Pillaging and plundering SGX with Software-based Fault Injection Attacks

Kit Murdock

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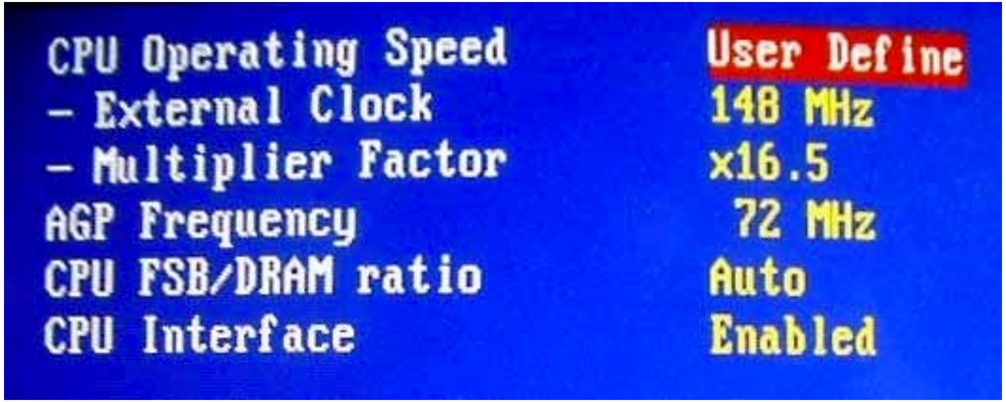
Overclocking


CPU Operating Speed
User Define
- External Clock
148 MHz
- Multiplier Factor
x16.5
AGP Frequency
72 MHz
CPU FSB/DRAM ratio
Auto
CPU Interface
Enabled

