Keys to the Cloud: Formal Analysis and Concrete Attacks on Encrypted Web Storage

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In-Browser Encryption

Sensitive data on the Web

- Ever more private data online
- TLS protects data over the wire
- Data at rest on untrusted cloud servers at risk
- Attack on server = disaster

Solution

Client-side encryption

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Name	Key Derivation	Encryption	Integrity	Metadata Integrity	Sharing
Wuala	PBKDF2	AES, RSA	HMAC	✓	✓(PKI)
SpiderOak	PBKDF2	AES, RSA	HMAC	✓	✓
Mega	AES-ECB	AES, RSA	CBC-MAC	✓	✓(PKI)
BoxCryptor	PBKDF2	AES	None	✗	✗
CloudFogger	PBKDF2	AES, RSA	None	✗	✓(PKI)
1Password	PBKDF2-SHA1	AES	None	✗	✓
LastPass	PBKDF2-SHA256	AES, RSA	None	✗	✓
PassPack	SHA256	AES	None	✓	✓
RoboForm	PBKDF2	AES, DES	None	✗	✓
Clipperz	SHA256	AES	SHA256	✓	✗
ConfiChair	PBKDF2	RSA, AES	SHA1	✓	✓(PKI)
Helios	N/A	El Gamal	SHA256	Zero-Knowledge Proof	N/A

Table : Example encrypted cloud storage websites

In-Browser Encryption

The pros

- Data stored encrypted on cloud
- Server never gets key
- Privacy selling point
- Avoid server-side computations

The cons

- Web client is even more critical
- ...but much easier to attack
- in-browser cryptography highly controversial

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In-Browser Encryption

JavaScript cryptography

- Trusted code delivery issue
- Lack of integrity of computations
- Key management

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Cloud Storage Protocols

Parameters

- u uses browser a to visit website b
- u can derive encryption/MAC keys K/K' and shared login secret $s_{u,b}$ from password p
- b stores for each u a table db of records $m \mapsto (e = Enc_K(x), Mac_{K'}(m, e))$
- a can decrypt and handle its local db synchronized with b using Sync and Update

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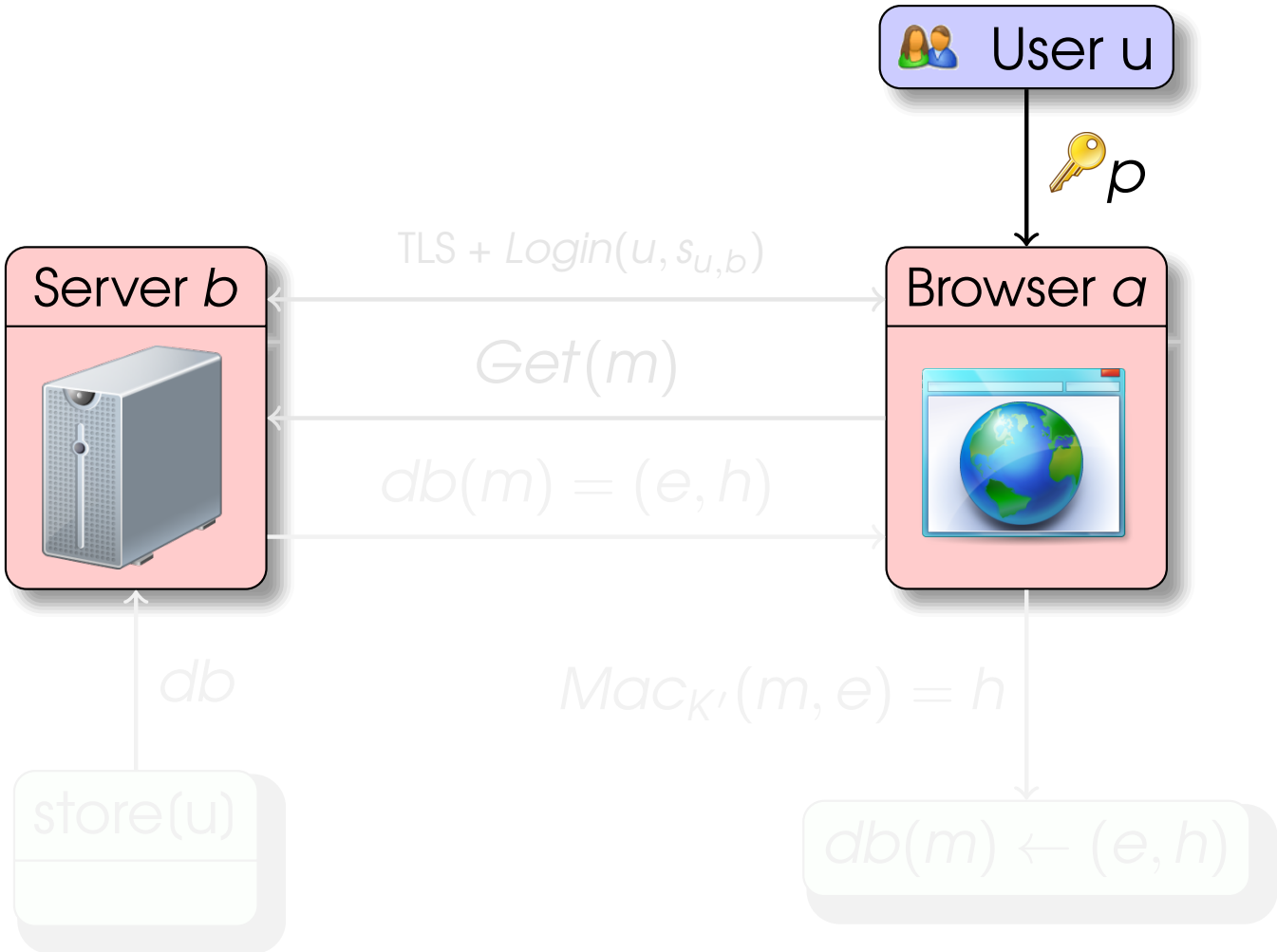
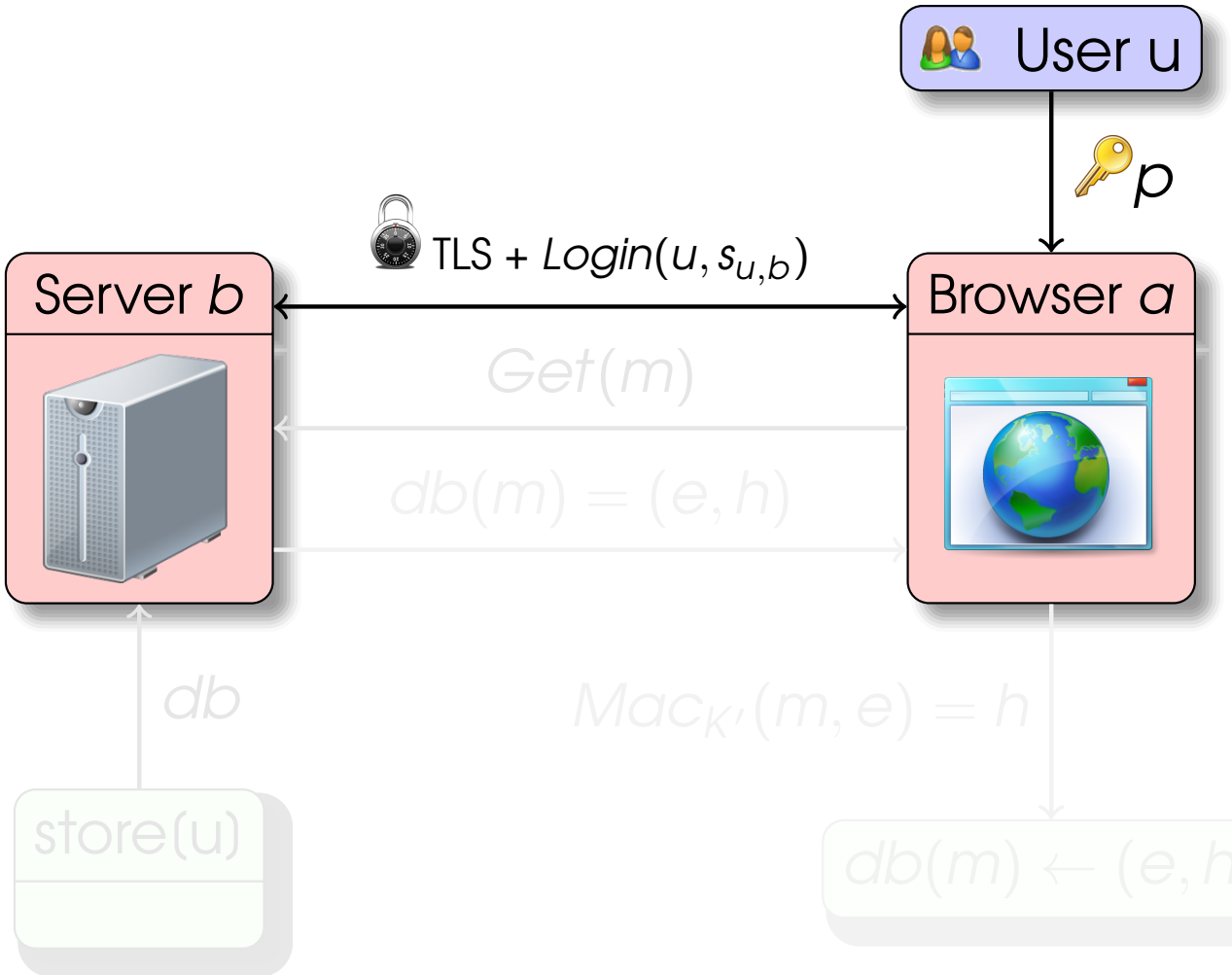
Synchronize Protocol



Synchronize Protocol



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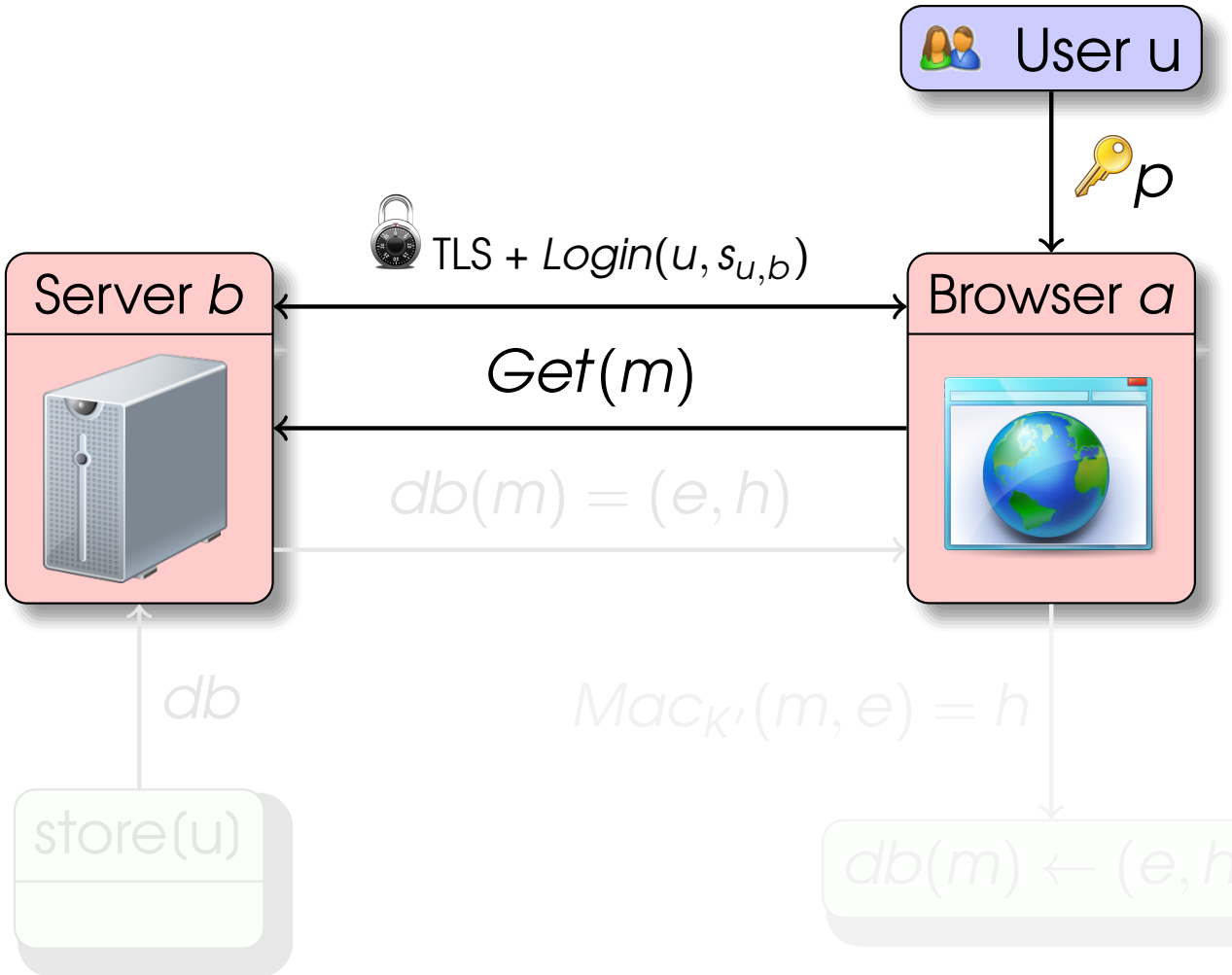

