PARASITE: PAssword Recovery Attack against Srp Implementations in ThE wild

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Mohamed Sabt

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Context and Motivations

A Few Words About PAKEs

What to expect from a PAKE, starting from a password:

- Authentication
- End up with strong key
- Resist to (offline) dictionary attack

Lots of different PAKEs (two main families: balanced - asymmetric).

Why Looking at PAKEs?

Recent interest (WPA3 and CFRG competition after patents expiration) with practical security considerations

- Dragonfly and WPA3: Dragonblood[1] and attack refinement[2]
- Partitioning Oracle Attack[3] applied to some OPAQUE implementations

Small leakage can be devastating

Case study: Secure Remote Password

[1] M.Vanhoef and E.Ronen *Dragonblood: Analyzing the Dragonfly Handshake of WPA3 and EAP-pwd*. In IEEE S&P. 2020

[2] D.Braga et al. *Dragonblood Is Still Leaking: Practical Cache-based Side-Channel in the Wild*. In ACSAC. 2020

[3] J.Len et al. *Partitioning Oracle Attack*. In USENIX Security. 2021

What about SRP?

Available for a long time => de facto standard for more than 20 years

What about SRP implementations in the wild ?

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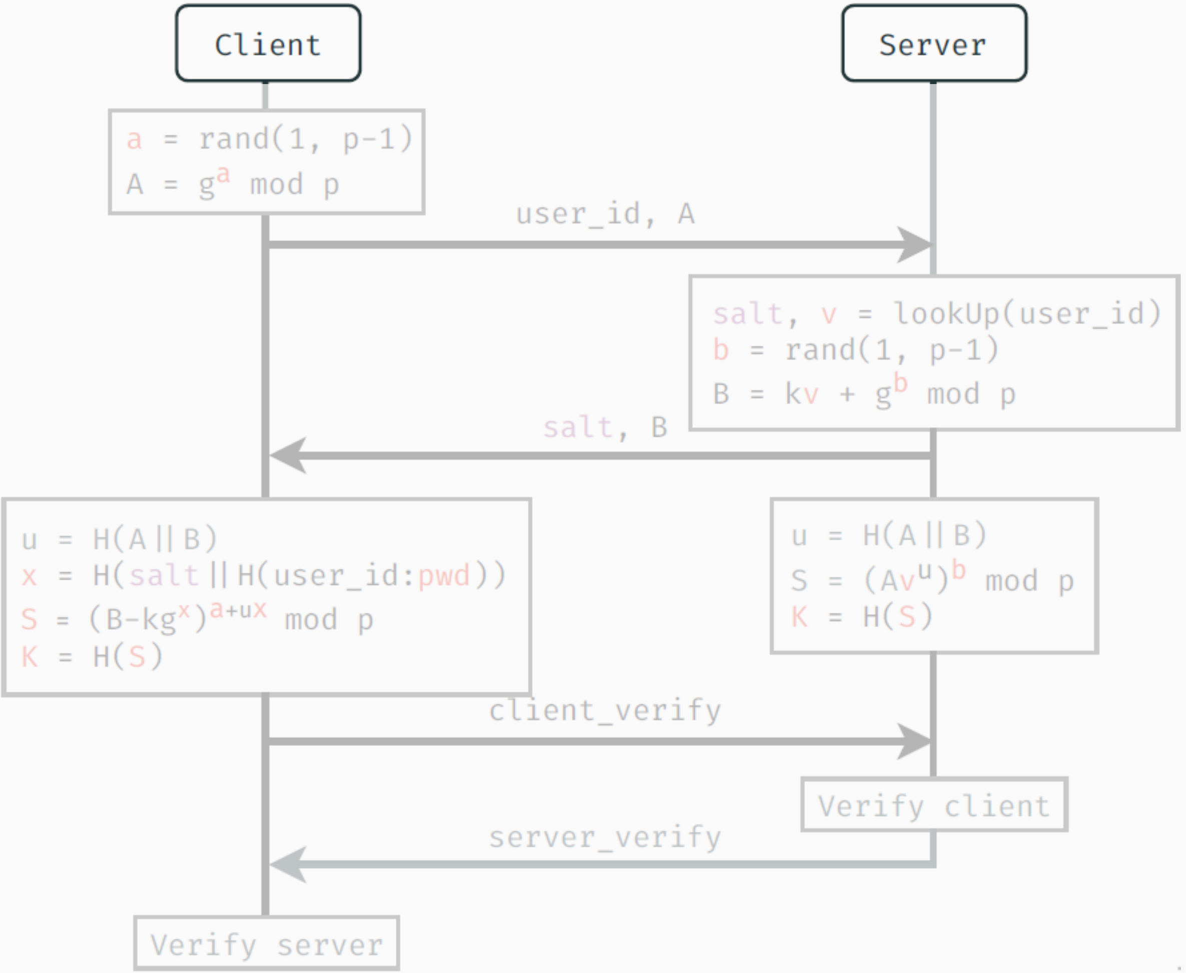
What about SRP implementations in the wild ?

- Recent work on SRP at ACNS[1]

[1] A.Russon Threat for the Secure Remote Password Protocol and a Leak in Apple’s Cryptographic Library. In ACNS. 2021

SRP Protocol Overview



Client

Server

$a = \text{rand}(1, p-1)$

$A = g^{a} \bmod p$

user_id, A

$\text{salt}, v = \text{lookUp}(\text{user\_id})$

$b = \text{rand}(1, p-1)$

$B = kv + g^{b} \bmod p$

salt, B

$u = H(A \,||\, B)$

$x = H(\text{salt} \,||\, H(\text{user\_id}:\text{pwd}))$

$S = (B - kg^{x})^{a+ux} \bmod p$

$K = H(S)$

$u = H(A \,||\, B)$

$S = (Av^{u})^{b} \bmod p$

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client_verify

Verify client

server_verify

Verify server

SRP Protocol Overview

pwd

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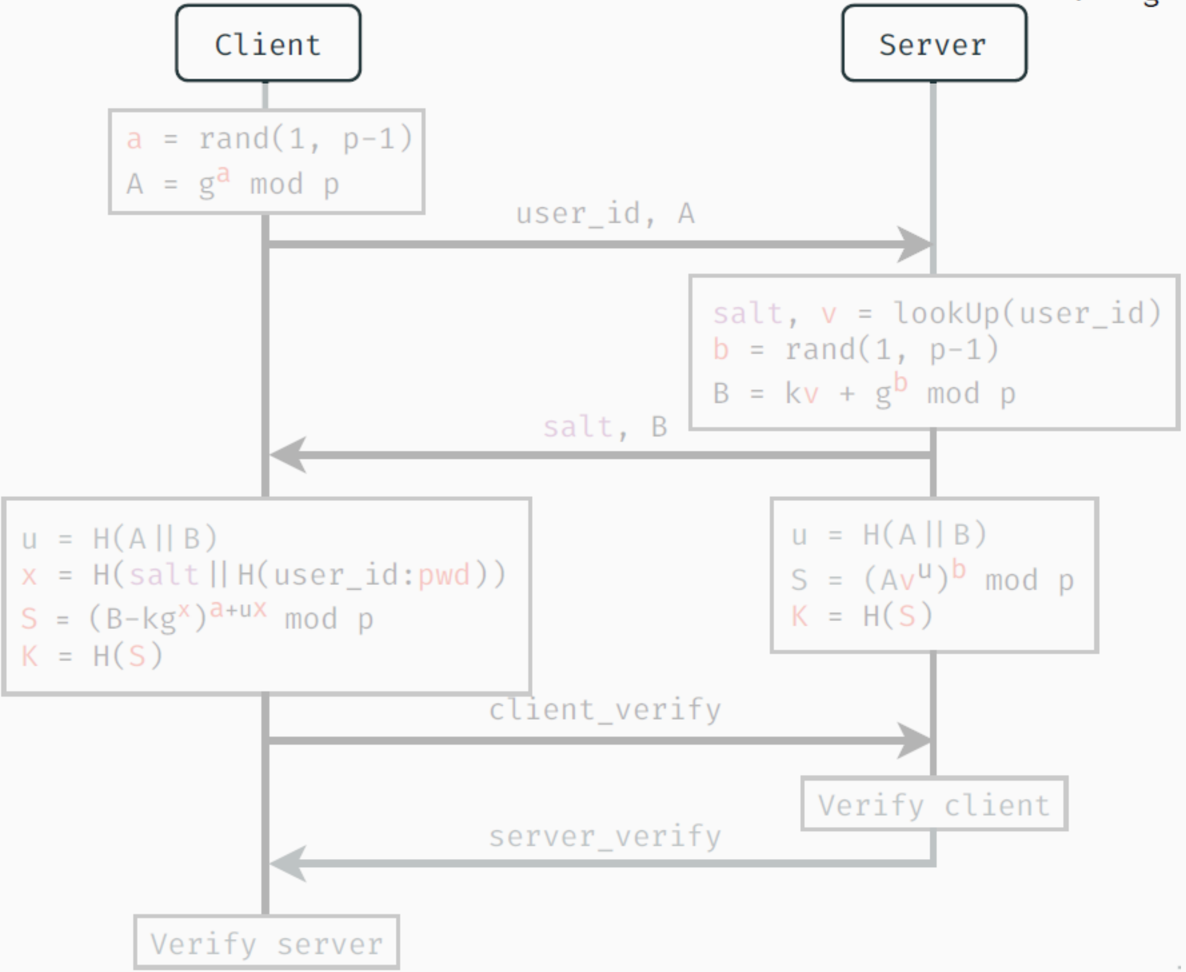

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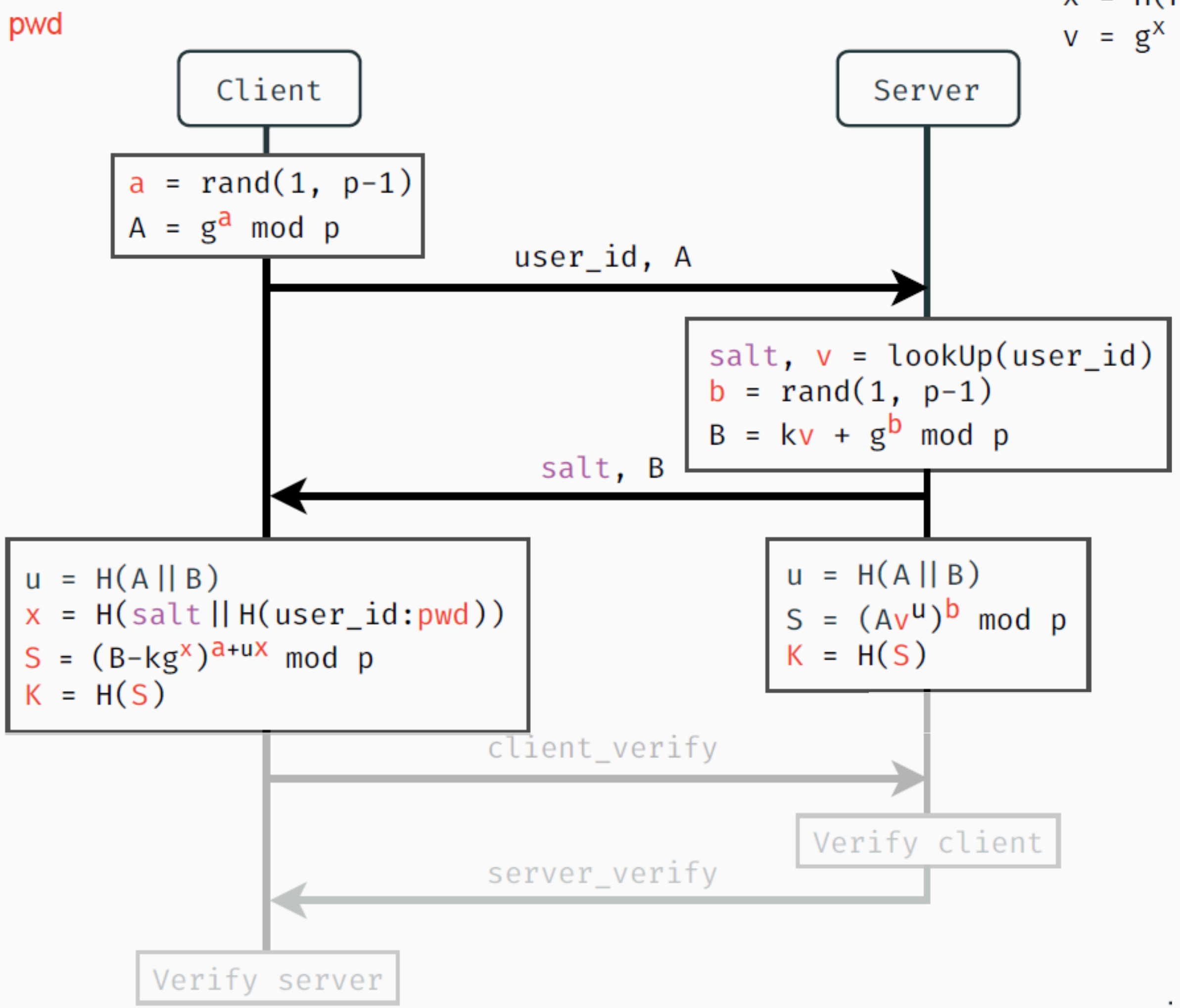

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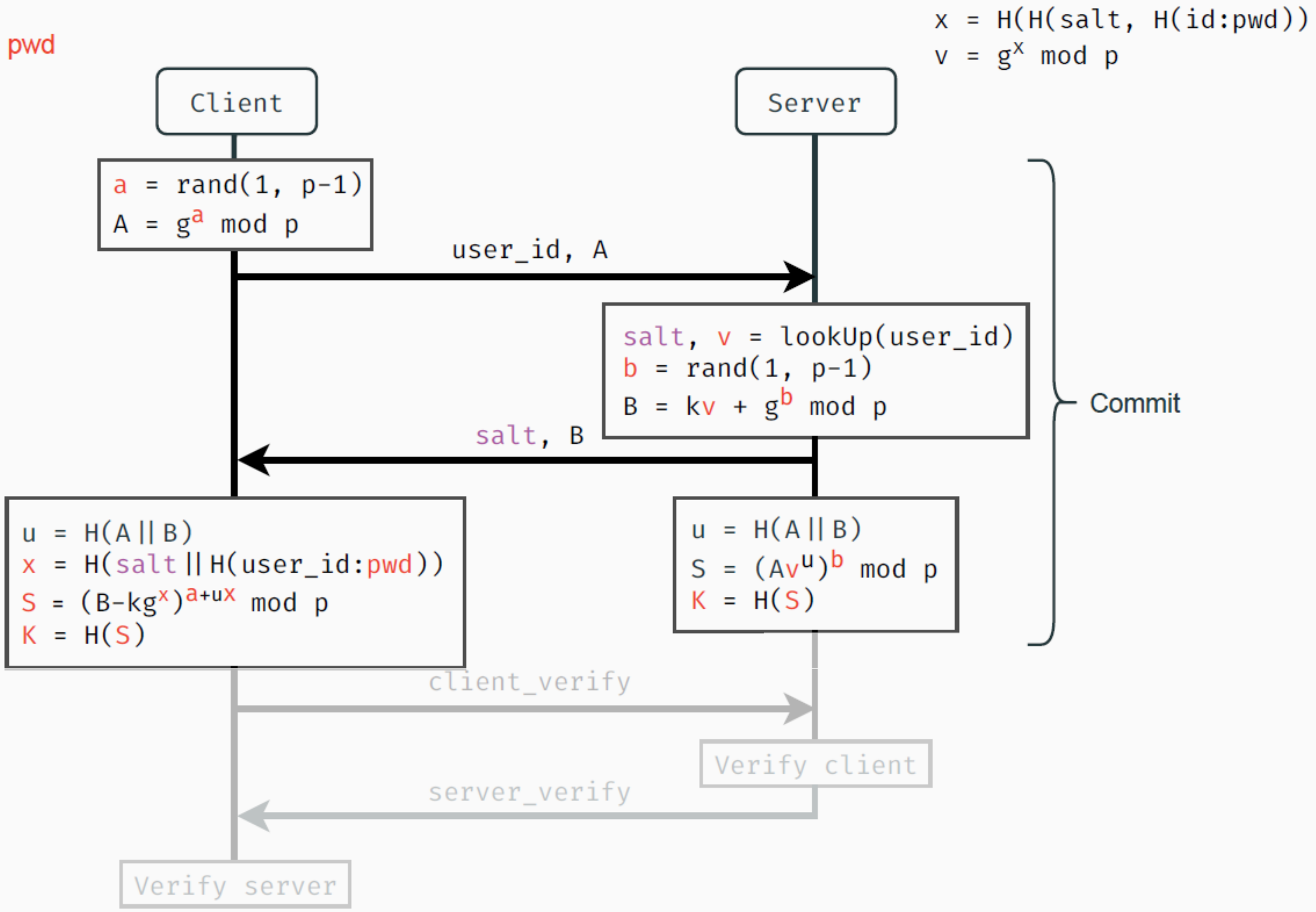

