CopyCat: Controlled Instruction-Level Attacks on Enclaves

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29TH USENIX SECURITY SYMPOSIUM

AUGUST 12–14, 2020

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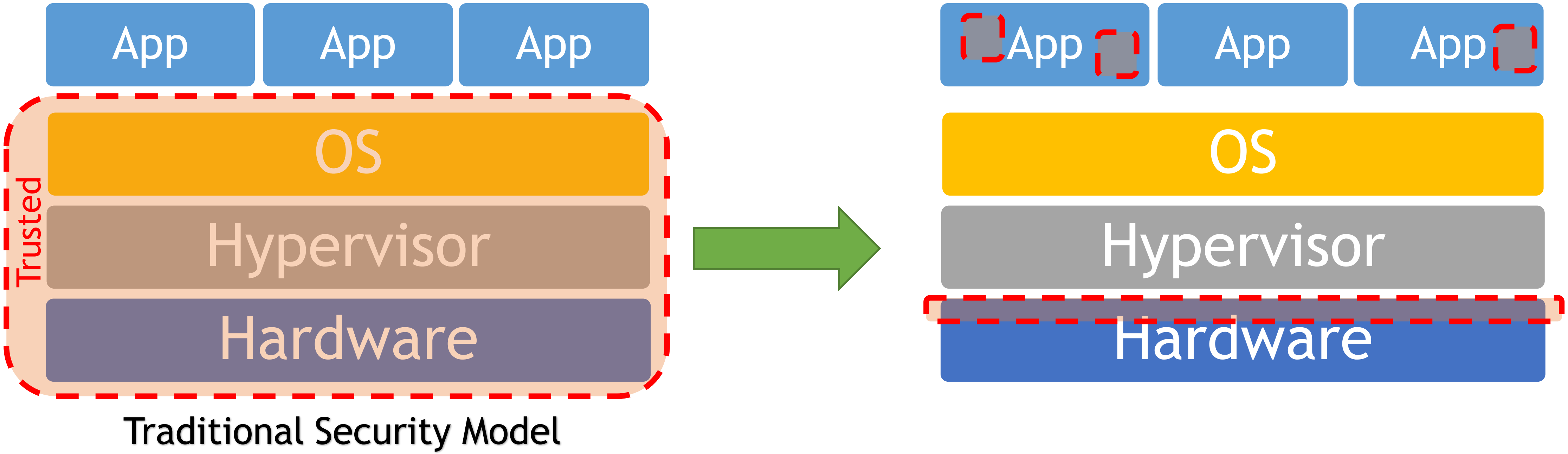
Trusted Execution Environment (TEE) - Intel SGX

- Intel Software Guard eXtensions (SGX)



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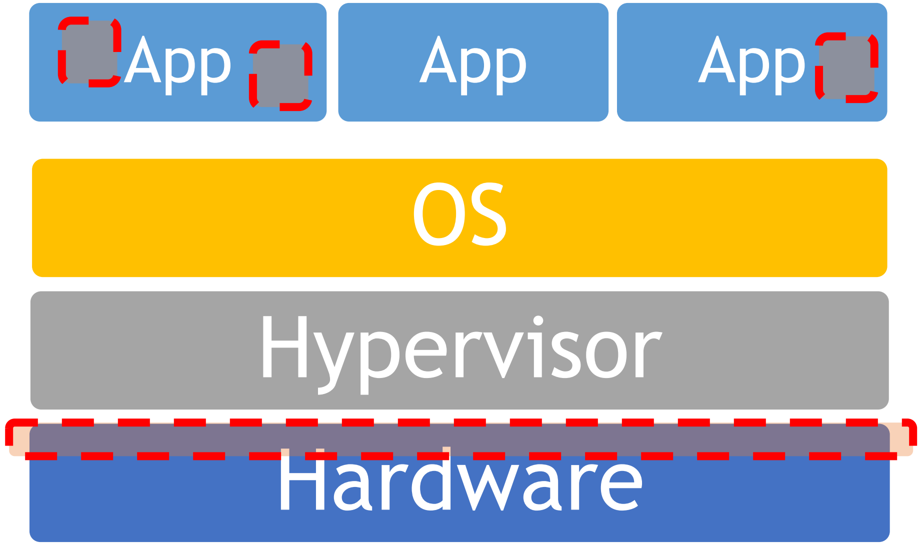

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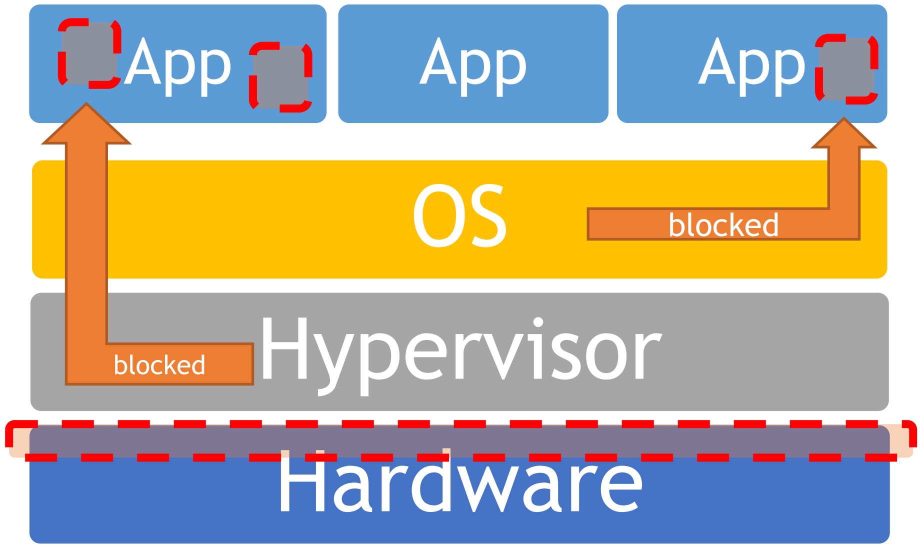
- Protects against system level adversary

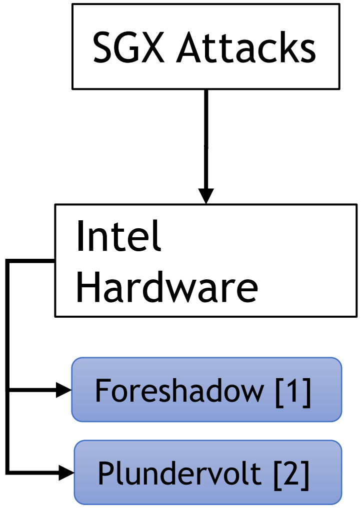


New Attacker Model:

Attacker gets full control over OS

Intel SGX Attack Taxonomy

- Intel's Responsibility
  - Microcode Patches / Hardware mitigation
  - TCB Recovery
    - Old Keys are Revoked
    - Remote attestation succeeds only with mitigation.