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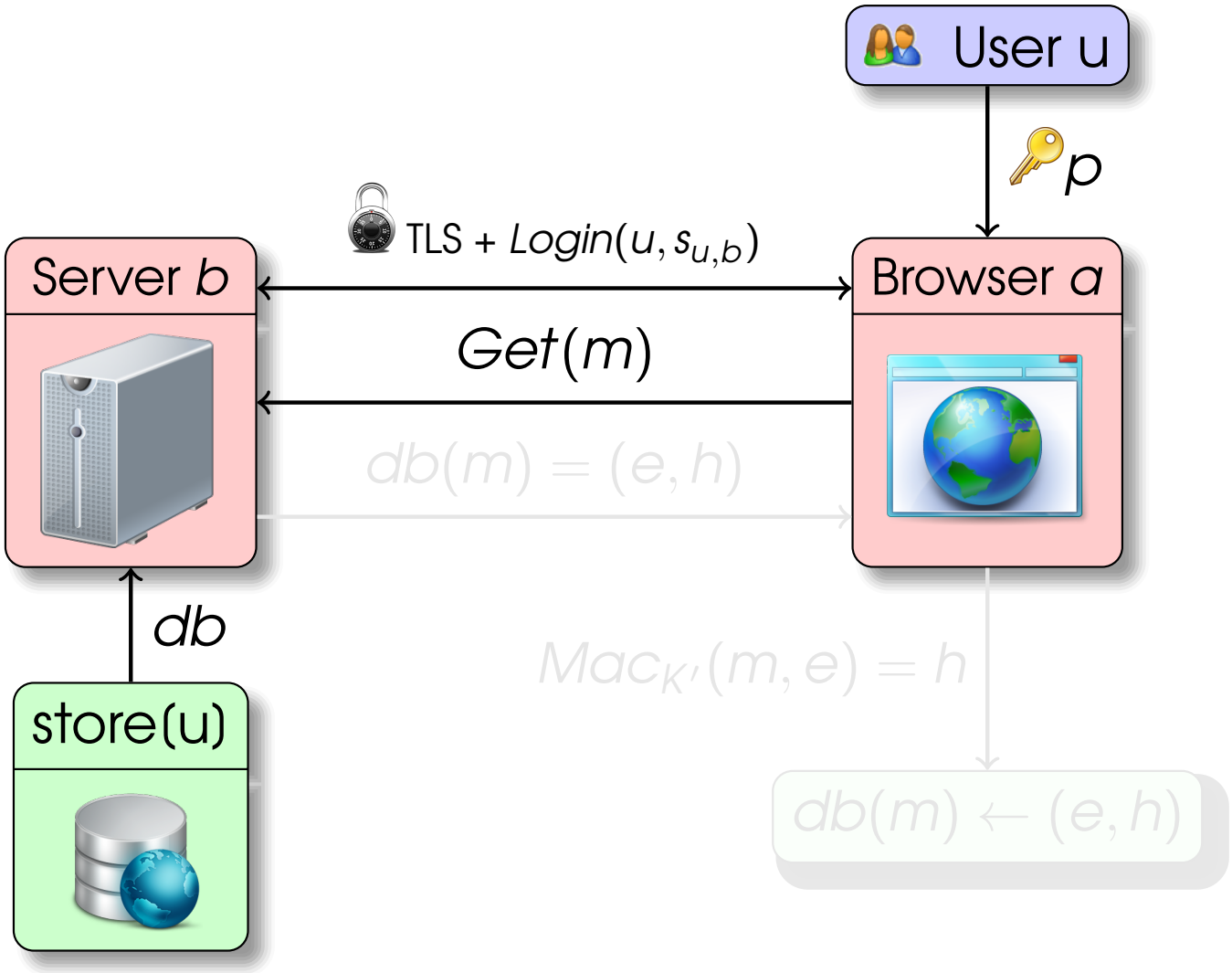

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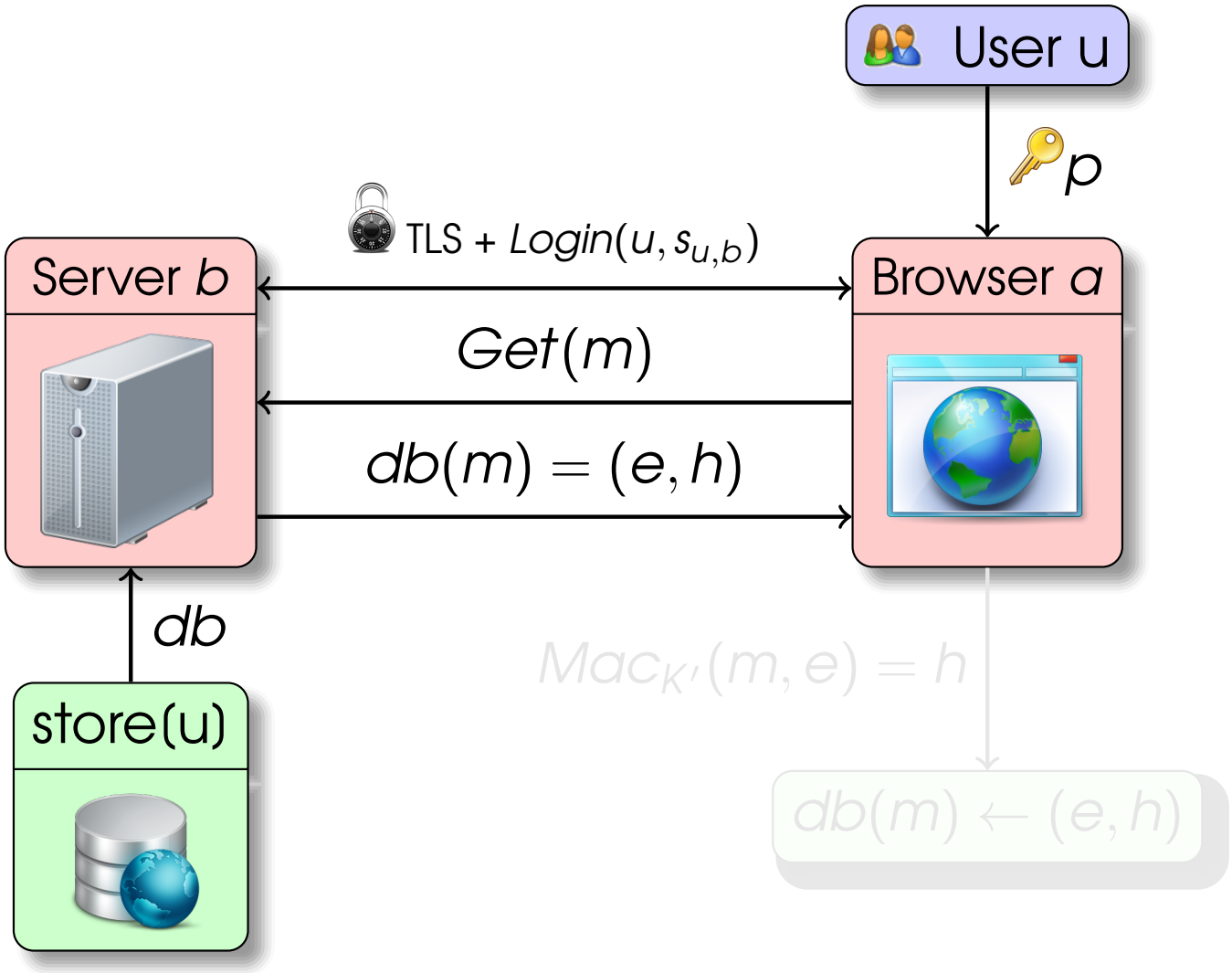

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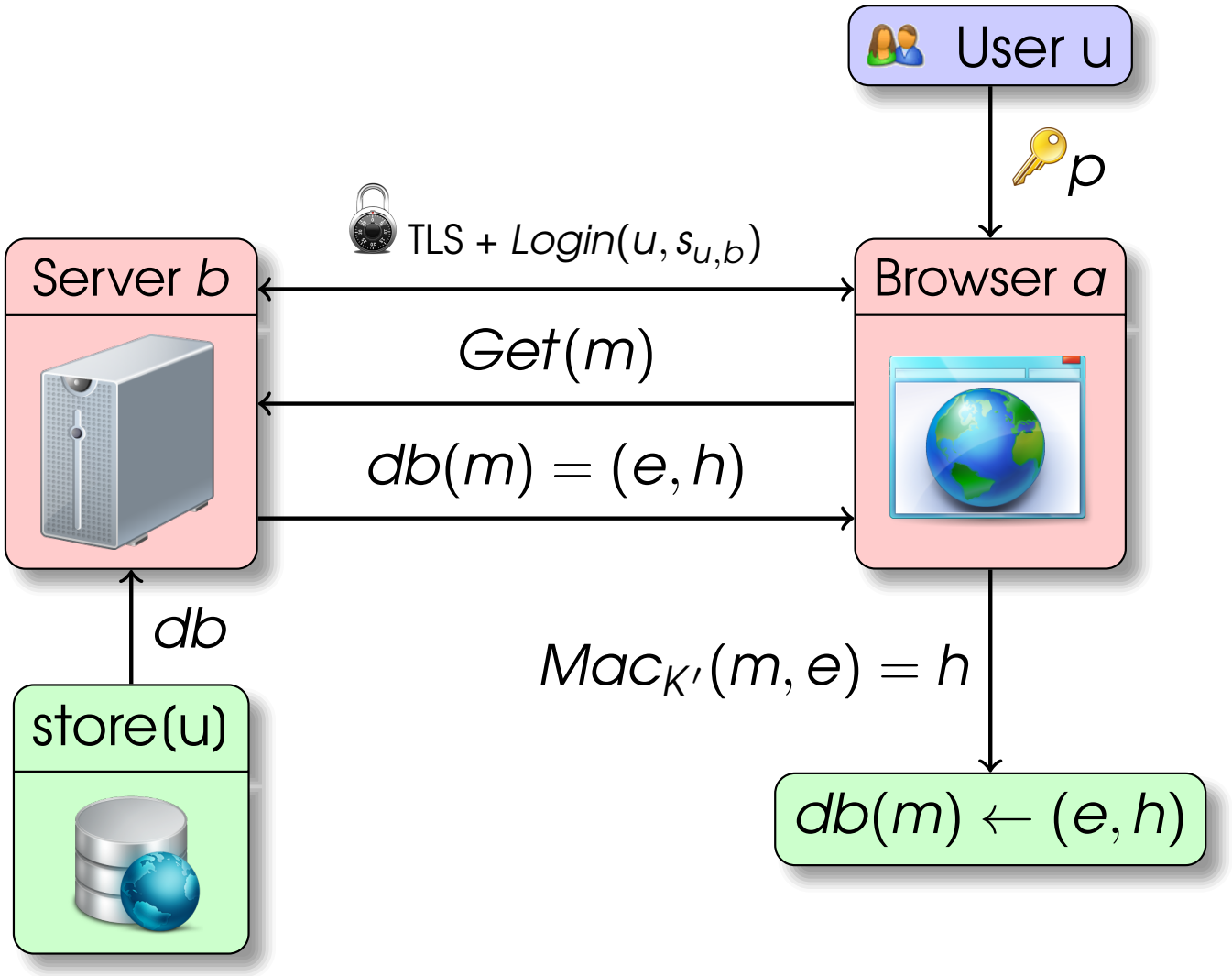
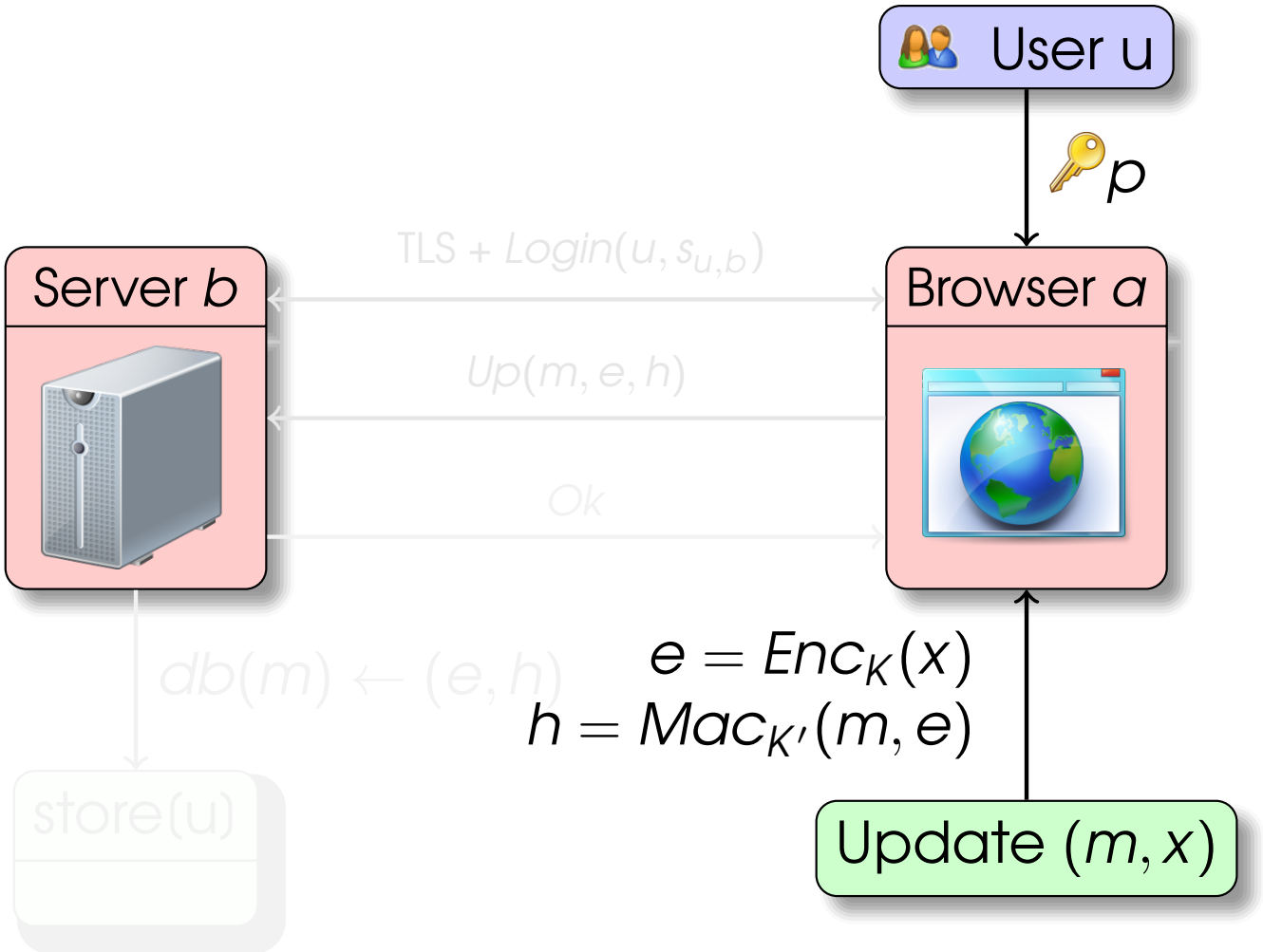