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salt, B

Commit

$u = H(A \| B)$

$x = H(salt \| H(user\_id{:}pwd))$

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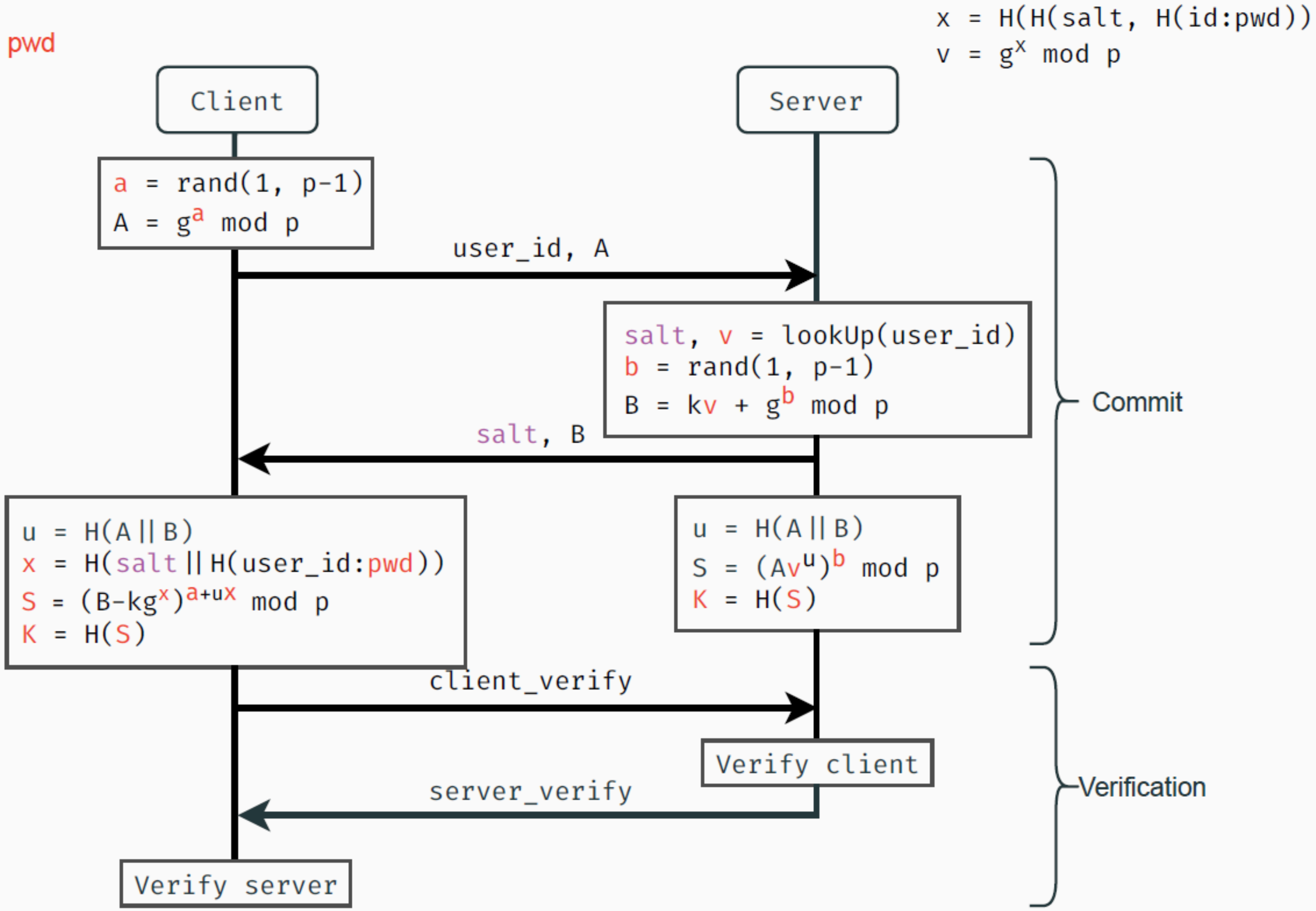

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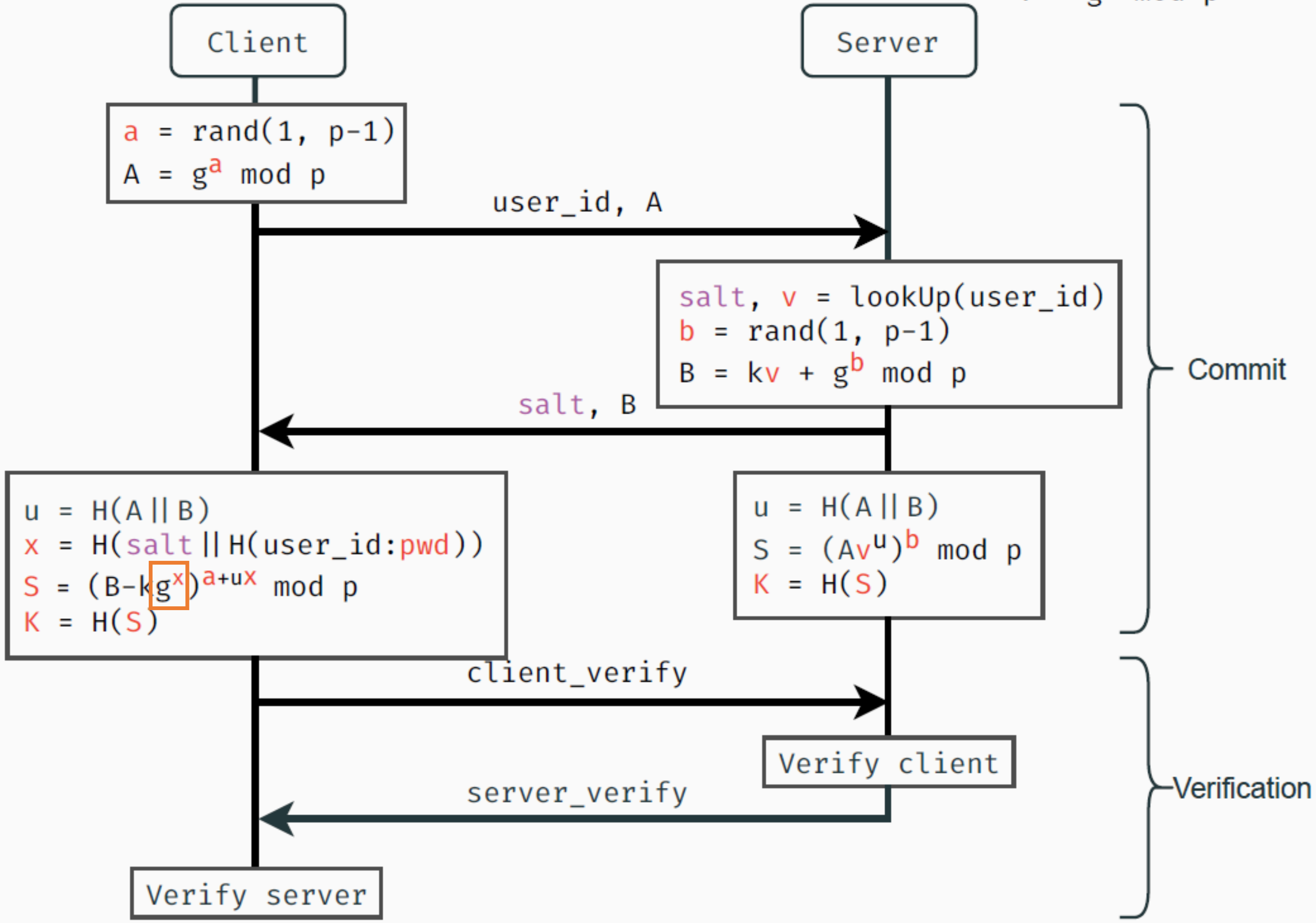

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Verification

Contributions

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1. Study of various SRP implementations

2. Highlight a leakage in the root library used for big number arithmetic (OpenSSL)

3. Design PoCs of an offline dictionary attack recovering the password on impacted projects

4. Outline the importance of SCA, especially for PAKEs

Our Main Result

A cache-attack that lets us extract information during OpenSSL modular exponentiation allowing to recover the password in a single measure.

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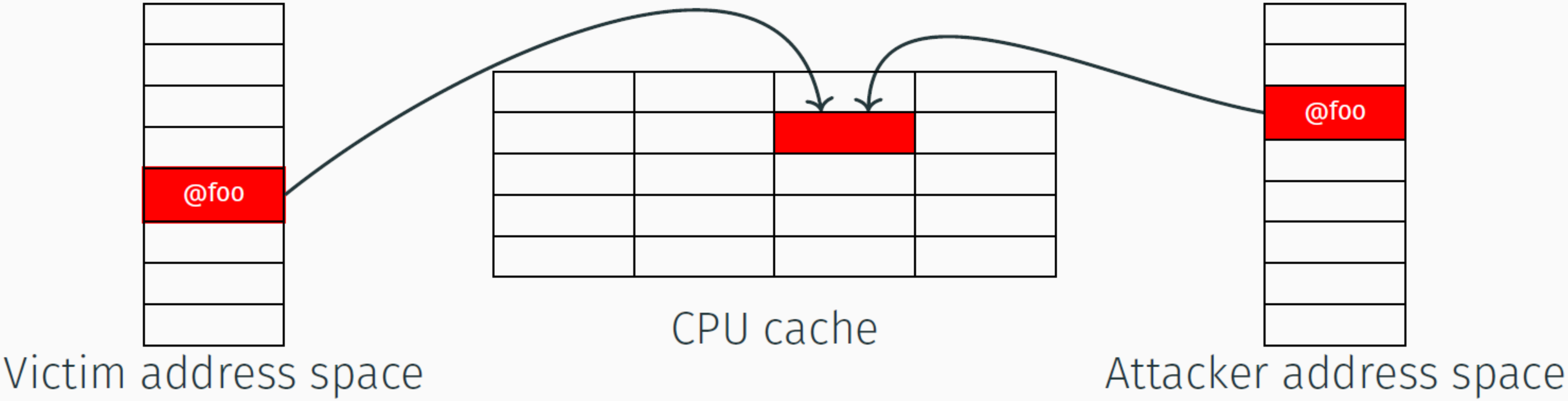
FLUSH+RELOAD[1]



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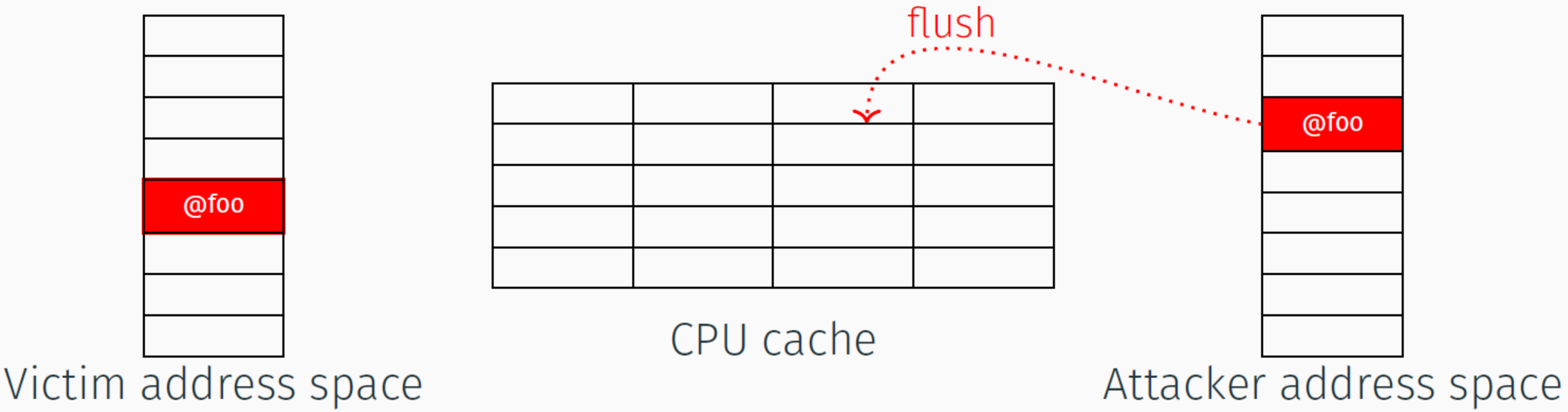

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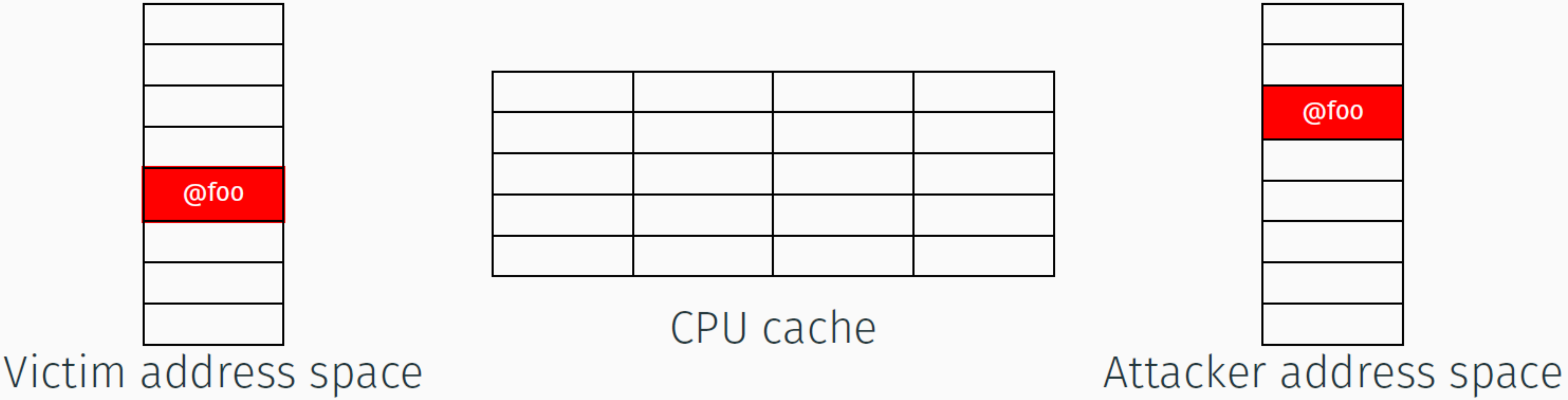