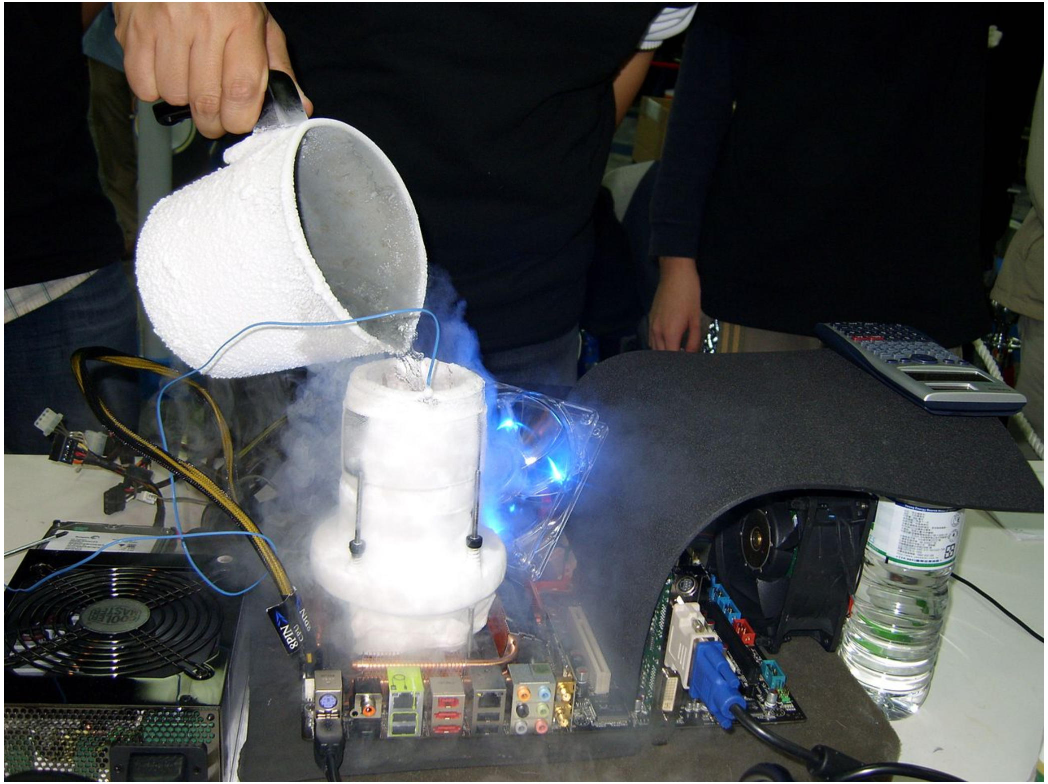


Image attribution: Rico Shen

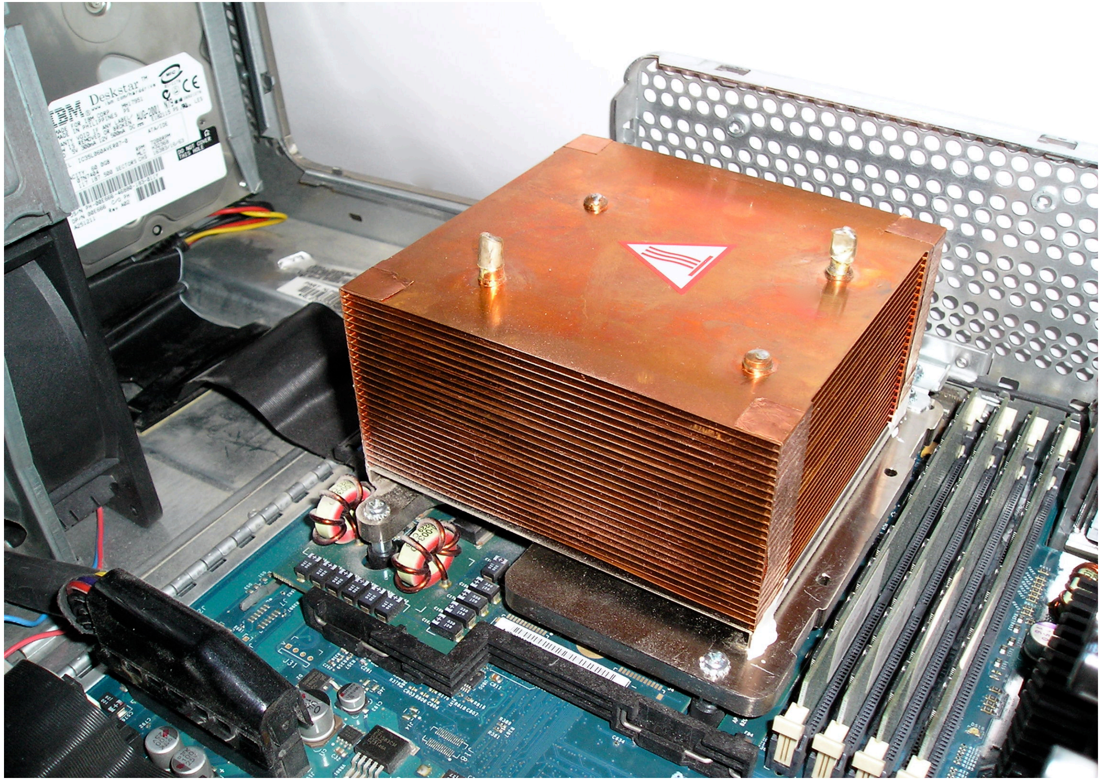
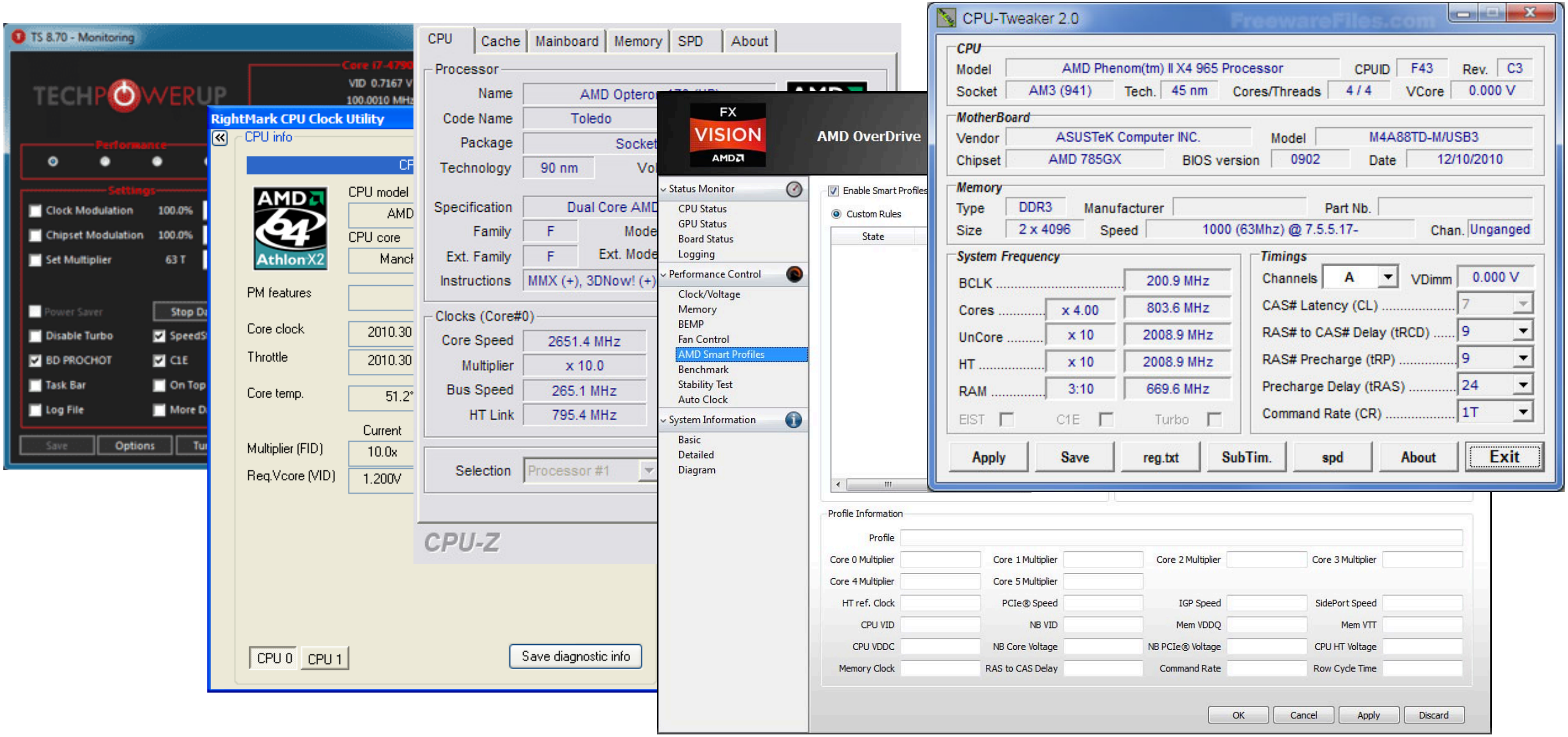


