FLUSH+RELOAD a High Resolution, Low Noise, L3 Cache Side-channel Attack

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Memory Sharing

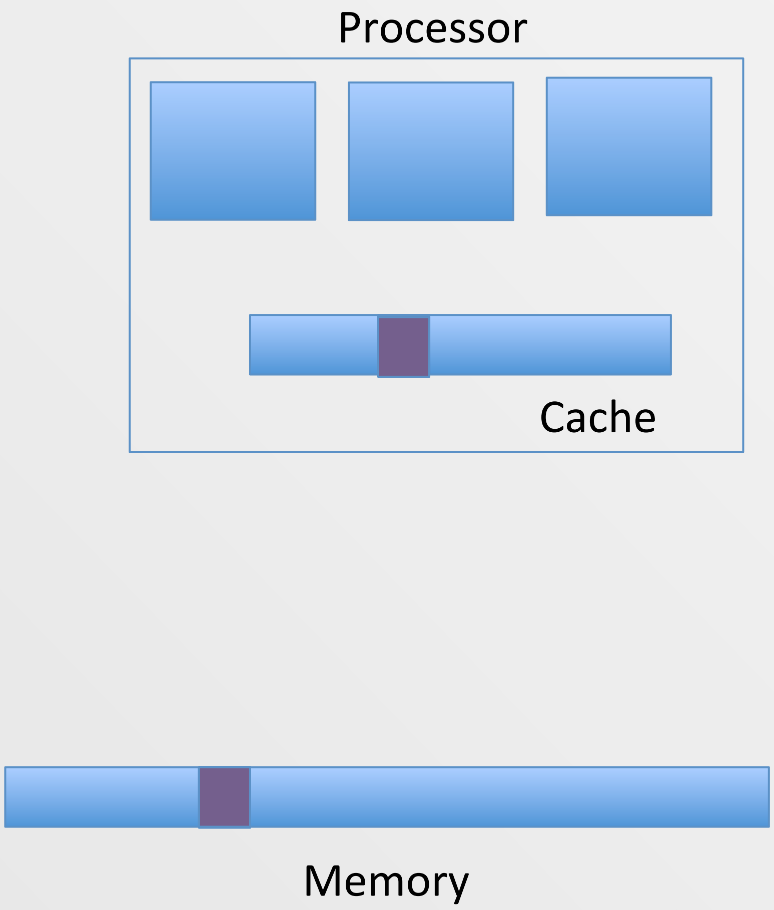
- Techniques for reducing the overall memory footprint of the system.
  - Shared text segments
  - Shared libraries
  - Memory de-duplication
- Considered safe, i.e. equivalent to no sharing

Outline

- Cache Architecture and the FLUSH+RELOAD attack
- RSA and Square-and-multiply exponentiation
- Attacking the GnuPG implementation of RSA