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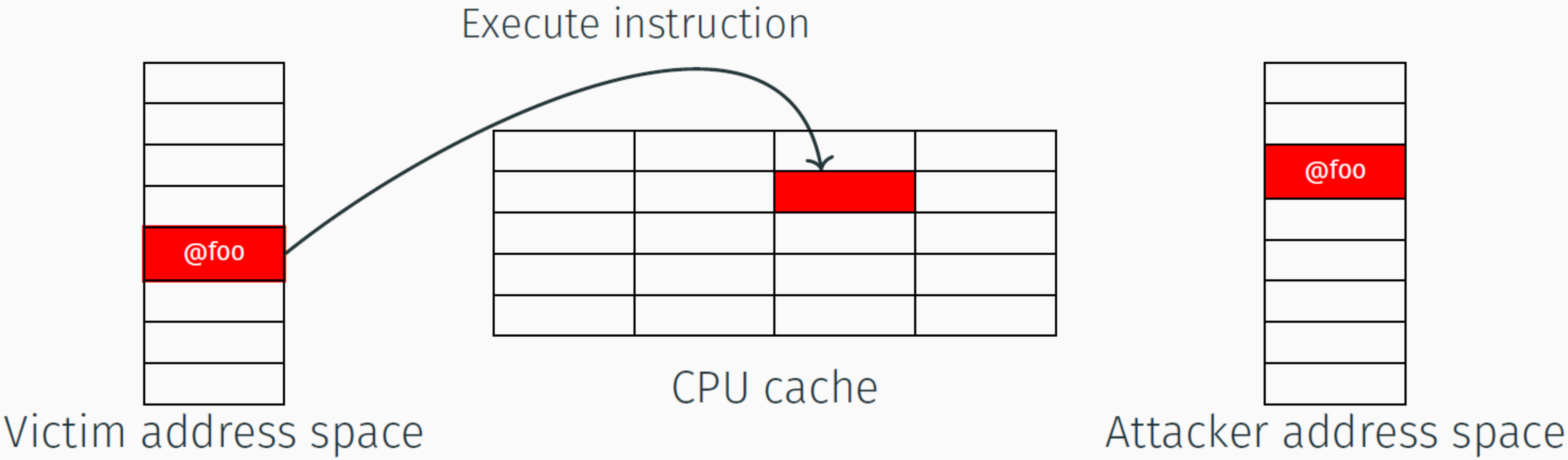

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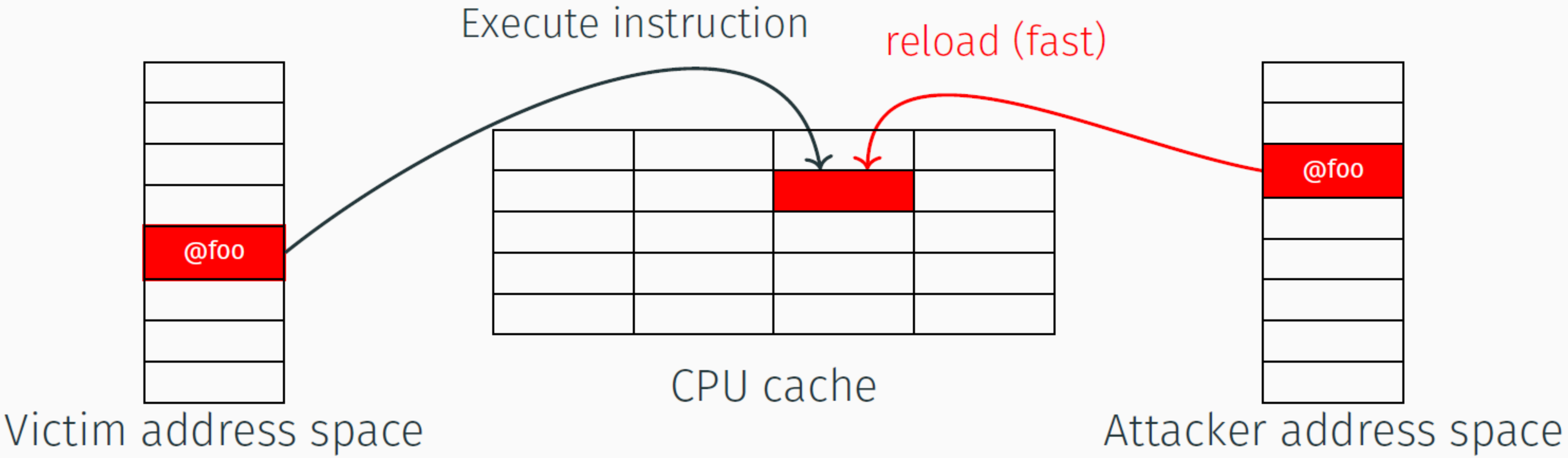

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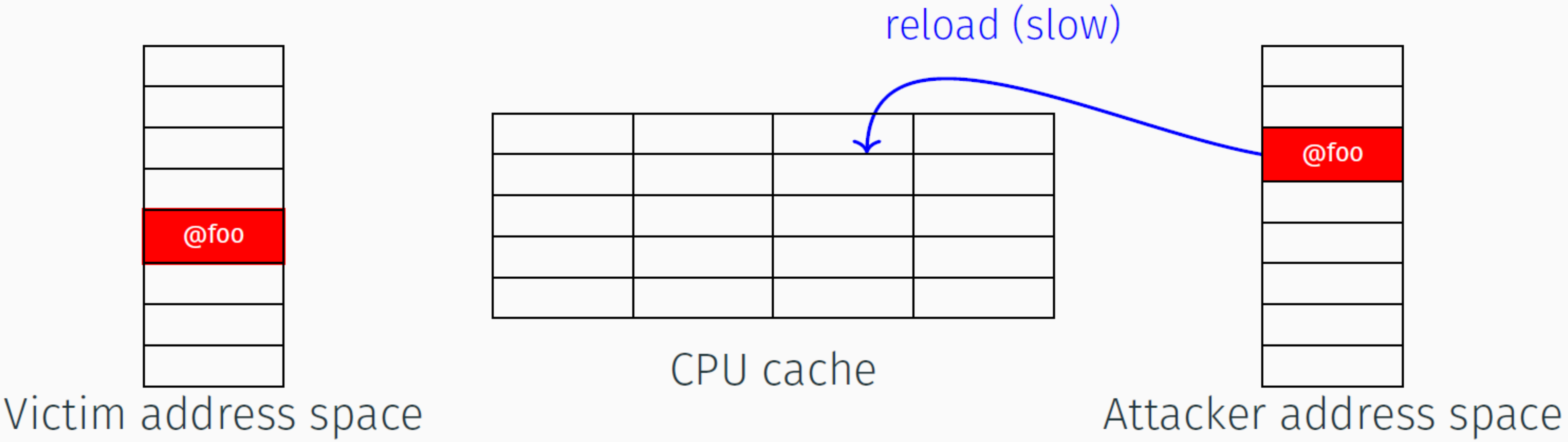

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    - Fast ⇒ the victim already executed
    - Slow ⇒ the victim did not

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Passive offline attack

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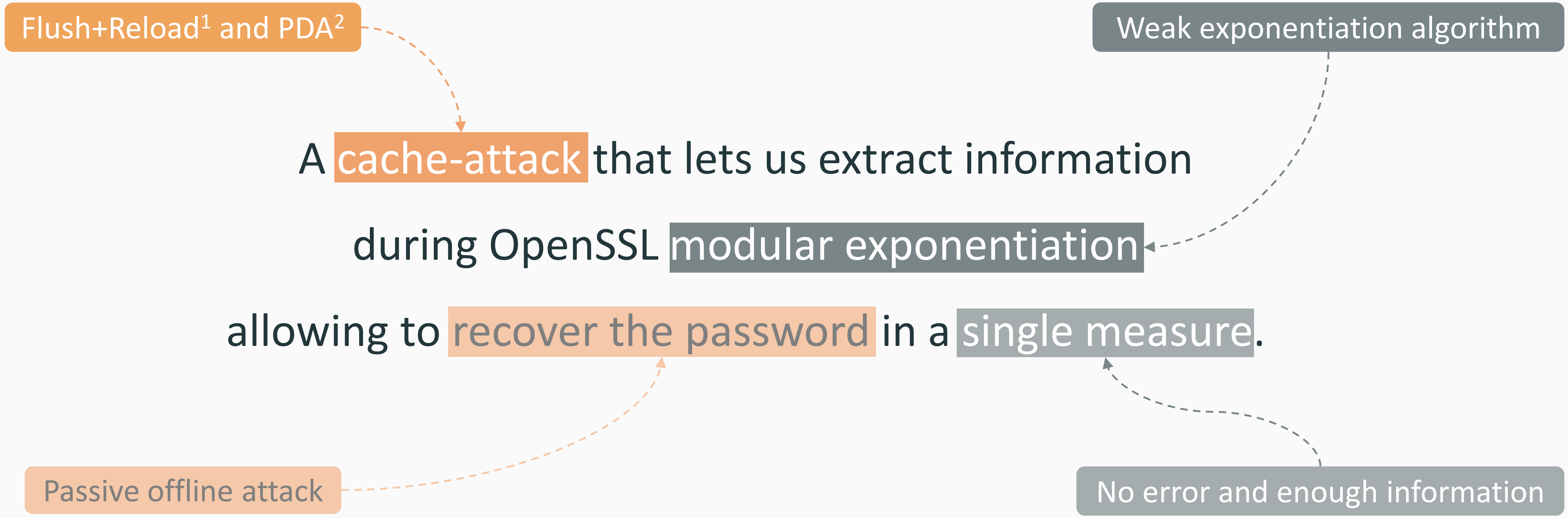

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Passive offline attack

No error and enough information

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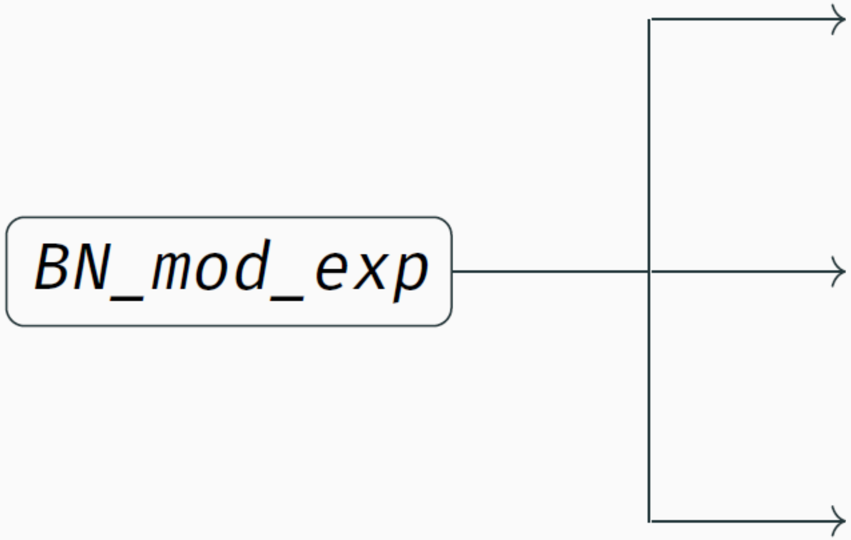
The Vulnerability

Modular exponentiation in OpenSSL

BN_mod_exp

Modular exponentiation in OpenSSL



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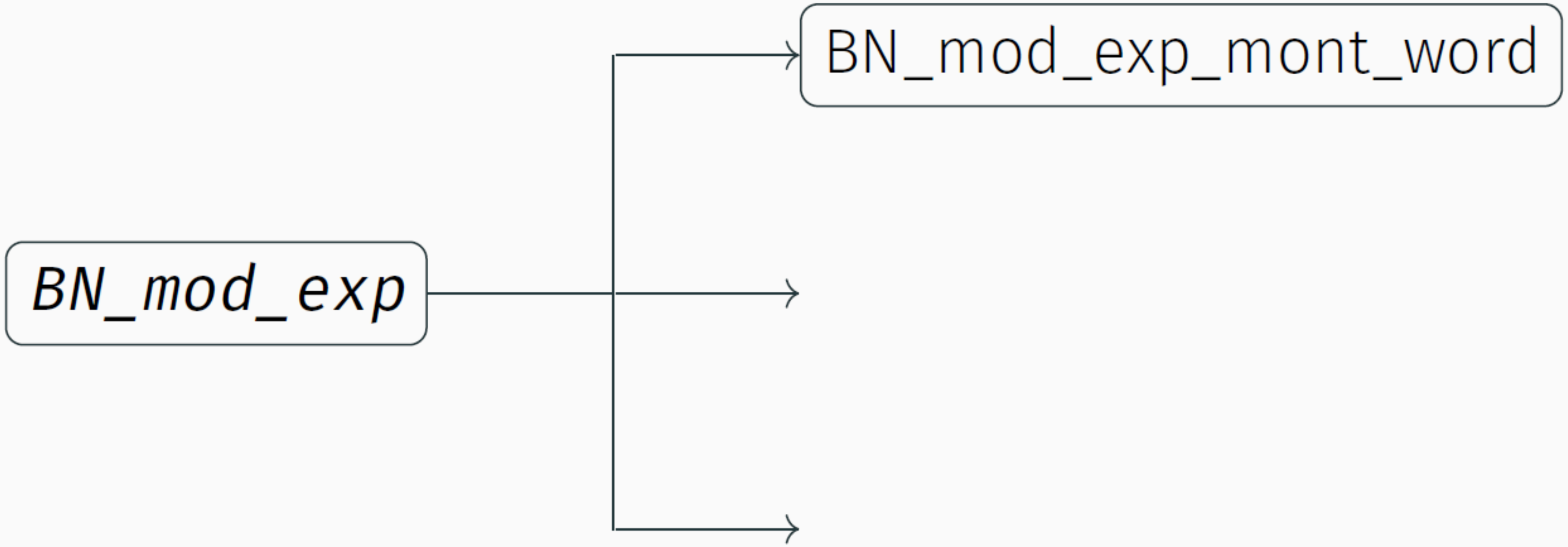