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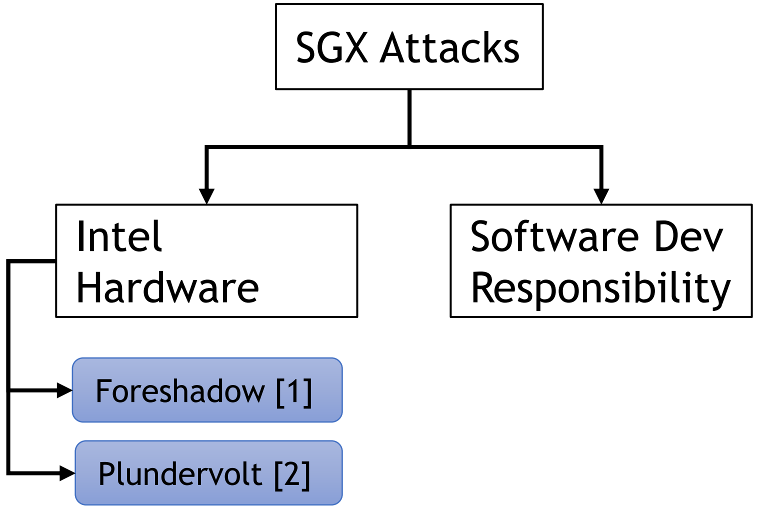

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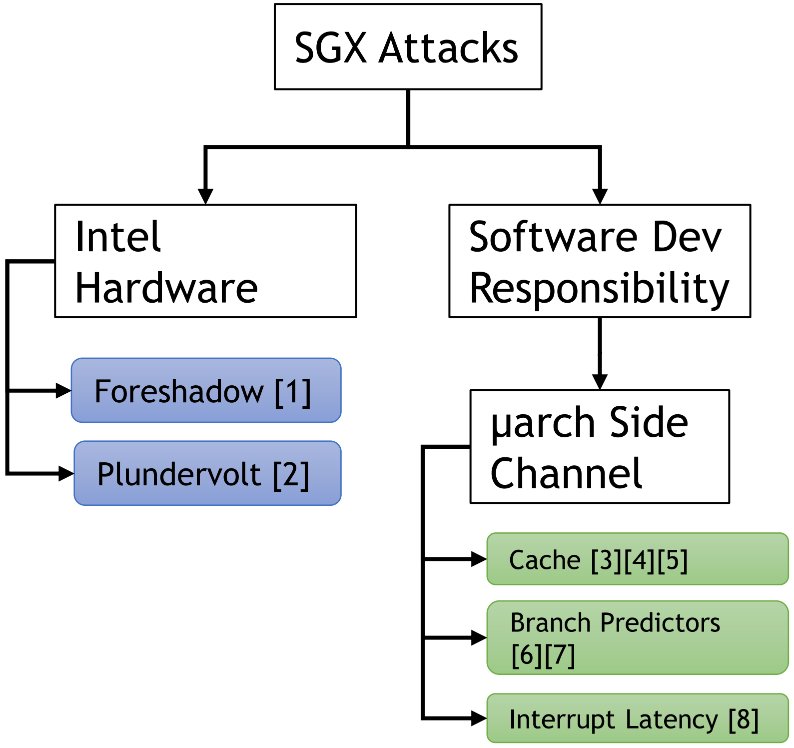
- μarch Side Channel
  - Constant-time Coding
  - Flushing and Isolating buffers
  - Probabilistic



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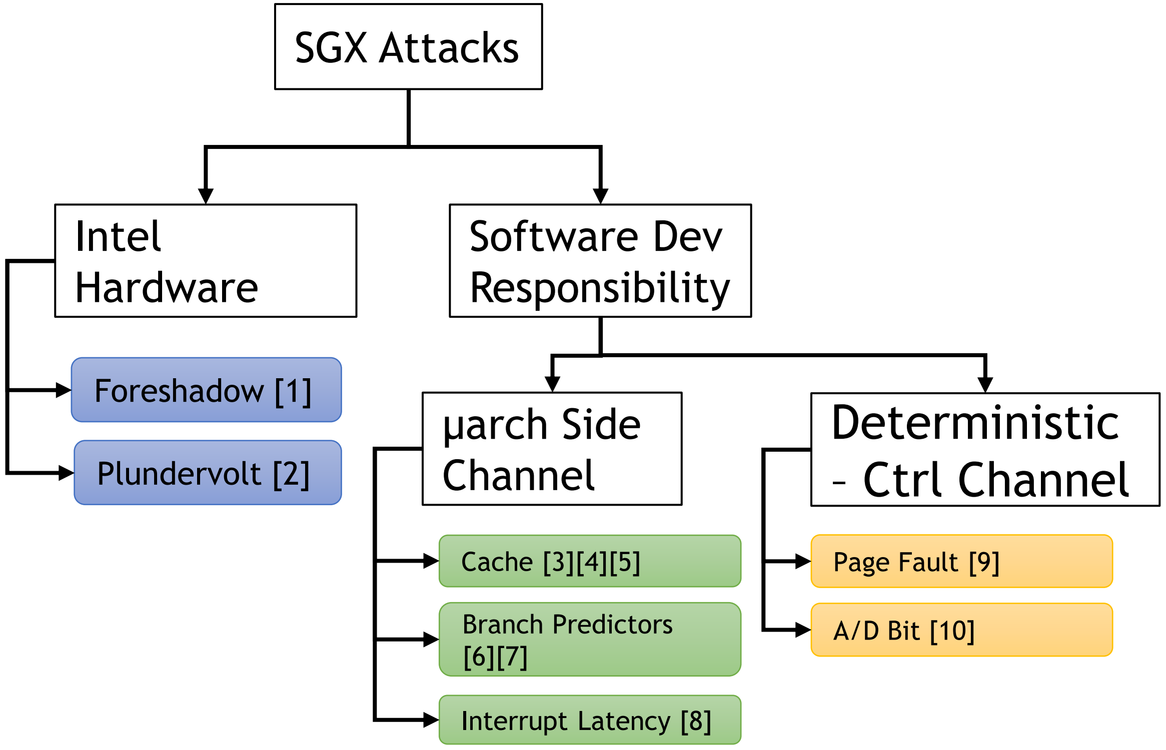
- Deterministic Attacks
  - Page Fault, A/D Bit, etc. (4kB Granularity)



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CopyCat Attack

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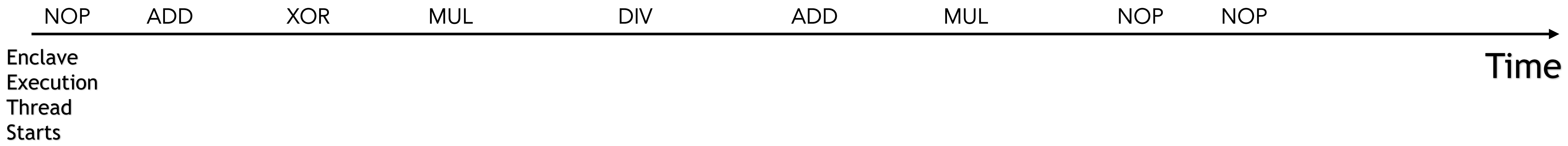
- Malicious OS controls the interrupt handler