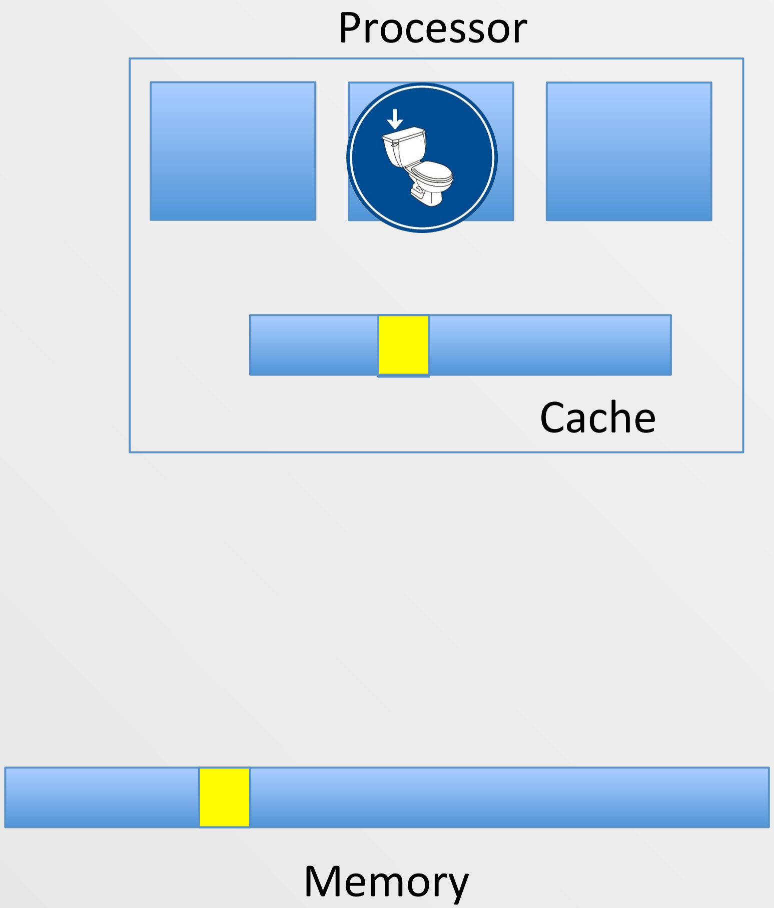
The X86 Cache

- Memory is slower than the processor
- The cache utilises locality to bridge the gap
  - Divides memory into *lines*
  - Stores recently used lines
- Shared caches improve performance for multi-core processors



Cache Consistency

- Memory and cache can be in inconsistent states
  - Rare, but possible
- Solution: Flushing the cache contents
  - Ensures that the next load is served from the memory

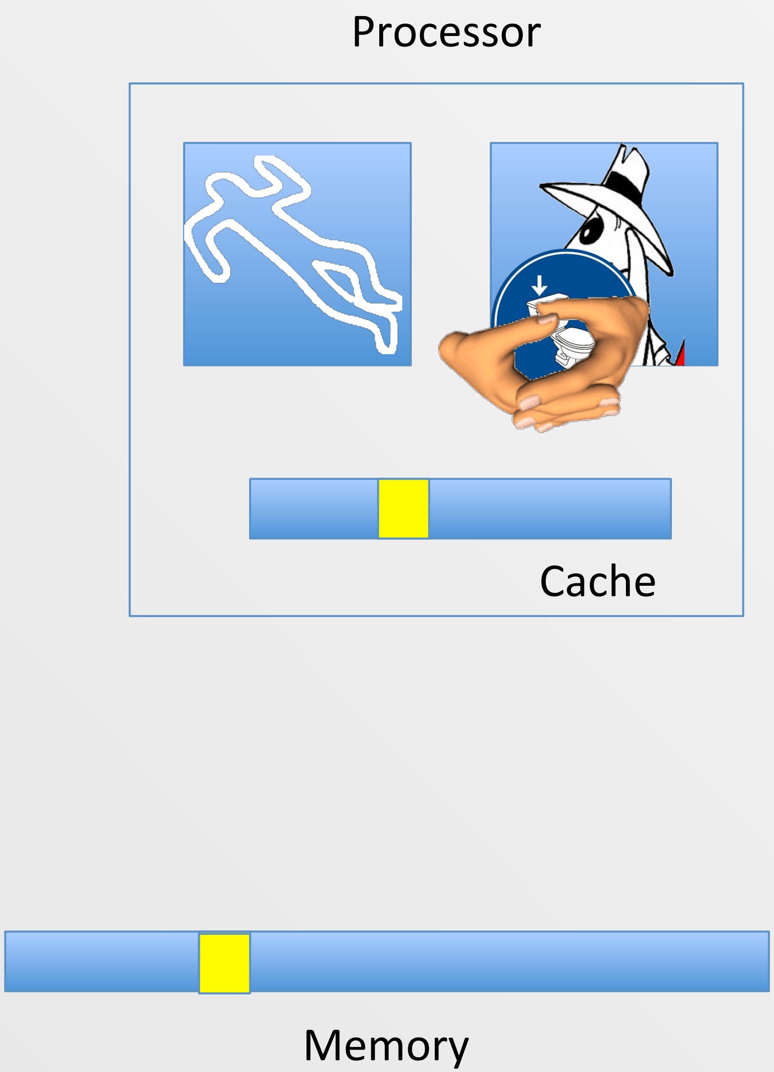


The FLUSH+RELOAD Technique

- Exploits cache behaviour to leak information on victim access to shared memory.
- Spy monitors victim's access to shared code
  - Spy can determine what victim does
  - Spy can infer the data the victim operates on

FLUSH+RELOAD

- **FLUSH** memory line
- Wait a bit
- Measure time to **RELOAD** line
  - slow-> no access
  - fast-> access
- Repeat