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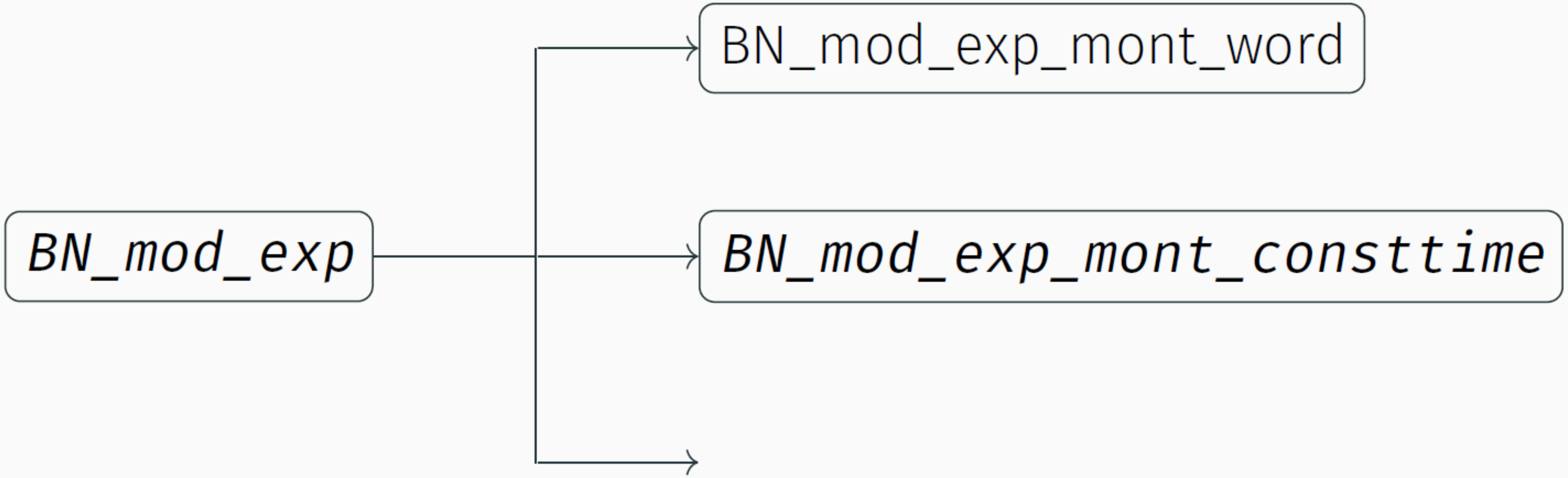

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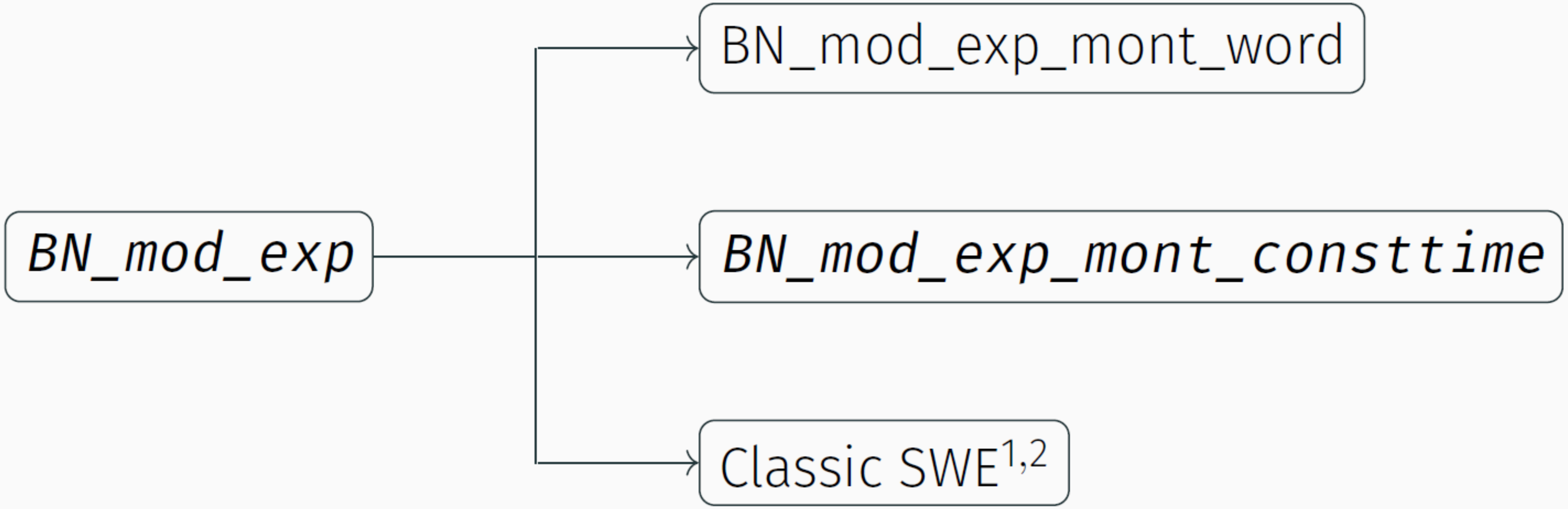

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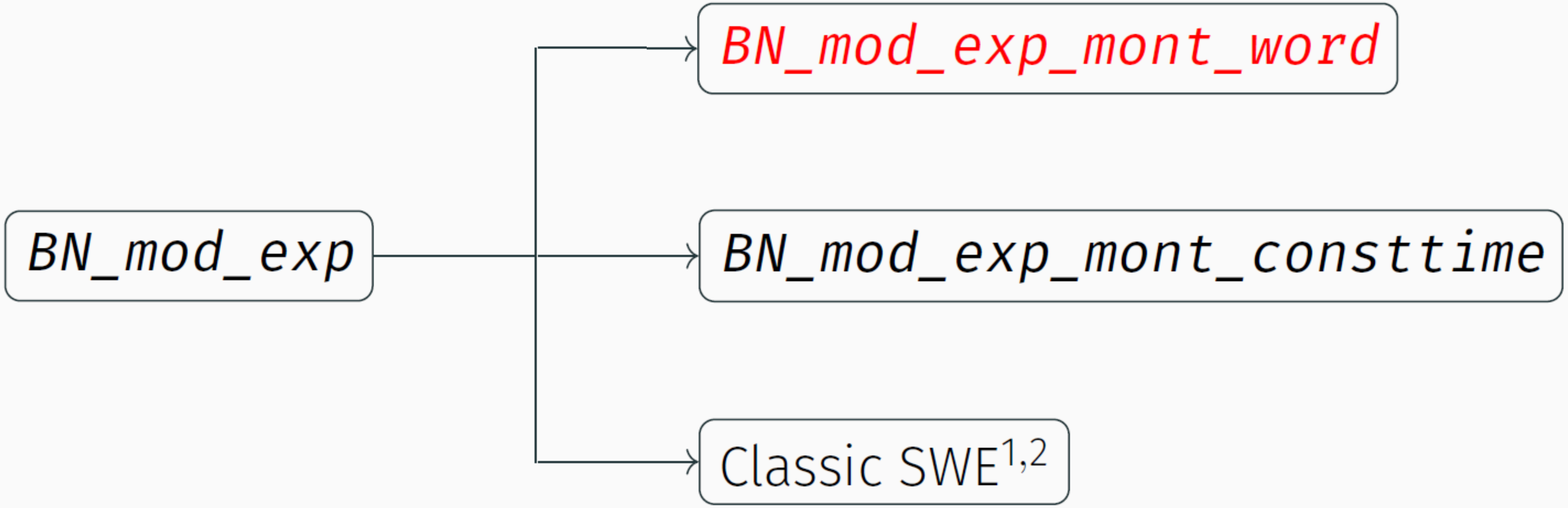

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Optimized Square-and-Multiply

$bin(e) =$ 1 1 0 1 0 . . .

$res = g^e mod\, p$

w is a processor word (e.g. 64 bits)

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def BN_mod_exp_mot_word(g, w, p):
    …
    w = g                     # uint64_t
    res = BN_to_mont_word(w)  # bigum
    for b in range(bitlen-2, 0, -1):
        next_w = w x w
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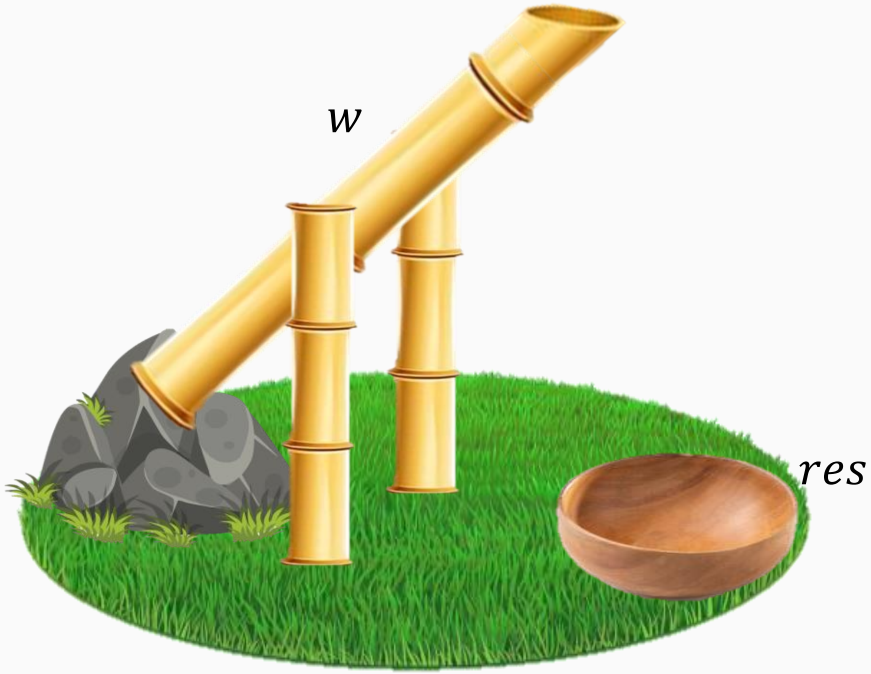

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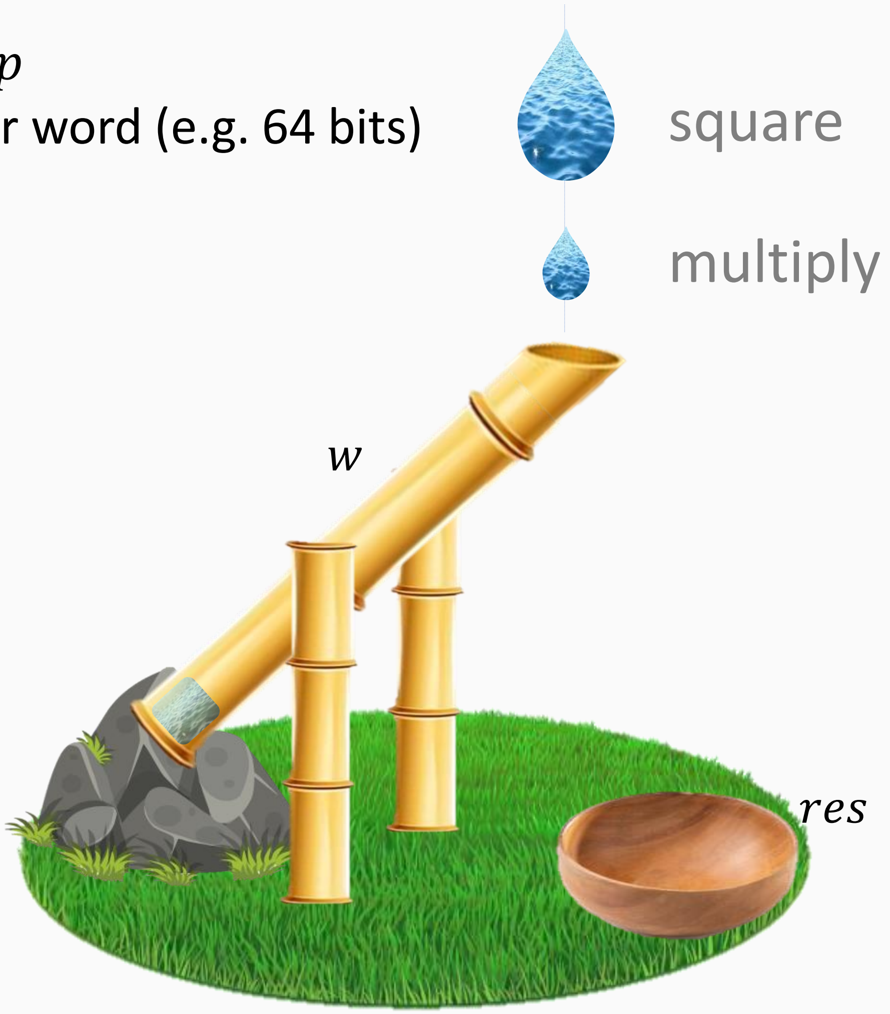

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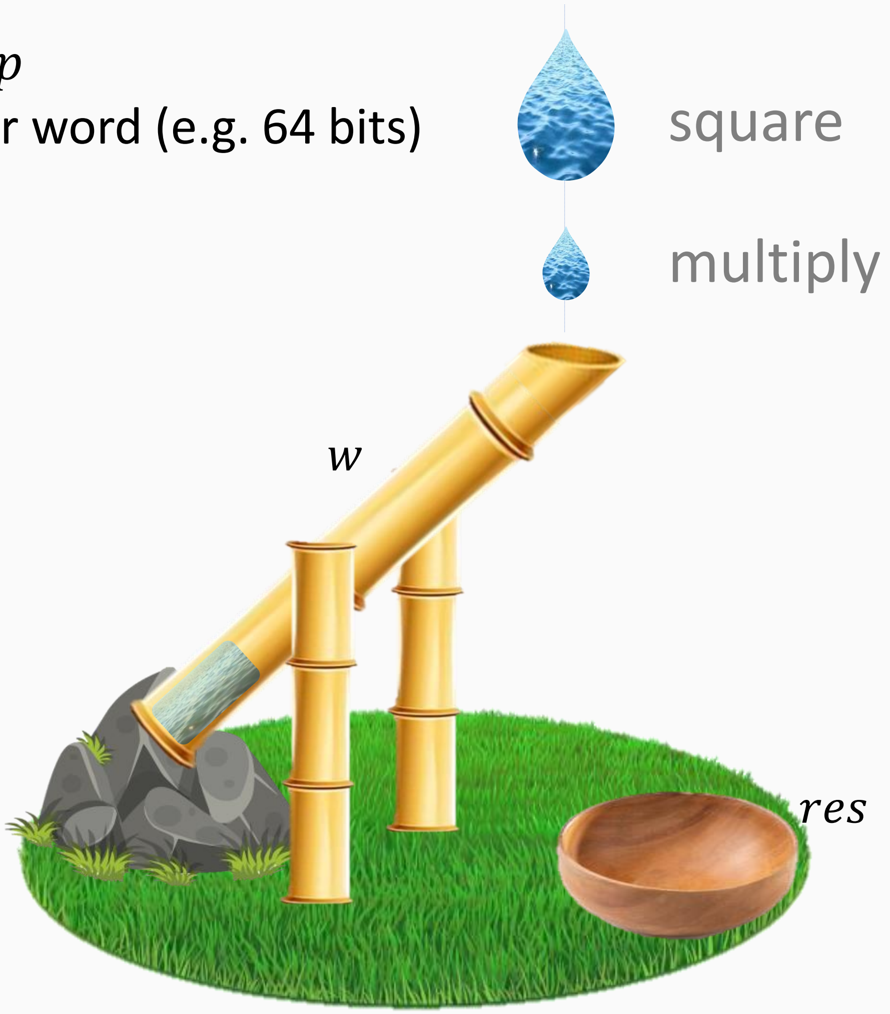

