A Primer on Cache Attacks

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Outline

- Mastik
- Flush + Reload
- Prime + Probe

Mastik

- **M**icro-**A**rchitectural **S**ide-channel **T**ool**K**it
- https://github.com/0xADE1A1DE/Mastik
- Aims:
  - Collate information on side-channel attacks
  - Overcome the barrier to entry into the area
  - Shift focus to cryptanalysis

Mastik: status

- Reasonably solid implementation of four attacks:
  - Prime+Probe (L1-D, L1-I, L3)
  - Flush+Reload
  - Flush+Flush
  - CacheBleed
- Only Intel x86-64 on Linux
- Limited documentation and testing
- No user feedback

Computer Revolution

		Processor speed	Memory latency
1977		1 MHz	500 ns
2020		20×3700 MHz	50 ns

Bridging Speed Gap

- Utilize locality
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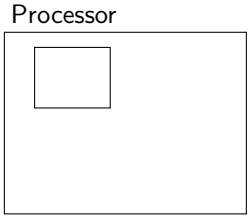

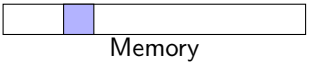

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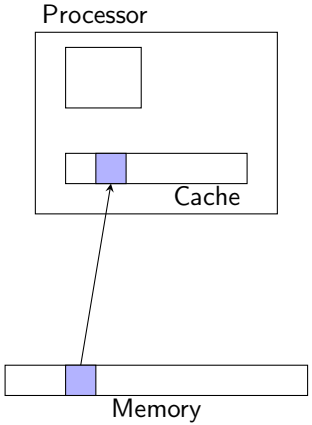

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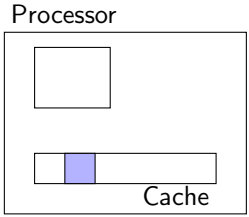

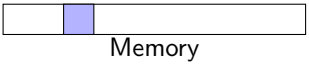

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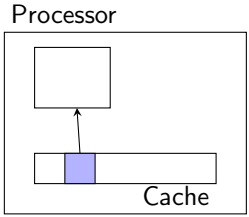

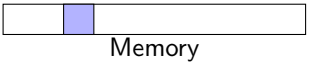

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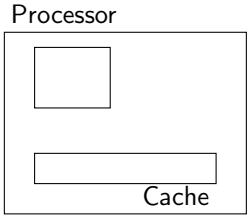

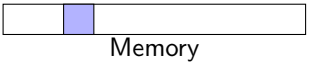

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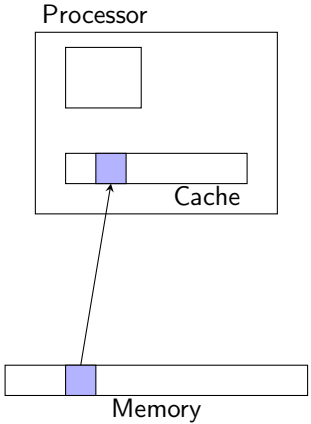

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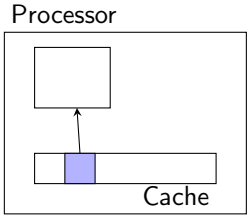

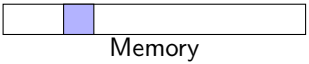

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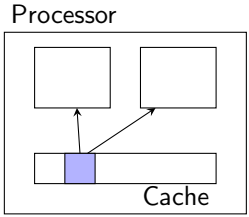
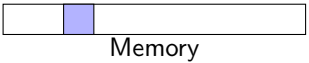
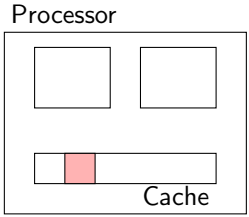
- Share cache
  - improve performance of multi-core processors

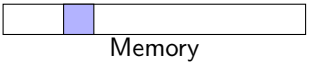




Maintaining Consistency

- Memory and cache can be inconsistent
  - rare but possible





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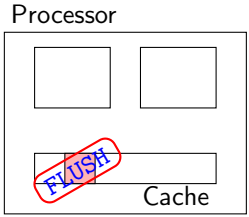

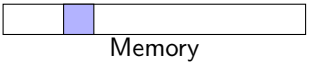

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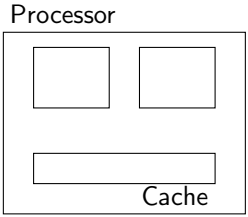

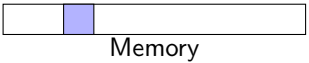

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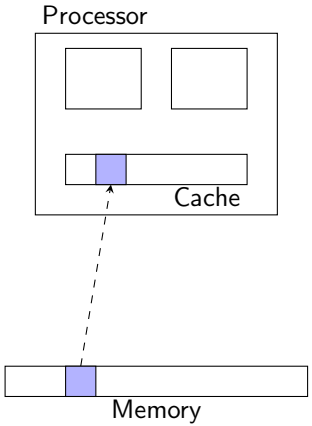

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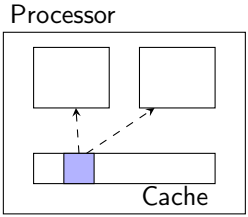

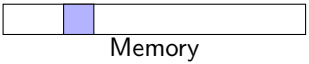

Flush + Reload [GBK11, YF14]

- **Flush** memory line
- Wait (victim executes)
- Measure time to **Reload** line
  - slow → no victim access
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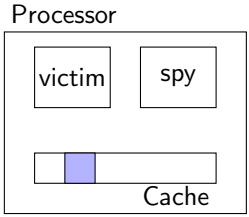
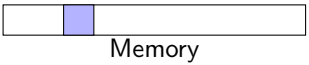
- (Repeat)





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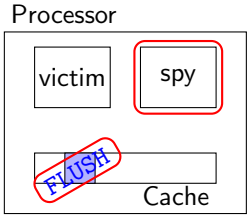

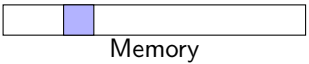

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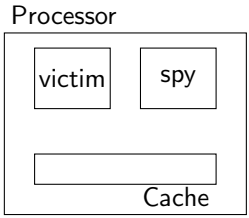

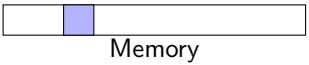

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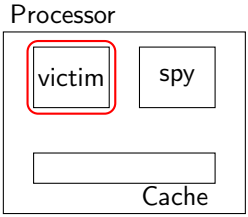

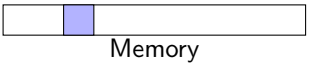

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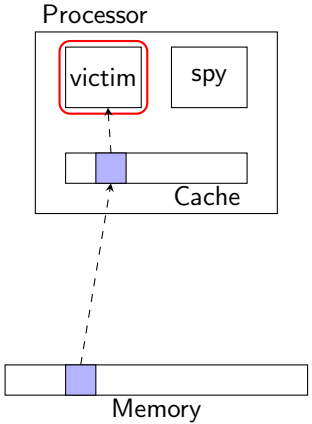

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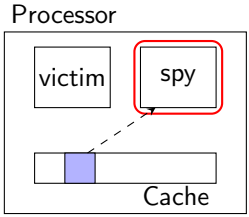