RSA

- RSA is a public key cryptographic scheme
- The main operation is modular exponentiation, i.e. calculating

$$b^e \bmod n$$

- The exponent e used for decryption and for signing is secret

Square-and-Multiply Exponentiation

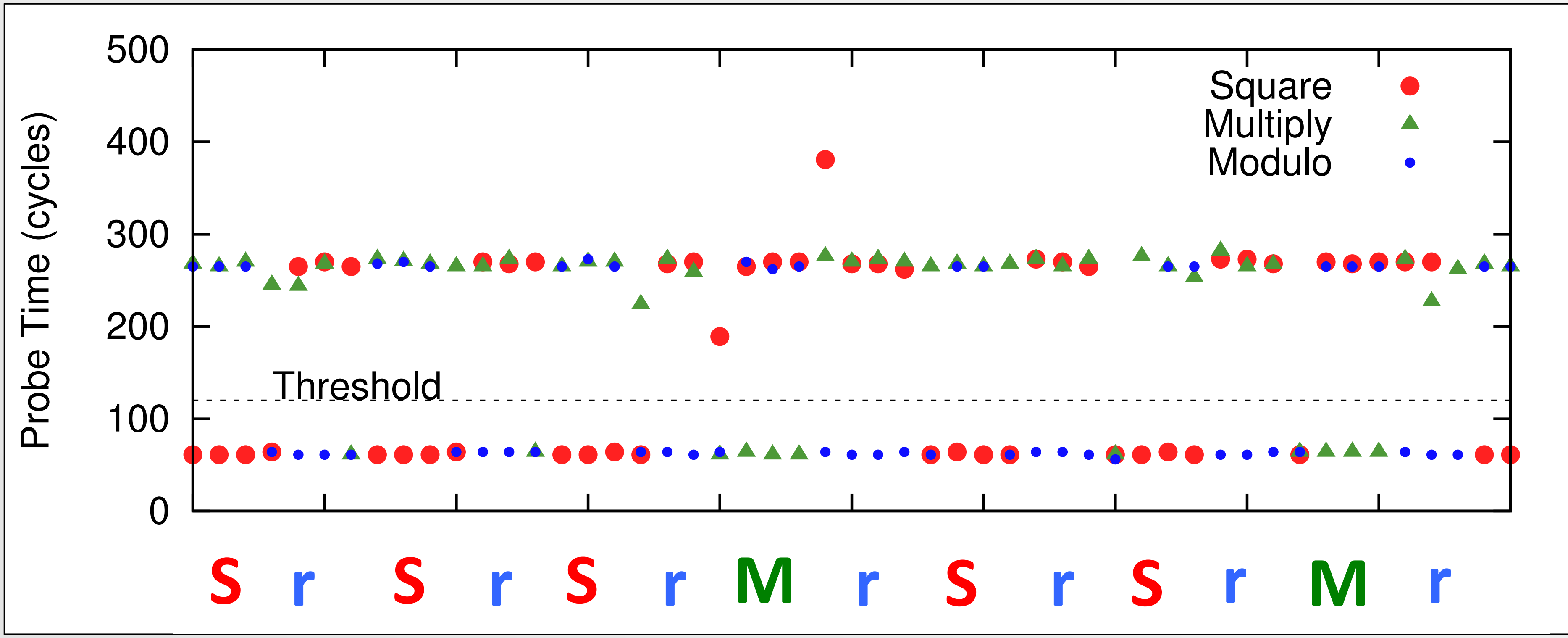
- Scans the exponent from the MSB to the LSB
- For clear bits does
  Square-Reduce
- For set bits does
  Square-Reduce-
  Multiply-Reduce
- The sequence of operations reveals the (secret) exponent

$x \leftarrow 1$
for $i \leftarrow |e|-1$ **downto** 0 do
    $x \leftarrow x^2 \bmod n$
    if $(e_i = 1)$ **then**
        $x = xb \bmod n$
    endif
done
return x