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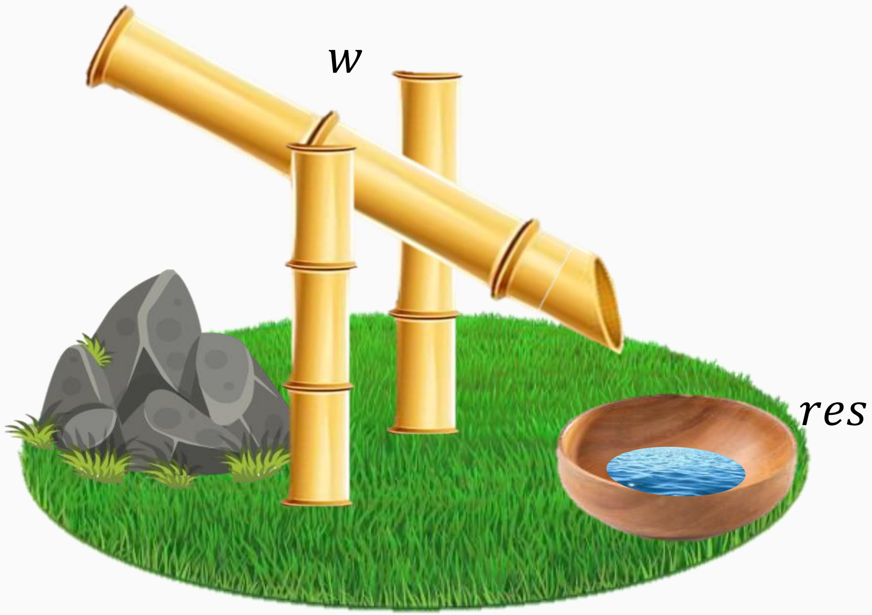

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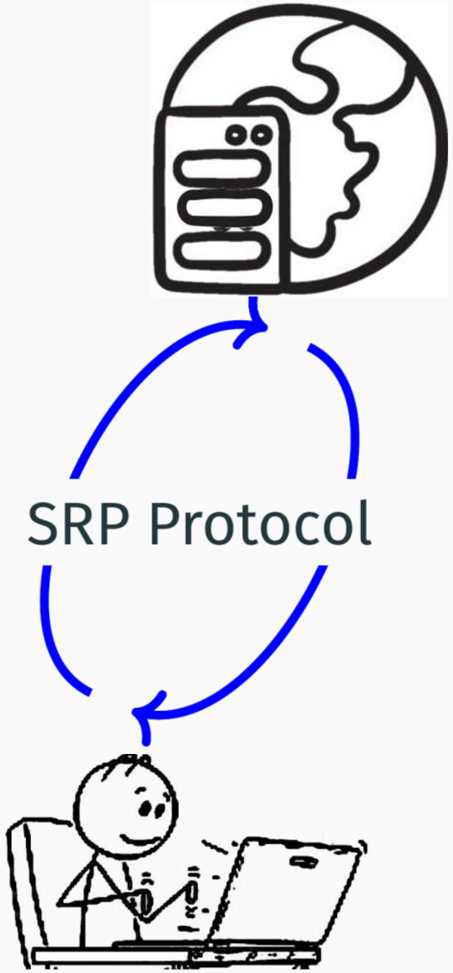
Exploiting the Leakage

Attacker Model

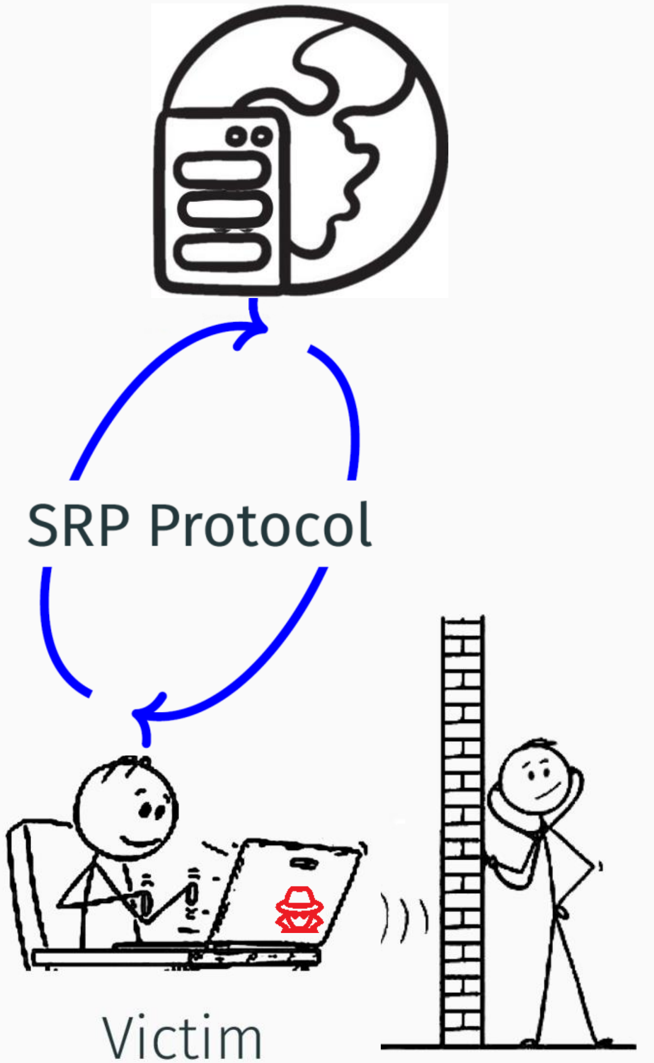
- Unprivileged spyware on the victim station
- Victim tries to connect
- MitM can help to gather more information (optional)

