Dragonblood is Still Leaking: Practical Cache-based Side-Channel in the Wild

Daniel De Almeida Braga
Pierre-Alain Fouque
Mohamed Sabt

CORGIS - March, 15^{th} 2021

Context and Motivations

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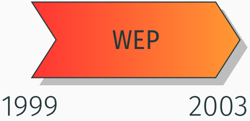

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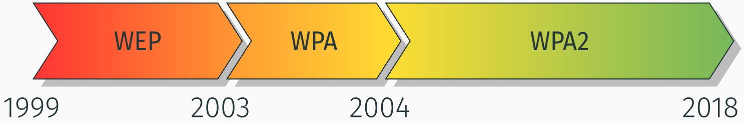

Offline dictionary attack

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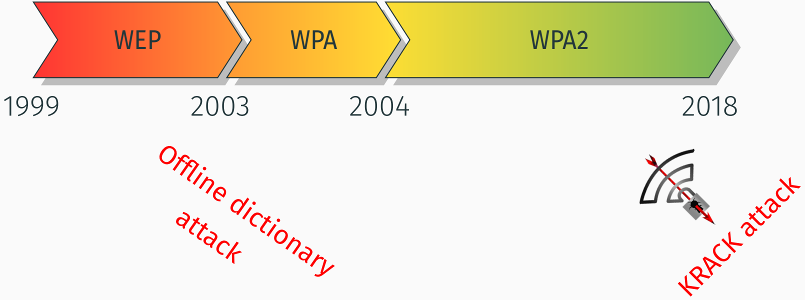

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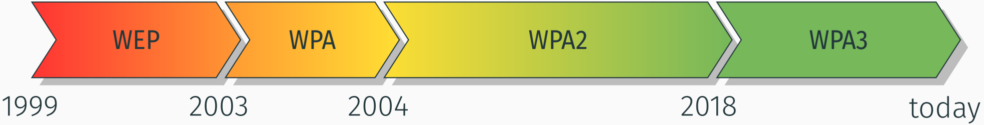


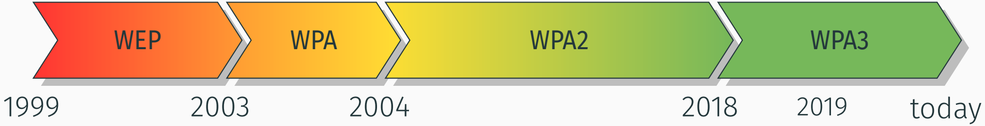
+ More secure
+ Based on a PAKE (Dragonfly[1])

[1] D. Harkins, 2015, *Dragonfly Key Exchange*, RFC 7664

PAKE: Password Authenticated Key Exchange

- PAKE protocols aim to combine the Key Exchange and authentication parts
- Password is used to:
  - Authenticate the user
  - Derive strong cryptographic material
- No offline dictionary attack

Context and Motivations



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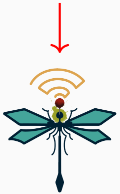

Dragonblood[1] attacks

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

Side Channel Attacks

```python
def processPassword(pwd):
    if "a" in pwd:
        res = long_processing(pwd)
    else:
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    return res
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Gain information through timing:

⏱ 0.5 seconds ⇒ no *a*

⏱ 10 seconds ⇒ *a*

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```python
def processPassword2(pwd):
    if "a" in pwd:
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    else:
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Gain information through timing:

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Side Channel Attacks

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```
def processPassword2(pwd):
    if "a" in pwd:
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    else:
        res = long_processing2(pwd)
    return res
```

Gain information execution flow:

- Execute `long_processing` ⇒ *a*
- Else, no *a* in pwd

Contributions

1. Show that current countermeasures are not sufficient for cache-based side-channel

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2. Mount an offline dictionary attack to recover the password
3. Provide a PoC on Real-World-like scenarios (**IWD** and FreeRadius)
4. Raise awareness on how practical these attacks are

Our main result

A cache based side channel attack

let us extract information during

the password conversion with

an offline dictionary attack

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Unintended information leakage

