** Registered(u) |
in(c_1, x);
let (=u, x_q, =p_{wd}) = dec(check(x, k_U^{+}), k_{PE}^{-}) **in**
out(c_2, zk_S(k_{PE}^{-}, x_q, p_{wd}; sign(enc((u,x_q), k_S^{+}), k_{PS}^{-}), x, u).

But these annotations are <u>not</u> appropriate when proxy is compromised

let store′ = **in**(c_2, z);
let (β_1,β_2,β_3) = ver_S(z) **in**
let (x_u,x_q) = dec(check(β_1, k_{PS}^{+}), k_S^{-}) **in**
assert Authenticate(x_u,x_q).

let policy = **assume** $\forall$ u, q. (Request(u, q) $\wedge$ Registered(u) $\Rightarrow$ Authenticate(u, q)) ...

new k_U^{-} : SigKey(PubEnc(T_1)); **new** k_{PS}^{-} : SigKey(PubEnc(T_2)) ;
new k_{PE}^{-} : DecKey(T_1); **new** k_S^{-} : DecKey(T_2) ;
new p_{wd} : Private ;
(user | proxy′ | store′ | policy)

typedef T_1 = Triple(x_u : Un, {x_q : Un | Request(x_u, x_q)}, x_p : Private)
typedef T_2 = Pair(x_u : Un, {x_q : Un | Request(x_u, x_q) $\wedge$ Registered(x_u)})

let user = **new** q : Un; **assume** Request(u, q) |
out(c_1, sign(enc((u,q,p_{wd}), k_{PE}^{+}), k_U^{-})).

let bad_proxy = **out**(c_{pub}, (k_{PE}^{-}, k_{PS}^{-}, p_{wd})).

let store’ = **in**(c_2, z);
let (β_1,β_2,β_3) = ver_S(z) **in**
let (x_u,x_q) = dec(check(β_1, k_{PS}^{+}), k_S^{-}) **in**
assert Authenticate(x_u,x_q).

let policy = **assume** $\forall$ u, q. (Request(u, q) ~~$\wedge$ Registered(u)~~ $\Rightarrow$ Authenticate(u, q)) ...

assume Compromised(p).

new k_U^{-} : SigKey(PubEnc(T_1));
new k_{PE}^{-} : DecKey(T_1);
new p_{wd} : Private ;
new k_{PS}^{-} : SigKey(PubEnc(T_2)) ;
new k_S^{-} : DecKey(T_2) ;
(user | bad_proxy | store’ | policy)

typedef PrivateUnlessP = {Private | ¬Compromised(p)} ∨ {Un | Compromised(p)}
typedef T_1 = Triple(x_u : Un, {x_q : Un | Request(x_u, x_q)}, x_p : PrivateUnlessP)
typedef T_2 = Pair(x_u : Un, {x_q : Un | Request(x_u, x_q) ∧ Registered(x_u)})

let user = **new** q : Un; **assume** Request(u, q) |
out(c_1, sign(enc((u,q,p_{wd}), k_{PE}^{+}), k_U^{-})).

let bad_proxy = **out**(c_{pub}, (k_{PE}^{-}, k_{PS}^{-}, p_{wd})).

let store’ = **in**(c_2, z);
let (β_1,β_2,β_3) = ver_S(z) **in**
let (x_u,x_q) = dec(check(β_1, k_{PS}^{+}), k_S^{-}) **in**
assert Authenticate(x_u,x_q).

let policy = **assume** ∀ u, q. (Request(u, q) ~~∧ Registered(u)~~ ⇒ Authenticate(u, q)) ...

assume Compromised(p).

new k_U^{-} : SigKey(PubEnc(T_1));
new k_{PE}^{-} : DecKey(T_1);
new p_{wd} : PrivateUnlessP;

new k_{PS}^{-} : SigKey(PubEnc(T_2)) ;
new k_S^{-} : DecKey(T_2) ;