Classical Workflow



Victim

Classical Workflow

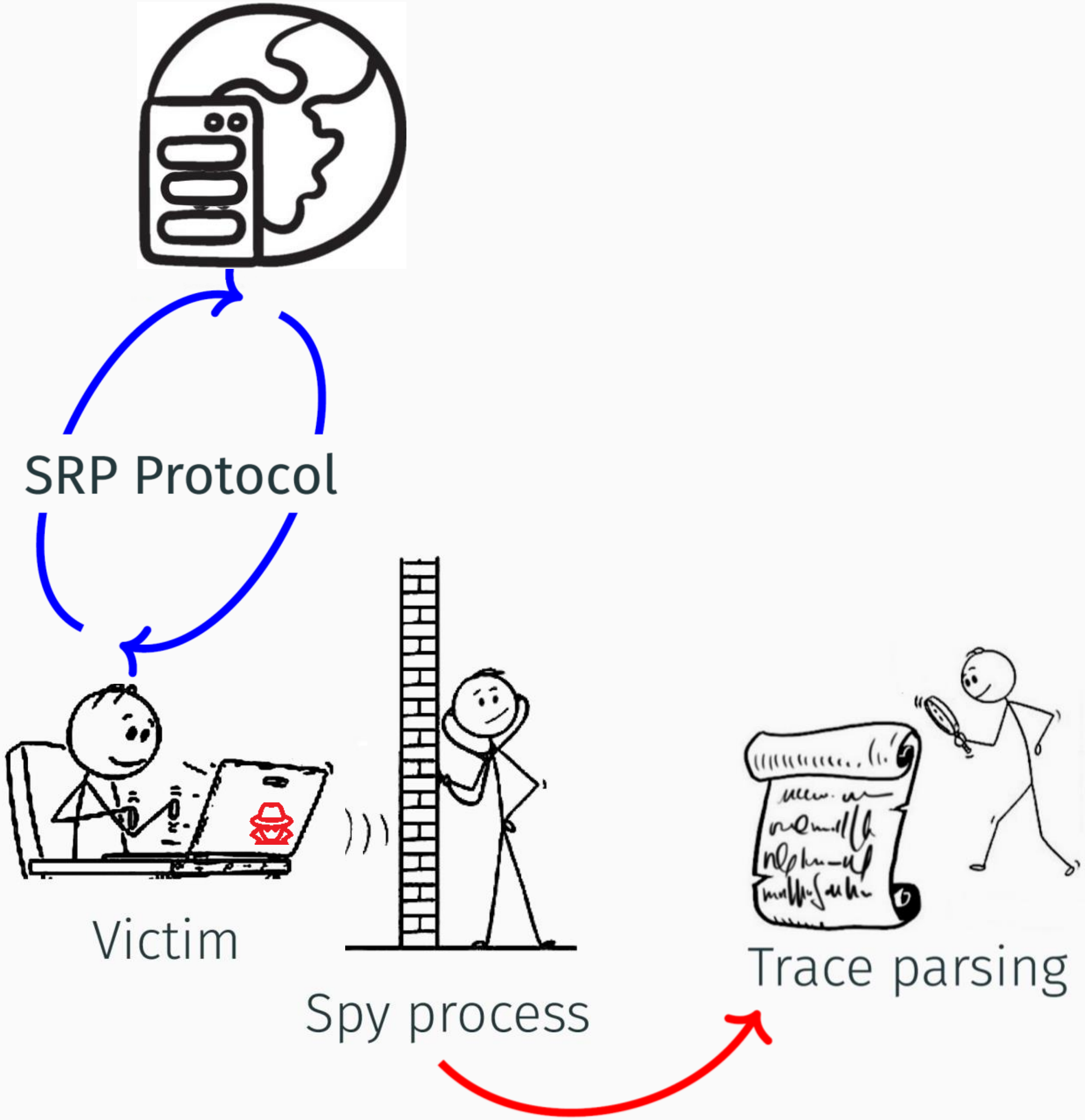


SRP Protocol

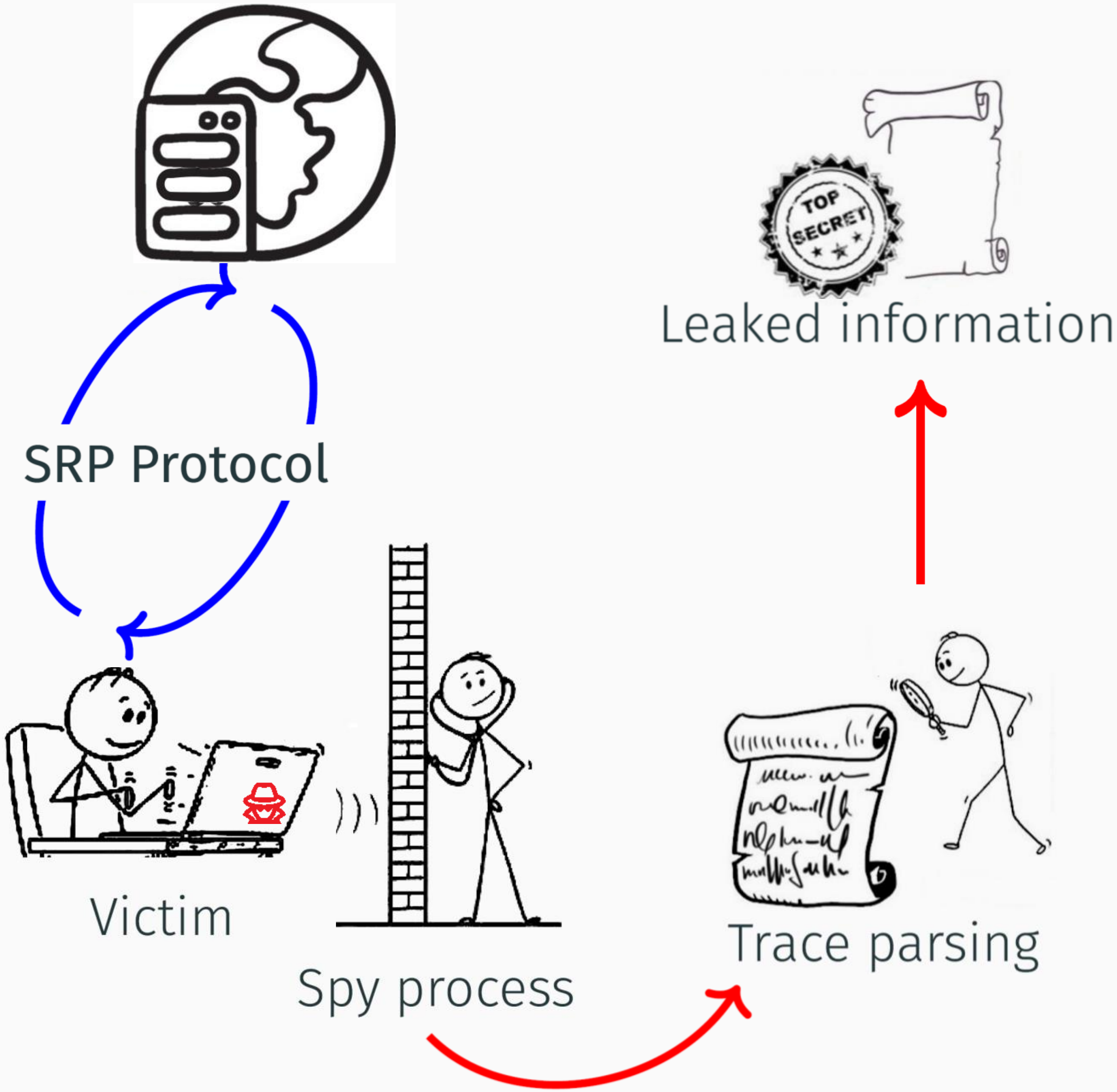
Victim

Spy process

Classical Workflow



Classical Workflow



SRP Protocol

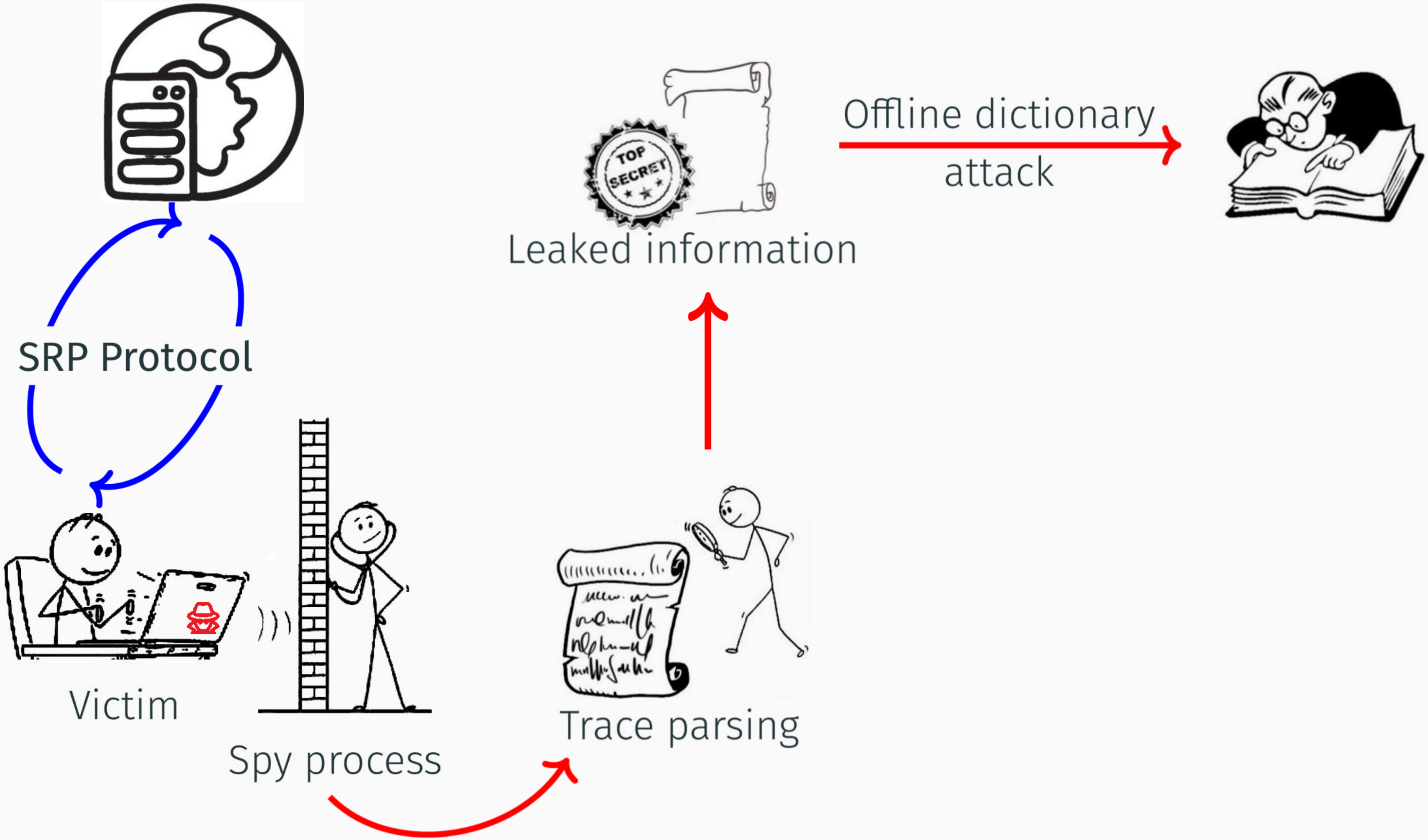
Leaked information

Victim

Spy process

Trace parsing

Classical Workflow



SRP Protocol

Victim

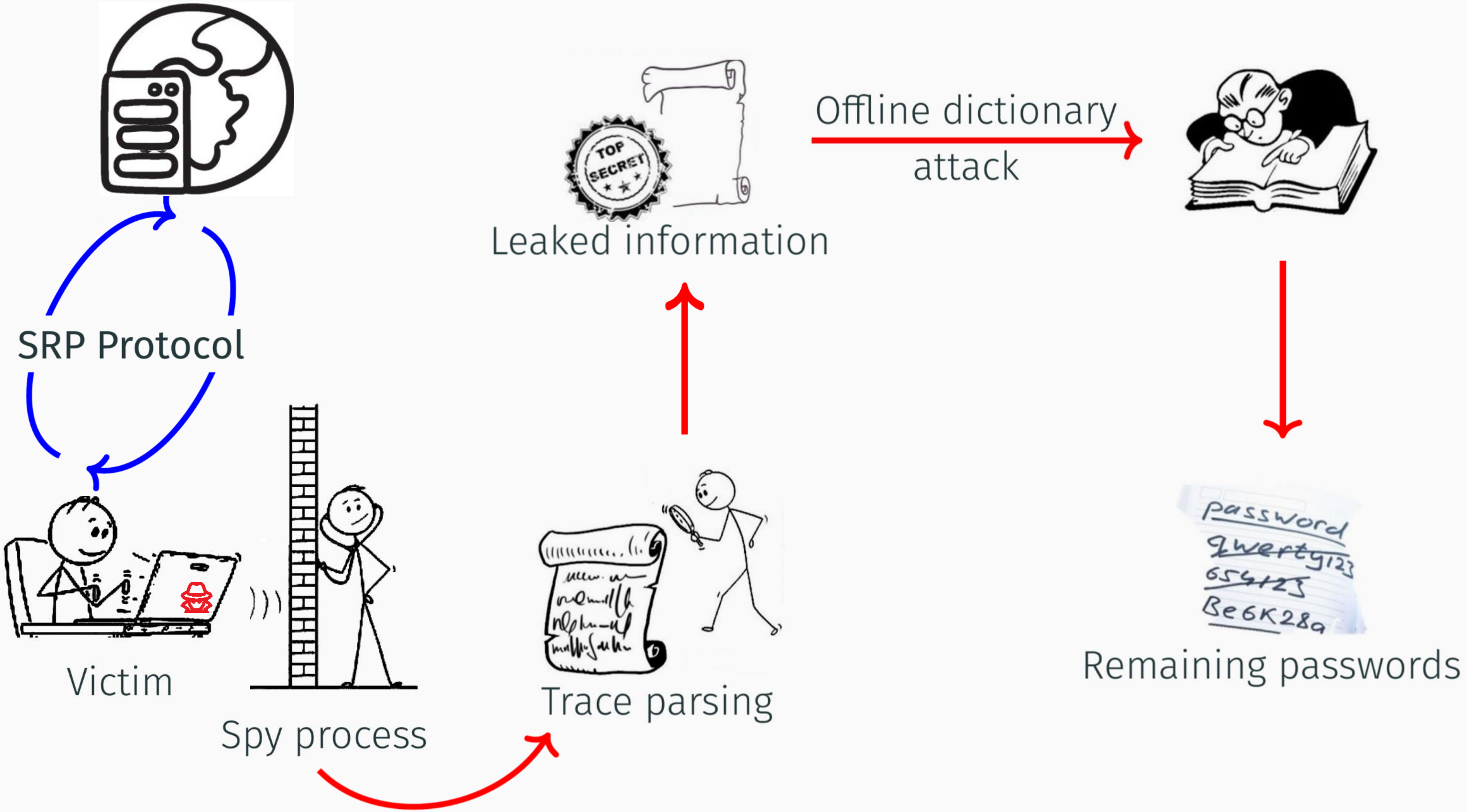
Spy process

Trace parsing

Leaked information

Offline dictionary attack

Classical Workflow



SRP Protocol

Victim

Spy process

Trace parsing

Leaked information

Offline dictionary attack

Remaining passwords

Trace Acquisition

```
def BN_mod_exp_mot_word(g, w, p):
    …
    w = g                     # uint64_t
    res = BN_to_mont_word(w)  # bigum
    for b in range(bitlen-2, 0, -1):
        next_w = w x w
        if next_w/w != w:
            res = BN_mod_mul(res, w, p)
            next_w = 1
        w = next_w
        res = BN_sqr(res)
        if BN_is_bit_set(x, b):
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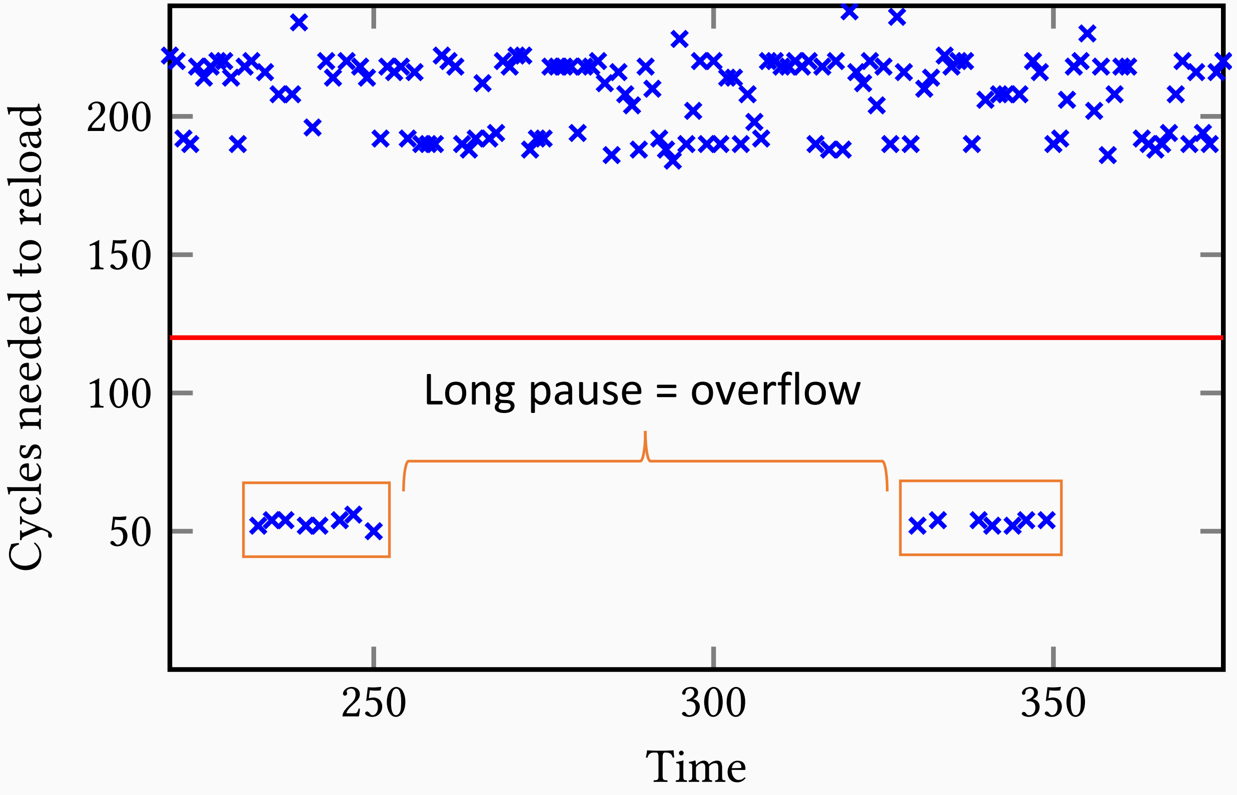
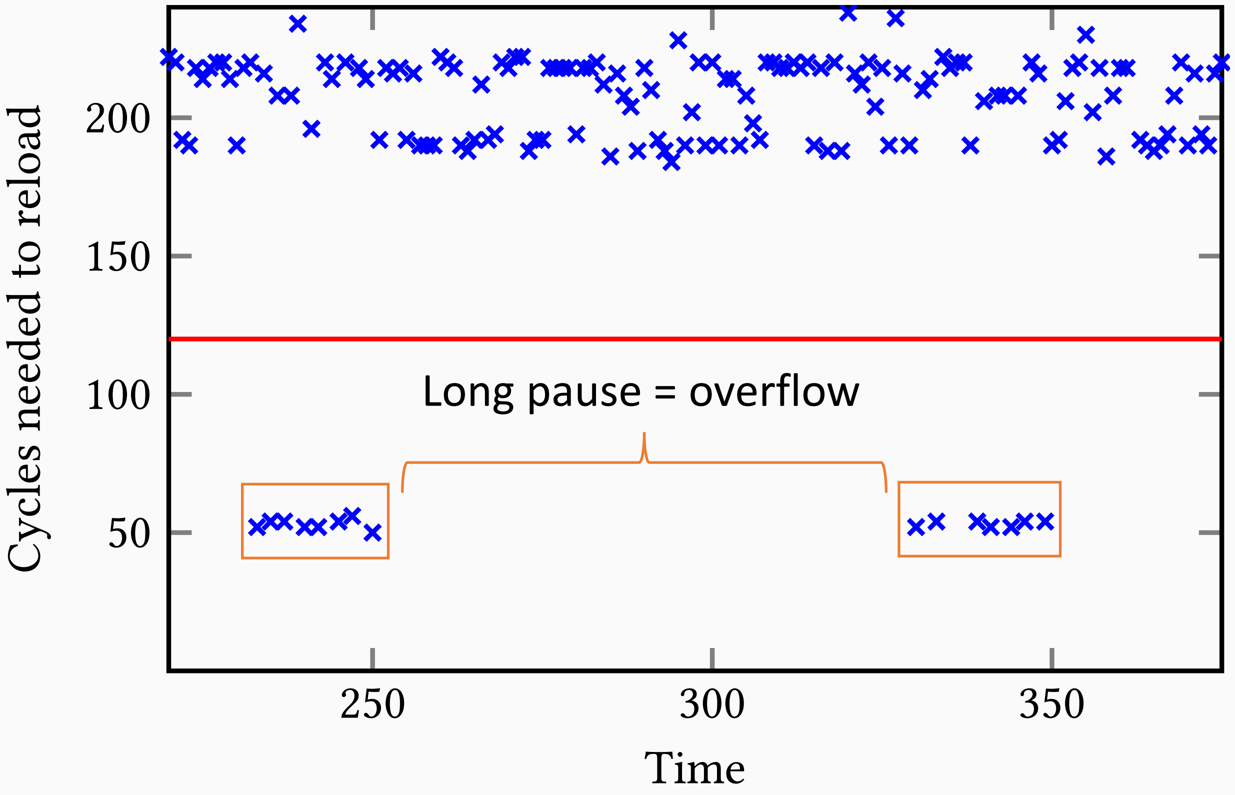


Trace Interpretation



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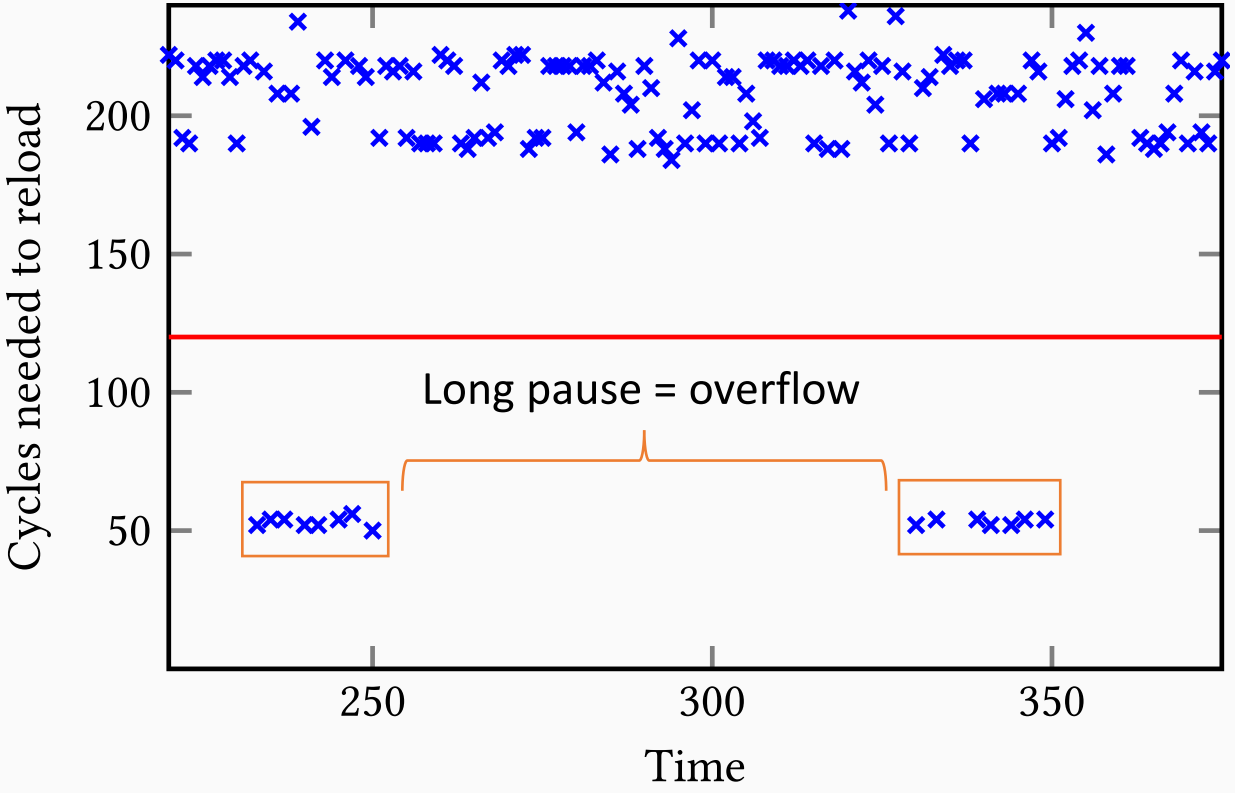


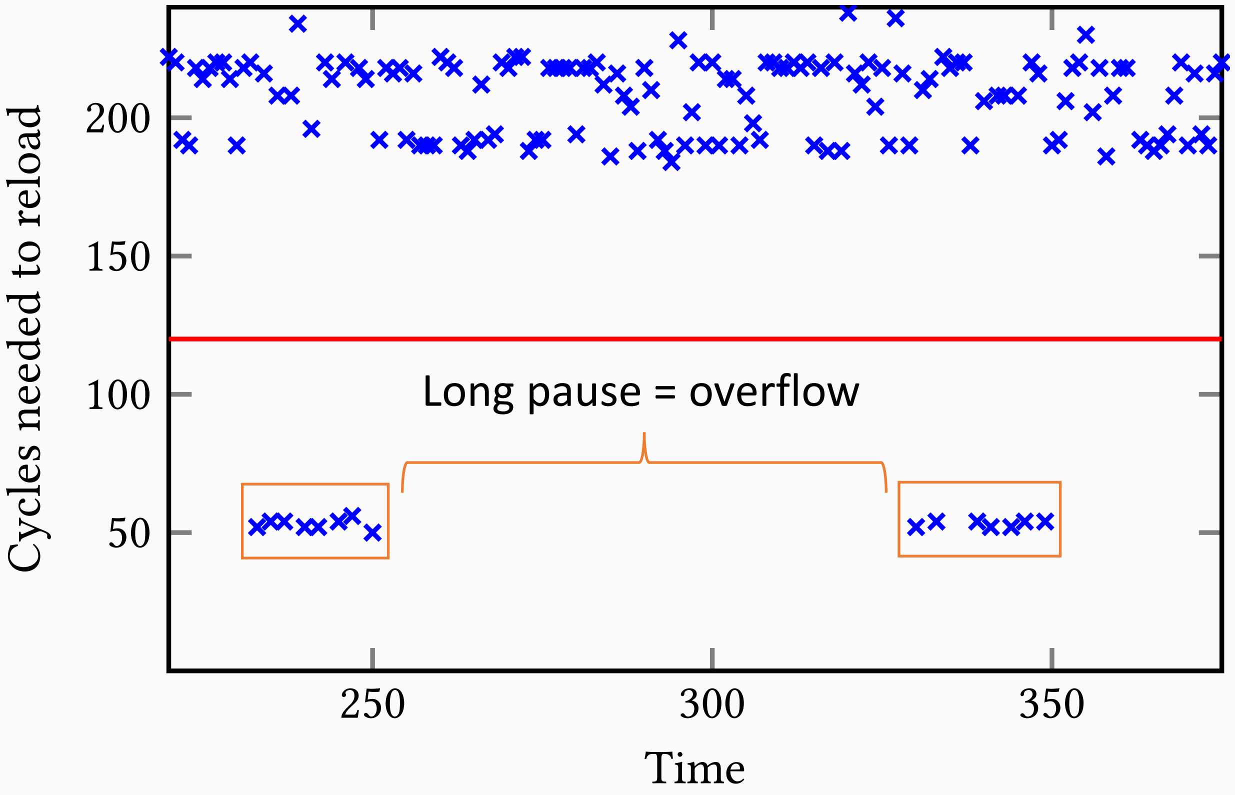
Rules ($b \in \{0,1\}$):

Vvvv -> $111b$

Vvvvv -> $yyyyb, yyyy \in \{110b, 10bb, 0111\}$

Vv.....v -> $0 \ldots 0yyyyb$

Trace Interpretation



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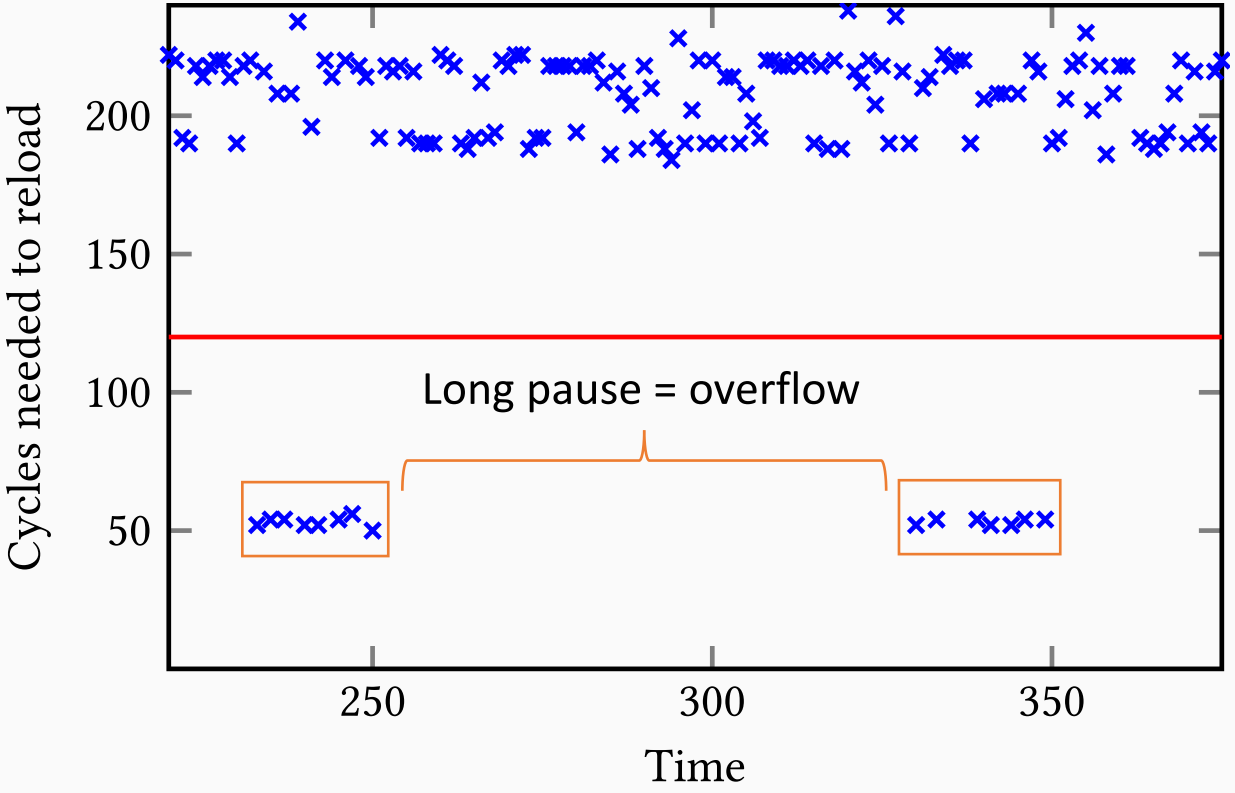