Update protocol



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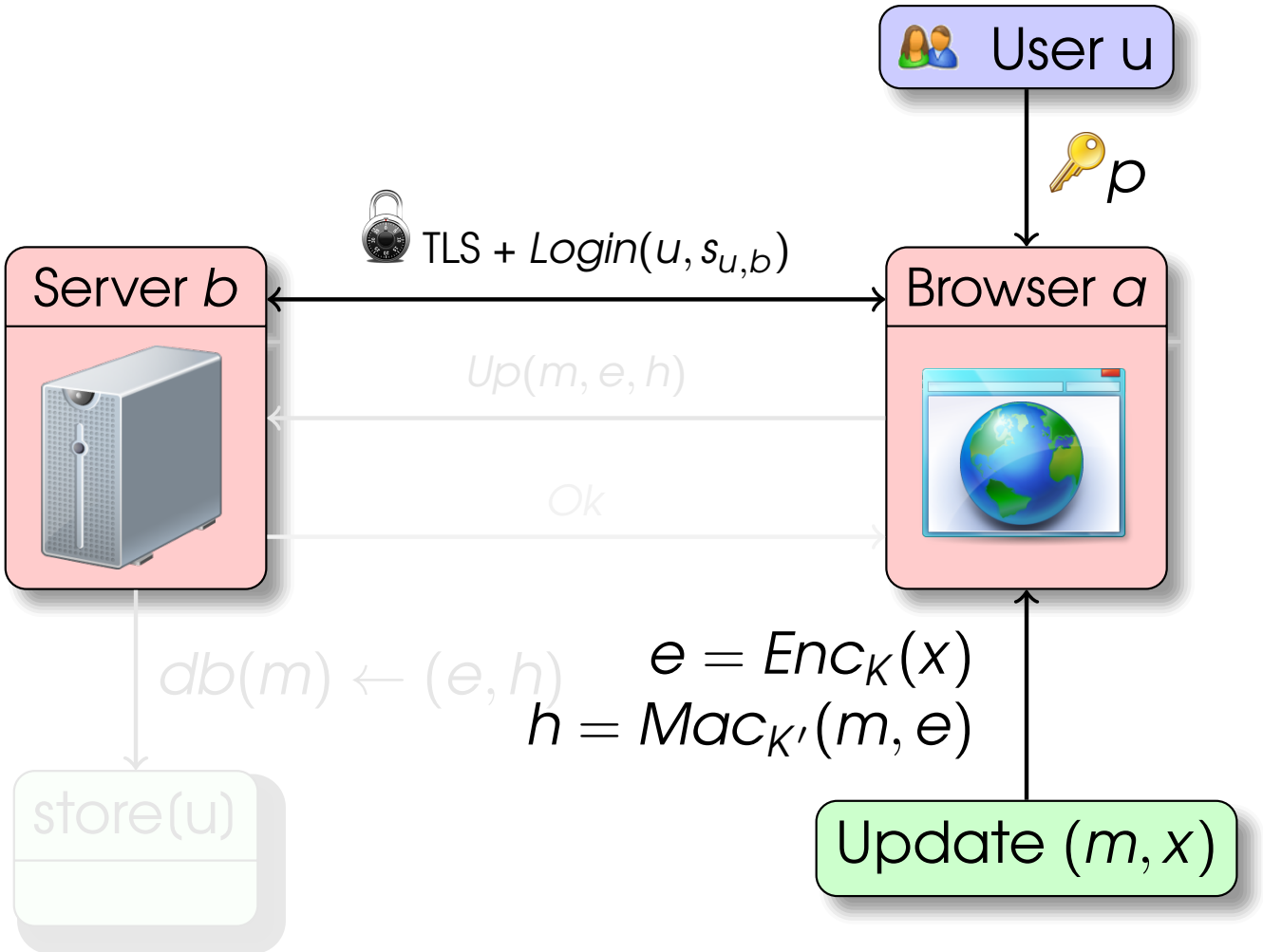

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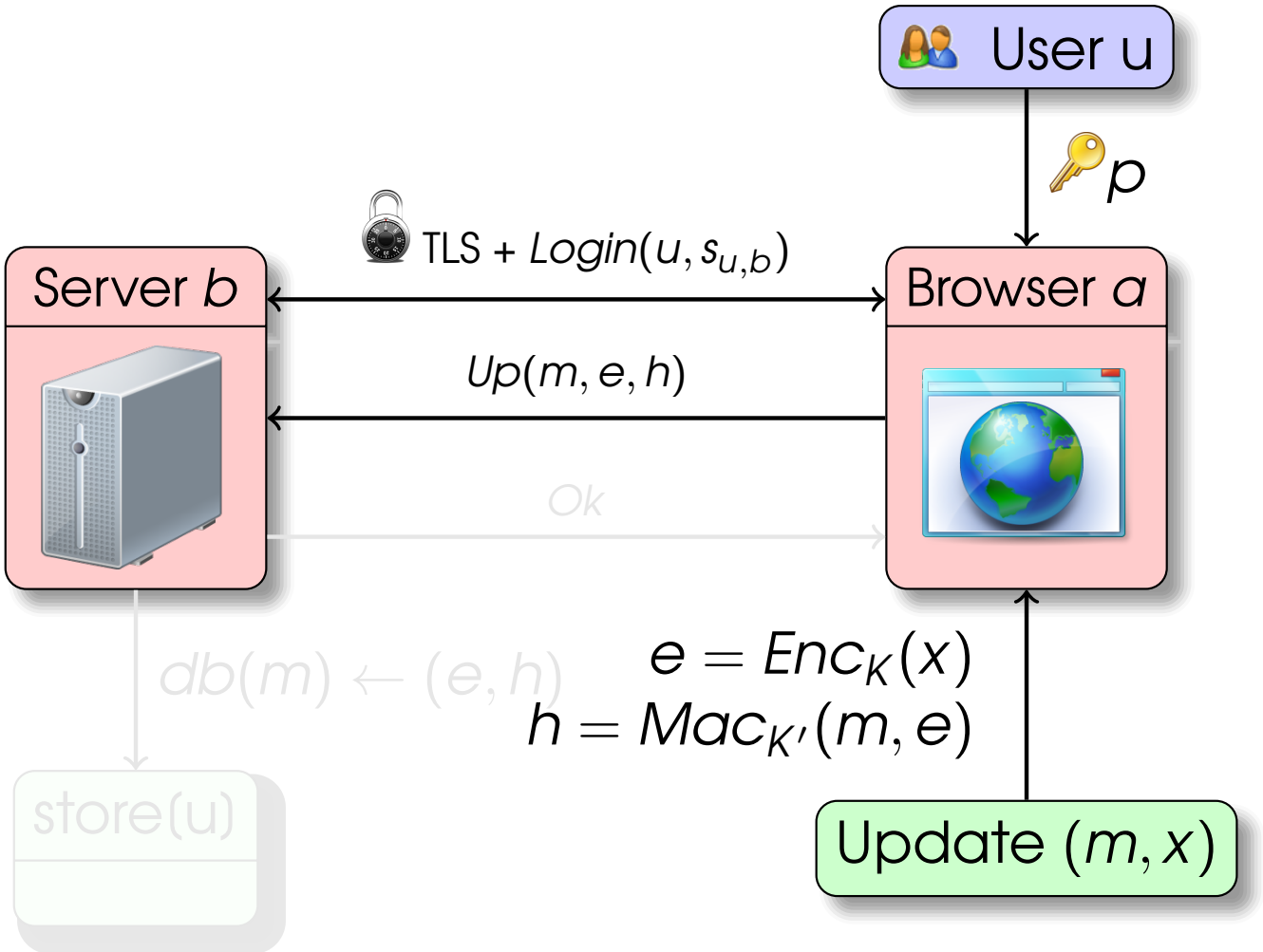