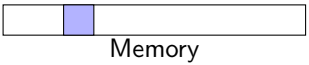

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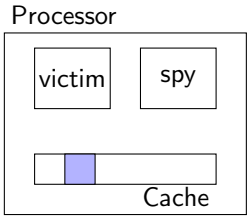
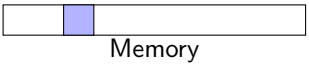
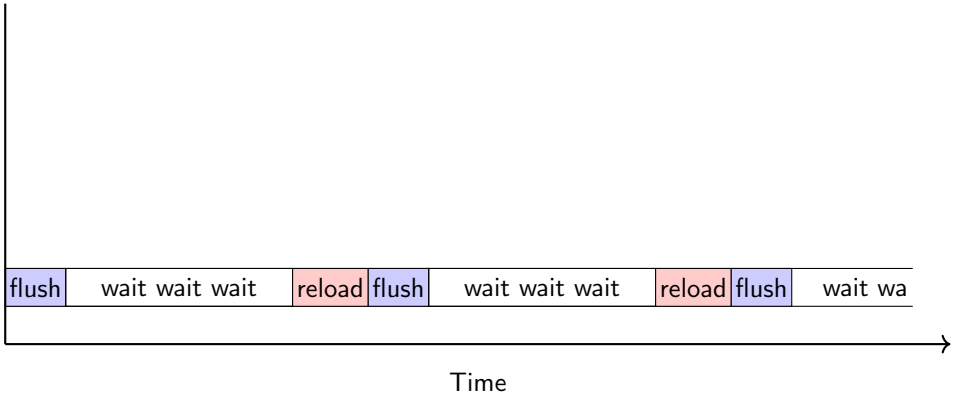




Flush + Reload: in action



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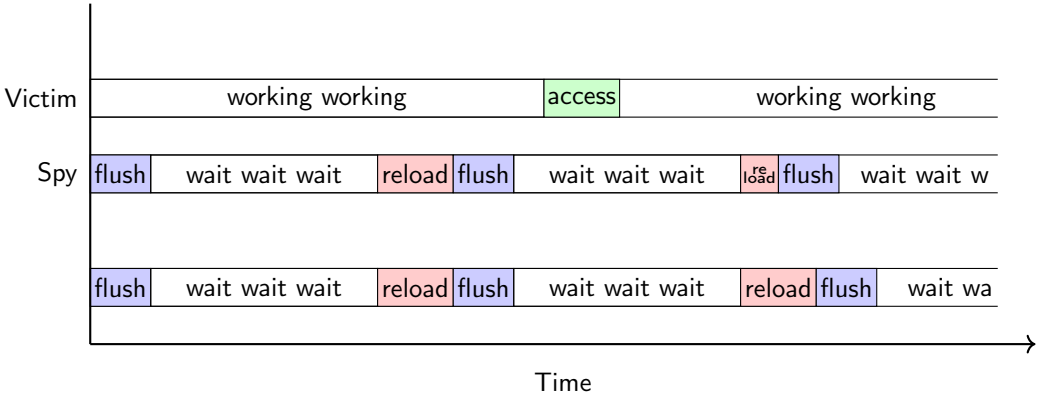

Flush + Reload: code

```
mfence                  ; ensure in-order execution
rdtscp                  ; get start time
mov %eax, %esi          ; store start time
mov (%ebx), %eax        ; access memory
rdtscp                  ; get finish time
sub %esi, %eax          ; subtract start and finish time
clflush 0 (%ebx)        ; flush cache line
```

Flush + Reload: demo1

- FR-access

GnuPG 1.4.13 Modular Exponentiation

Compute $x = b^d \bmod n$

$x \leftarrow 1$
for $i \leftarrow |d|-1$ **downto** 0 **do**
    $x \leftarrow x^2 \bmod n$
    if $(d_i = 1)$ **then**
        $x \leftarrow x \cdot b \bmod n$
return x

GnuPG 1.4.13 Modular Exponentiation

Compute $x = b^d \bmod n$

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x ← 1
for i ← |d|−1 downto 0 do
    x ← x^2 mod n
    if (d_i = 1) then
        x ← x·b mod n
return x
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Example: $b{=}11,\ d{=}5{=}101_2,\ n{=}100$

$$\begin{aligned} & 11^5 \bmod 100 \\ & \quad = 161051 \bmod 100 \\ & \quad = 51 \end{aligned}$$

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Operation	x	i	d_i
	1	2	101

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Operation	x	i	d_i
	1	2	101
Square	1	2	101

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Square	1	2	101
Reduce	1	2	101

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Operation	x	i	d_i
	1	2	101
Square	1	2	101
Reduce	1	2	101
Multiply	11	2	101

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Square	1	2	101
Reduce	1	2	101
Multiply	11	2	101
Reduce	11	2	101

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Operation	x	i	d_i
	1	2	101
Square	1	2	101
Reduce	1	2	101
Multiply	11	2	101
Reduce	11	2	101
Square	121	1	101

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Square	121	1	101
Reduce	21	1	101