(user | bad_proxy | store’ | policy)

typedef PrivateUnlessP = {Private | ¬Compromised(p)} ∨ {Un | Compromised(p)}
typedef T_1 = Triple(x_u : Un, {x_q : Un | Request(x_u, x_q)}, x_p : PrivateUnlessP)
typedef T_2 = Pair(x_u : Un, {x_q : Un | Request(x_u, x_q) ∧ Registered(x_u)})
typedef T_2unlessP = {T_2 | ¬Compromised(p)} ∨ {Un | Compromised(p)}

let user = **new** q : Un; **assume** Request(u, q) |
out(c_1, sign(enc((u,q,p_{wd}), k_{PE}^+), k_U^-)).

let bad_proxy = **out**(c_{pub}, (k_{PE}^-, k_{PS}^-, p_{wd})).

let store’ = **in**(c_2, z);
let (β_1,β_2,β_3) = ver_S(z) **in**
let (x_u,x_q) = dec(check(β_1, k_{PS}^+), k_S^-) **in**
assert Authenticate(x_u,x_q).

let policy = **assume** ∀ u, q. (Request(u, q) ~~∧ Registered(u)~~ ⇒ Authenticate(u, q)) ...
assume Compromised(p).

new k_U^- : SigKey(PubEnc(T_1));
new k_{PE}^- : DecKey(T_1);
new p_{wd} : PrivateUnlessP;
(user | bad_proxy | store’ | policy)

new k_{PS}^- : SigKey(PubEnc(T_2unlessP));
new k_S^- : DecKey(T_2unlessP);

...
typedef T_1 = Triple(x_u : Un, {x_q : Un | Request(x_u, x_q)}, x_p : PrivateUnlessP)
...

let store′ = **in**(c_2, z);
  let (β_1,β_2,β_3) = **ver**$_S$**(z)** **in**
  let (x_u,x_q) = dec(check(β_1, k_{PS}^+), k_S^-) **in**
  assert Authenticate(x_u,x_q).

let policy = **assume** ∀ u, q. (Request(u, q) ~~∧ Registered(u)~~ ⇒ Authenticate(u, q)) ...

  assume Compromised(p).

new k_U^- : SigKey(PubEnc(T_1));
new k_{PE}^- : DecKey(T_1);
new p_{wd} : PrivateUnlessP;
(user | bad_proxy | store′ | policy)

new k_{PS}^- : SigKey(PubEnc(T_2unlessP));
new k_S^- : DecKey(T_2unlessP);

…
typedef T_1 = Triple(x_u : Un, {x_q : Un | Request(x_u, x_q)}, x_p : PrivateUnlessP)
…

stmt *S* = $\text{check}(\beta_1, k_{PS}^+) = \text{enc}((\beta_3,\alpha_2), k_S^+) \wedge \text{dec}(\text{check}(\beta_2, k_U^+), \alpha_1) = (\beta_3,\alpha_2,\alpha_3)$

let store’ = **in**(c_2, z);
let (β_1,β_2,β_3) = **ver_S(z)** **in**
let (x_u,x_q) = dec(check(β_1, k_{PS}^+), k_S^-) **in**
assert Authenticate(x_u,x_q).

let policy = **assume** ∀ u, q. (Request(u, q) ~~∧ Registered(u)~~ ⇒ Authenticate(u, q)) …
assume Compromised(p).

new k_U^- : SigKey(PubEnc(T_1));
new k_{PE}^- : DecKey(T_1);
new p_{wd} : PrivateUnlessP;
(user | bad_proxy | store’ | policy)

new k_{PS}^- : SigKey(PubEnc(T_2unlessP));
new k_S^- : DecKey(T_2unlessP);

…
typedef T_1 = Triple(x_u : Un, {x_q : Un | Request(x_u, x_q)}, x_p : PrivateUnlessP)
…

stmt $S = \exists \alpha_1,\alpha_2,\alpha_3.\mathrm{check}(\beta_1,k_{PS}^{+}) = \mathrm{enc}((\beta_3,\alpha_2), k_S^{+}) \wedge \mathrm{dec}(\mathrm{check}(\beta_2, k_U^{+}), \alpha_1) = (\beta_3,\alpha_2,\alpha_3$

let store’ = **in**(c_2, z);
    let (β_1,β_2,β_3) = **ver_S(z)** **in**
    let (x_u,x_q) = dec(check(β_1, k_{PS}^{+}), k_S^{-}) **in**
    assert Authenticate(x_u,x_q).