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FLUSH+RELOAD[1] and PDA[2]

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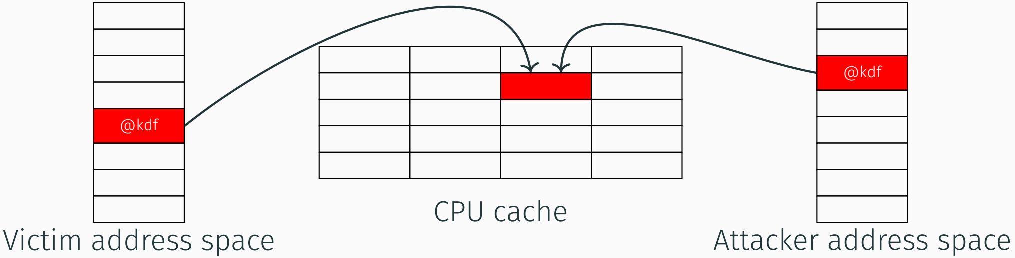
[1] Y. Yarom et al. *Flush+Reload: a High Resolution, Low Noise, L3 Cache Side-Channel Attack*. In USENIX Security Symposium. 2014.
[2] T. Allan et al. *Amplifying side channels through performance degradation*. In ACSAC. 2016



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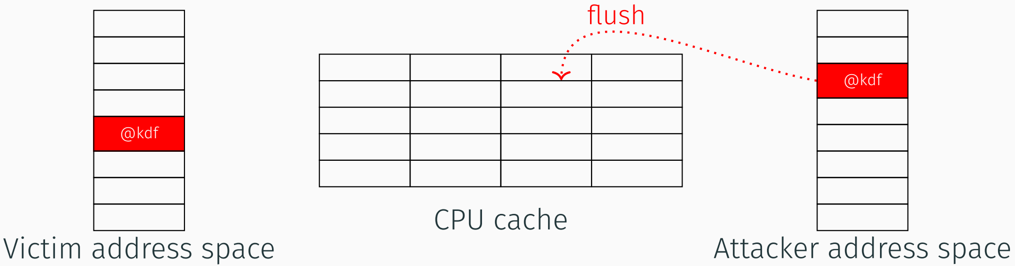
FLUSH+RELOAD[1]



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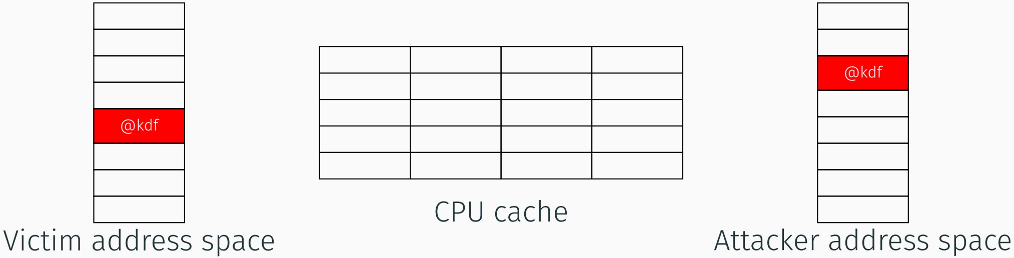

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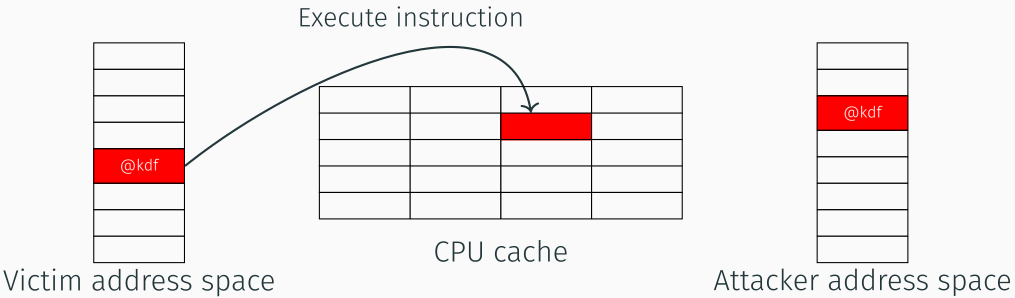