GnuPG 1.4.13 Modular Exponentiation

Compute $x = b^d \bmod n$

```
x ← 1
for i ← |d|−1 downto 0 do
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    if (d_i = 1) then
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```

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Flush + Reload: demo

- FR-gnupg-1.4.13

Flush + Reload: pros & cons

+ Simple
+ Very fews false positive
+ Resolution of memory line

Flush + Reload: pros & cons

+ Simple
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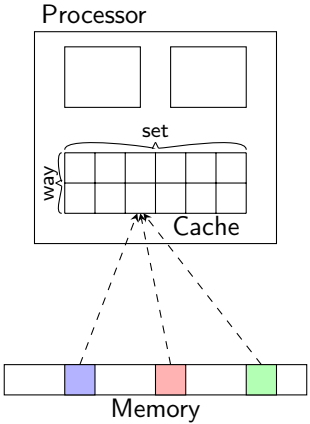
- Only work with shared memory
- Require flush instruction

Set Associative Caches

- Memory lines map to cache sets



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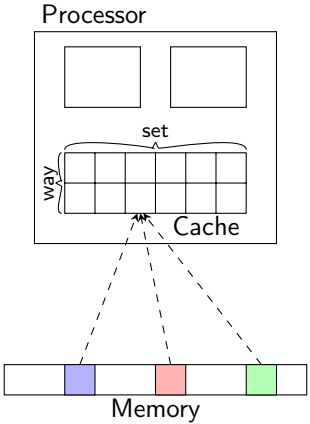

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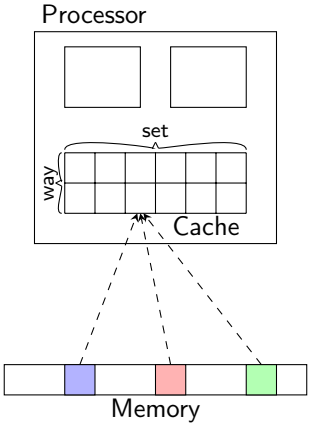

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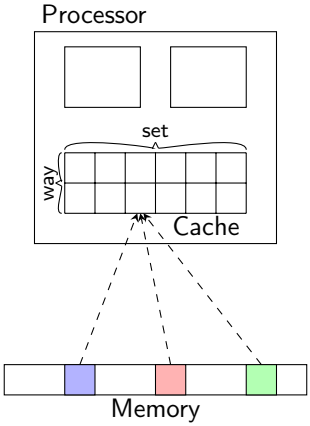

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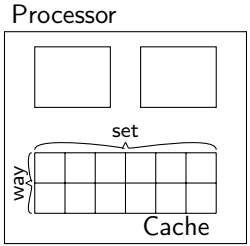

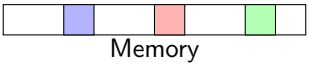

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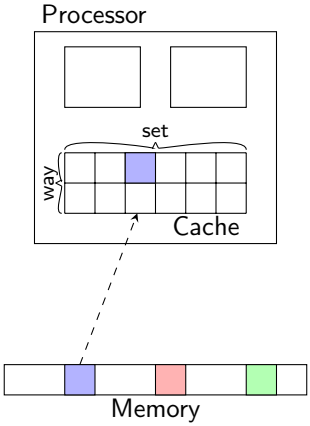

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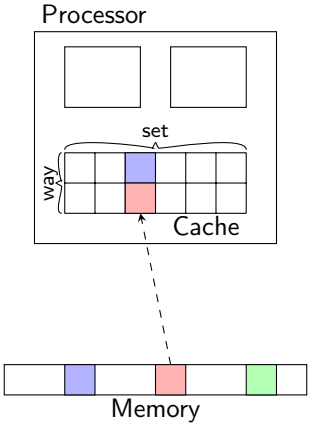

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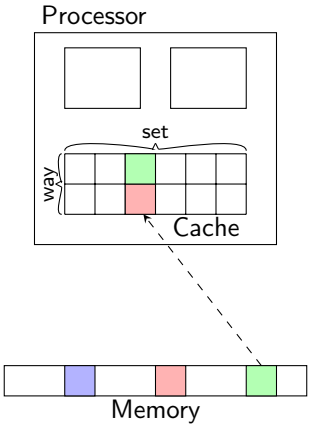

Prime + Probe [OST05, Per05]

- (Allocate cache-sized memory buffer)
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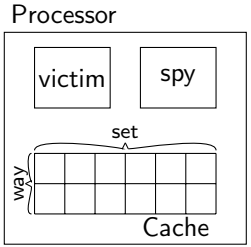

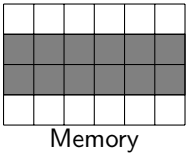

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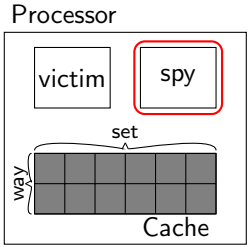

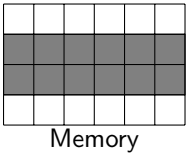

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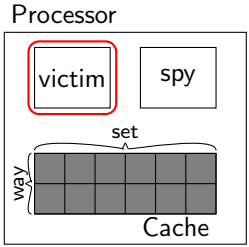

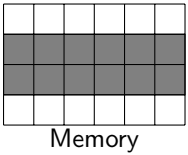

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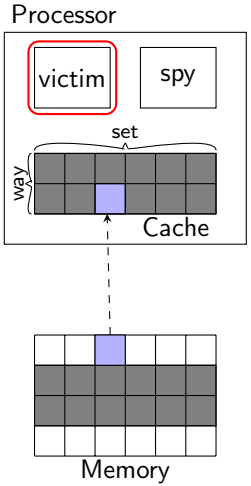

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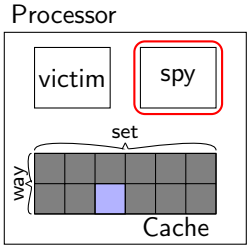

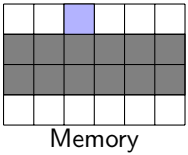

Prime + Probe: sample victim data rattle

```
volatile char buffer[4096];

int main(int ac, char **av) {
  for (;;) {
    for (int i=0; i<64000; i++)
      buffer[800] += i;