let policy = **assume** ∀ u, q. (Request(u, q) ~~∧ Registered(u)~~ ⇒ Authenticate(u, q)) …

assume Compromised(p).

new k_U^{-} : SigKey(PubEnc(T_1));
new k_{PE}^{-} : DecKey(T_1);
new p_{wd} : PrivateUnlessP;
(user | bad_proxy | store’ | policy)

new k_{PS}^{-} : SigKey(PubEnc(T_2unlessP));
new k_S^{-} : DecKey(T_2unlessP);

…
typedef T_1 = Triple(x_u : Un, {x_q : Un | Request(x_u, x_q)}, x_p : PrivateUnlessP)
…

stmt $S = \exists \alpha_1,\alpha_2,\alpha_3.\mathrm{check}(\beta_1,k_{PS}^{+}) = \mathrm{enc}((\beta_3,\alpha_2), k_S^{+}) \wedge \mathrm{dec}(\mathrm{check}(\beta_2, \underline{k_U^{+}}), \alpha_1) = (\beta_3,\alpha_2,\alpha_3)$
:VerKey(PubEnc(T_1))

let store' = **in**(c_2, z);
let (β_1,β_2,β_3) = **vers(z) in**
let (x_u,x_q) = dec(check(β_1, k_{PS}^{+}), k_S^{-}) **in**
assert Authenticate(x_u,x_q).

let policy = **assume** ∀ u, q. (Request(u, q) ~~∧ Registered(u)~~ ⇒ Authenticate(u, q)) …

assume Compromised(p).

new k_U^{-} : SigKey(PubEnc(T_1));
new k_{PE}^{-} : DecKey(T_1);
new p_{wd} : PrivateUnlessP;
(user | bad_proxy | store' | policy)

new k_{PS}^{-} : SigKey(PubEnc(T_2unlessP));
new k_S^{-} : DecKey(T_2unlessP);

…

typedef T_1 = Triple(x_u : Un, {x_q : Un | Request(x_u, x_q)}, x_p : PrivateUnlessP)

…

stmt $S = \exists \alpha_1,\alpha_2,\alpha_3.\mathrm{check}(\beta_1,k_{PS}^+) = \mathrm{enc}((\beta_3,\alpha_2), k_S^+) \wedge \mathrm{dec}\underset{:\mathrm{PubEnc}(T_1)}{\underline{(\mathrm{check}(\beta_2, k_U^+)}}, \alpha_1) = (\beta_3,\alpha_2,\alpha_3)$

let store’ = **in**(c_2, z);
  let (β_1,β_2,β_3) = **ver$_S$(z) in**
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$\wedge$ Request(β_3, α_2)

let store′ = **in**(c_2, z);
let (β_1,β_2,β_3) = **ver$_S$(z) in**
let (x_u,x_q) = dec(check(β_1, k_{PS}^{+}), k_S^{-}) **in**
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(user | bad_proxy | store′ | policy)

new k_{PS}^{-} : SigKey(PubEnc(T_2unlessP));
new k_S^{-} : DecKey(T_2unlessP);

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(user | bad_proxy | store’ | policy)

new k_{PS}^{-} : SigKey(PubEnc(T_2unlessP));
new k_S^{-} : DecKey(T_2unlessP);

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stmt $S = \exists\alpha_1,\alpha_2,\alpha_3.\text{check}(\beta_1,k_{PS}^+) = \text{enc}((\underline{\beta_3,\alpha_2}), k_S^+) \wedge \text{dec}(\text{check}(\beta_2, k_U^+), \alpha_1) = (\beta_3,\alpha_2,\alpha_3)$
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new p_{wd} : PrivateUnlessP;
(user | bad_proxy | store′ | policy)

new k_{PS}^- : SigKey(PubEnc(T_2unlessP));
new k_S^- : DecKey(T_2unlessP);