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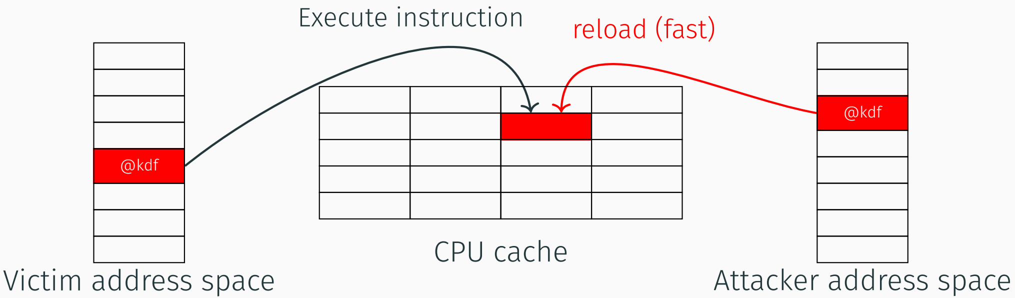

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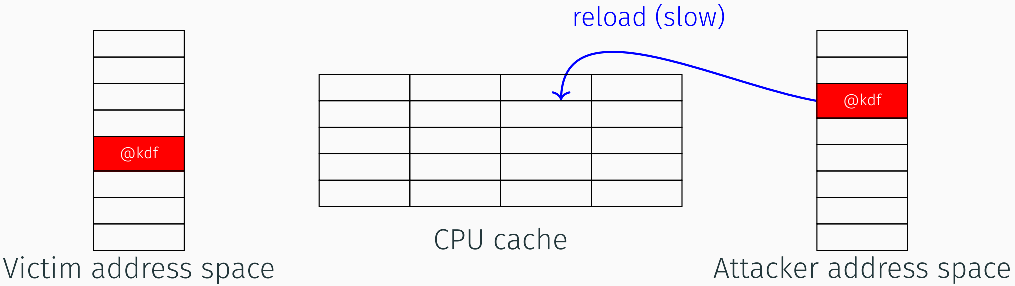

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Password to point on an Elliptic Curve

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Password to point on an Elliptic Curve

Passive attacker can eliminate wrong passwords from a list

Dragonfly Protocol Overview

A and B agree on a prime order group $E(\mathbb{F}_p)$, of order q

Dragonfly

Alice (A)		**Bob (B)**
$P \leftarrow \mathbf{p2g}(pwd, A, B)$		$P \leftarrow \mathbf{p2g}(pwd, A, B)$
	Commit $\longrightarrow$	
	$\longleftarrow$	
Key derivation		Key derivation
	Confirmation $\longrightarrow$	
	$\longleftarrow$	

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Dragonfly - Password Conversion (EC)

HuntingAndPecking($pwd, A, B, k = 40$)

$found,\ i =$ **false**, 1
while not $found$ **or** $i < k$:
    $seed = Hash(A, B, pwd, i)$
    $x_{cand} = KDF(seed, label)$
    if x_{cand} is a point's coordinate :
        if not $found$:
            $found,\ x, seed_x =$ **true**, $x_{cand},\ seed$
            $pwd = get\_random()$
    $i\ = i + 1$
$y = set\_compressed\_point\_coordinate(x, seed_x)$
return (x, y)

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← : new iteration

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  if x_{cand} is a point's coordinate : → `mask = get_random()` `do_blind_verif(`x_{cand}`, mask)`

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                                                     do_blind_verif(x_cand, mask) ← PDA
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Dictionary Reduction

	Iter. required for A, B	Iter. required for A, B’
Leakage	3	
password1		
password2		
password3		
password4		
…		
passwordn		

Dictionary Reduction

	Iter. required for A, B	Iter. required for A, B’
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password3	3	
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Leakage	3	2
password1	1	
password2	3	
password3	3	
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...	...	
passwordn	3	