Image attribution: Charles Gaudette



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DVFS

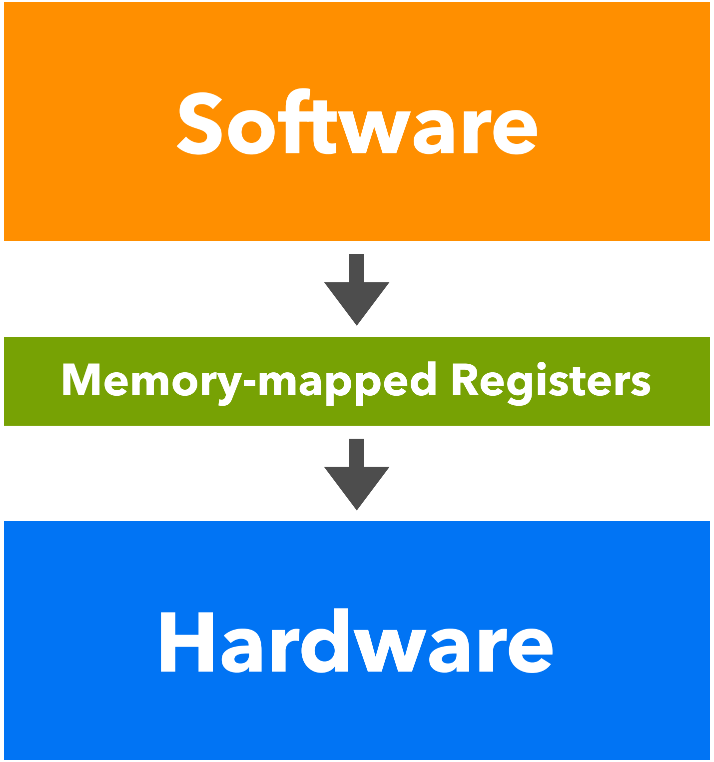
Dynamic Voltage and Frequency Scaling

Resilient and reliable

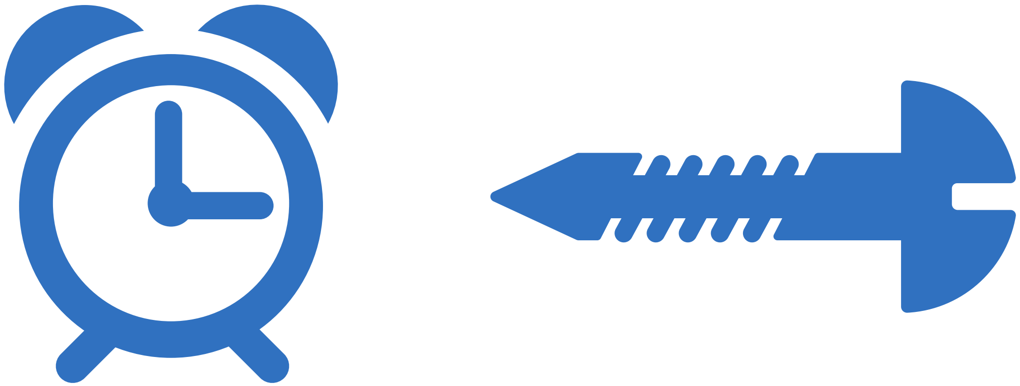
Very fast responses

High–assurance and low running costs

Memory Mapped Registers...