CopyCat Attack

- Malicious OS controls the interrupt handler
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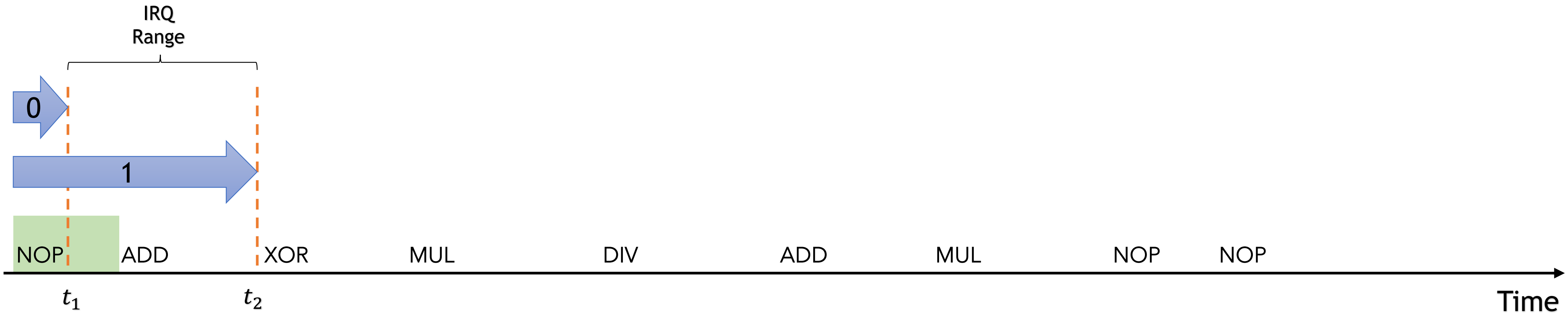

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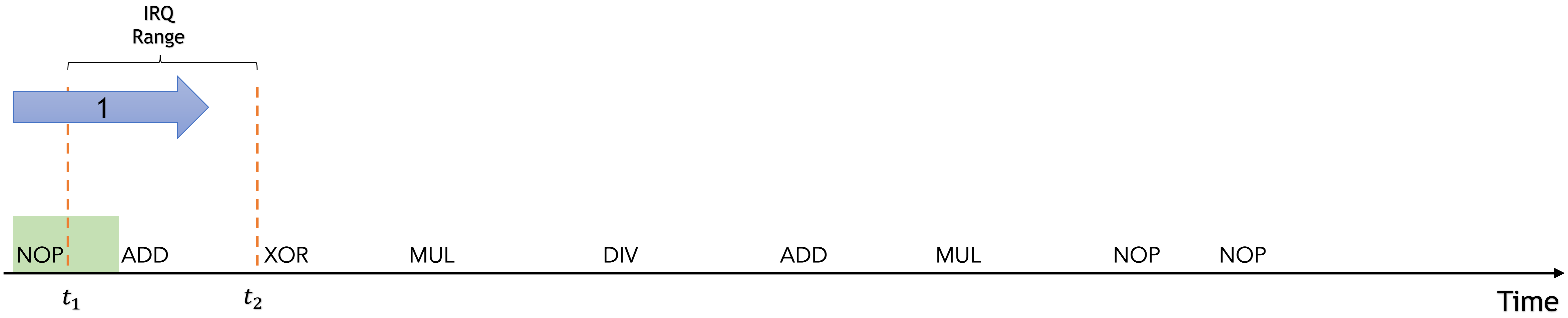

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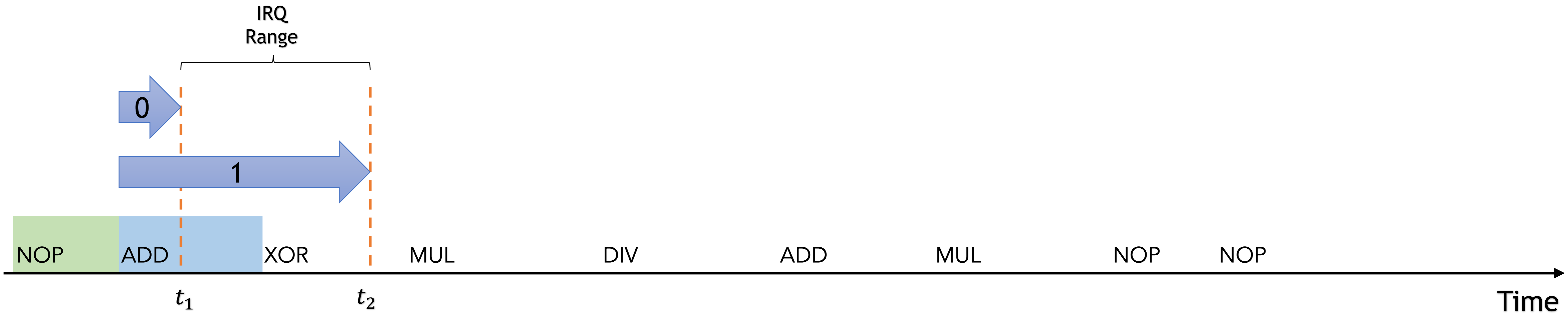

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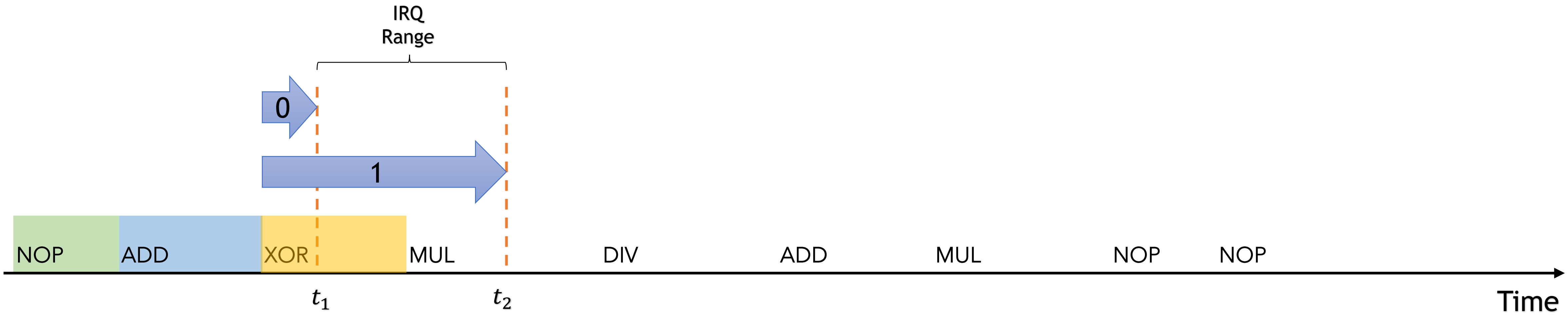