Dictionary Reduction

	Iter. required for A, B	Iter. required for A, B’
Leakage	3	2
password1	1	X
password2	3	8
password3	3	2
password4	4	X
…	…	…
passwordn	3	1

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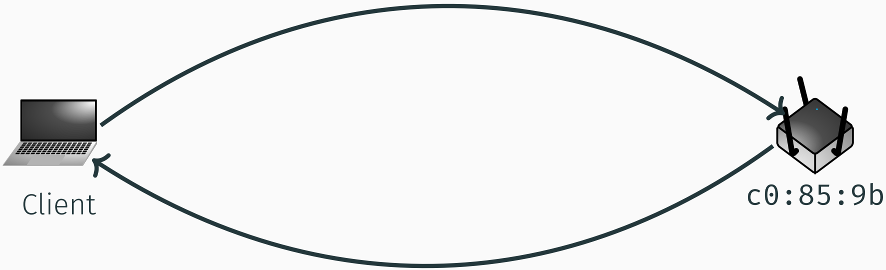
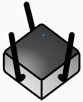
Attacker Model



Attacker Model

Client



`c0:85:9b`

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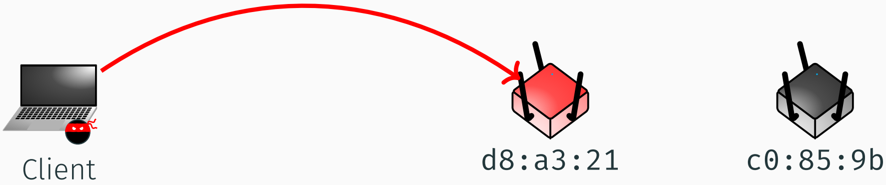

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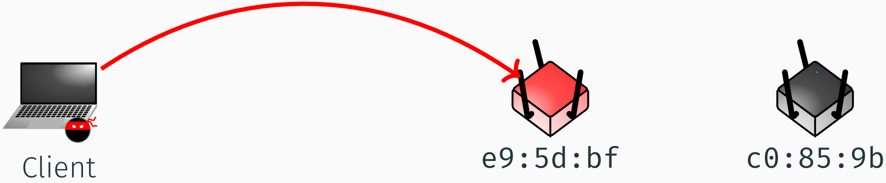
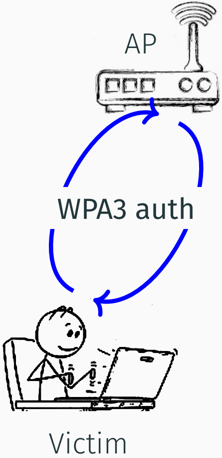


Core Idea



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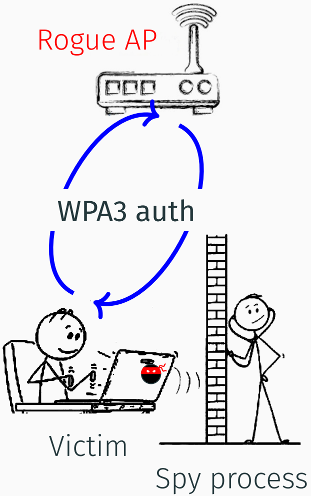

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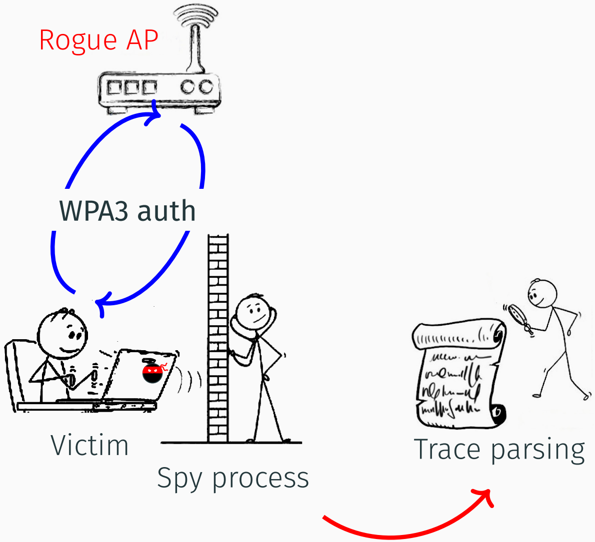