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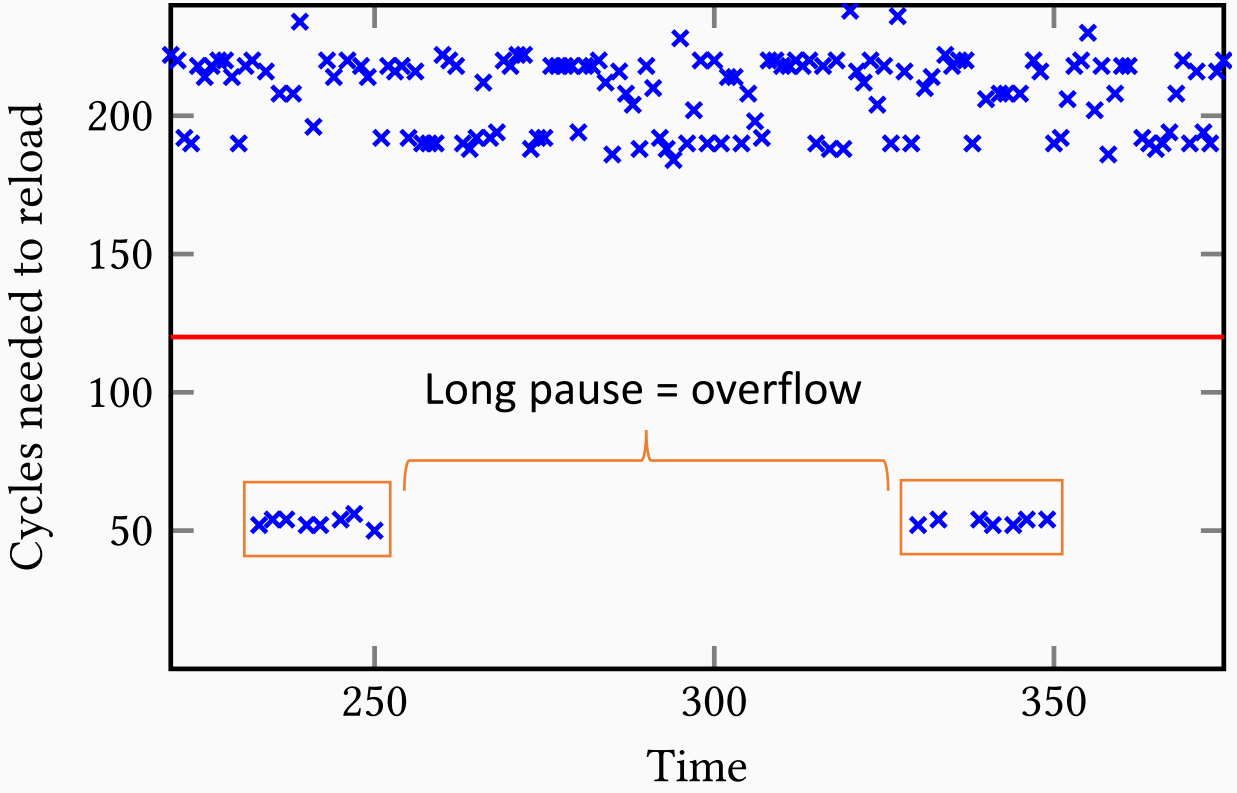

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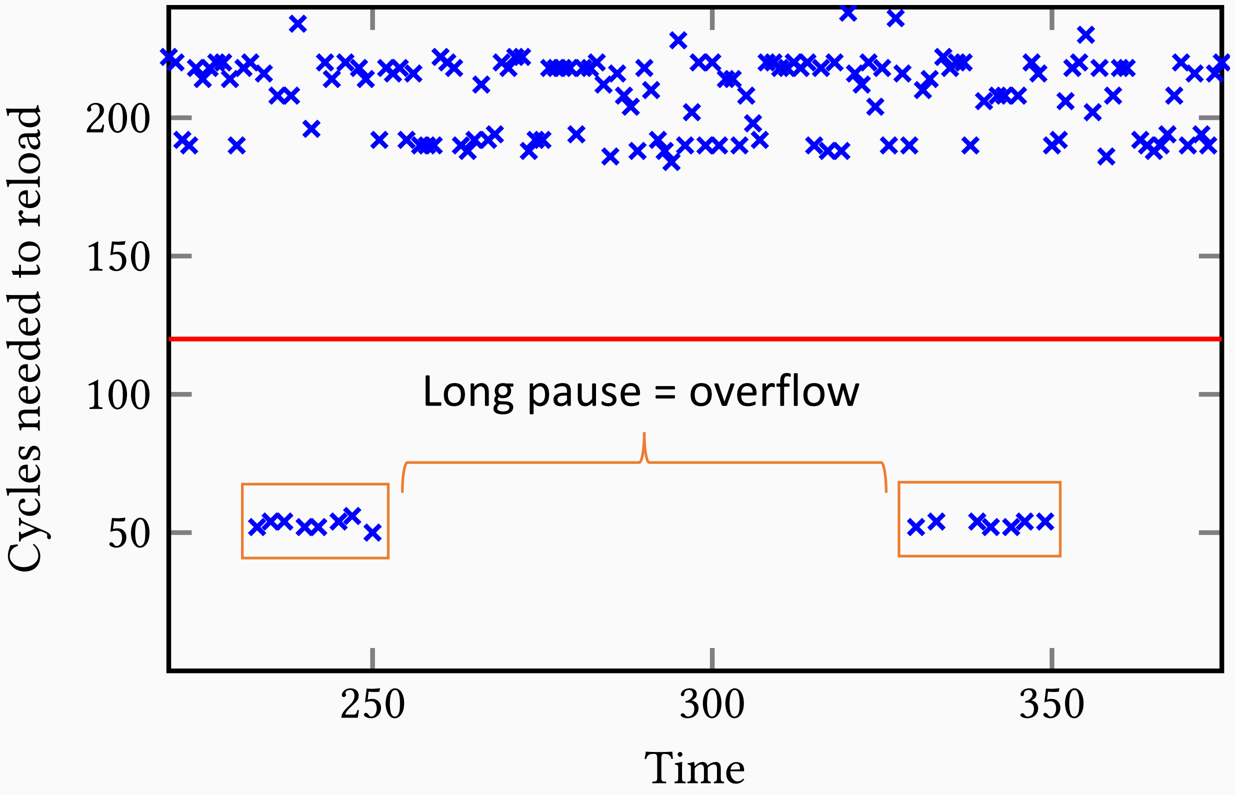

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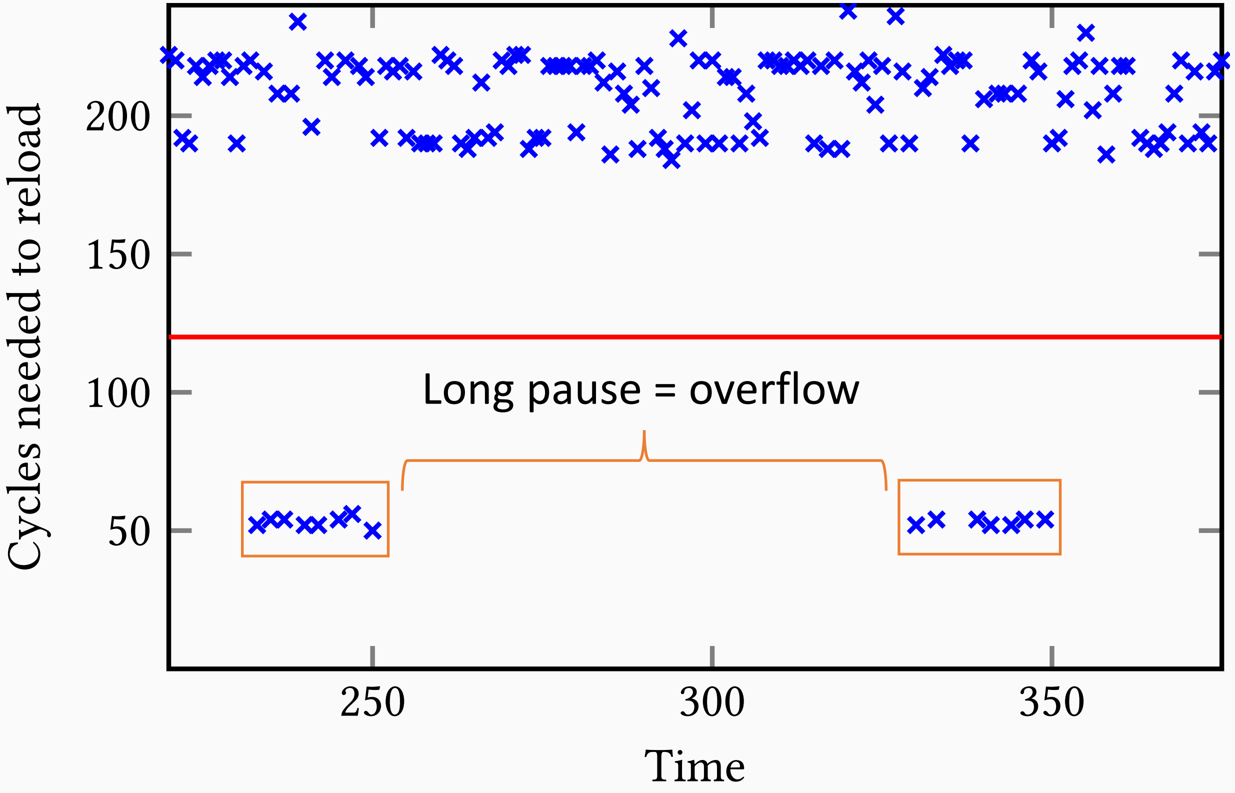

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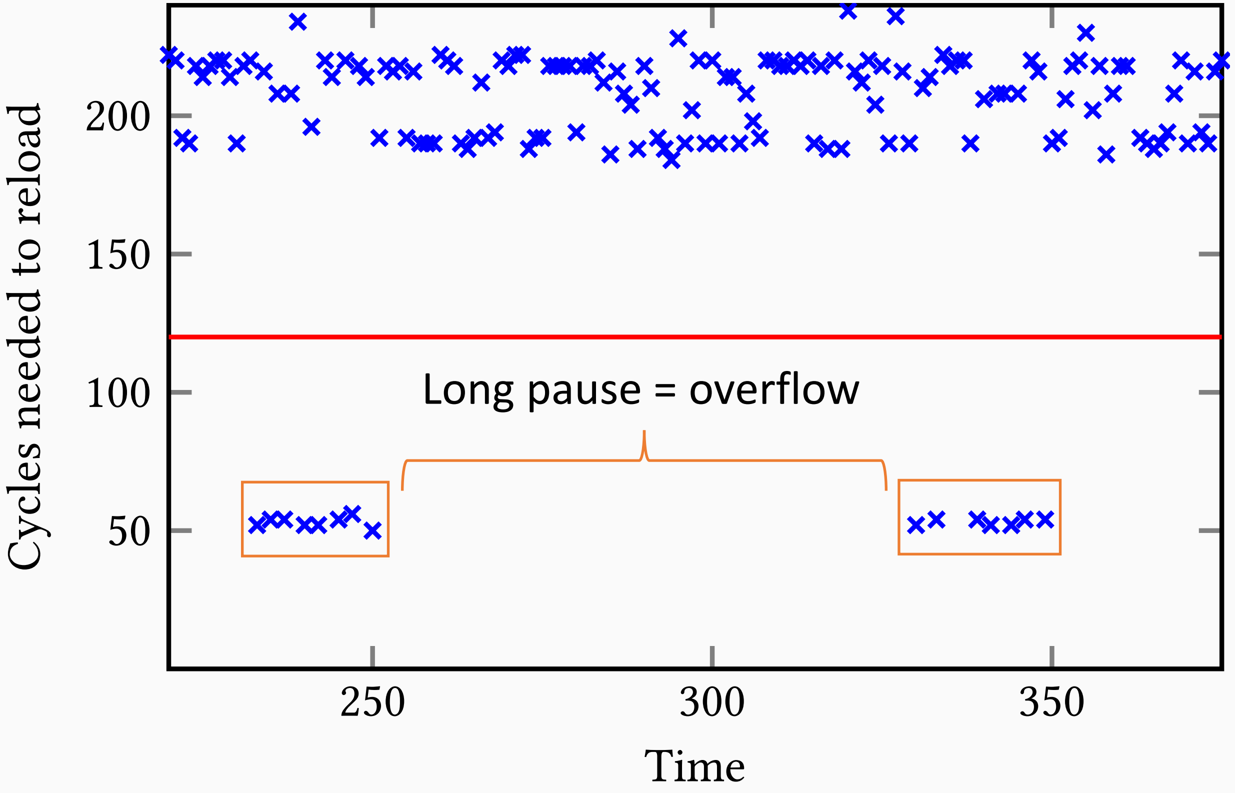

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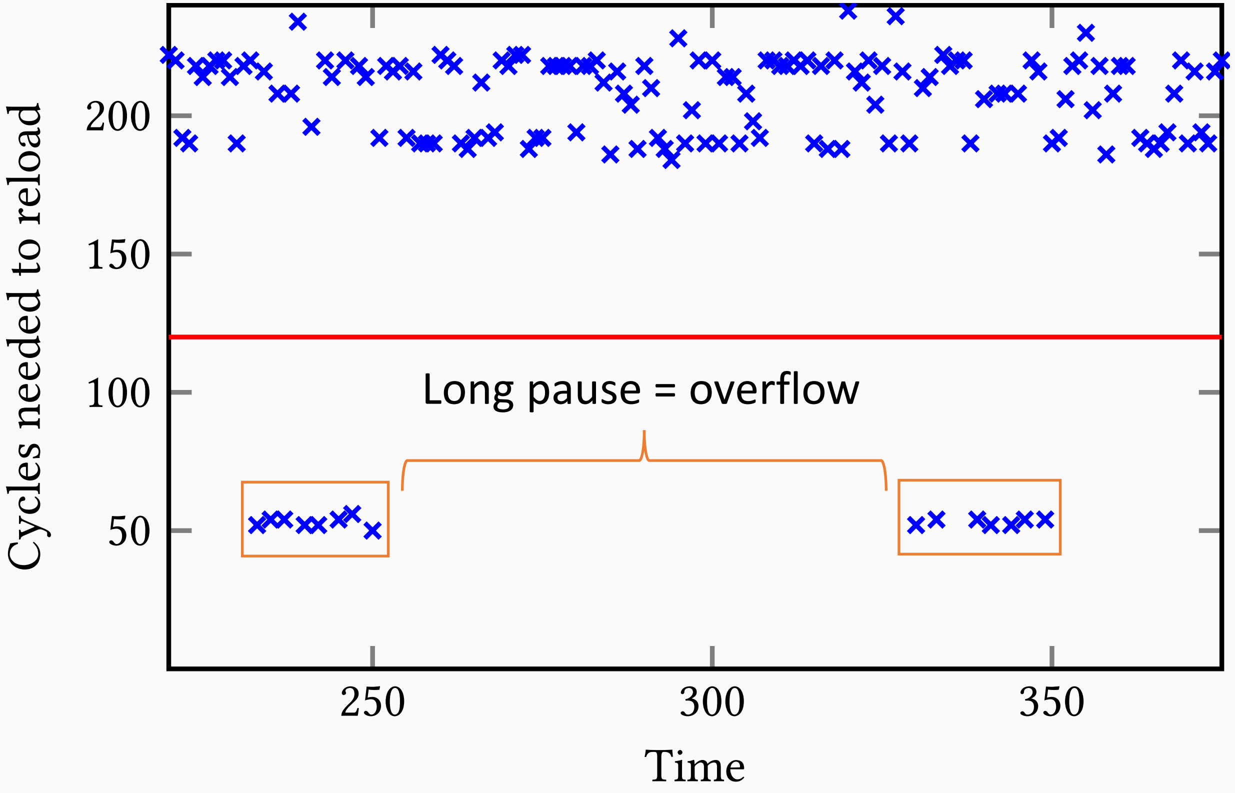

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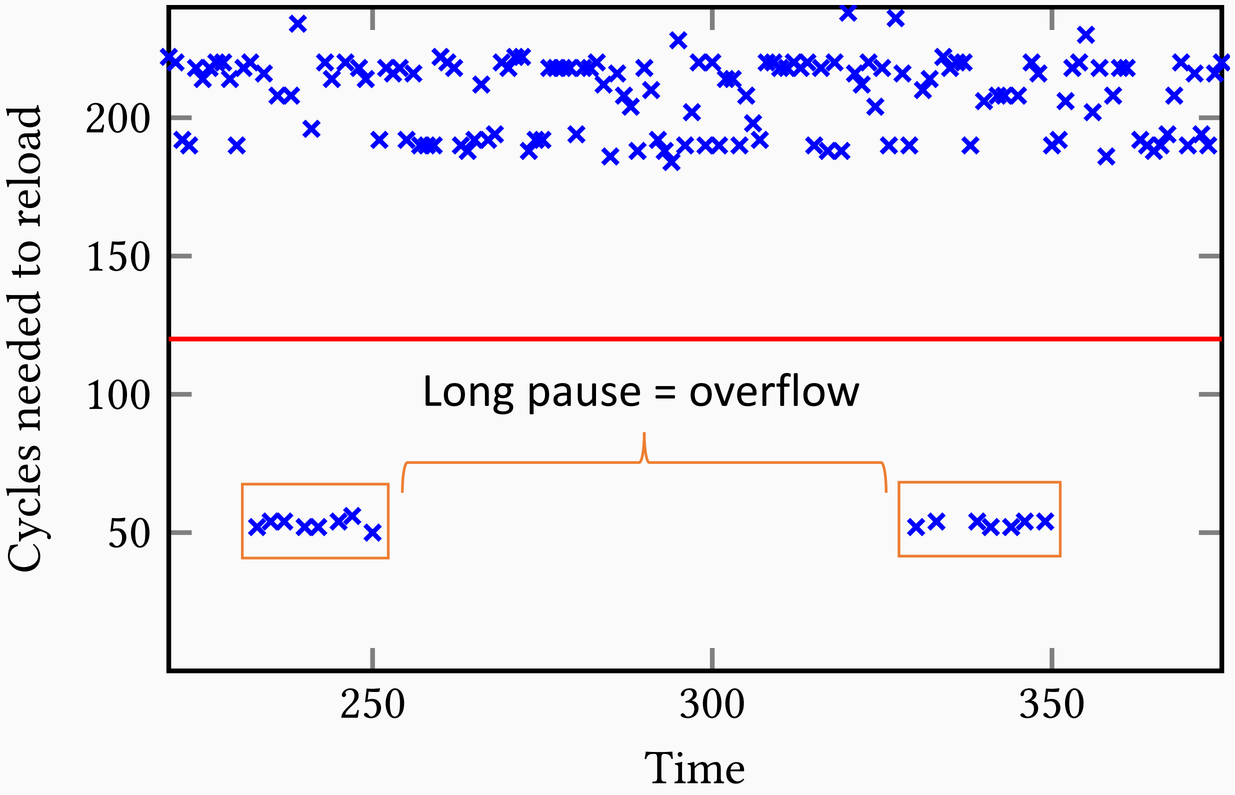

Long pause = overflow

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Vvvv Vvvvv Vvvvvv Vvvvv Vvvvv Vvvvv Vvvv
111b yyyyb 0yyyyb yyyyb yyyyb yyyyb bbbb

Dictionary Attack

Client : $x = H(salt \,||\, H(user\_id{:}password))$
$v = g^x \bmod p$

Dictionary Attack

Client : x = H(salt || H(user_id:password))
v = g^x mod p

Rules ($b \in \{0,1\}$):

Xxxx	->	$111b$
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Recovered: `1 1 1 b y y y y b 0 y y y y b 1 1 1 b 0 y y y y b`

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```
Recovered:     1 1 1 b y y y y b 0 y y y y b 1 1 1 b 0 y y y y b

   pwd_1       1 0 1 0 0 0 0 0 1 0 1 0 0 0 0 0 1 0 0 0 0 0 0 1 1
   pwd_2       1 1 0 0 1 0 1 1 1 1 1 1 1 0 0 0 0 0 1 0 1 1 1 0 1
   pwd_3       0 1 1 1 0 0 0 0 0 0 0 0 1 0 0 1 0 0 0 0 1 1 0 0 0
   pwd_4       1 1 1 1 1 1 0 0 0 0 1 0 1 1 0 1 1 1 0 0 0 1 1 1 1
   pwd_5       0 1 1 1 1 0 1 1 1 1 0 0 1 0 1 1 1 0 0 0 0 1 0 0 0
   …
   pwd_n       1 0 0 0 1 1 0 0 0 0 0 0 0 0 0 1 1 0 1 1 0 0 1 0 1
```