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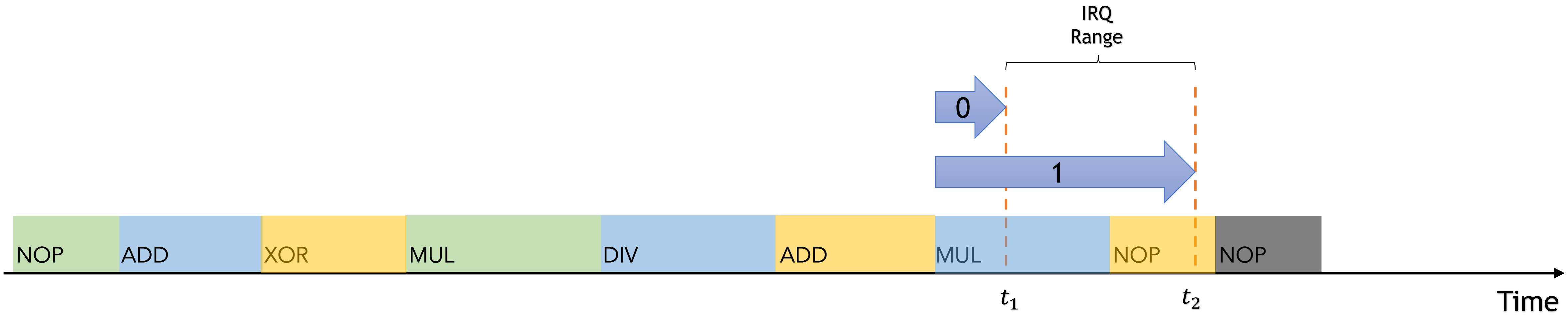

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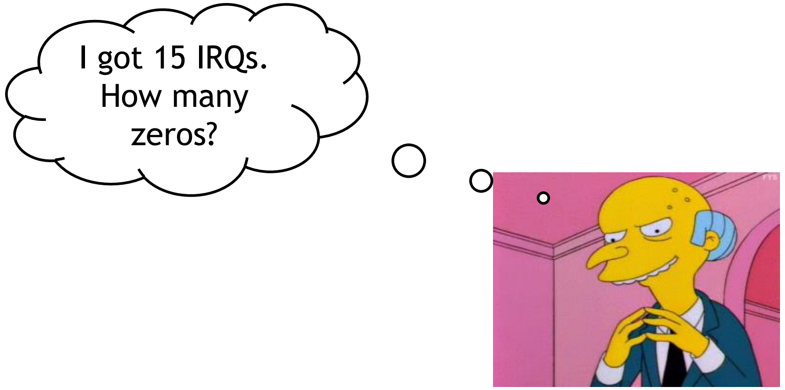

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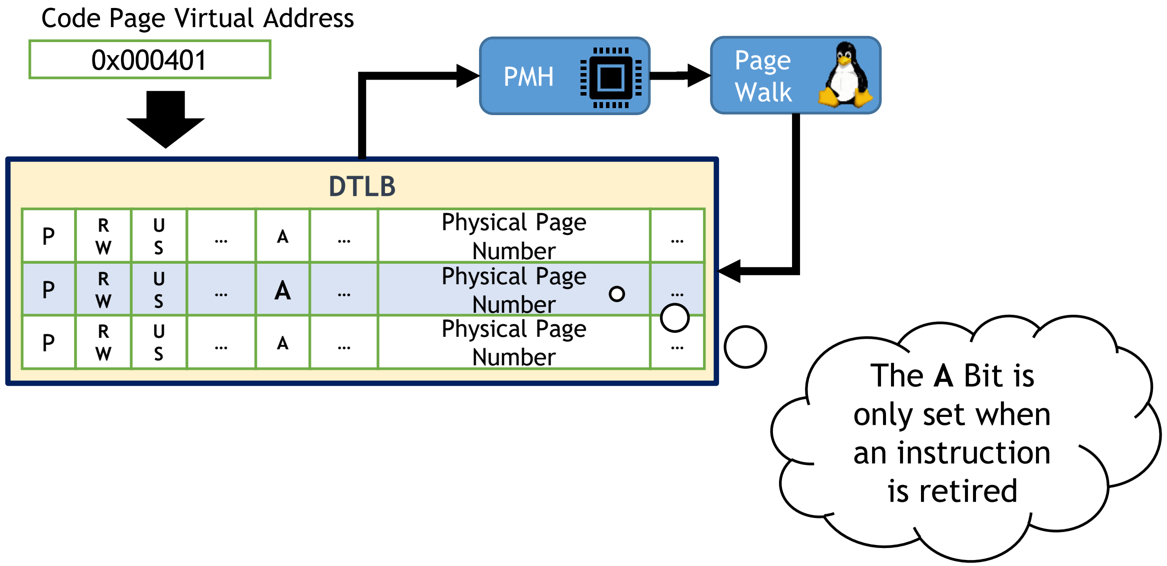

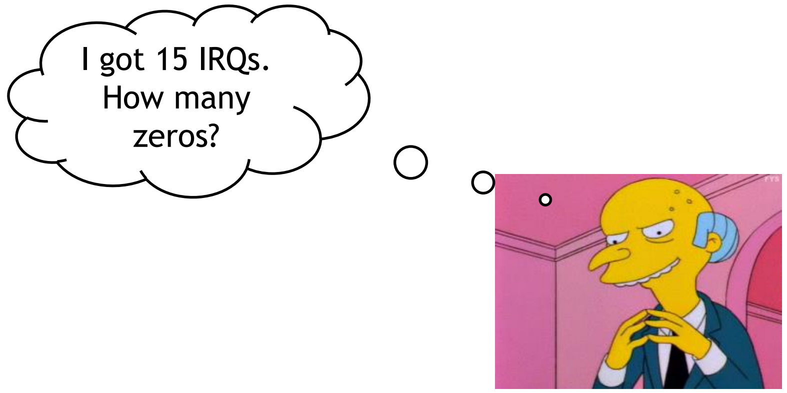

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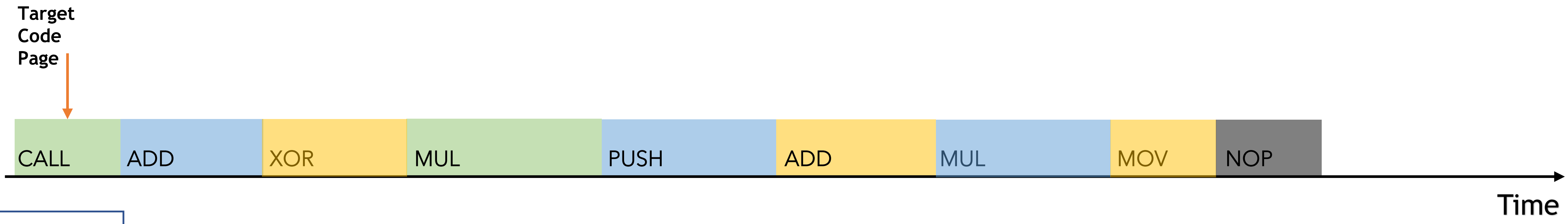