    for (int i=0; i<64000; i++)
      buffer[1800] += i;
  }
}
```

Prime + Probe: demo

- Cache finger print of the rattle program

Prime + Probe: attack first-round AES

plaintext

ciphertext

Prime + Probe: attack first-round AES

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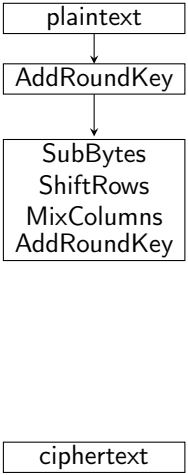

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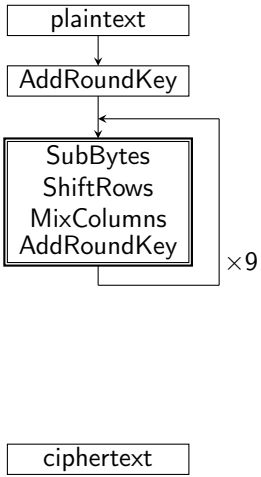

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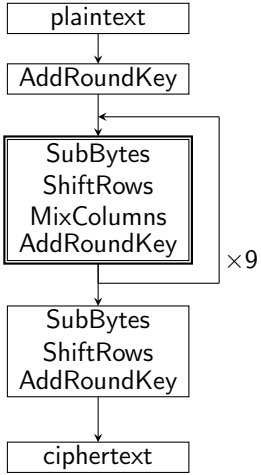

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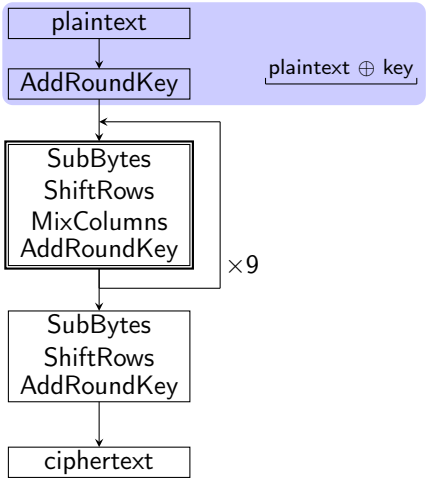

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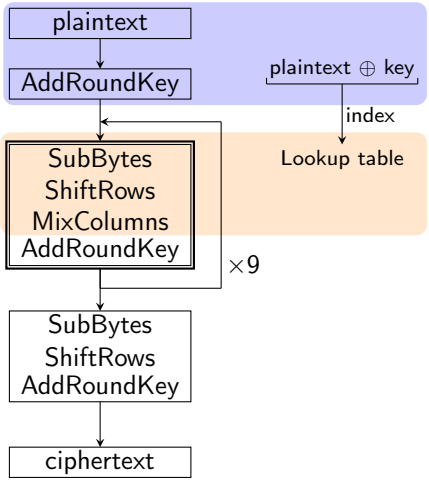

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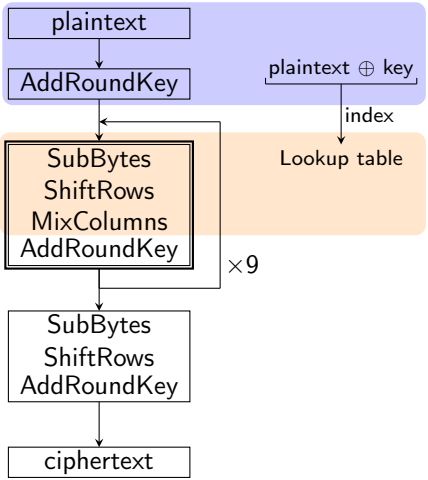

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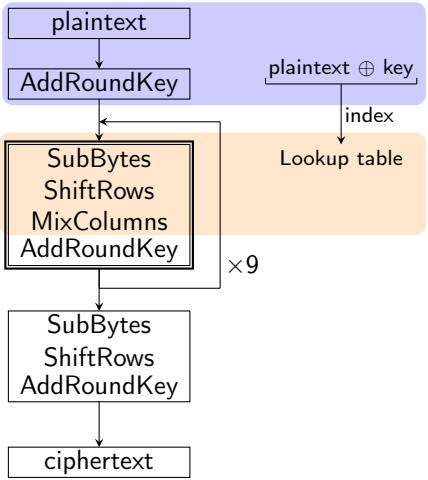

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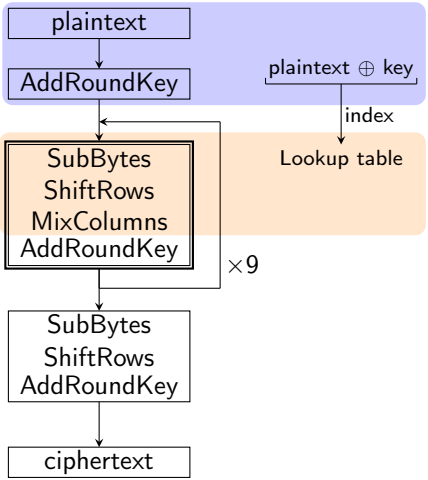

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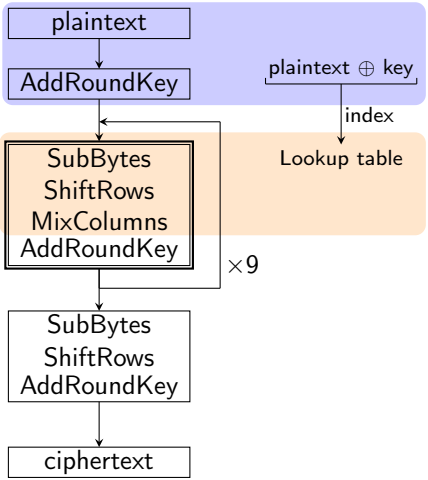

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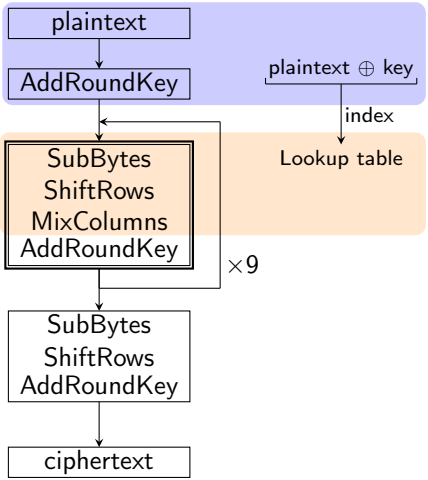

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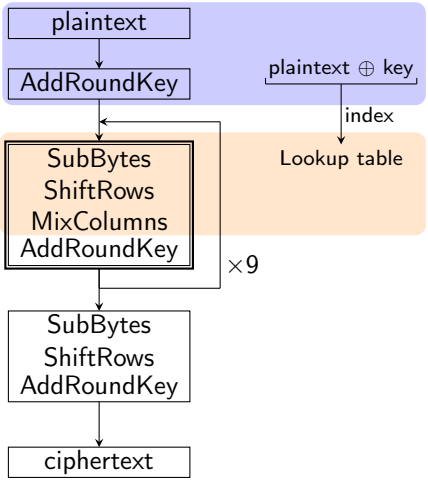

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→ eliminate impossible keys to one cache set

Prime + Probe: attack first-round AES (cont.)

- Actual experiments have noise

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  - ...
  - $p_{\mu_{15}}$: average of samples whose 4 MSBs of the plaintext byte are 1111

Prime + Probe: attack first-round AES (cont.)

$$p_{t_0} = [\quad t_0^0 \quad , \quad t_0^1 \quad , \ldots , \quad t_0^{63} \quad]$$

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$$p_{\mu_0} = [\ \mathsf{avg}_0(t^0)\ ,\ \mathsf{avg}_0(t^1)\ , \ldots ,\ \mathsf{avg}_0(t^{63})\ ]$$

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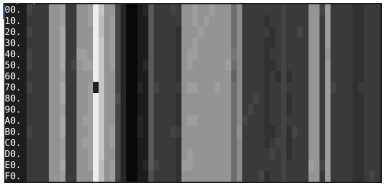
p_{\mu_1} &= [\ \mathsf{avg}_1(t^0)\ ,\ \mathsf{avg}_1(t^1)\ , \ldots ,\ \mathsf{avg}_1(t^{63})\ ] \\
&\cdots \\
p_{\mu_{15}} &= [\ \mathsf{avg}_{15}(t^0),\ \mathsf{avg}_{15}(t^1), \ldots ,\ \mathsf{avg}_{15}(t^{63})\ ]
\end{aligned}
$$

Prime + Probe: attack first-round AES (cont.)

$$
\begin{aligned}
p_{t_0} &= [\ t_0^0\ ,\ t_0^1\ ,\ldots,\ t_0^{63}\ ] \\
p_{t_1} &= [\ t_1^0\ ,\ t_1^1\ ,\ldots,\ t_1^{63}\ ] \\
&\cdots \\
p_{t_n} &= [\ t_n^0\ ,\ t_n^1\ ,\ldots,\ t_n^{63}\ ]
\end{aligned}
$$



$$
\begin{aligned}
p_{\mu_0} &= [\ \mathsf{avg}_0(t^0)\ ,\ \mathsf{avg}_0(t^1)\ ,\ldots,\ \mathsf{avg}_0(t^{63})\ ] \\
p_{\mu_1} &= [\ \mathsf{avg}_1(t^0)\ ,\ \mathsf{avg}_1(t^1)\ ,\ldots,\ \mathsf{avg}_1(t^{63})\ ] \\
&\cdots \\
p_{\mu_{15}} &= [\ \mathsf{avg}_{15}(t^0),\ \mathsf{avg}_{15}(t^1),\ldots,\ \mathsf{avg}_{15}(t^{63})\ ]
\end{aligned}
$$

Prime + Probe: attack first-round AES (cont.)

$$
\begin{aligned}
p_{t_0} &= [\ t_0^0\ ,\ t_0^1\ , \ldots ,\ t_0^{63}\ ] \\
p_{t_1} &= [\ t_1^0\ ,\ t_1^1\ , \ldots ,\ t_1^{63}\ ] \\
&\cdots \\
p_{t_n} &= [\ t_n^0\ ,\ t_n^1\ , \ldots ,\ t_n^{63}\ ]
\end{aligned}
$$

$$
\begin{aligned}
p_{\mu} &= [\ \mathsf{avg}_n(t^0)\ ,\ \mathsf{avg}_n(t^1)\ , \ldots ,\ \mathsf{avg}_n(t^{63})\ ] \\
p_{\mu_0} &= [\ \mathsf{avg}_0(t^0)\ ,\ \mathsf{avg}_0(t^1)\ , \ldots ,\ \mathsf{avg}_0(t^{63})\ ] \\
p_{\mu_1} &= [\ \mathsf{avg}_1(t^0)\ ,\ \mathsf{avg}_1(t^1)\ , \ldots ,\ \mathsf{avg}_1(t^{63})\ ] \\
&\cdots \\
p_{\mu_{15}} &= [\ \mathsf{avg}_{15}(t^0),\ \mathsf{avg}_{15}(t^1), \ldots ,\ \mathsf{avg}_{15}(t^{63})\ ]
\end{aligned}