Password	**X value**

Dictionary Attack

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```

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Recovered:	1	1	1	b	y	y	y	y	b	0	y	y	y	y	b	1	1	1	b	0	y	y	y	y	b
pwd_1	1	0	1	0	0	0	0	0	1	0	1	0	0	0	0	0	1	0	0	0	0	0	0	1	1
pwd_2	1	1	0	0	1	0	1	1	1	1	1	1	1	0	0	0	0	0	1	0	1	1	1	0	1
pwd_3	0	1	1	1	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0	0	1	1	0	0	0
pwd_4	1	1	1	1	1	1	0	0	0	0	1	0	1	1	0	1	1	1	0	0	0	1	1	1	1
pwd_5	0	1	1	1	1	0	1	1	1	1	0	0	1	0	1	1	1	0	0	0	0	1	0	0	0
…																									
pwd_n	1	0	0	0	1	1	0	0	0	0	0	0	0	0	0	1	1	0	1	1	0	0	1	0	1

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Dictionary Attack

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Recovered: 1 1 1 b y y y y b 0 y y y y b 1 1 1 b 0 y y y y b

Password	X value	Diff score
pwd_1	1 0 1 0 0 0 0 0 1 0 1 0 0 0 0 0 1 0 0 0 0 0 0 1 1	15
pwd_2	1 1 0 0 1 0 1 1 1 1 1 1 1 0 0 0 0 0 1 0 1 1 1 0 1	14
pwd_3	0 1 1 1 0 0 0 0 0 0 0 0 1 0 0 1 0 0 0 0 1 1 0 0 0	11
pwd_4	1 1 1 1 1 1 0 0 0 0 1 0 1 1 0 1 1 1 0 0 0 1 1 1 1	0
pwd_5	0 1 1 1 1 0 1 1 1 1 0 0 1 0 1 1 1 0 0 0 0 1 0 0 0	11
…		
pwd_n	1 0 0 0 1 1 0 0 0 0 0 0 0 0 0 1 1 0 1 1 0 0 1 0 1	12

Single Measurement Attack

- Very accurate measurement
- Each bit of information halves the number of possible passwords
  - k bits of information => 2^{-k} probability of false positive/negative

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- Each bit of information halves the number of possible passwords
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For a n bits exponent, we get $\mathrm{k} = 0.4n + 2$ bits on average (verified empirically)

SHA-1: 66 bits of information

SHA-256: 104 bits of information

Practical Impact

Impacted Projects

- Lots of project using OpenSSL are impacted, including
  - OpenSSL TLS-SRP
  - Apple HomeKit ADK
  - PySRP (used in ProtonMail python client)
  - GoToAssit (?)

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Wait, how are big numbers managed in high level languages ?...

Impacted Languages

- Many reference libraries are based on OpenSSL to manage bignums
- They usually (never ?) manage the flag properly
  - Ruby/openssl
  - Javascript node-bignum
  - Erlang OTP

All SRP implementations using these packages / libraries would be affected!

Mitigations & Conclusion

Mitigations

Two choices:

- Patch this particular issue by adding the proper flag
  - Most projects use the bignum API, not the whole SRP
  - Difficult to propagate
  - Root cause remains

- Switch to a secure by default implementation (flag for insecure/optimized)
  - No flag = secure implementation (potential performance loss)
  - All projects are patched at once

Mitigations

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- Patch this particular issue by adding the proper flag ← OpenSSL's choice
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- Switch to a secure by default implementation (flag for insecure/optimized)
  - No flag = secure implementation (potential performance loss)
  - All projects are patched at once

Patching process

After OpenSSL, we contacted impacted to help with a patch:

- Apple HomeKit ADK
- node-bignum
- Ruby/openssl
- PySRP
- protonmail-python-client
- Erlang OTP

Conclusion

- Practical attack against SRP implementations
  - Vulnerability inherited by lots of projects
  - Easy to exploit because we can use each recover bits independently

Long term lesson: be careful with SCA, especially in PAKE implementation

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- Practical attack against SRP implementations
  - Vulnerability inherited by lots of projects
  - Easy to exploit because we can use each recover bits independently

Long term lesson: be careful with SCA, especially in PAKE implementation

- Leakage in a weak generic function
  - Other protocols with small base may also use it
  - Contact use if you think of one!

Thank you for your attention!

https://gitlab.inria.fr/ddealmei/poc-openssl-srp

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