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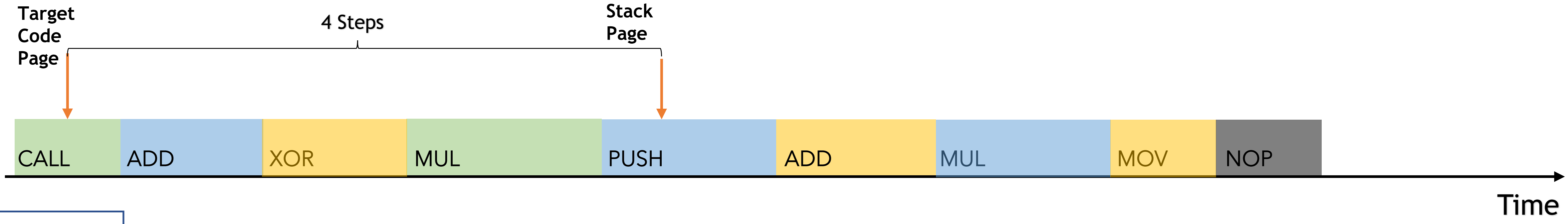

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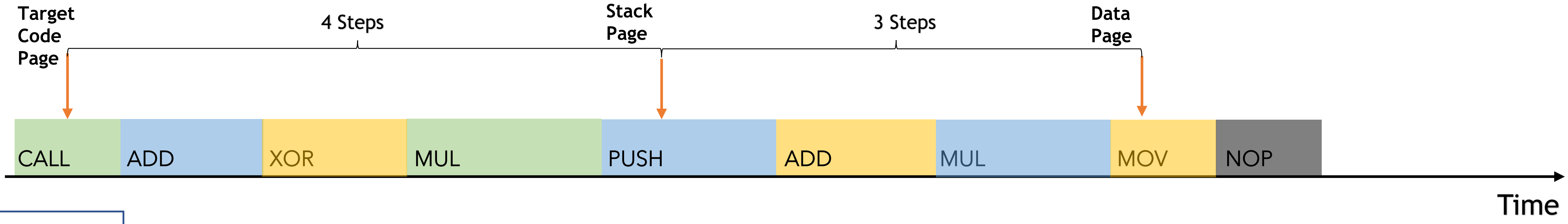
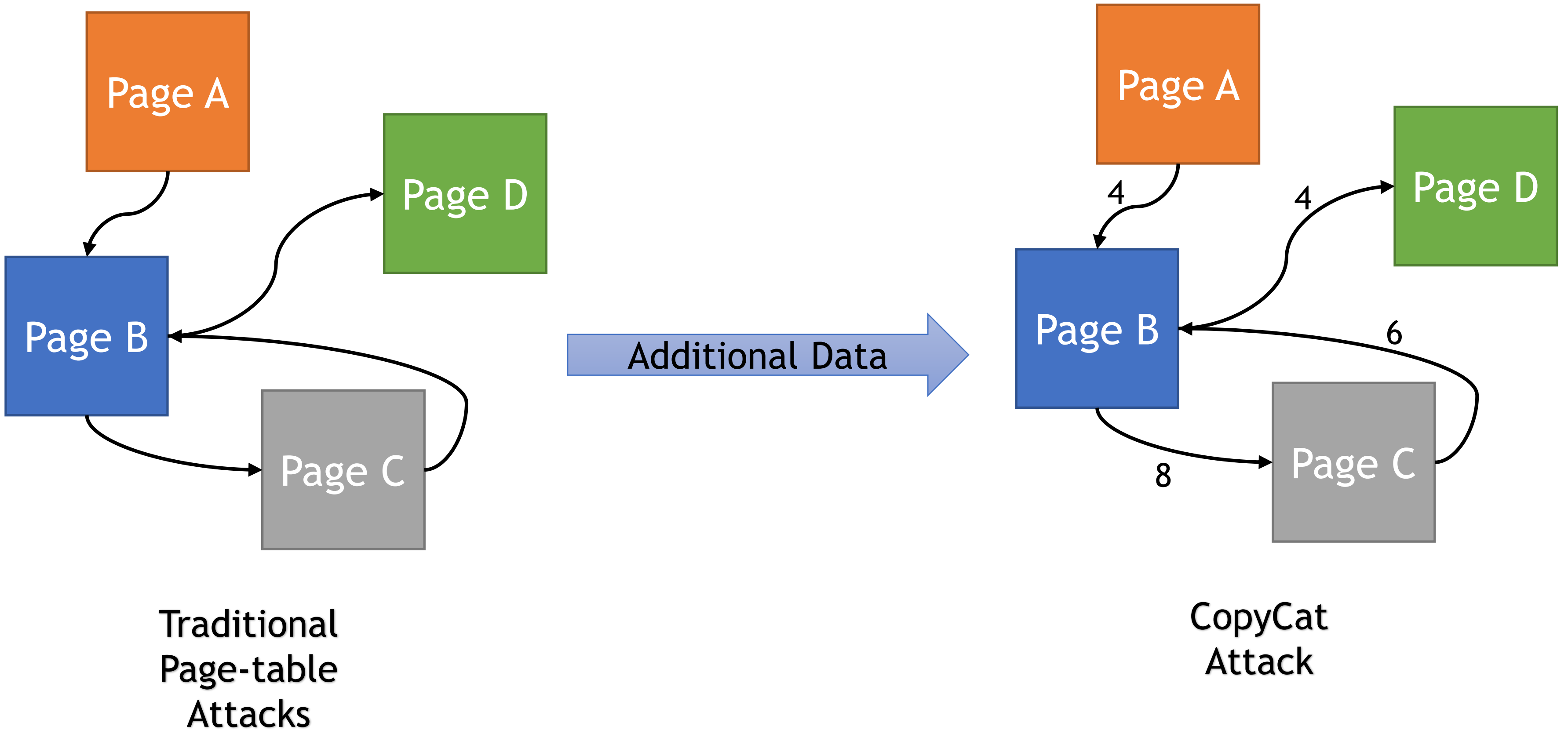


CopyCat Attack

- Previous Controlled Channel attacks leak Page Access Patterns
- CopyCat additionally leaks number of instructions per page



CopyCat – Leaking Branches


```c
if(c == 0) {
  r = add(r, d);
}
else {
  r = add(r, s);
}
```