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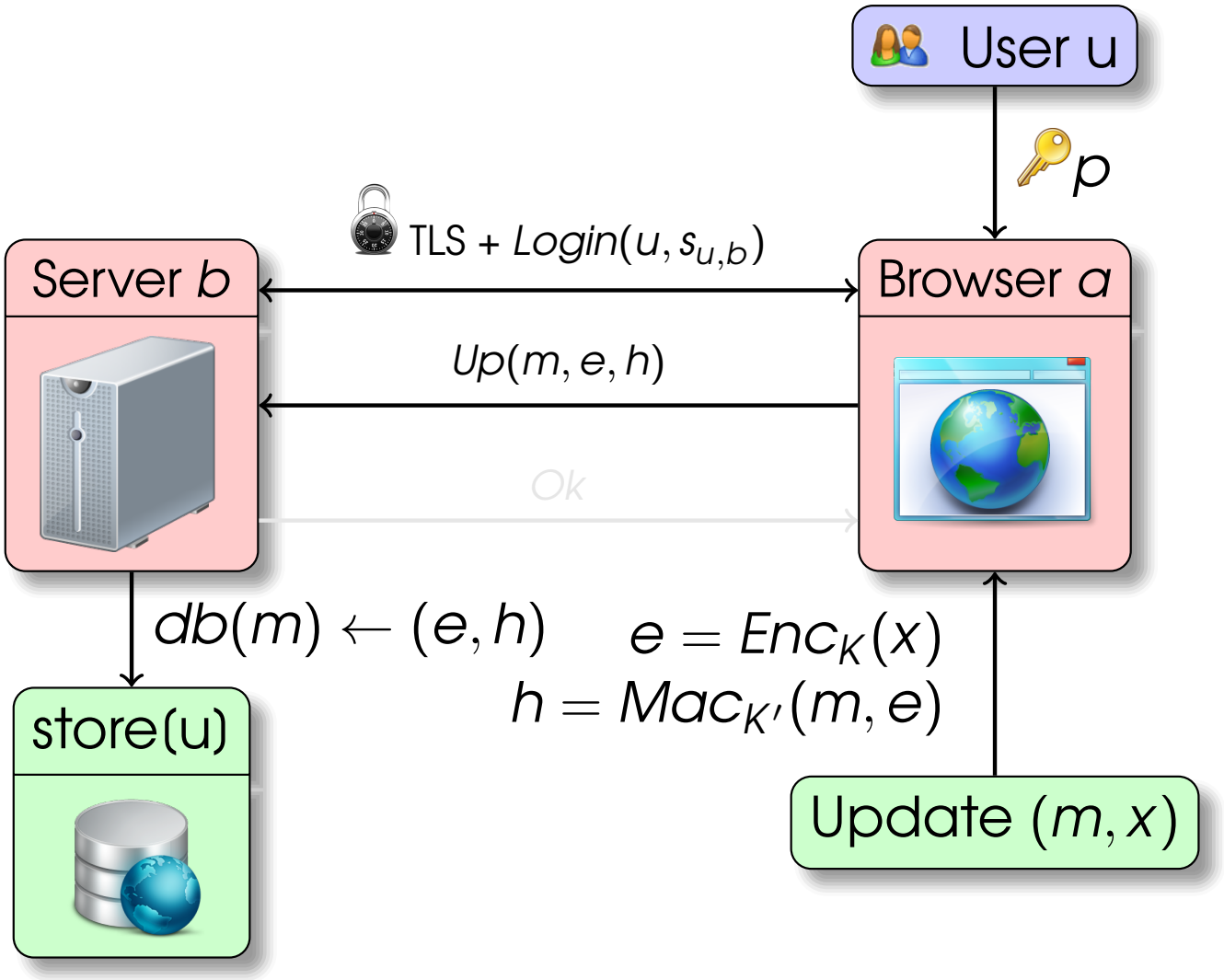

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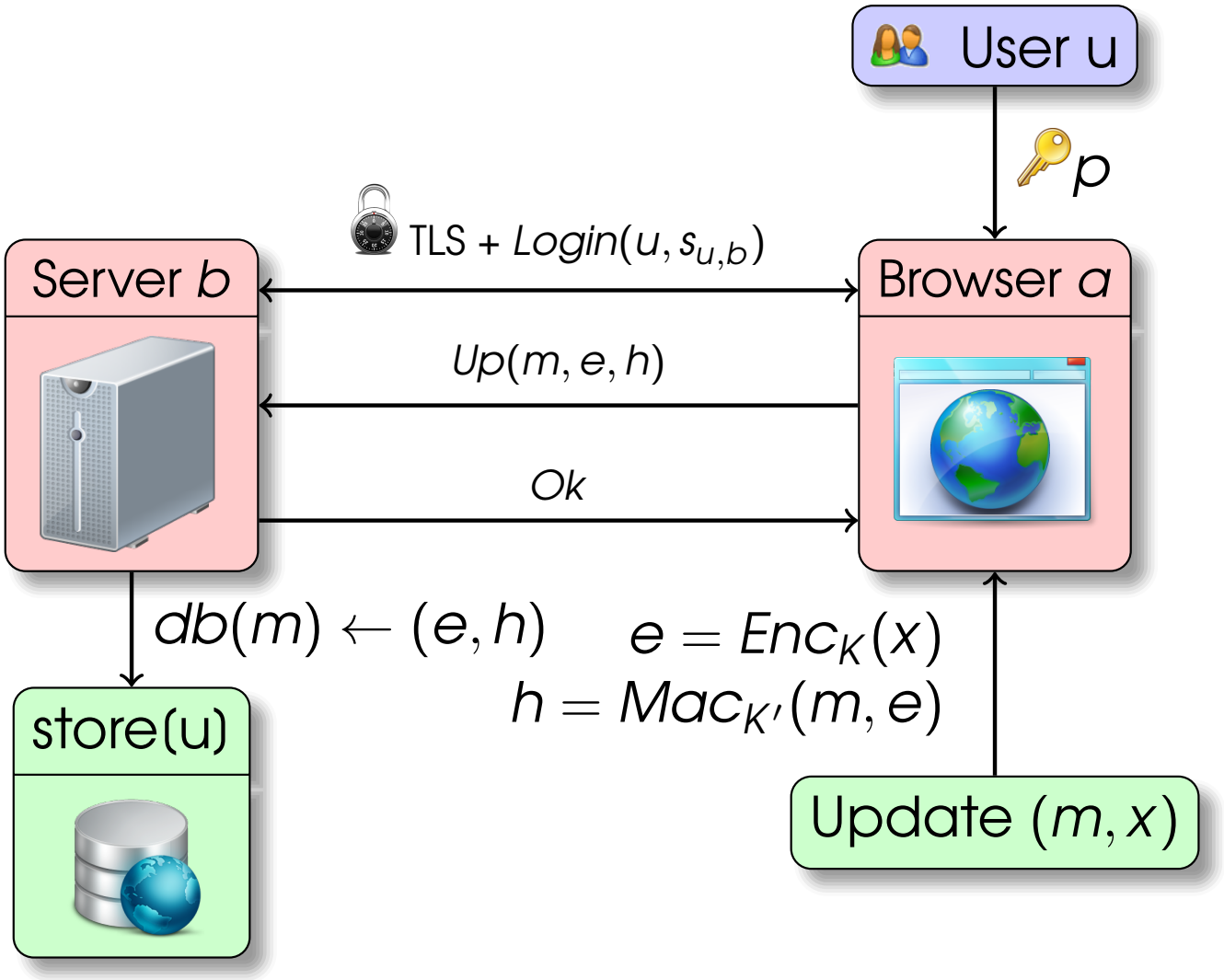

Attacker model

Dolev-Yao attacker

- compromised server
- network attacker
- browser cache inspection

Web login protocol

In the browser

- Must implicitly authenticate user in protocol
- Must avoid asking user for p for every operation
- Where to cache K and K'?

Cookie-based sessions

- Cookie set by server; attached to following requests by browser
- Session table on server indexed by cookie can maintain state across requests
- Cookies sent even if request caused by third party

Web attacker model

- CSRF: URL of private action triggered on user's behalf using session cookies
- XSS: data executed as JavaScript (`eval`, `innerHTML`)
- Insecure session cookie
- Open redirector
- Phishing
- Clickjacking
- ...

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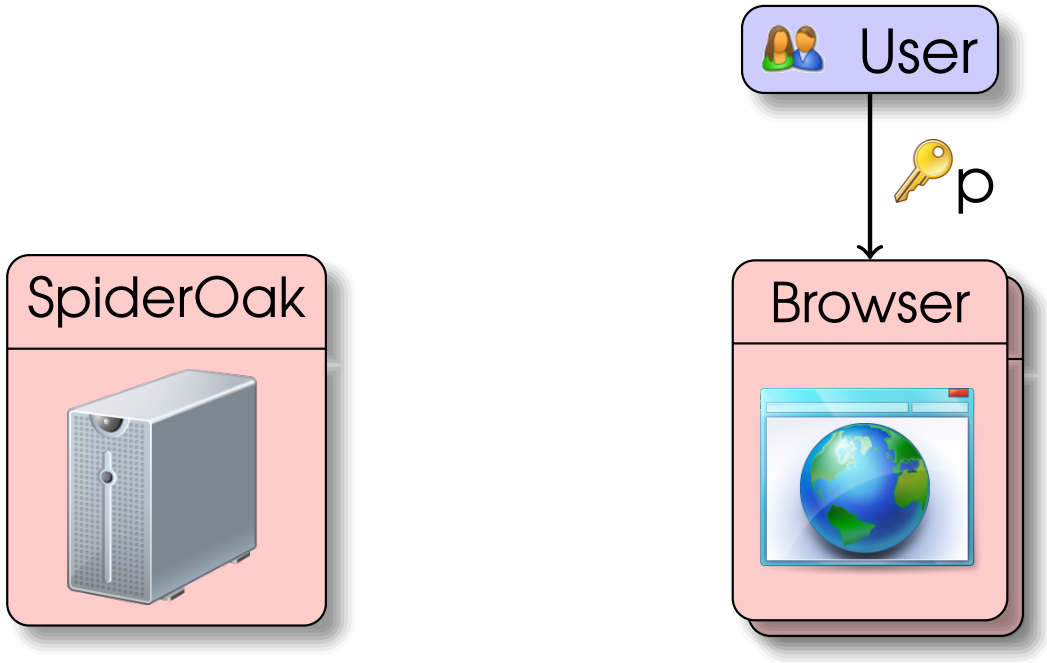
SpiderOak login



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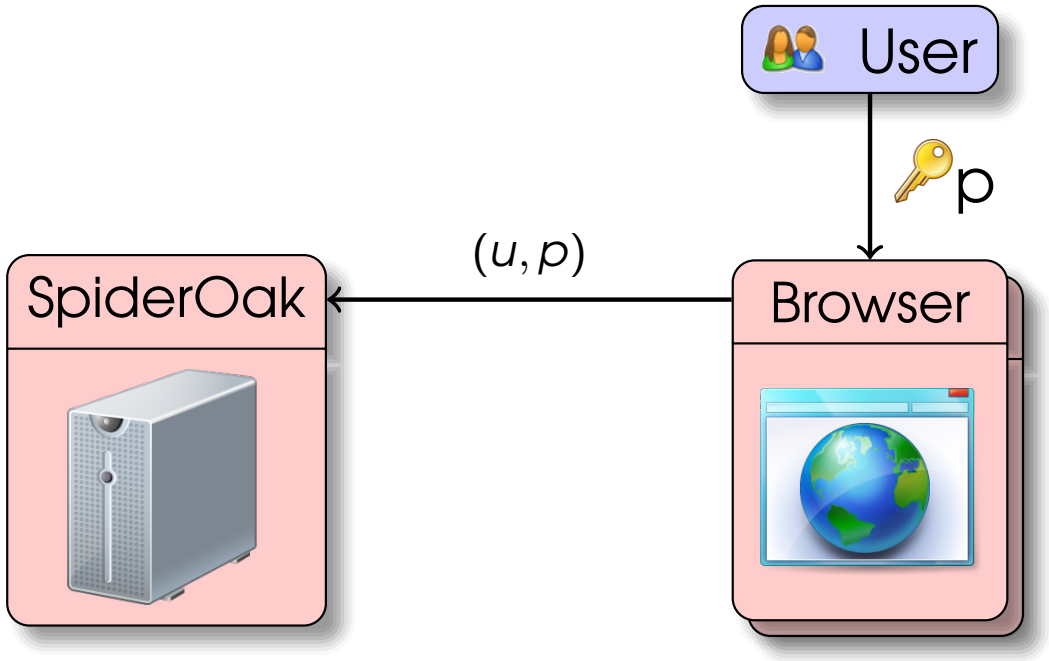