…
typedef T_1 = Triple(x_u : Un, {x_q : Un | Request(x_u, x_q)}, x_p : PrivateUnlessP)
…

$$\begin{aligned}\exists \alpha_1,\alpha_2,\alpha_3.\text{check}(\beta_1,k_{PS}^+) = \text{enc}((\beta_3,\alpha_2), k_S^+) &\wedge \text{dec}(\text{check}(\beta_2, k_U^+), \alpha_1) = (\beta_3,\alpha_2,\alpha_3)\\ &\wedge \text{Request}(\beta_3, \alpha_2)\\ &\wedge \beta_3 = x_u \wedge \alpha_2 = x_q\end{aligned}$$

let store’ = **in**(c_2, z);
let (β_1,β_2,β_3) = **ver_s(z)** **in**
let (x_u,x_q) = dec(check(β_1, k_{PS}^+), k_S^-) **in**
assert Authenticate(x_u,x_q).

let policy = **assume** ∀ u, q. (Request(u, q) ~~∧ Registered(u)~~ ⇒ Authenticate(u, q)) …

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new k_U^- : SigKey(PubEnc(T_1));
new k_{PE}^- : DecKey(T_1);
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(user | bad_proxy | store’ | policy)

new k_{PS}^- : SigKey(PubEnc(T_2unlessP));
new k_S^- : DecKey(T_2unlessP);

...

typedef T_1 = Triple(x_u : Un, {x_q : Un | Request(x_u, x_q)}, x_p : PrivateUnlessP)

...

$$\exists \alpha_1,\alpha_2,\alpha_3.\mathrm{check}(\beta_1,k_{PS}^+) = \mathrm{enc}((\beta_3,\alpha_2), k_S^+) \wedge \mathrm{dec}(\mathrm{check}(\beta_2, k_U^+), \alpha_1) = (\beta_3,\alpha_2,\alpha_3)$$
$$\wedge\ \mathrm{Request}(x_u, x_q)$$

let store' = **in**(c_2, z);
  let (β_1,β_2,β_3) = **ver$_s$(z)** **in**
  let (x_u,x_q) = dec(check(β_1, k_{PS}^+), k_S^-) **in**
  assert Authenticate(x_u,x_q).

let policy = **assume** ∀ u, q. (Request(u, q) ~~∧ Registered(u)~~ ⇒ Authenticate(u, q)) ...

assume Compromised(p).

new k_U^- : SigKey(PubEnc(T_1));
new k_{PE}^- : DecKey(T_1);
new p_{wd} : PrivateUnlessP;
(user | bad_proxy | store' | policy)

new k_{PS}^- : SigKey(PubEnc(T_2unlessP));
new k_S^- : DecKey(T_2unlessP);

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typedef T_1 = Triple(x_u : Un, {x_q : Un | Request(x_u, x_q)}, x_p : PrivateUnlessP)
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$$\exists \alpha_1,\alpha_2,\alpha_3.\mathrm{check}(\beta_1,k_{PS}^{+}) = \mathrm{enc}((\beta_3,\alpha_2), k_S^{+}) \wedge \mathrm{dec}(\mathrm{check}(\beta_2, k_U^{+}), \alpha_1) = (\beta_3,\alpha_2,\alpha_3) \wedge \mathrm{Request}(x_u, x_q)$$

✓ Transformed protocol type-checks
even when proxy is compromised
⇒ secure despite compromise

let store′ = **in**(c_2, z);
    let (β_1,β_2,β_3) = **ver$_s$(z) in**
    let (x_u,x_q) = dec(check(β_1, k_{PS}^{+}), k_S^{-}) **in**
    assert Authenticate(x_u,x_q).

let policy = **assume** ∀ u, q. (Request(u, q) ~~∧ Registered(u)~~ ⇒ Authenticate(u, q)) …