C Code

Compile

```
test %eax, %eax
je label
mov %edx, %esi
label:
call add
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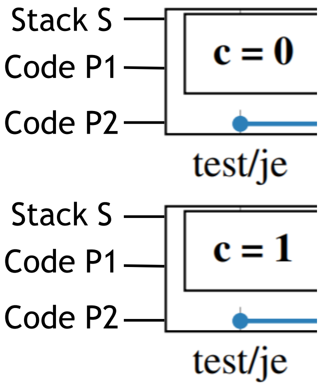

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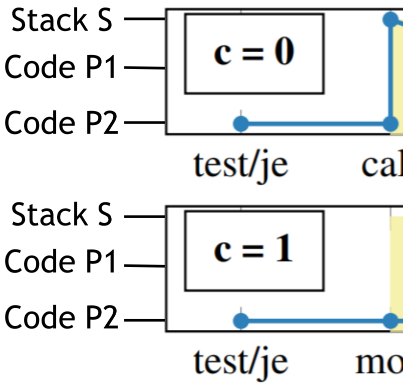

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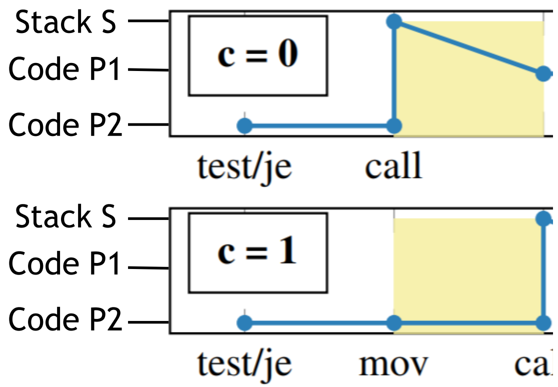

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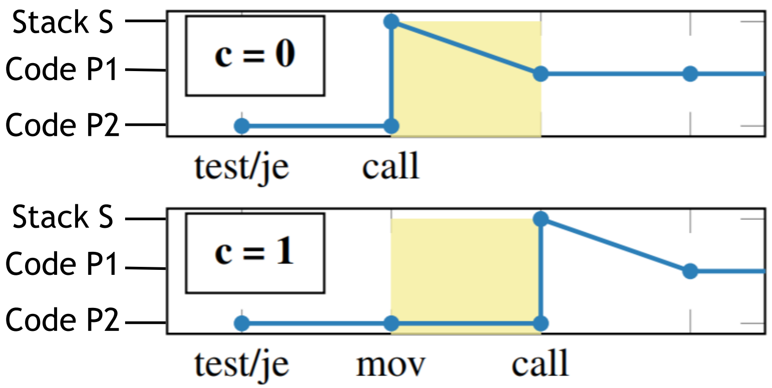

Crypto means Crpyptoattacks

Binary Extended Euclidean Algorithm (BEEA)

- Previous attacks only leak some of the branches w/ some noise

procedure $\textsc{ModInv}(u, \text{modulus } v)$
    $b_i \leftarrow 0\ d_i \leftarrow 1, u_i \leftarrow u, v_i = v,$
    while $isEven(u_i)$ **do**
        $u_i \leftarrow u_i/2$
        if $isOdd(b_i)$ **then**
            $b_i \leftarrow b_i - u$
        $b_i \leftarrow b_i/2$
    while $isEven(v_i)$ **do**
        $v_i \leftarrow v_i/2$
        if $isOdd(d_i)$ **then**
            $d_i \leftarrow d_i - u$
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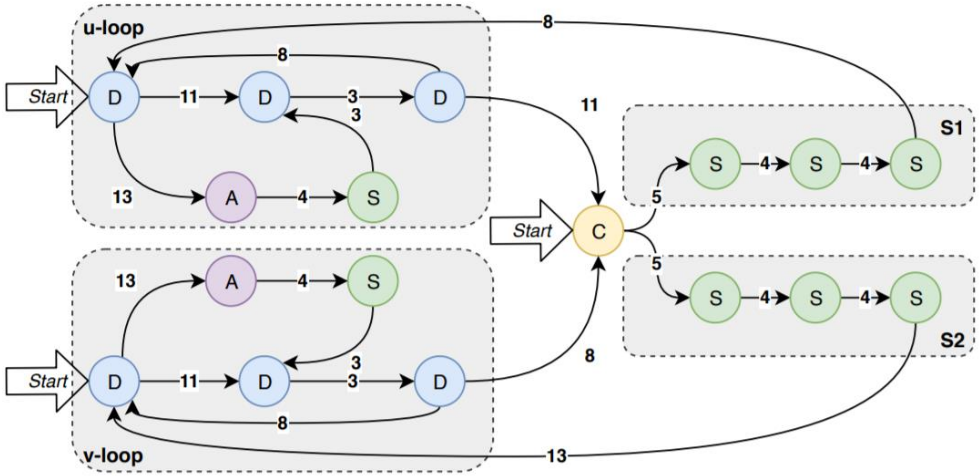
    if $u_i > v_i$ **then**
        $u_i \leftarrow u_i - v_i,\ b_i \leftarrow b_i - d_i$
    else
        $v_i \leftarrow v_i - u_i,\ d_i \leftarrow d_i - b_i$
    return d_i

Binary Extended Euclidean Algorithm

- Previous attacks only leak some of the branches w/ some noise
- CopyCat synchronously leaks all the branches wo/ any noise



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- Single-trace Attack during DSA signing: $k_{inv} = k^{-1} \, mod \, n$
  - Iterative over the entire recovered trace with n as input → k_{inv}
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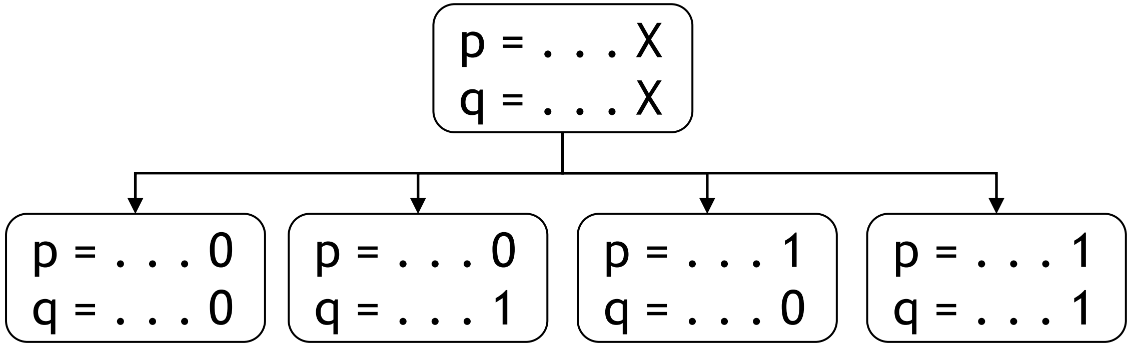

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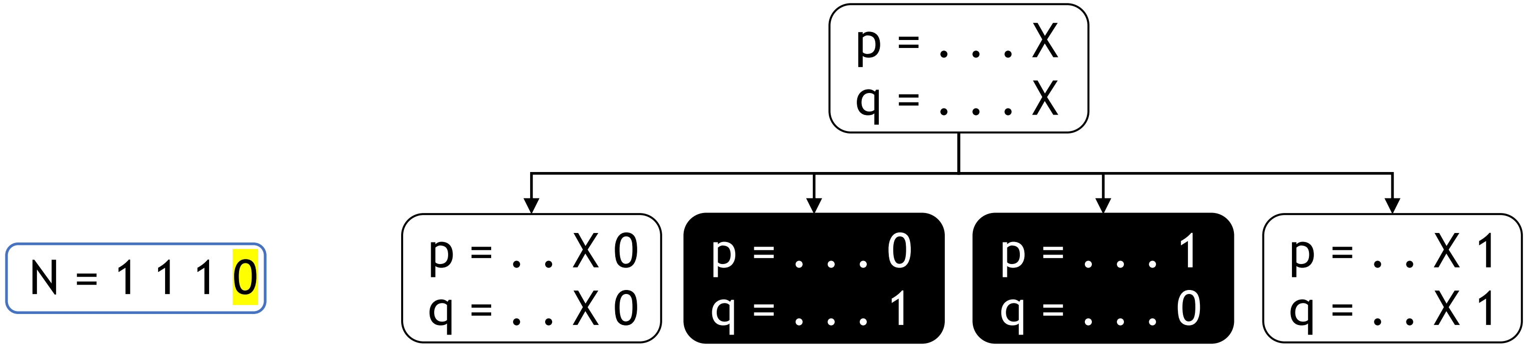