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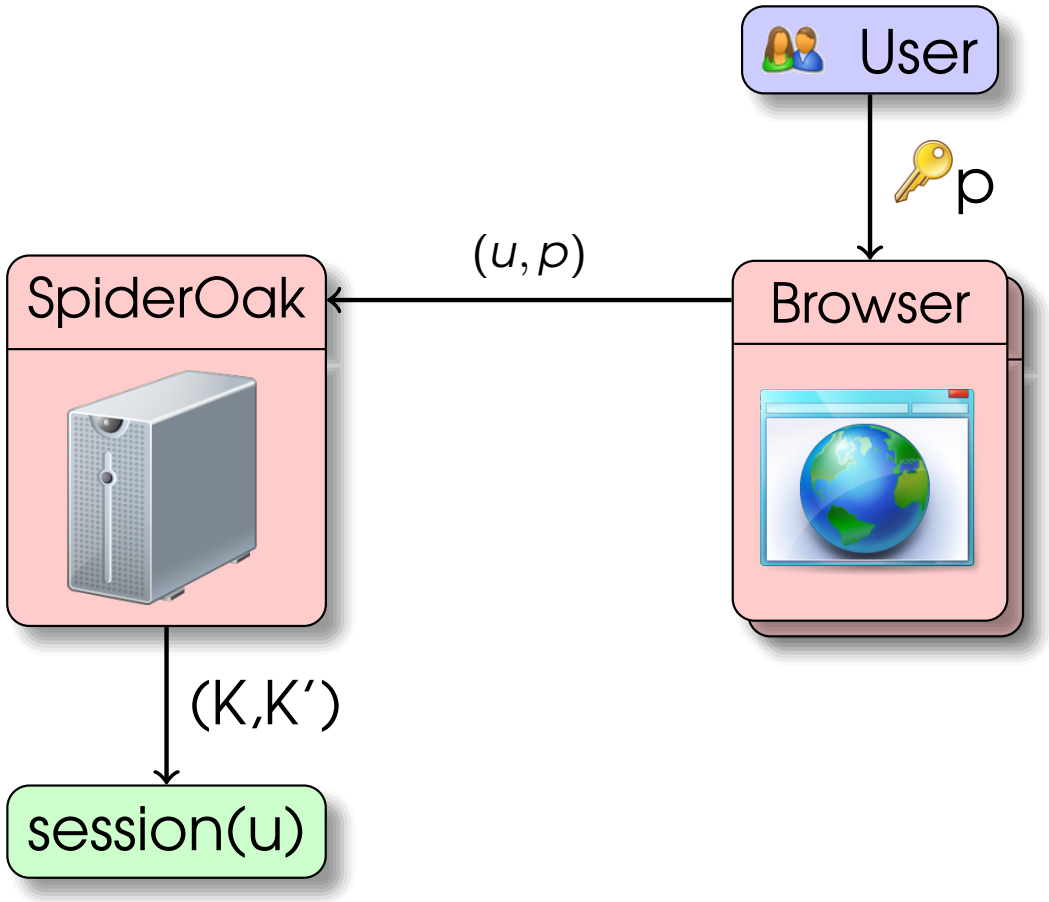

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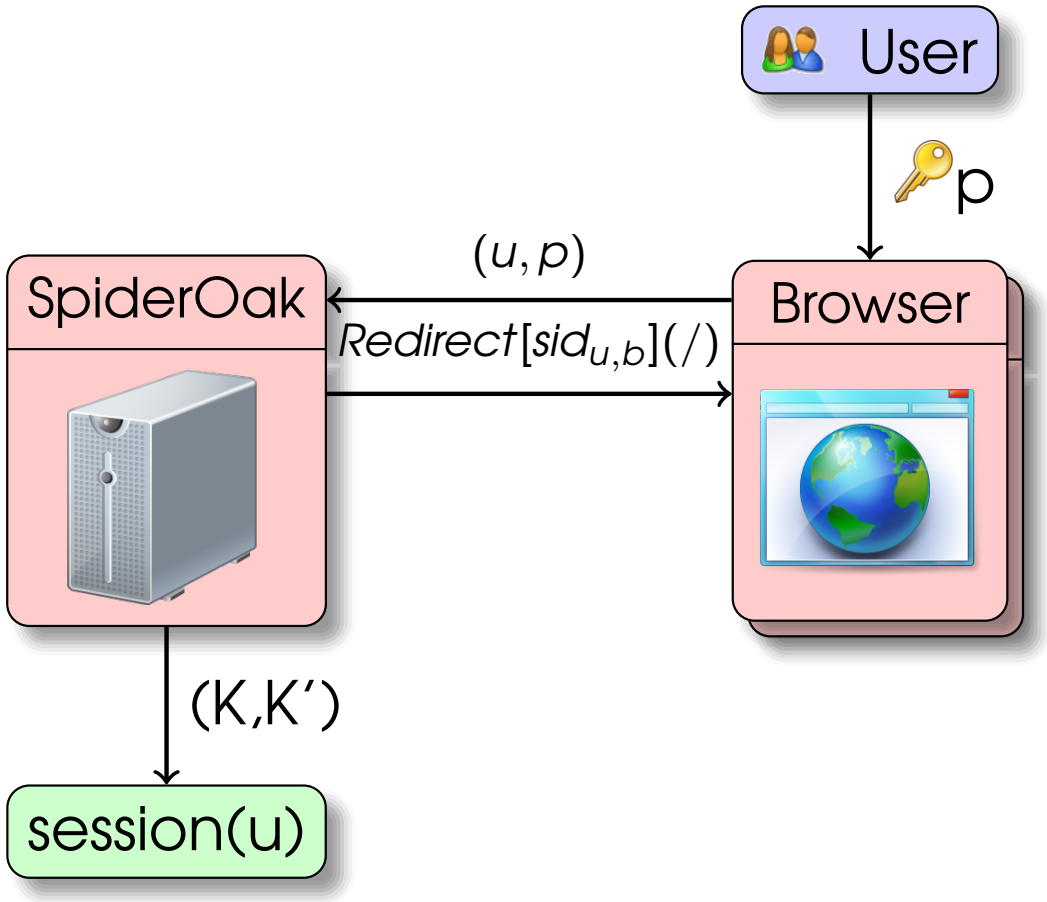

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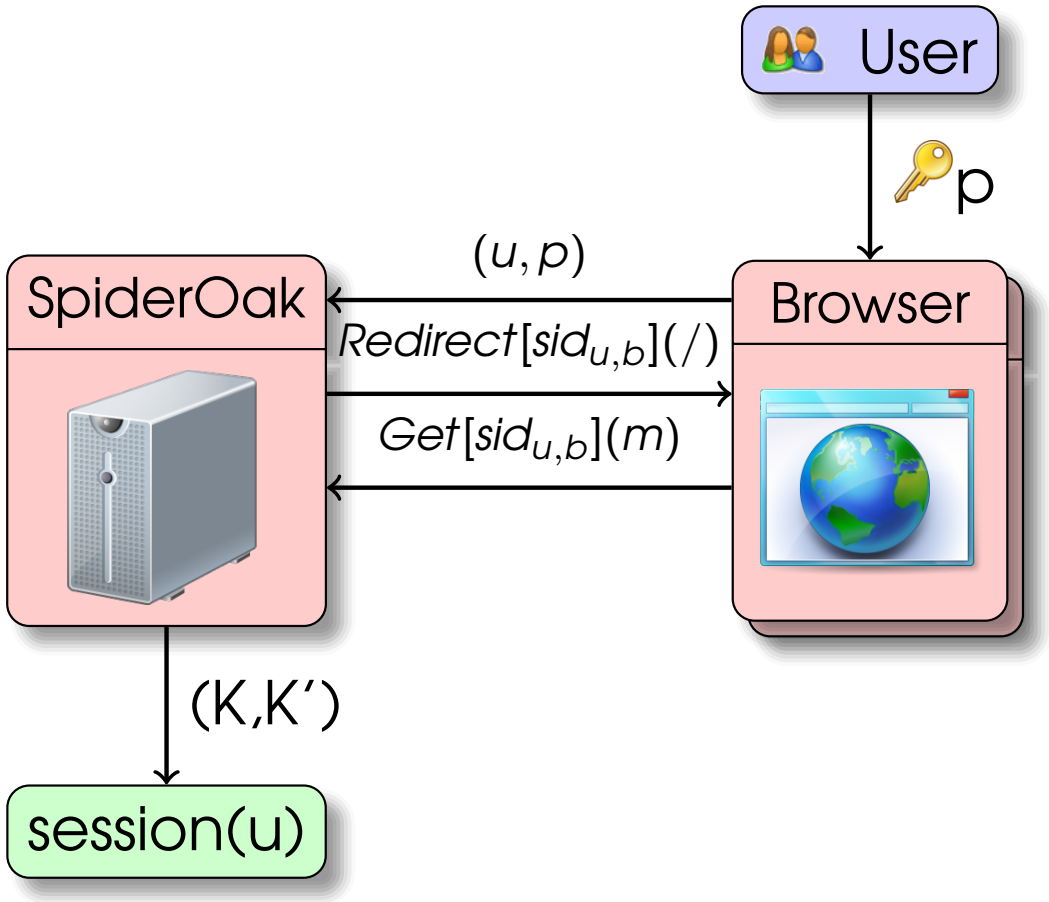

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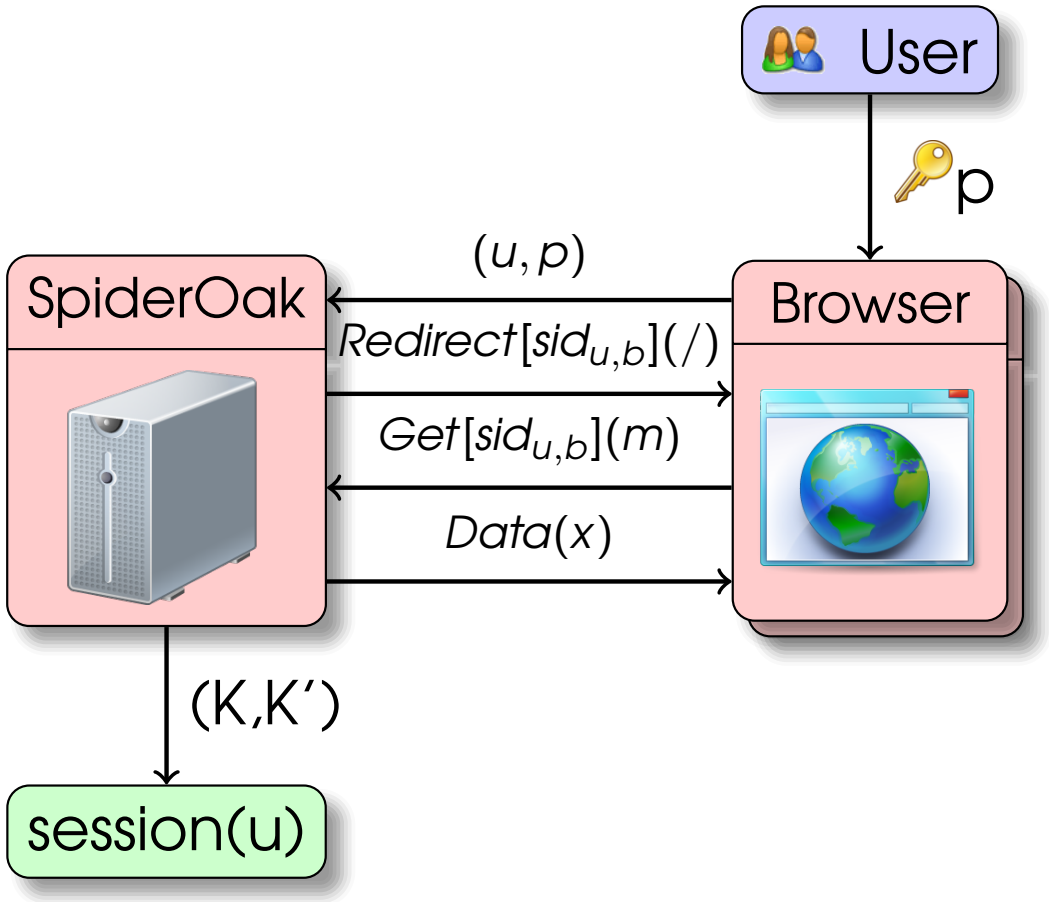