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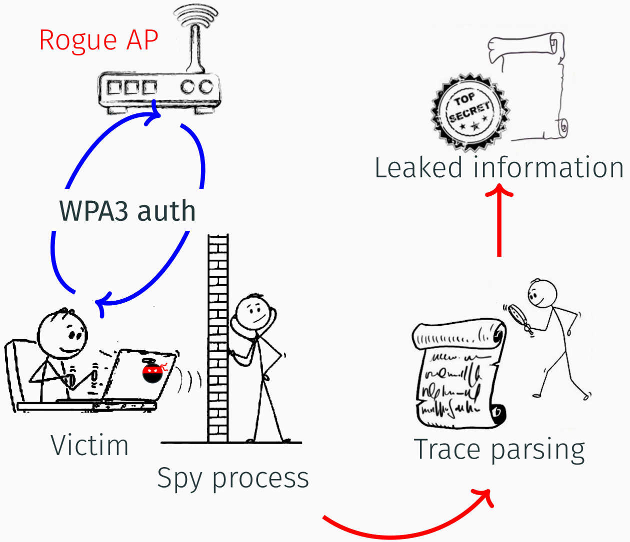
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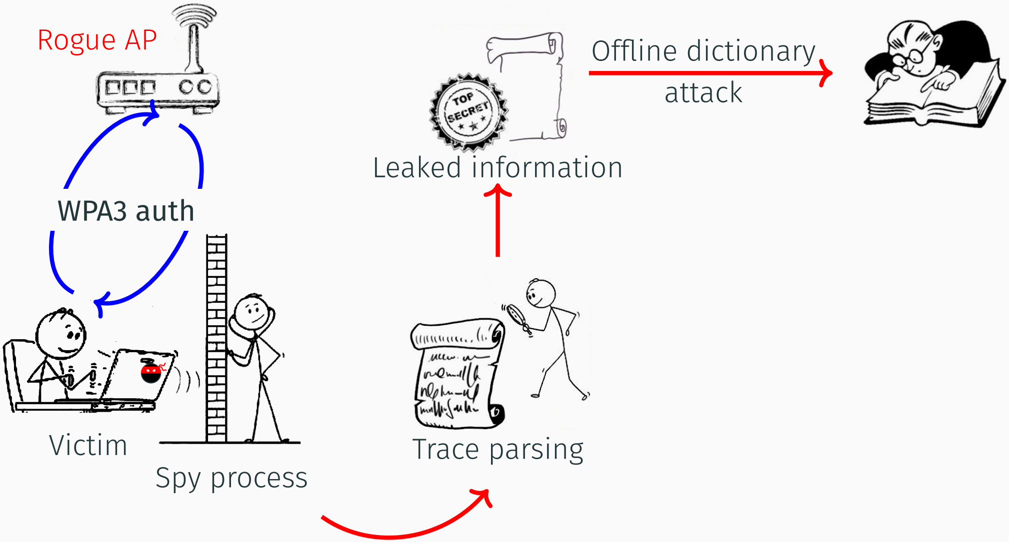
WPA3 auth
Victim
Spy process
Leaked information
TOP SECRET
Trace parsing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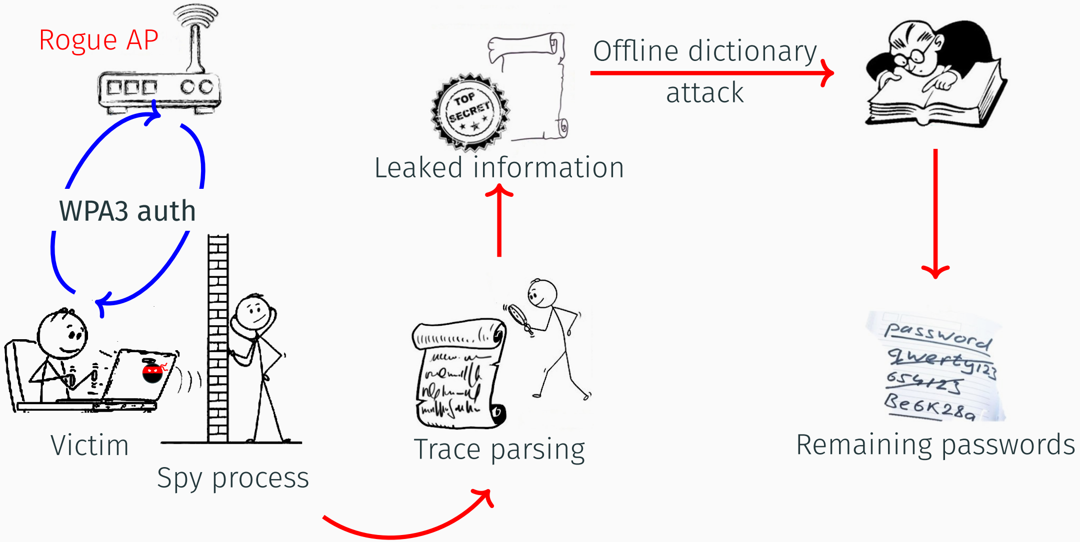
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Remaining passwords