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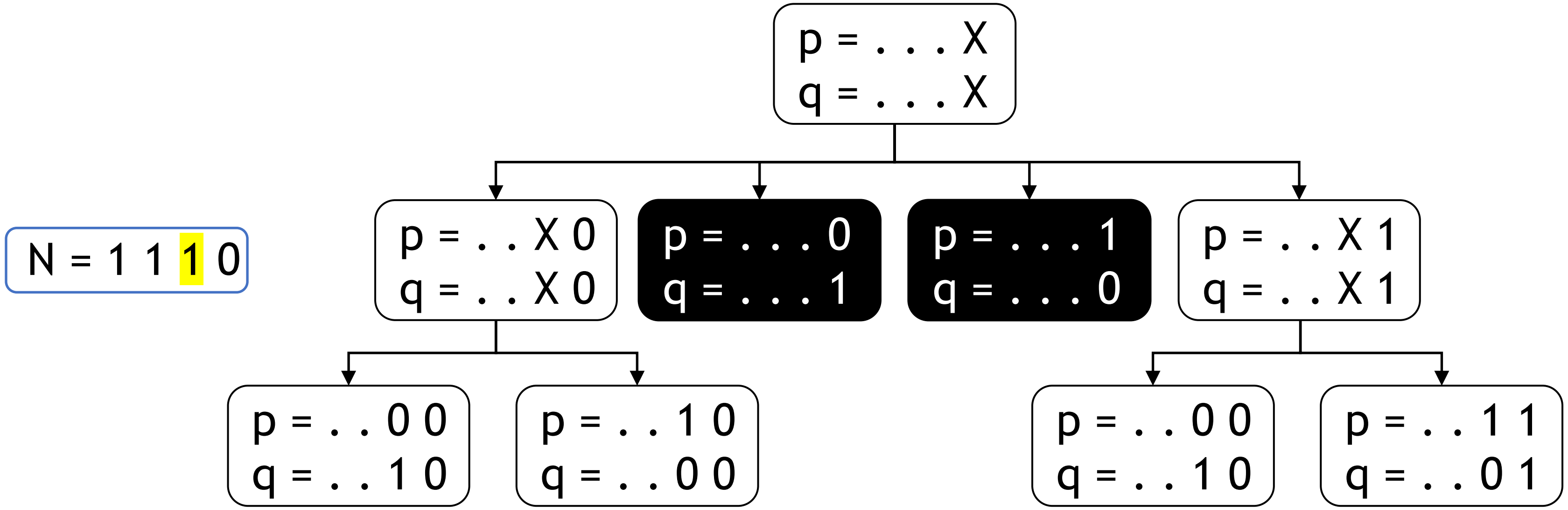

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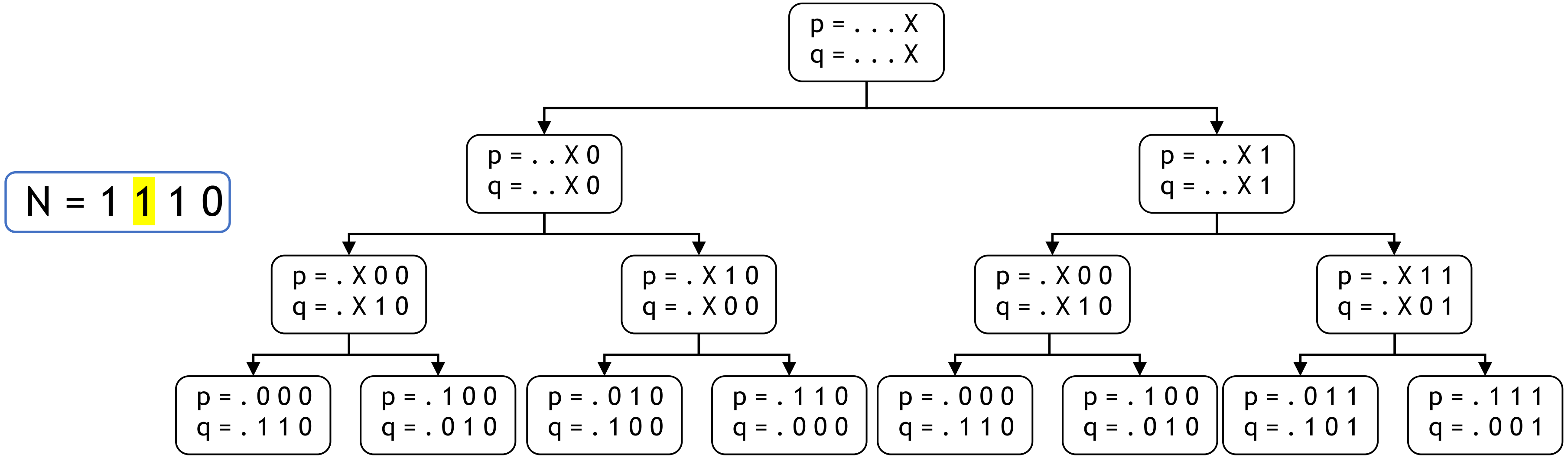

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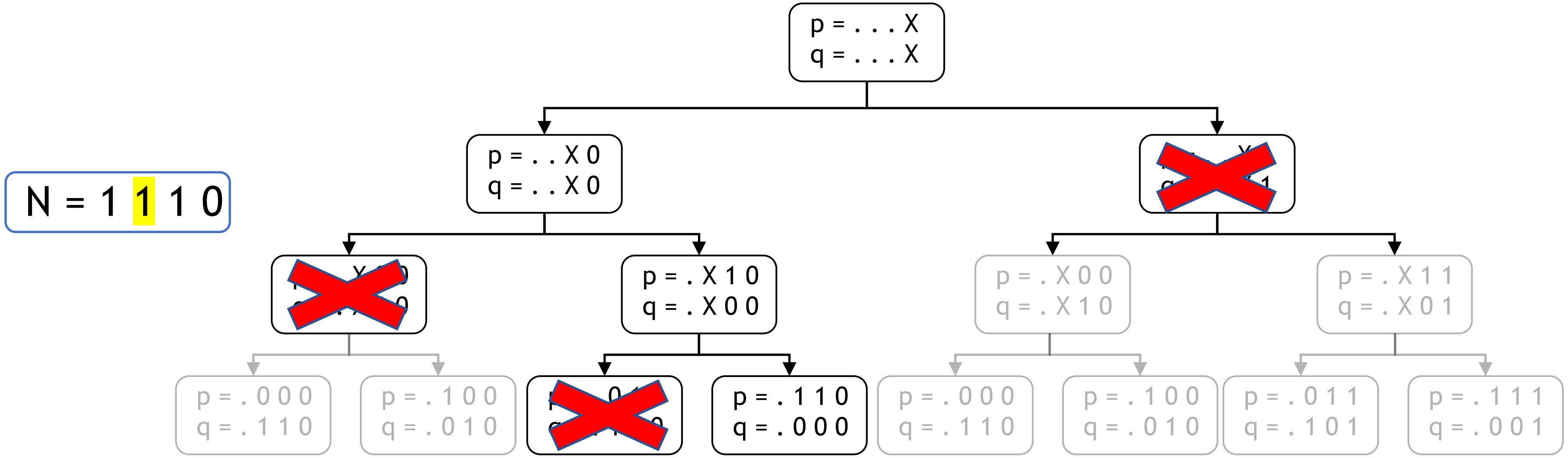

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  - Branch and prune Algorithm with the help of the recovered trace
- Single-trace Attack during RSA Key Generation: $d = e^{-1} \, mod \, \lambda(N)$

CopyCat on WolfSSL – Cryptanalysis Results

- Executed each attack 100 times.
- DSA $k^{-1}\ mod\ n$
  - Average 22,000 IRQs
  - 75 ms to iterate over an average of 6,320 steps
- RSA $q^{-1}\ mod\ p$
  - Average 106490 IRQs
  - 365 ms to iterate over an average of 39,400 steps
- RSA $e^{-1}\ mod\ \lambda(N)$
  - $e^{-1}\ mod\ \lambda(N)$
  - Average 230,050 IRQs
  - 800ms to iterate over an average of 81,090 steps
- Experimental traces always match the leakage model in all experiments → Successful single-trace key recovery

How about other Crypto libraries?

- Libgcrypt uses a variant of BEEA
  - Single trace attack on DSA, Elgamal, ECDSA, RSA Key generation
- OpenSSL uses BEEA for computing GCD
  - Single trace attack on RSA Key generation when computing $\gcd(q-1, p-1)$

	Operation (Subroutine)	Implementation	Secret Branch	Exploitable	Computation → Vulnerable Callers	Single-Trace Attack
WolfSSL	Scalar Multiply (wc_ecc_mulmod_ex)	Montgomery Ladder w/ Branches	✔	✔	$(k \times G) \rightarrow$ wc_ecc_sign_hash	✘
	Greatest Common Divisor (fp_gcd)	Euclidean (Divisions)	✔	✘	N/A	N/A
	Modular Inverse (fp_invmod)	BEEA	✔	✔	$(k^{-1} \bmod n) \rightarrow$ wc_DsaSign $(q^{-1} \bmod p) \rightarrow$ wc_MakeRsaKey $(e^{-1} \bmod \Lambda(N)) \rightarrow$ wc_MakeRsaKey	✔ ✔ ✔
Libgcrypt	Greatest Common Divisor (mpi_gcd)	Euclidean (Divisions)	✔	✘	N/A	N/A