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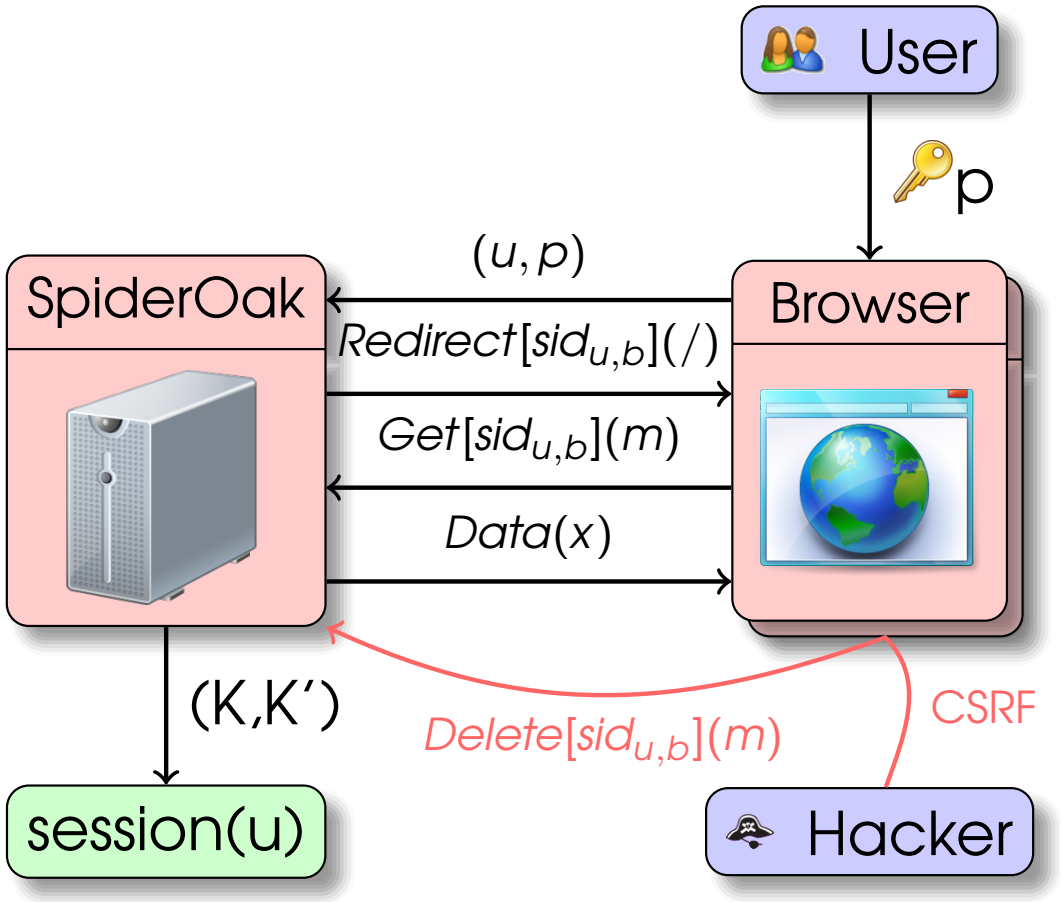
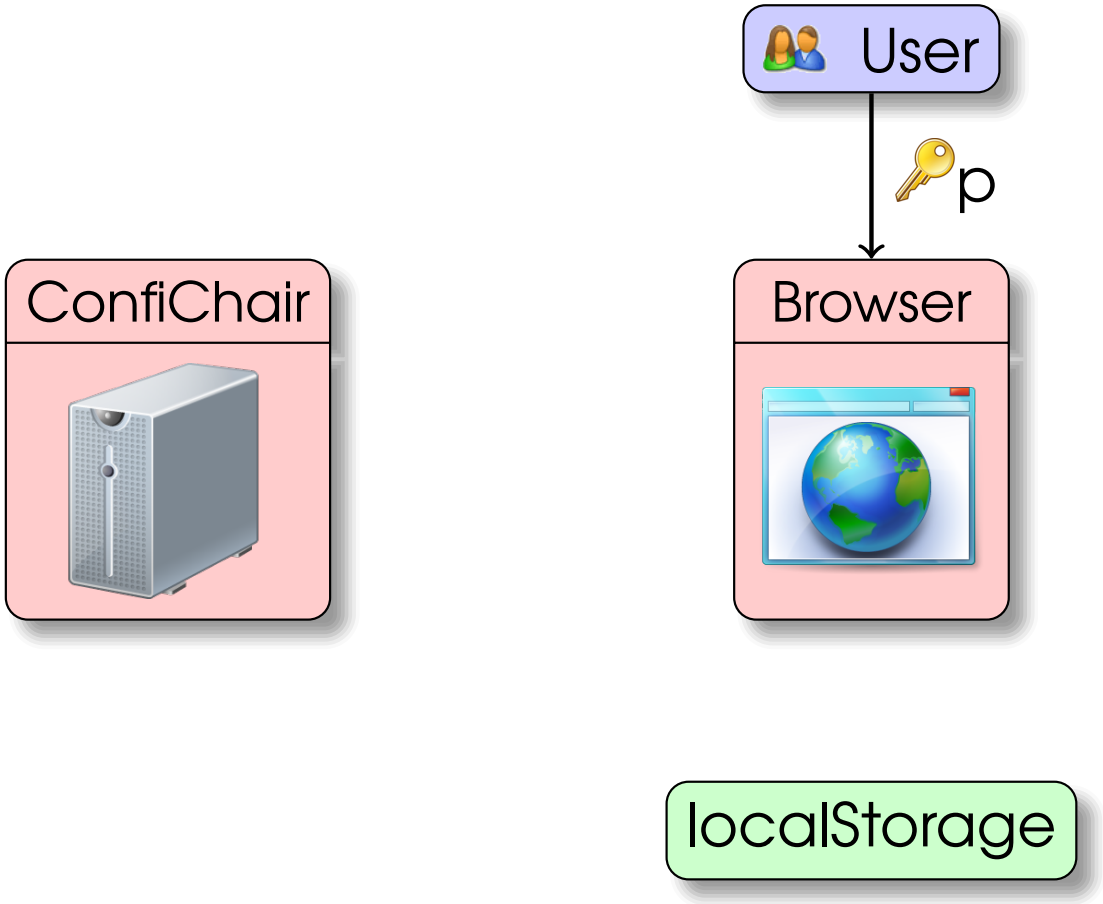


ConfiChair login



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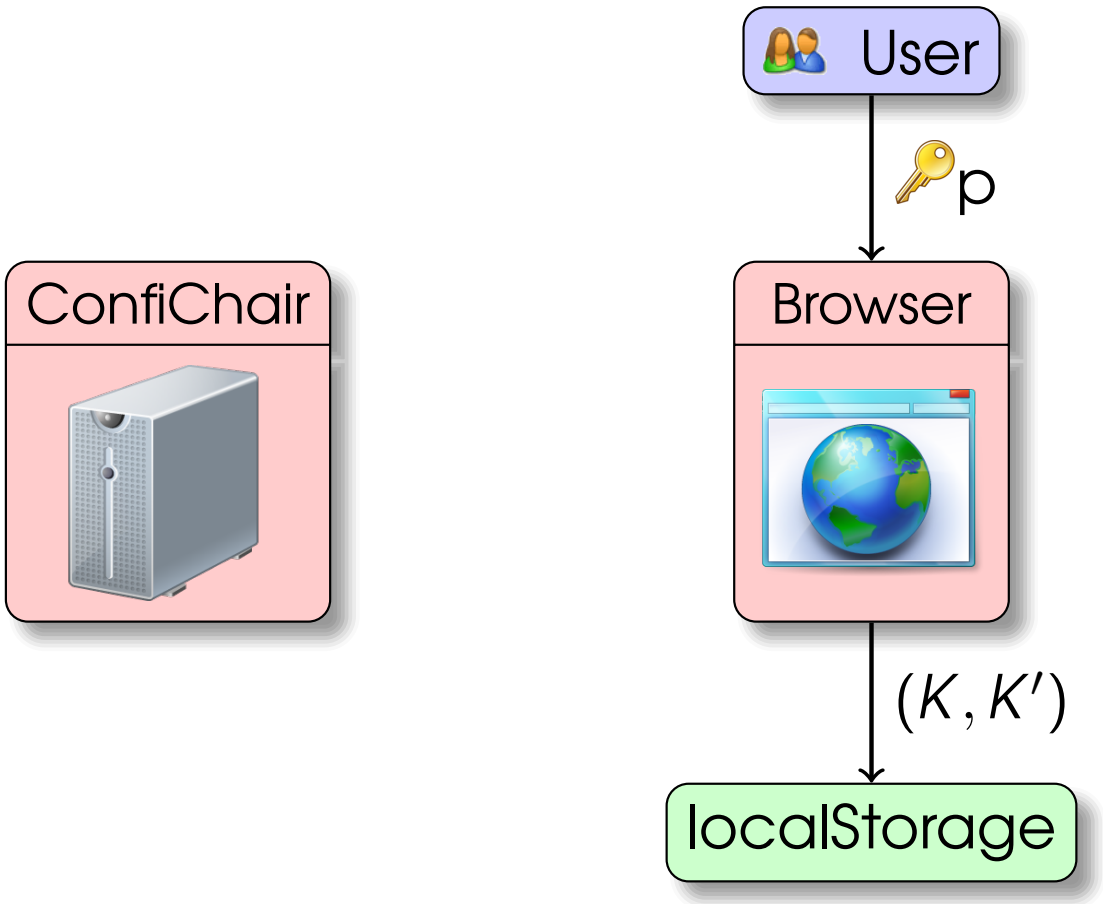

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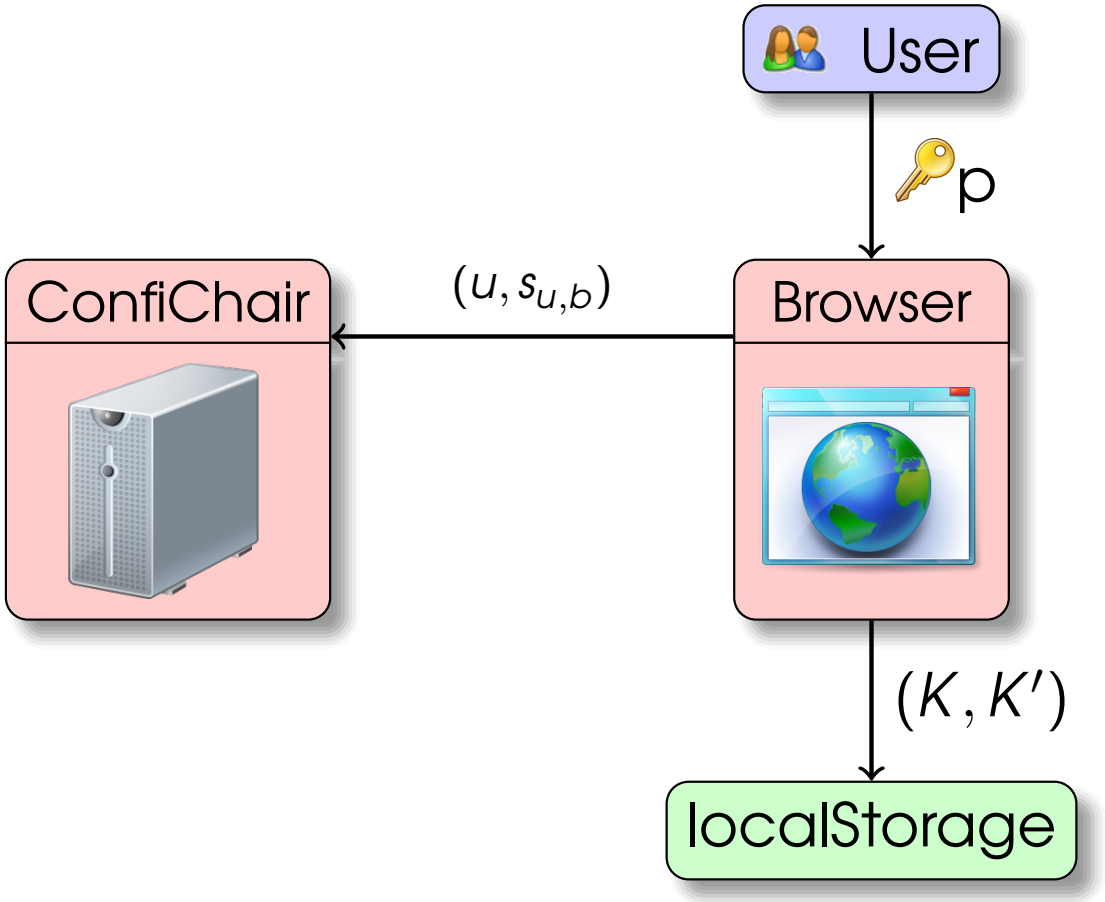