$$

Prime + Probe: attack first-round AES (cont.)

$$
\begin{aligned}
p_{t_0} &= [\ t_0^0\ ,\ t_0^1\ , \ldots ,\ t_0^{63}\ ] \\
p_{t_1} &= [\ t_1^0\ ,\ t_1^1\ , \ldots ,\ t_1^{63}\ ] \\
&\cdots \\
p_{t_n} &= [\ t_n^0\ ,\ t_n^1\ , \ldots ,\ t_n^{63}\ ]
\end{aligned}
$$

$$
\begin{aligned}
p_{\mu} &= [\ \mathsf{avg}_n(t^0)\ ,\ \mathsf{avg}_n(t^1)\ , \ldots ,\ \mathsf{avg}_n(t^{63})\ ] \\
p_{\mu_0} &= [\ \mathsf{avg}_0(t^0)\ ,\ \mathsf{avg}_0(t^1)\ , \ldots ,\ \mathsf{avg}_0(t^{63})\ ] \\
p_{\mu_1} &= [\ \mathsf{avg}_1(t^0)\ ,\ \mathsf{avg}_1(t^1)\ , \ldots ,\ \mathsf{avg}_1(t^{63})\ ] \\
&\cdots \\
p_{\mu_{15}} &= [\ \mathsf{avg}_{15}(t^0),\ \mathsf{avg}_{15}(t^1), \ldots ,\ \mathsf{avg}_{15}(t^{63})\ ]
\end{aligned}
$$

$$\tilde{p}_{\mu_0} = p_{\mu_0} - p_{\mu}$$

Prime + Probe: attack first-round AES (cont.)

$$
\begin{aligned}
p_{t_0} &= [\ t_0^0\ ,\ t_0^1\ , \ldots ,\ t_0^{63}\ ] \\
p_{t_1} &= [\ t_1^0\ ,\ t_1^1\ , \ldots ,\ t_1^{63}\ ] \\
&\cdots \\
p_{t_n} &= [\ t_n^0\ ,\ t_n^1\ , \ldots ,\ t_n^{63}\ ]
\end{aligned}
$$

$$
\begin{aligned}
p_{\mu} &= [\ \mathsf{avg}_n(t^0)\ ,\ \mathsf{avg}_n(t^1)\ , \ldots ,\ \mathsf{avg}_n(t^{63})\ ] \\
p_{\mu_0} &= [\ \mathsf{avg}_0(t^0)\ ,\ \mathsf{avg}_0(t^1)\ , \ldots ,\ \mathsf{avg}_0(t^{63})\ ] \\
p_{\mu_1} &= [\ \mathsf{avg}_1(t^0)\ ,\ \mathsf{avg}_1(t^1)\ , \ldots ,\ \mathsf{avg}_1(t^{63})\ ] \\
&\cdots \\
p_{\mu_{15}} &= [\ \mathsf{avg}_{15}(t^0),\ \mathsf{avg}_{15}(t^1), \ldots ,\ \mathsf{avg}_{15}(t^{63})\ ]
\end{aligned}
$$

$$
\begin{aligned}
\tilde{p}_{\mu_0} &= p_{\mu_0} - p_{\mu} \\
\tilde{p}_{\mu_1} &= p_{\mu_1} - p_{\mu}
\end{aligned}
$$

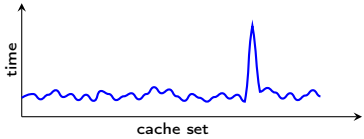
Prime + Probe: attack first-round AES (cont.)

$$
\begin{aligned}
p_{t_0} &= [\ t_0^0\ ,\ t_0^1\ ,\ \ldots,\ t_0^{63}\ ] \\
p_{t_1} &= [\ t_1^0\ ,\ t_1^1\ ,\ \ldots,\ t_1^{63}\ ] \\
&\ldots \\
p_{t_n} &= [\ t_n^0\ ,\ t_n^1\ ,\ \ldots,\ t_n^{63}\ ]
\end{aligned}
$$

$$
\begin{aligned}
p_{\mu} &= [\ \mathsf{avg}_n(t^0)\ ,\ \mathsf{avg}_n(t^1)\ ,\ldots,\ \mathsf{avg}_n(t^{63})\ ] \\
p_{\mu_0} &= [\ \mathsf{avg}_0(t^0)\ ,\ \mathsf{avg}_0(t^1)\ ,\ldots,\ \mathsf{avg}_0(t^{63})\ ] \qquad \tilde{p}_{\mu_0} = p_{\mu_0} - p_{\mu} \\
p_{\mu_1} &= [\ \mathsf{avg}_1(t^0)\ ,\ \mathsf{avg}_1(t^1)\ ,\ldots,\ \mathsf{avg}_1(t^{63})\ ] \qquad \tilde{p}_{\mu_1} = p_{\mu_1} - p_{\mu} \\
&\ldots \\
p_{\mu_{15}} &= [\ \mathsf{avg}_{15}(t^0),\ \mathsf{avg}_{15}(t^1),\ldots,\ \mathsf{avg}_{15}(t^{63})\ ] \qquad \tilde{p}_{\mu_{15}} = p_{\mu_{15}} - p_{\mu}
\end{aligned}
$$

Prime + Probe: attack first-round AES (cont.)

$$
\begin{aligned}
p_{t_0} &= [\ t_0^0\ ,\ t_0^1\ ,\ \ldots,\ t_0^{63}\ ] \\
p_{t_1} &= [\ t_1^0\ ,\ t_1^1\ ,\ \ldots,\ t_1^{63}\ ] \\
&\ldots \\
p_{t_n} &= [\ t_n^0\ ,\ t_n^1\ ,\ \ldots,\ t_n^{63}\ ]
\end{aligned}
$$

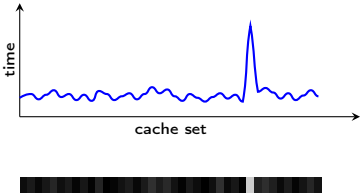


$$
\begin{aligned}
p_{\mu} &= [\ \mathsf{avg}_n(t^0)\ ,\ \mathsf{avg}_n(t^1)\ ,\ldots,\ \mathsf{avg}_n(t^{63})\ ] \\
p_{\mu_0} &= [\ \mathsf{avg}_0(t^0)\ ,\ \mathsf{avg}_0(t^1)\ ,\ldots,\ \mathsf{avg}_0(t^{63})\ ] \\
p_{\mu_1} &= [\ \mathsf{avg}_1(t^0)\ ,\ \mathsf{avg}_1(t^1)\ ,\ldots,\ \mathsf{avg}_1(t^{63})\ ] \\
&\ldots \\
p_{\mu_{15}} &= [\ \mathsf{avg}_{15}(t^0),\ \mathsf{avg}_{15}(t^1),\ldots,\ \mathsf{avg}_{15}(t^{63})\ ]
\end{aligned}
$$

$$
\begin{aligned}
\tilde{p}_{\mu_0} &= p_{\mu_0} - p_{\mu} \\
\tilde{p}_{\mu_1} &= p_{\mu_1} - p_{\mu} \\
\tilde{p}_{\mu_{15}} &= p_{\mu_{15}} - p_{\mu}
\end{aligned}
$$

Prime + Probe: attack first-round AES (cont.)

$$
\begin{aligned}