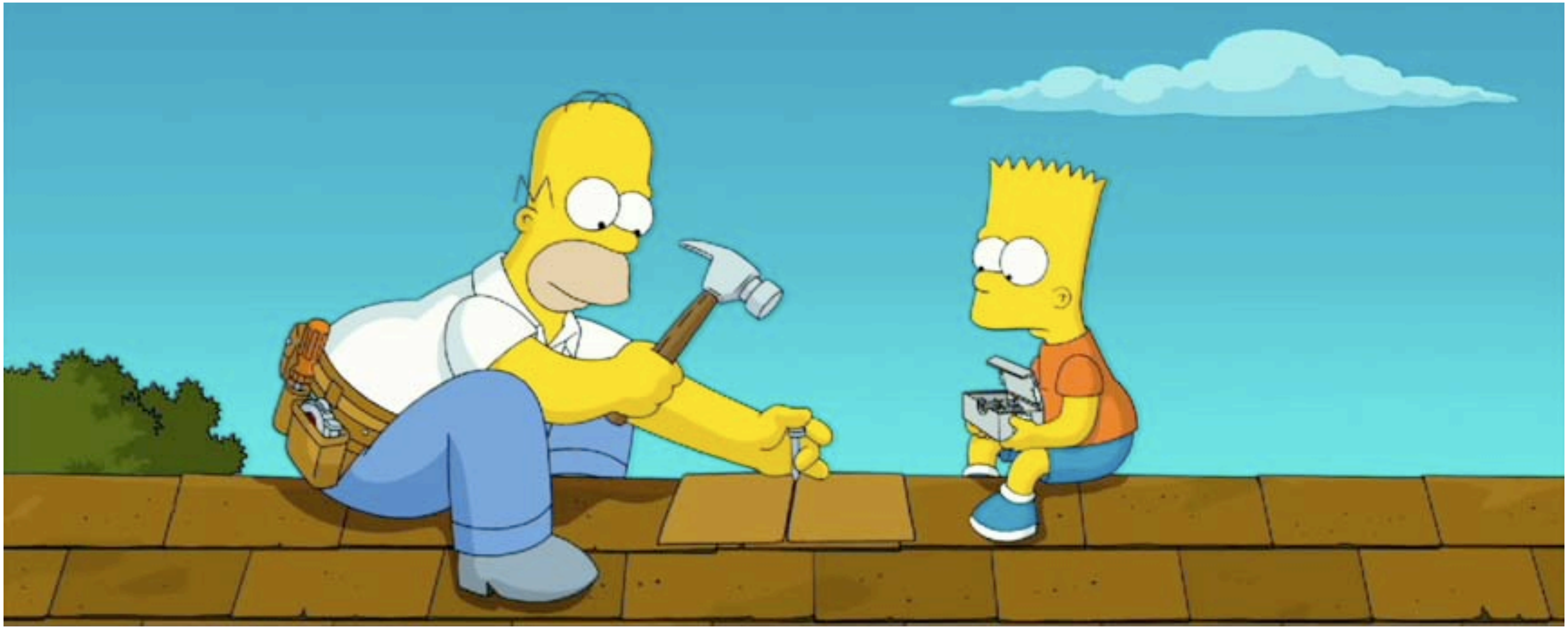
assume Compromised(p).

new k_U^{-} : SigKey(PubEnc(T_1));
new k_{PE}^{-} : DecKey(T_1);
new p_{wd} : PrivateUnlessP;
(user | bad_proxy | store′ | policy)

new k_{PS}^{-} : SigKey(PubEnc(T_2unlessP));
new k_S^{-} : DecKey(T_2unlessP);