Practical Results

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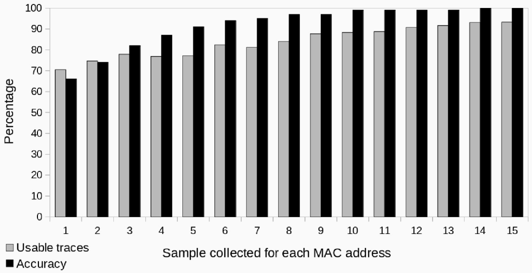

Practical Results

	Dict. size	Cost on AWS	Avg traces for full reduction
Rockyou	$1.4 \cdot 10^7$	$0,00037$ €	16
CrackStation	$3.5 \cdot 10^7$	$0,0011$ €	17
HaveIBeenPwned	$5.5 \cdot 10^8$	0,014 €	20
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Number of the Required Traces / Cost to Prune all Wrong Passwords

IWD v1.9 ✓

2020-08-03	sae: Fix a side channel leak on the password	Daniel DE ALMEIDA BRAGA	2	-40/+135

FreeRadius to be fixed in 3.0.22

merge constant time fixes from "master" ...

```
Based on a patch from Daniel De Almeida Braga.

The code is now largely the same between master and v3.0.x,
which makes it easier to see that it's correct
```

Additional vulnerability (found after the paper submission)

HuntingAndPecking(*pwd*, *A*, *B*, *k*)

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found, i = false, 1
while not found or i < k :
    seed = Hash(A, B, pwd, i)
    x_cand = KDF(seed, label)
    if x_cand is a point's coordinate :
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    i = i + 1
y = set_compressed_point_coordinate(x, save_seed)
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    $i\ = i + 1$

$y = set\_compressed\_point\_coordinate(x, save\_seed)$ $\leftarrow$: leaks the seed's parity

return (x, y)

Dictionary Reduction

	seed's parity for A, B	seed's parity for A, B'
Leakage	0	
password1		
password2		
password3		
password4		
...		
passwordn		

Dictionary Reduction

	seed's parity for A, B	seed's parity for A, B'
Leakage	0	
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password2	0	
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...	...	
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```