Attacking GnuPG

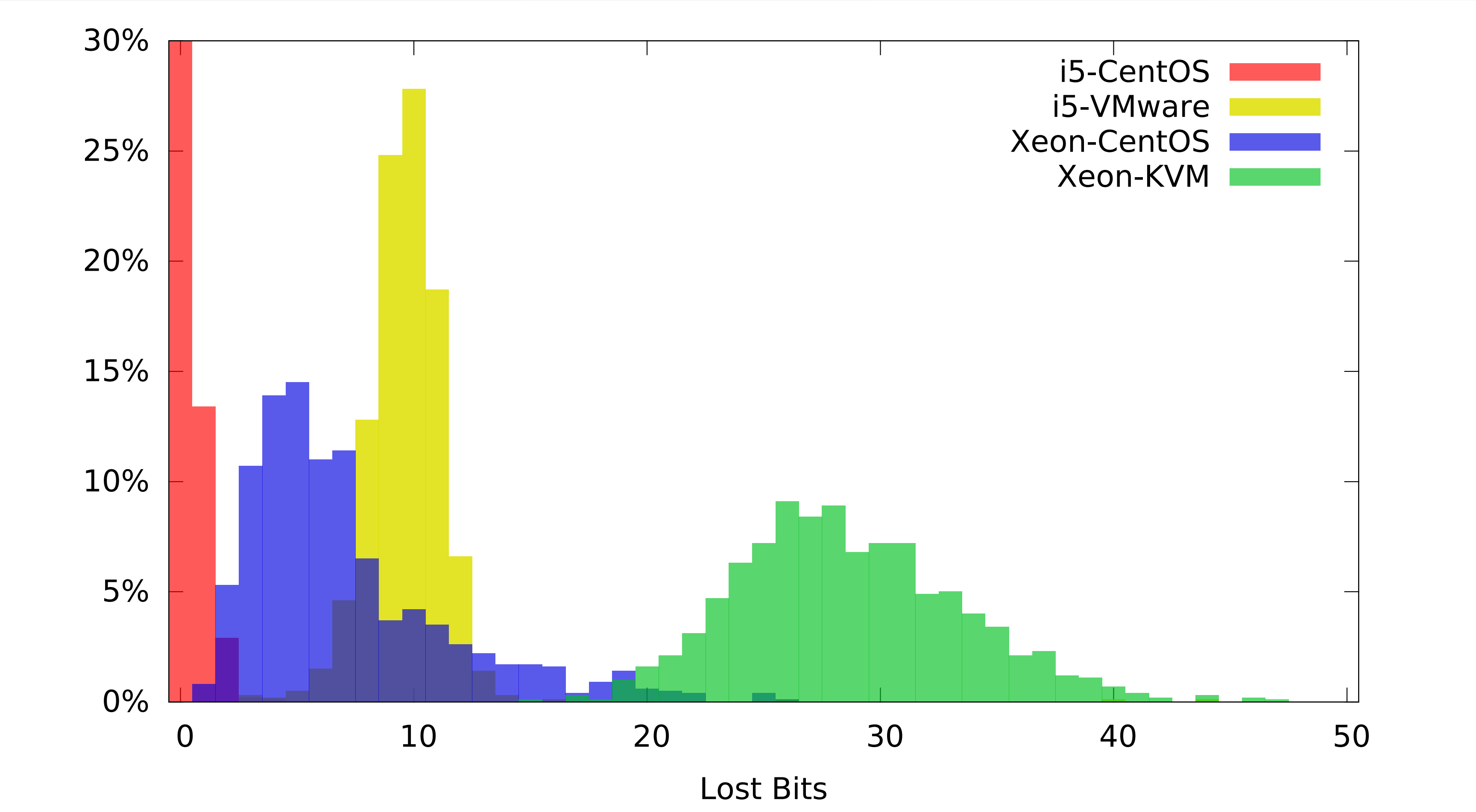
- Achieve sharing of the victim code
- Use FLUSH+RELOAD to recover the sequence of operations of the modular exponentiation
- Divide time into slots of 2048 cycles (about 0.6μs)
- In each slot, probe a memory line in the code of the Square, Multiply and Modulo-reduce functions

A Sample Trace



0 0 1 0 1

Results



30%
25%
20%
15%
10%
5%
0%
0
10
20
30
40
50
Lost Bits
i5-CentOS
i5-VMware
Xeon-CentOS
Xeon-KVM

Applications

- Attacking the default OpenSSL implementations of ECDSA
- Synchronous cross-VM final round attack on AES
- Trace the use of vi
- Potential: keystroke timing, network use statistics…

Lessons

- It is hard to limit the extent of sharing. E.g. "read-only" is more than read only.
- Use constant-time implementations of cryptographic primitives.
- Apply the principle of least privilege