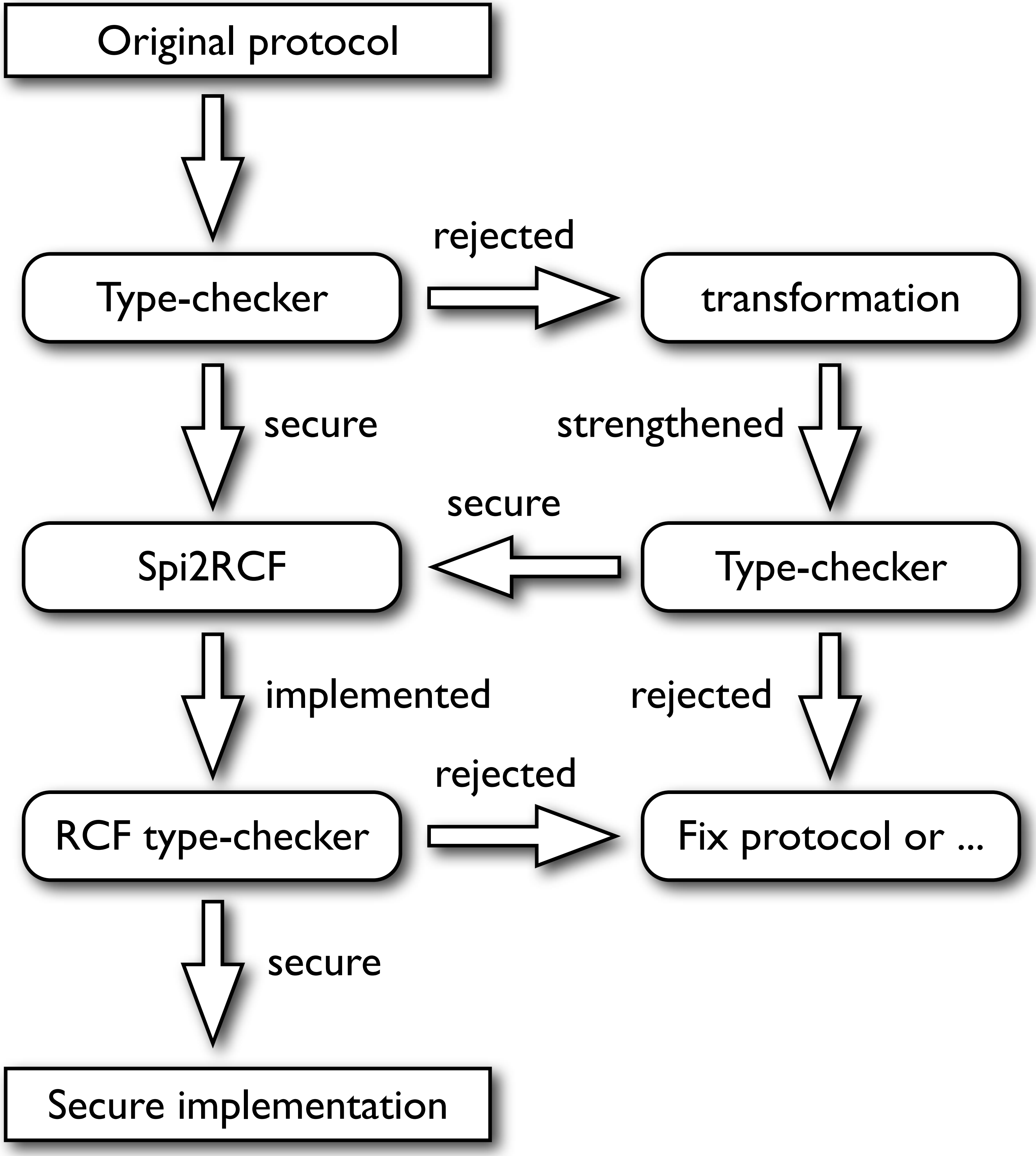
Implementation

- Transformation and type-checker written in O'Caml (~2000+6000 LOC)
- Both available under the Apache License:
  http://www.infsec.cs.uni-sb.de/projects/zk-compromise/
  http://www.infsec.cs.uni-sb.de/projects/zk-typechecker/



Spi2RCF

- Automatically generates symbolic implementations
  - in a core subset of ML (Refined Concurrent PCF) [Bengtson et. al., CSF '08]
  - again we use a type-checker to validate the generated implementation



Original protocol

Type-checker

rejected

transformation

secure

strengthened

Spi2RCF

secure

Type-checker

implemented

rejected

RCF type-checker

rejected

Fix protocol or ...

secure

Secure implementation

Future Work

- Apply transformation to more protocols
- Optimize transformation
  - could use ideas from [Corin et. al, CSF '07]
  - translation validation approach will help (no need to redo any proofs)
- Automatically generate concrete implementations of protocols using zero-knowledge
  - implementing ZK proof system is hard
  - efficiency is a big challenge

Thank you

Related Work

- Strengthening crypto protocols using transformations

  [Goldreich, Micali & Wigderson, STOC '87]

  - Add ZK to multi-party protocol secure against honest-but-curious participants to protect against compromise
  - Computational cryptography, broadcast communication

  [Katz & Yung, CRYPTO '03] [Cortier et al. ESORICS '07]

  - From passive (eavesdropping) to active attackers

  [Bellare, Canetti & Krawczyk, STOC '98]

  - Transformation removes authentication assumption

  [Datta, Derek, Mitchell & Pavlovic, JCS '05]

  - Methodology for modular protocol design using generic protocol transformations

Related Work (continued)