p_{t_0} &= [\ t_0^0\ ,\ t_0^1\ ,\ \ldots,\ t_0^{63}\ ] \\
p_{t_1} &= [\ t_1^0\ ,\ t_1^1\ ,\ \ldots,\ t_1^{63}\ ] \\
&\ldots \\
p_{t_n} &= [\ t_n^0\ ,\ t_n^1\ ,\ \ldots,\ t_n^{63}\ ]
\end{aligned}
$$

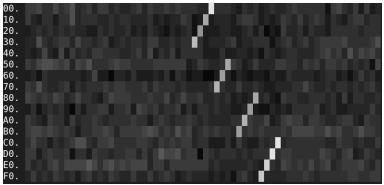


$$
\begin{aligned}
p_{\mu} &= [\ \mathsf{avg}_n(t^0)\ ,\ \mathsf{avg}_n(t^1)\ ,\ \ldots,\ \mathsf{avg}_n(t^{63})\ ] \\
p_{\mu_0} &= [\ \mathsf{avg}_0(t^0)\ ,\ \mathsf{avg}_0(t^1)\ ,\ \ldots,\ \mathsf{avg}_0(t^{63})\ ] \\
p_{\mu_1} &= [\ \mathsf{avg}_1(t^0)\ ,\ \mathsf{avg}_1(t^1)\ ,\ \ldots,\ \mathsf{avg}_1(t^{63})\ ] \\
&\ldots \\
p_{\mu_{15}} &= [\ \mathsf{avg}_{15}(t^0),\ \mathsf{avg}_{15}(t^1),\ \ldots,\ \mathsf{avg}_{15}(t^{63})\ ]
\end{aligned}
$$

$$
\begin{aligned}
\tilde{p}_{\mu_0} &= p_{\mu_0} - p_{\mu} \\
\tilde{p}_{\mu_1} &= p_{\mu_1} - p_{\mu} \\
\tilde{p}_{\mu_{15}} &= p_{\mu_{15}} - p_{\mu}
\end{aligned}
$$

Prime + Probe: attack first-round AES (cont.)

$$
\begin{aligned}
p_{t_0} &= [\ t_0^0\ ,\ t_0^1\ ,\ \ldots,\ t_0^{63}\ ] \\
p_{t_1} &= [\ t_1^0\ ,\ t_1^1\ ,\ \ldots,\ t_1^{63}\ ] \\
&\cdots \\
p_{t_n} &= [\ t_n^0\ ,\ t_n^1\ ,\ \ldots,\ t_n^{63}\ ]
\end{aligned}
$$



$$
\begin{aligned}
p_{\mu} &= [\ \mathsf{avg}_n(t^0)\ ,\ \mathsf{avg}_n(t^1)\ ,\ldots,\ \mathsf{avg}_n(t^{63})\ ] \\
p_{\mu_0} &= [\ \mathsf{avg}_0(t^0)\ ,\ \mathsf{avg}_0(t^1)\ ,\ldots,\ \mathsf{avg}_0(t^{63})\ ] \\
p_{\mu_1} &= [\ \mathsf{avg}_1(t^0)\ ,\ \mathsf{avg}_1(t^1)\ ,\ldots,\ \mathsf{avg}_1(t^{63})\ ] \\
&\cdots \\
p_{\mu_{15}} &= [\ \mathsf{avg}_{15}(t^0),\ \mathsf{avg}_{15}(t^1),\ldots,\ \mathsf{avg}_{15}(t^{63})\ ]
\end{aligned}
$$

$$
\begin{aligned}
\tilde{p}_{\mu_0} &= p_{\mu_0} - p_{\mu} \\
\tilde{p}_{\mu_1} &= p_{\mu_1} - p_{\mu} \\
\tilde{p}_{\mu_{15}} &= p_{\mu_{15}} - p_{\mu}
\end{aligned}
$$

Prime + Probe: demo

- First-round AES

Prime + Probe: attack first-round AES (cont.)

- Recall Prime + Probe has a resolution of cache set

$\rightarrow$ detect which cache set is (not) accessed

Prime + Probe: attack first-round AES (cont.)

- Recall Prime + Probe has a resolution of cache set

$\rightarrow$ detect which cache set is (not) accessed

- A table spans over $16 = 2^4$ sets

$\rightarrow$ reveal top 4 bits at best

Prime + Probe: attack first-round AES (cont.)

- Recall Prime + Probe has a resolution of cache set

$\rightarrow$ detect which cache set is (not) accessed

- A table spans over $16 = 2^4$ sets

$\rightarrow$ reveal top 4 bits at best

- To recover the remaining bits
  - combine with second-round cryptanalysis
  - attack final round instead
  - etc.

Prime + Probe: attack first-round AES (cont.)

- Recall Prime + Probe has a resolution of cache set

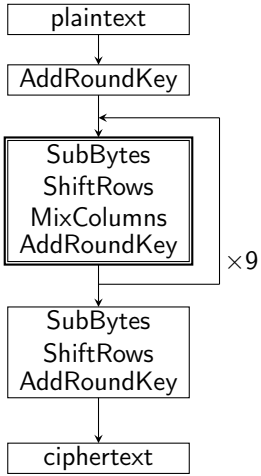
$\rightarrow$ detect which cache set is (not) accessed

- A table spans over $16 = 2^4$ sets

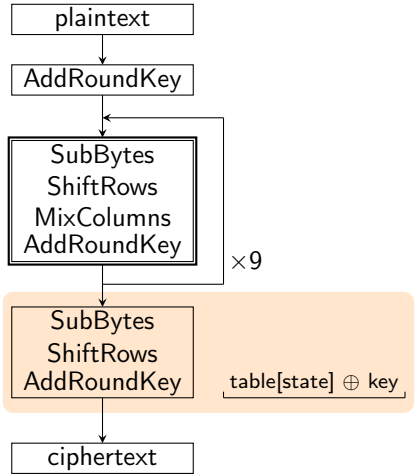
$\rightarrow$ reveal top 4 bits at best

- To recover the remaining bits
  - combine with second-round cryptanalysis
  - attack final round instead
  - etc.

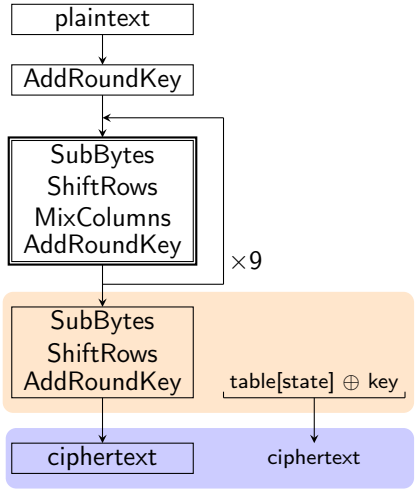
Prime + Probe: attack final-round AES



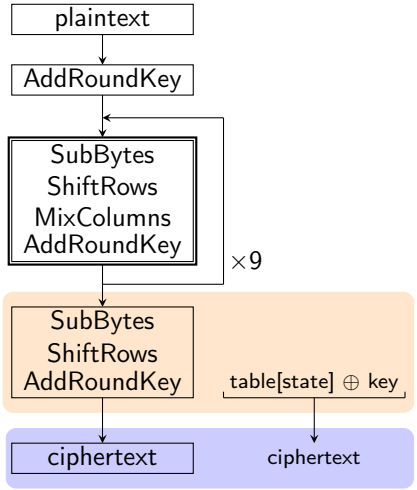
Prime + Probe: attack final-round AES



Prime + Probe: attack final-round AES

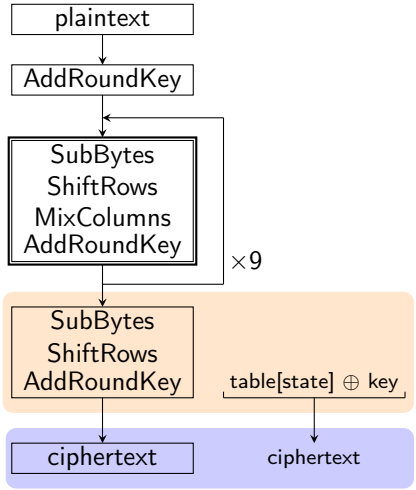


Prime + Probe: attack final-round AES



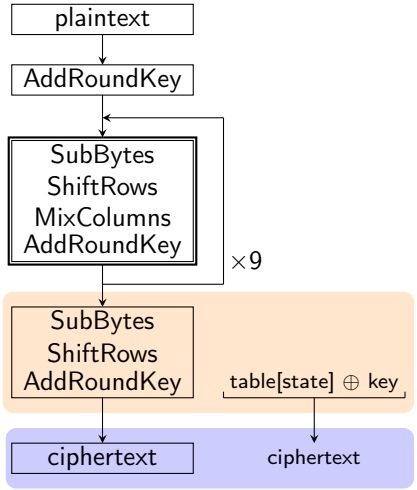
- Know ciphertext + guess key → table index

Prime + Probe: attack final-round AES



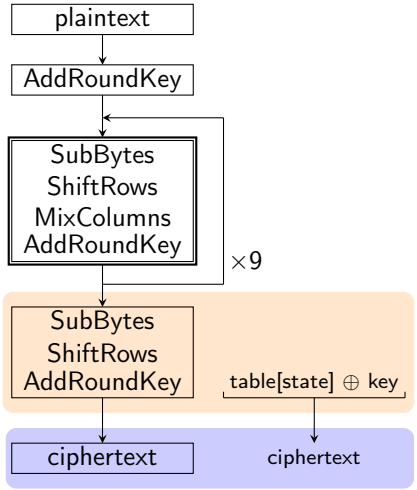
- Know ciphertext + guess key → table index
- Exploit SBox confusion property

Prime + Probe: attack final-round AES



- Know ciphertext + guess key → table index