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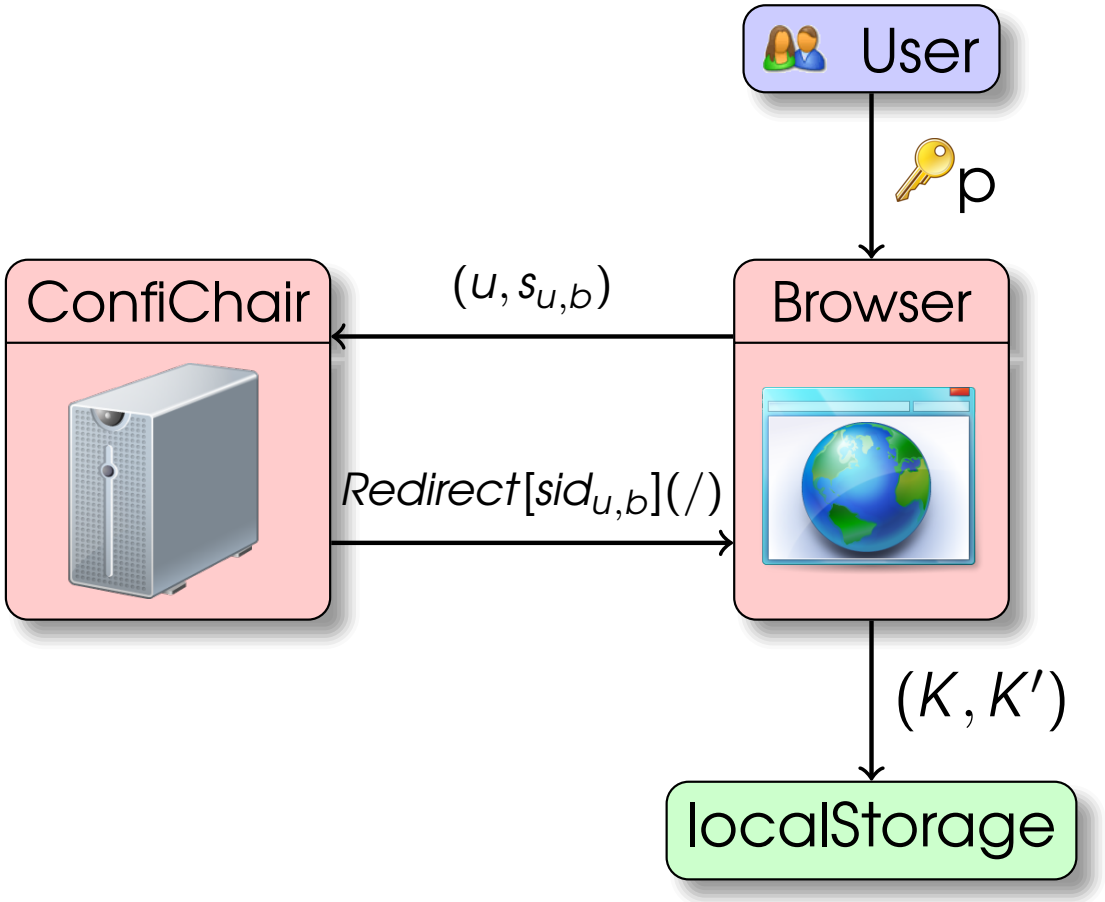

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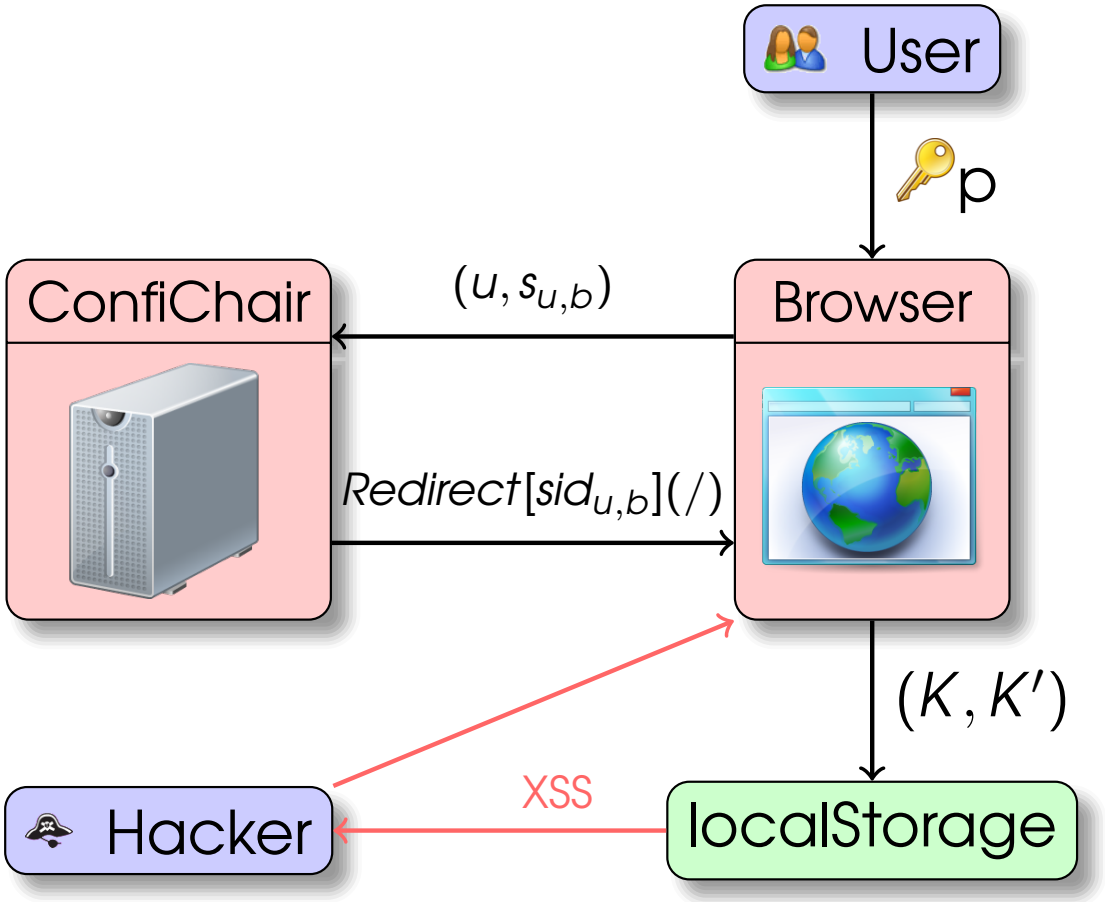

WebSpi

Formal analysis of cloud storage websites

- Applied pi-calculus model can easily reflect the application's cryptographic protocol
- Can a web attack be used to break a provably secure protocol?
- Can we make the cryptographic protocol more robust against common web threats?

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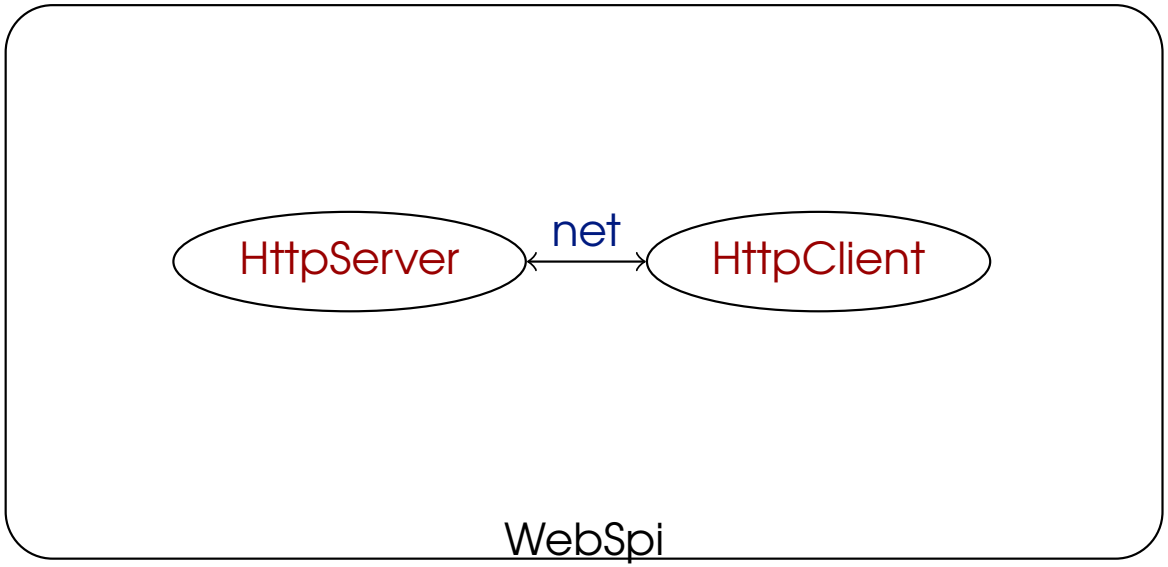
WebSpi overview



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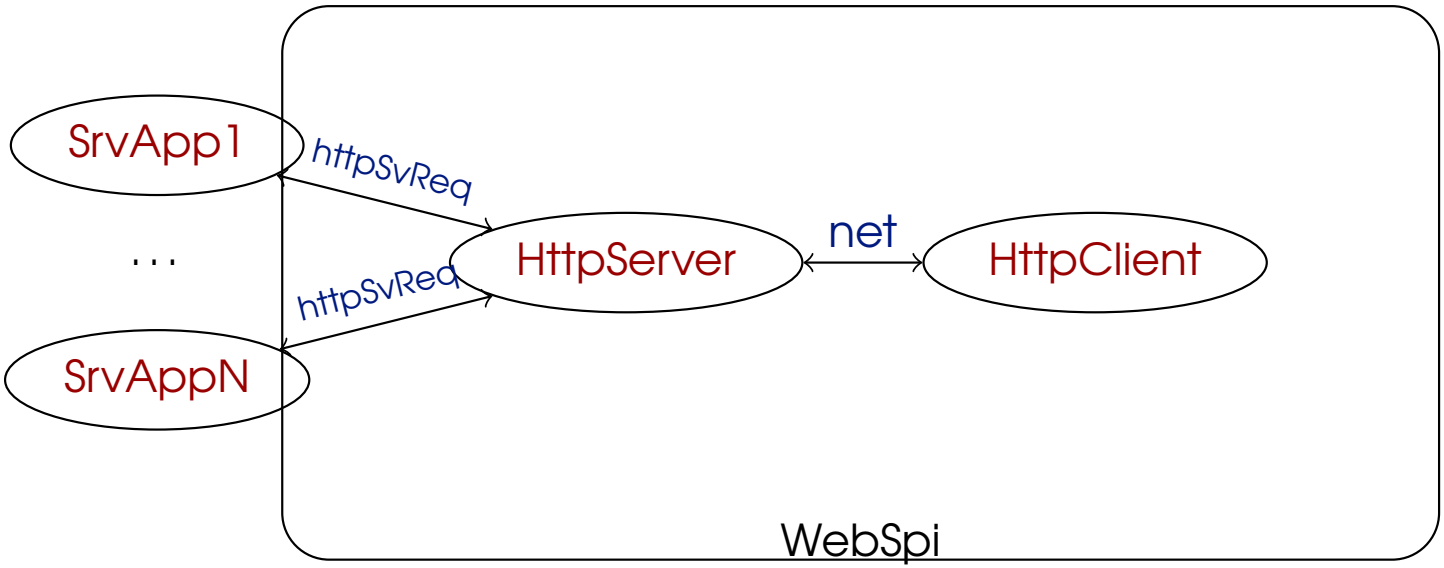

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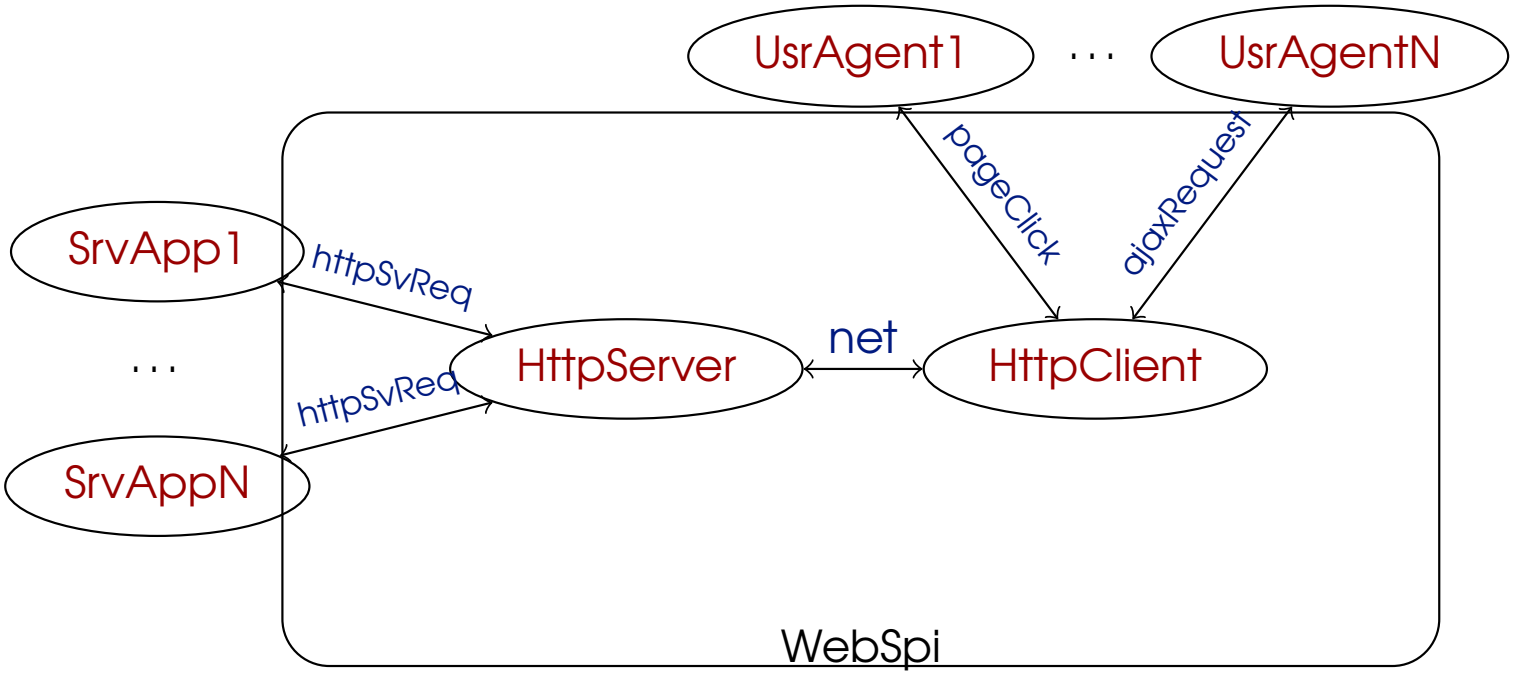