- Generating protocols from high-level specifications

  [Corin, Dénielou, Fournet, Bhargavan & Leifer, CSF ’07]

  - Multi-party session specifications transformed to F# implementations that are secure despite compromise
  - Very efficient generated implementation
  - No secrecy and data binding (recently addressed)
  - More recent transformation uses translation validation using type-checker (original one was proven correct)
    - They still need to prove local sequentiality by hand
  - Main difference: session specifications have no crypto
    - Our approach applies both to existing crypto protocols and to the ones generated from specs

```
typedef PrivateUnlessP = {Private | ¬Compromised(p)} ∨ {Un | Compromised(p)}
typedef $T_1$ = Triple($x_u$ : Un, {$x_q$ : Un | Request($x_u$, $x_q$)}, $x_p$:PrivateUnlessP)
typedef $T_2$ = Pair($x_u$ : Un, {$x_q$ : Un | Request($x_u$, $x_q$) ∧ Registered($x_u$)})
typedef $T_2$unlessP = {$T_2$ | ¬Compromised(p)} ∨ {Un | Compromised(p)}
new $k_U^-$ : SigKey(PubEnc($T_1$));
new $k_{PE}^-$ : DecKey($T_1$);
new $k_{PS}^-$ : SigKey(PubEnc($T_2$unlessP));
new $k_S^-$ : DecKey($T_2$unlessP);
new $p_{wd}$ : Private; (user | proxy | store | policy)



let user = new q : Un; assume Request(u, q) |
           out($c_1$, sign(enc((u,q,$p_{wd}$), $k_{PE}^+$), $k_U^-$)).

let proxy = assume Registered(u) |
           in($c_1$, x);
           let (=u, $x_q$, =$p_{wd}$) = dec(check(x, $k_U^+$), $k_{PE}^-$) in
           out($c_2$, sign(enc((u,$x_q$), $k_S^+$), $k_{PS}^-$)).

let store = in($c_2$, z);
           let ($x_u$,$x_q$) = dec(check(z, $k_{PS}^+$), $k_S^-$) in
           assert Authenticate($x_u$,$x_q$).

let policy = assume ∀ u, q. (Request(u, q) ∧ Registered(u) ⇒ Authenticate(u, q)) |

              assume Compromised(p) ⇒ ∀ u. Registered(u) |

              assume Compromised(u) ⇒ ∀ q. Request(u, q).
```

typedef PrivateUnlessP = {Private | ¬Compromised(p)} ∨ {Un | Compromised(p)}
typedef T_1 = Triple(x_u : Un, {x_q : Un | Request(x_u, x_q)}, x_p:PrivateUnlessP)
typedef T_2 = Pair(x_u : Un, {x_q : Un | Request(x_u, x_q) ∧ Registered(x_u)})
typedef T_2unlessP = {T_2 | ¬Compromised(p)} ∨ {Un | Compromised(p)}
new k_U^- : SigKey(PubEnc(T_1));
new k_{PE}^- : DecKey(T_1);
new k_{PS}^- : SigKey(PubEnc(T_2unlessP));
new k_S^- : DecKey(T_2unlessP);
new p_{wd} : Private; (user | proxy | store | policy)

stmt S = check(β_1,k_{PS}^+) = enc((β_3,α_2), k_S^+) ∧ dec(check(β_2, k_U^+), α_1) = (β_3,α_2,α_3)

let user = **new** q : Un; **assume** Request(u, q) |
out(c_1, sign(enc((u,q,p_{wd}), k_{PE}^+), k_U^-)).

let proxy = **assume** Registered(u) |
in(c_1, x);
let (=u, x_q, =p_{wd}) = dec(check(x, k_U^+), k_{PE}^-) **in**
out(c_2, sign(enc((u,x_q), k_S^+), k_{PS}^-)).

let store = **in**(c_2, z);
let (x_u,x_q) = dec(check(z, k_{PS}^+), k_S^-) **in**
assert Authenticate(x_u,x_q).

let policy = **assume** ∀ u, q. (Request(u, q) ∧ Registered(u) ⇒ Authenticate(u, q)) |
assume Compromised(p) ⇒ ∀ u. Registered(u) |
assume Compromised(u) ⇒ ∀ q. Request(u, q).

Thank you