- Exploit SBox confusion property
- Compute correlation between known and guessed key
  - high correlation indicates correct key guess

Prime + Probe: attack final-round AES



- Know ciphertext + guess key → table index
- Exploit SBox confusion property
- Compute correlation between known and guessed key
  - high correlation indicates correct key guess
- Recover full key

Prime + Probe: attack final-round AES

$p_{t_0} = [t_0^0,\ t_0^1, \ldots, t_0^{16}, t_0^{17}, \ldots, t_0^{63}]$ 

Prime + Probe: attack final-round AES

$$p_{t_0} = [t_0^0,\ t_0^1, \ldots, t_0^{16}, t_0^{17}, \ldots, t_0^{63}]$$

$$p_{t_1} = [t_1^0,\ t_1^1, \ldots, t_1^{16}, t_1^{17}, \ldots, t_1^{63}]$$

Prime + Probe: attack final-round AES

$$p_{t_0} = [t_0^0,\ t_0^1, \ldots, t_0^{16}, t_0^{17}, \ldots, t_0^{63}]$$

$$p_{t_1} = [t_1^0,\ t_1^1, \ldots, t_1^{16}, t_1^{17}, \ldots, t_1^{63}]$$ 

$\ldots$

$$p_{t_n} = [t_n^0,\ t_n^1, \ldots, t_n^{16}, t_n^{17}, \ldots, t_n^{63}]$$

Prime + Probe: attack final-round AES

$$p_{t_0} = [t_0^0,\ t_0^1, \ldots, t_0^{16}, t_0^{17}, \ldots, t_0^{63}]$$
$$p_{t_1} = [t_1^0,\ t_1^1, \ldots, t_1^{16}, t_1^{17}, \ldots, t_1^{63}]$$
$$\ldots$$
$$p_{t_n} = [t_n^0,\ t_n^1, \ldots, t_n^{16}, t_n^{17}, \ldots, t_n^{63}]$$

$$k_{t_{00}} = [\ 0, 15, \ldots, -1, -1, \ldots,\ 0]$$

Prime + Probe: attack final-round AES

$$p_{t_0} = [t_0^0,\ t_0^1, \ldots, t_0^{16}, t_0^{17}, \ldots, t_0^{63}]$$
$$p_{t_1} = [t_1^0,\ t_1^1, \ldots, t_1^{16}, t_1^{17}, \ldots, t_1^{63}]$$
$$\ldots$$
$$p_{t_n} = [t_n^0,\ t_n^1, \ldots, t_n^{16}, t_n^{17}, \ldots, t_n^{63}]$$

$$k_{t_{00}} = [\ 0, 15, \ldots, -1, -1, \ldots,\ 0]$$
$$k_{t_{01}} = [\ 0, -1, \ldots, -1, 15, \ldots,\ 0]$$

Prime + Probe: attack final-round AES

$$p_{t_0} = [t_0^0,\ t_0^1, \ldots, t_0^{16}, t_0^{17}, \ldots, t_0^{63}]$$
$$p_{t_1} = [t_1^0,\ t_1^1, \ldots, t_1^{16}, t_1^{17}, \ldots, t_1^{63}]$$
$$\ldots$$
$$p_{t_n} = [t_n^0,\ t_n^1, \ldots, t_n^{16}, t_n^{17}, \ldots, t_n^{63}]$$

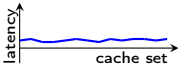
$$k_{t_{00}} = [\ 0,\ 15, \ldots, -1, -1, \ldots,\ 0]$$
$$k_{t_{01}} = [\ 0, -1, \ldots, -1,\ 15, \ldots,\ 0]$$
$$k_{t_{02}} = [\ 0, -1, \ldots, -1, -1, \ldots,\ 0]$$

Prime + Probe: attack final-round AES

$$p_{t_0} = [t_0^0,\ t_0^1, \ldots, t_0^{16}, t_0^{17}, \ldots, t_0^{63}]$$
$$p_{t_1} = [t_1^0,\ t_1^1, \ldots, t_1^{16}, t_1^{17}, \ldots, t_1^{63}]$$
$$\ldots$$
$$p_{t_n} = [t_n^0,\ t_n^1, \ldots, t_n^{16}, t_n^{17}, \ldots, t_n^{63}]$$

$$k_{t_{00}} = [\ 0,\ 15, \ldots, -1, -1, \ldots,\ 0]$$
$$k_{t_{01}} = [\ 0, -1, \ldots, -1,\ 15, \ldots,\ 0]$$
$$k_{t_{02}} = [\ 0, -1, \ldots, -1, -1, \ldots,\ 0]$$
$$\ldots$$
$$k_{t_{\mathrm{FF}}} = [\ 0, -1, \ldots,\ 15, -1, \ldots,\ 0]$$

Prime + Probe: attack final-round AES

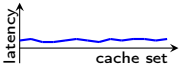


$$p_{t_0} = [t_0^0,\ t_0^1, \ldots, t_0^{16}, t_0^{17}, \ldots, t_0^{63}]$$
$$p_{t_1} = [t_1^0,\ t_1^1, \ldots, t_1^{16}, t_1^{17}, \ldots, t_1^{63}]$$
$$\ldots$$
$$p_{t_n} = [t_n^0,\ t_n^1, \ldots, t_n^{16}, t_n^{17}, \ldots, t_n^{63}]$$

$$\tilde{p}_{t_{0,00}} = p_{t_0} \odot k_{t_0}$$

$$k_{t_{00}} = [\ 0, 15, \ldots, -1, -1, \ldots,\ 0]$$
$$k_{t_{01}} = [\ 0, -1, \ldots, -1, 15, \ldots,\ 0]$$
$$k_{t_{02}} = [\ 0, -1, \ldots, -1, -1, \ldots,\ 0]$$
$$\ldots$$
$$k_{t_{\mathrm{FF}}} = [\ 0, -1, \ldots, 15, -1, \ldots,\ 0]$$

Prime + Probe: attack final-round AES



$p_{t_0} = [t_0^0,\ t_0^1, \ldots, t_0^{16}, t_0^{17}, \ldots, t_0^{63}]$

$p_{t_1} = [t_1^0,\ t_1^1, \ldots, t_1^{16}, t_1^{17}, \ldots, t_1^{63}]$

$\ldots$