	Modular Inverse (mpi_invm)	Modified BEEA [43, Vol II, §4.5.2]	✔	✔	$(k^{-1} \bmod n) \rightarrow$ {dsa,elgamal}.c::sign,_gcry_ecc_ecdsa_sign $(q^{-1} \bmod p) \rightarrow$ generate_{std,fips,x931} $(e^{-1} \bmod \Lambda(N)) \rightarrow$ generate_{std,fips,x931}	✔ ✔ ✔
OpenSSL	Greatest Common Divisor (BN_gcd)	BEEA	✔	✔	$gcd(q-1, p-1) \rightarrow$ RSA_X931_derive_ex	✔
	Modular Inverse (BN_mod_inverse_no_branch)	BEEA w/ Branches	✘	N/A	N/A	N/A
IPP Crypto	Greatest Common Divisor (ippsGcd_BN)	Modified Lehmer's GCD	✔	? ?	$gcd(q-1, e) \rightarrow$ cpIsCoPrime $gcd(p-1, q-1) \rightarrow$ isValidPriv1_rsa	N/A N/A
	Modular Inverse (cpModInv_BNU)	Euclidean (Divisions)	✔	✘	N/A	N/A

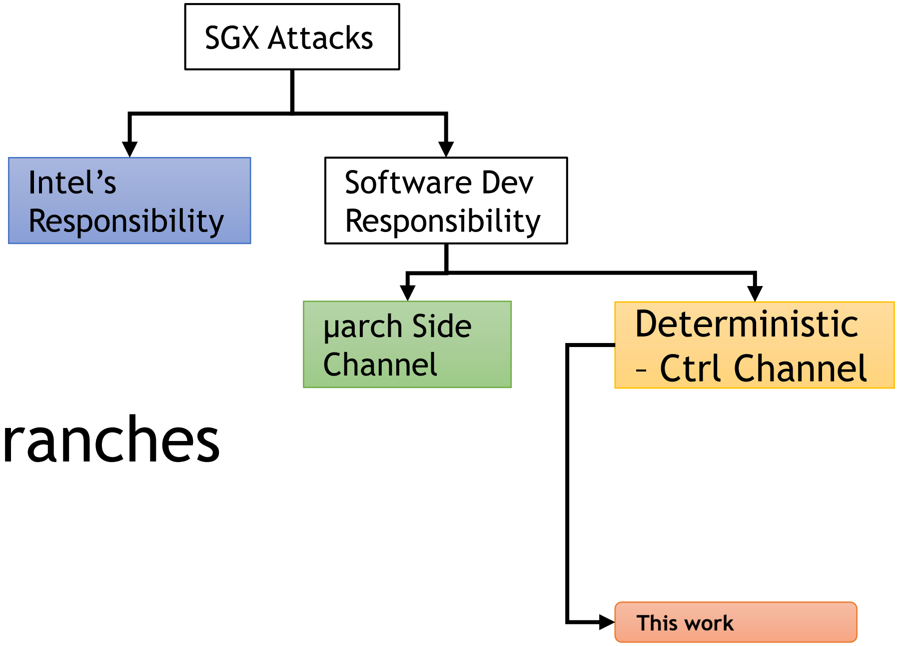
Responsible Disclosure

- WolfSSL fixed the issues in 4.3.0 and 4.4.0
  - Blinding for $k^{-1} \bmod n$ and $e^{-1} \bmod \lambda(N)$
  - Alternate formulation for $q^{-1} \bmod p$: $q^{p-2} \bmod p$
  - Using a constant-time (branchless) modular inverse [11]
- Libgcrypt fixed the issues in 1.8.6
  - Using a constant-time (branchless) modular inverse [11]
- OpenSSL fixed the issue in 1.1.1e
  - Using a constant-time (branchless) GCD algorithm [11]

[11] Bernstein, Daniel J., and Bo-Yin Yang. "Fast constant-time gcd computation and modular inversion." *CHES 2019*.

Conclusion

- Instruction Level Granularity
  - Imbalance number of instructions
  - Leak the outcome of branches
- Fully Deterministic and reliable
  - Millions of instructions tested
  - Attacks match the exact leakage model of branches
- Easy to scale and replicate
  - No reverse engineering of branches and microarchitectural components
  - Tracking all the branches synchronously
- Branchless programming is hard!



Questions?!

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https://github.com/jovanbulck/sgx-step