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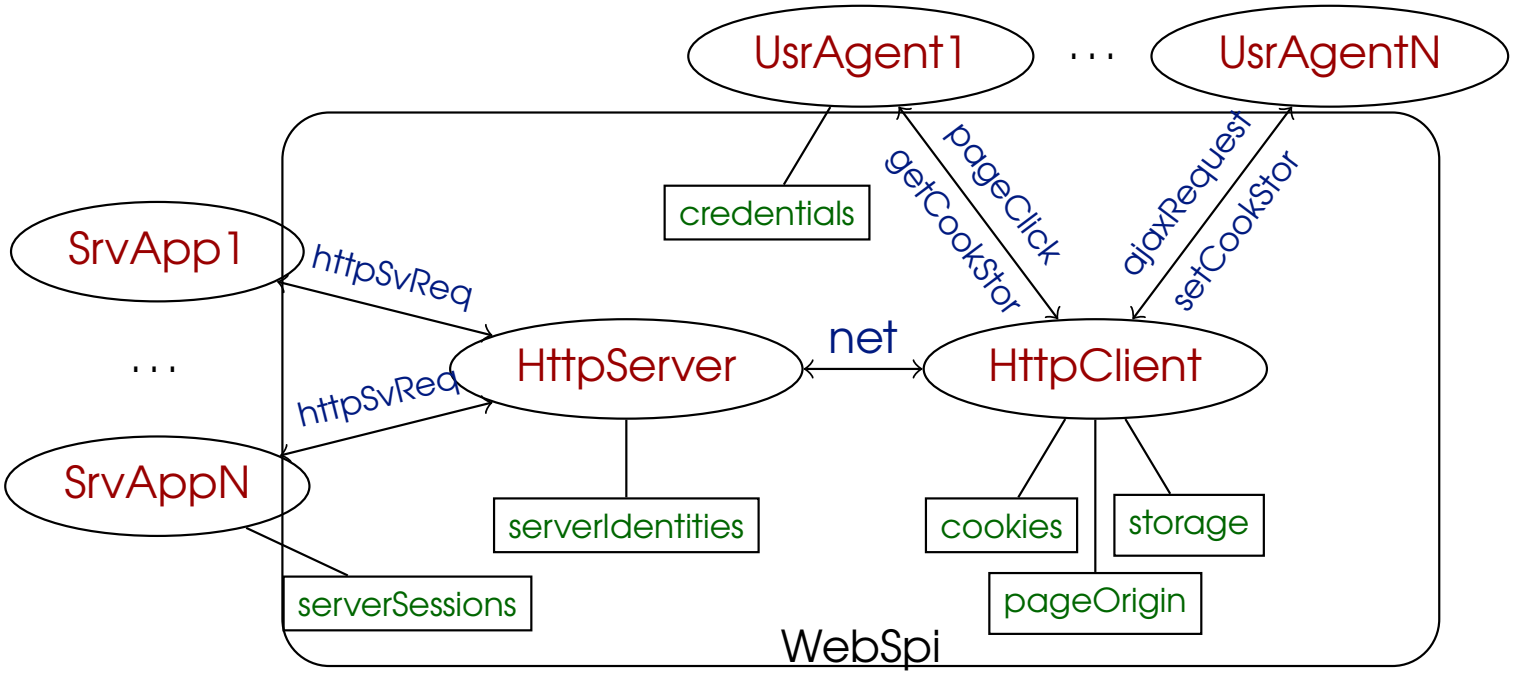

WebSpi model

Web client model

Client-side: process accepting requests on browser channels pageClick, ajaxRequest, getCookieStorage, setCookieStorage

Attacker model

- public net enables the standard Dolev-Yao *network attacker*
- a *compromised server* has its private key released
- *XSS* flaws are modeled by an AttackerProxy from net to the (secret) browser channels

WebSpi model

Verification

Security goals: correspondence assertions between user-defined events:

$$\forall M_1, \ldots M_k.\, e(M_1, \ldots M_k) \Rightarrow \varphi$$

Incompleteness

WebSpi not a complete model of the web.

- Still captures most common classes of attacks
- Extensible and actively developed

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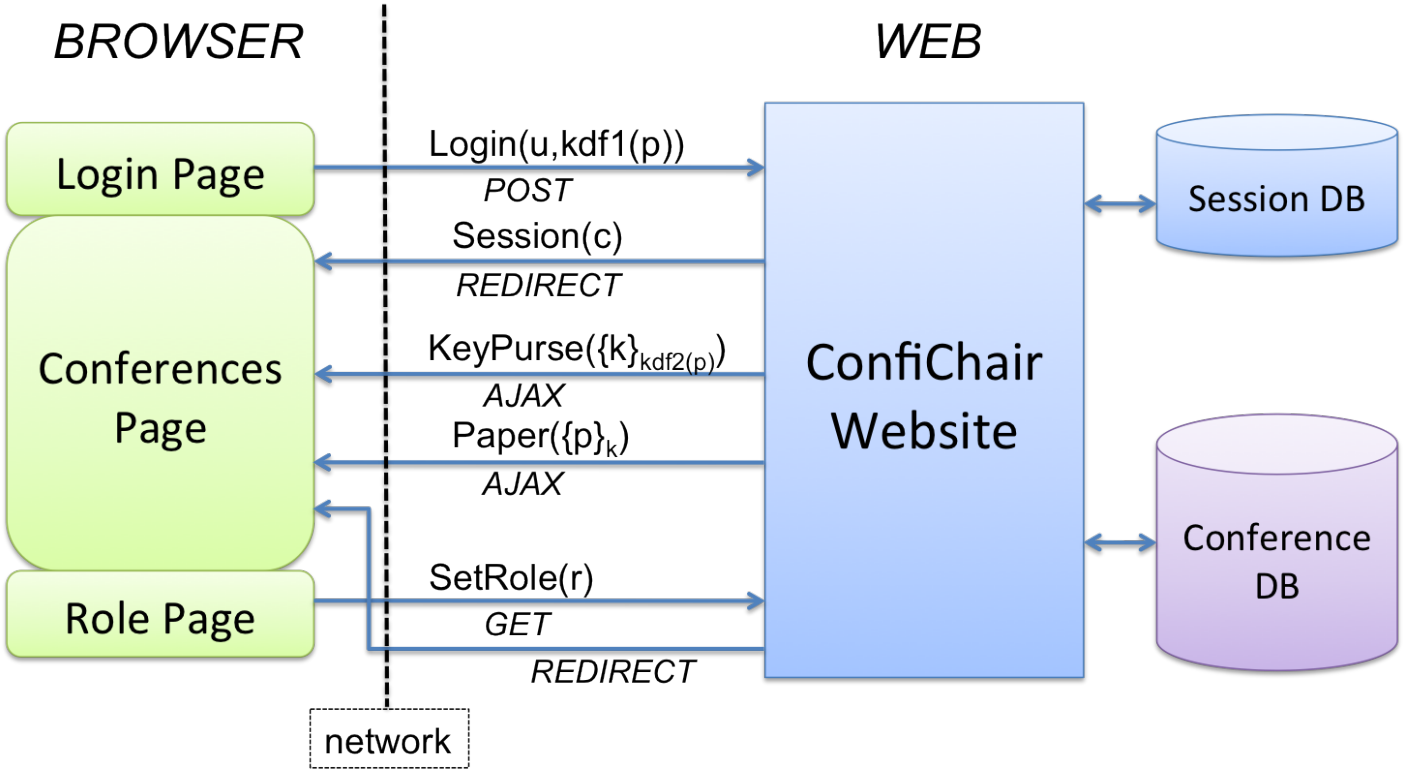
ConfiChair


BROWSER
WEB
Login Page
Conferences Page
Role Page
Login(u,kdf1(p))
POST
Session(c)
REDIRECT
KeyPurse({k}kdf2(p))
AJAX
Paper({p}k)
AJAX
SetRole(r)
GET
REDIRECT
network
ConfiChair Website
Session DB
Conference DB

ConfiChair login page

Login page

- LoginApp: server listening for requests on `/login`
- LoginUserAgent: JS and HTML of login page.
- waits for user to type username and password
- derives credential and sends it with username to LoginApp over HTTPS

```
let loginURI = uri(https(), confichair, loginPath(), noParams()) in
out(browserRequest(b),(loginURI, httpGet()));
in (newPage(b),(p:Page,=loginURI,d:bitstring));
get userData(=confichair, uid, pwd, paper) in
let cred = kdf1(pwd) in
in (getCookieStorage(b),(=p,cookiePair(cs,ch),od:Data));
out (setCookieStorage(b),(p,ch,storePassword(pwd)));
event LoginInit(confichair, b, uid);
out(pageClick(b),(p,loginURI,
        httpPost(loginFormReply(uid,cred))))
```

ConfiChair conference pages

Conference pages

- server-side ConferenceApp and client-side ConferenceUserAgent processes
- ConferencesUserAgent first retrieves user's keypurse using AJAX
- keypurse decrypted with stored key and stored in local storage

```
let keypurseURI = uri(https(), confichair,
    keyPursePath(), nullParams()) in
out (ajaxRequest(b),(p,keypurseURI,httpGet()));
in (ajaxResponse(b),(=p,=keypurseURI,JSON(x)));
in (getCookieStorage(b),
   (=p,cookiePair(cs,ch),storePassword(pwd)));
let keypurse(k) = adec(x, kdf2(pwd)) in
out (setCookieStorage(b),(p,ch,storeKeypurse(k)))
```

ConfiChair conference pages

Conference pages

At any point, user may request a paper to be downloaded and decrypted using key in keypurse

```
let paperURI = uri(https(), h, paperPath(), nullParams()) in
out (ajaxRequest(b),(p,paperURI,httpGet()));
in (ajaxResponse(b),(=p,=paperURI,JSON(y)));
in (getCookieStorage(b),
   (=p,cookiePair(cs,ch),storeKeypurse(k)));
let paper = adec(y,k) in event PaperReceived(paper))
```

ConfiChair security goals

Security goals

- Login authentication:

```
event(LoginAuthorized(confichair,id,u,c))
  ⟹event(LoginInit(confichair,b,id))
```

- Secrecy of papers:

```
in(paperChannel, paper:bitstring);
get userData(h, uId, k, =paper) in
 event PaperLeak(uId,paper).
query u:Id,p:bitstring; event(PaperLeak(id,p))
```

ConfiChair attacker

XSS vulnerability in Role Page

`http://confichair.org/?set-role=<script>S</script>`

If requested role is invalid, returned error page contains the unsanitized requested role name.

In RoleUserAgent, the page identifier is released

```
let roleURI = uri(https(), h, changeRolePath(), roleParams(x)) in
out(browserRequest(b),(roleURI, httpGet()));
in (newPage(b),(p:Page,=roleURI,y:bitstring));
out(pub, p)
```

Result of verification

Authentication goal is broken

Attacker can read the user's password from local storage and leak it to a malicious website

Paper privacy is broken

Attacker can read the paper decryption key from local storage and leak it to a malicious website

... in previous ProVerif analysis, same goals were valid against cloud attacker model.

Robustness against XSS

Robustness against XSS

- Can fix XSS, but there could be others
- As a first step, store (K, K') rather than p
- Server wraps all keys in keypurse with a fresh, short-lived key.
- The decryption script unwraps the input key before decryption
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- The decryption script unwraps the input key before decryption
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From implementation to model

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Thank you. Questions?

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