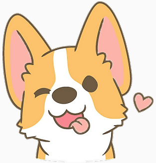
← : leaks the seed's parity

Underlying crypto library call

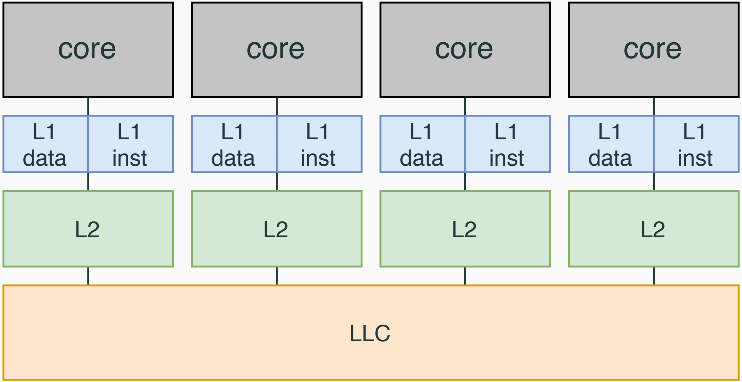
Future / Current work

- Find / adapt tools to perform thorough analysis of WPA3
  - Complete/Sound tools do not scale well
  - Scalable tools are (often) not complete
- Analyze various implementations
- Patch remaining vulnerabilities
- Enjoy secure WPA3 implementations

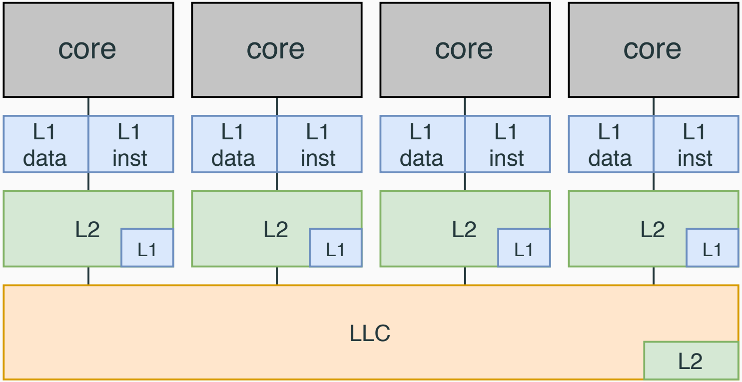
Questions?



Inclusive CPU cache

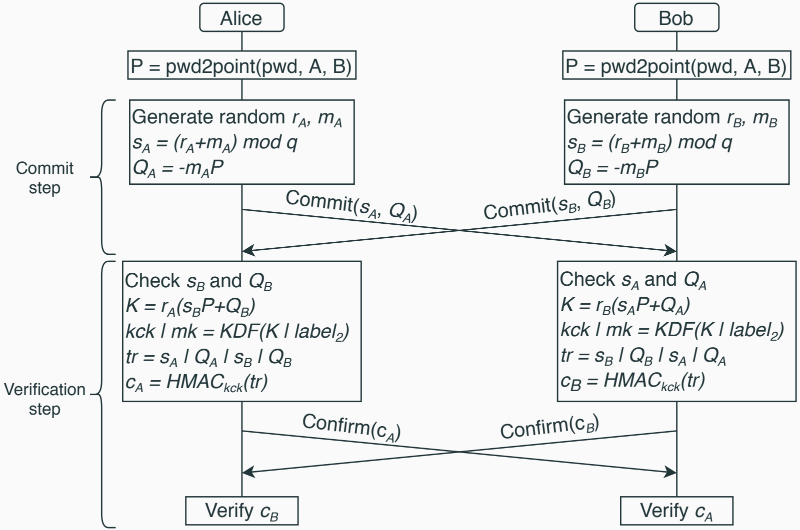


Inclusive CPU cache



Inclusive cache

Dragonfly workflow



Is (x, y) a point on a curve ?

Need to check if $x^3 + ax + b$ is a a quadratic residue on $\mathbb{F}_p$

is_x_on_curve(x)

```
y_sqr = x^3 + ax + b
return legendre_symbol(y_sqr, p) == 1
```

Is (x, y) a point on a curve ?

Need to check if $x^3 + ax + b$ is a a quadratic residue on $\mathbb{F}_p$

is_x_on_curve(x, qr, nqr)

```
mask = get_random()
y_sqr = x^3 + ax + b
blind_sqr = y_sqr × mask^2
if mask is odd :
    blind_sqr = blind_sqr × qr
    return legendre_symbol(blind_sqr) == −1
else
    blind_sqr = blind_sqr × nqr
    return legendre_symbol(blind_sqr) == 1
```