$p_{t_n} = [t_n^0,\ t_n^1, \ldots, t_n^{16}, t_n^{17}, \ldots, t_n^{63}]$

$\tilde{p}_{t_{0,00}} = p_{t_0} \odot k_{t_0}$

$\tilde{p}_{t_{1,00}} = p_{t_1} \odot k_{t_0}$

$k_{t_{00}} = [\ 0, 15, \ldots, -1, -1, \ldots,\ 0]$

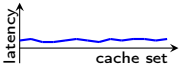
$k_{t_{01}} = [\ 0, -1, \ldots, -1, 15, \ldots,\ 0]$

$k_{t_{02}} = [\ 0, -1, \ldots, -1, -1, \ldots,\ 0]$

$\ldots$

$k_{t_{FF}} = [\ 0, -1, \ldots, 15, -1, \ldots,\ 0]$

Prime + Probe: attack final-round AES

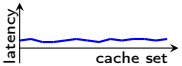


$$p_{t_0} = [t_0^0,\ t_0^1, \ldots, t_0^{16}, t_0^{17}, \ldots, t_0^{63}]$$
$$p_{t_1} = [t_1^0,\ t_1^1, \ldots, t_1^{16}, t_1^{17}, \ldots, t_1^{63}]$$
$$\ldots$$
$$p_{t_n} = [t_n^0,\ t_n^1, \ldots, t_n^{16}, t_n^{17}, \ldots, t_n^{63}]$$

$$\tilde{p}_{t_{0,00}} = p_{t_0} \odot k_{t_0}$$
$$\tilde{p}_{t_{1,00}} = p_{t_1} \odot k_{t_0}$$
$$\ldots$$
$$\tilde{p}_{t_{n,00}} = p_{t_n} \odot k_{t_0}$$

$$k_{t_{00}} = [\ 0, 15, \ldots, -1, -1, \ldots,\ 0]$$
$$k_{t_{01}} = [\ 0, -1, \ldots, -1, 15, \ldots,\ 0]$$
$$k_{t_{02}} = [\ 0, -1, \ldots, -1, -1, \ldots,\ 0]$$
$$\ldots$$
$$k_{t_{\mathrm{FF}}} = [\ 0, -1, \ldots, 15, -1, \ldots,\ 0]$$

Prime + Probe: attack final-round AES



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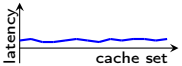

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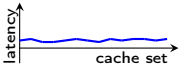

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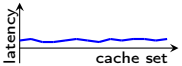

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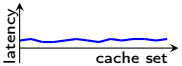

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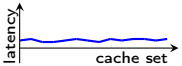

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$$\ldots \qquad \ldots$$
$$\ldots \qquad \tilde{p}_{\mu_{\mathrm{FF}}} = \mathsf{sum}(\tilde{p}_{t_{\mathrm{FF},\cdot}})$$
$$\ldots \qquad \rho_{15} = \sum \tilde{p}_{\mu_{\mathrm{FF}}}$$
$$\tilde{p}_{t_{n,\mathrm{FF}}} = p_{t_n} \odot k_{t_{\mathrm{FF}}}$$

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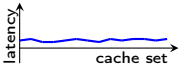

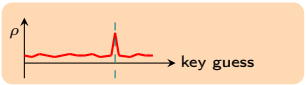

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$$\tilde{p}_{\mu_{\mathrm{FF}}} = \mathsf{sum}(\tilde{p}_{t_{\mathrm{FF},\cdot}})$$
$$\rho_{15} = \sum \tilde{p}_{\mu_{\mathrm{FF}}}$$

Prime + Probe: pros & cons

+ Work on non-shared memory

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- Resolution of cache set
- Suffer from false positive/negative

Comparison

Flush+Reload	**Prime+Probe**
more accurate	more generic
require shared memory	fewer prerequisites
identify cache line	identify cache set

Other Variants

- Evict + Time [OST05]
- Evict + Reload [GSM15]
- Flush + Flush [GMWM16]
- Prime + Abort [DKPT17]
- Prime + Scope [PTV21]
- Prefetch + Prefetch [GZZY22]
- etc.

Summary

- Mastik: toolkit to collect cache timing side-channel information
- General steps in cache attacks:

1. Prepare cache
2. (victim executes)
3. Get timing difference

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- Mastik: toolkit to collect cache timing side-channel information
- General steps in cache attacks:

	Flush + Reload
1. Prepare cache	clear cache line
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3. Get timing difference	reload cache line

Summary

- Mastik: toolkit to collect cache timing side-channel information
- General steps in cache attacks:

	Flush + Reload	Prime + Probe
1. Prepare cache	clear cache line	fill cache with own data
2. (victim executes)		
3. Get timing difference	reload cache line	re-access own data