CLKscrew

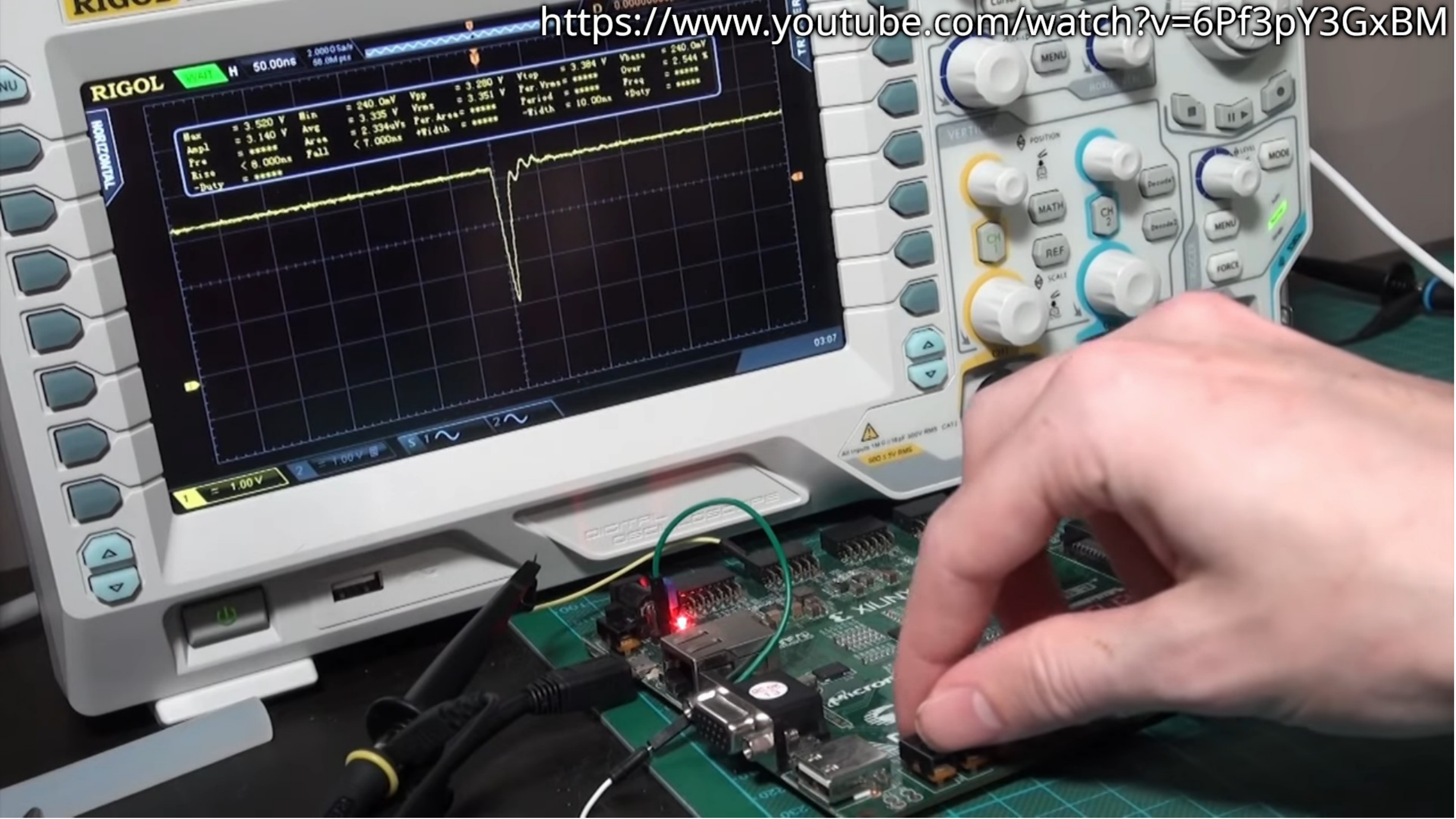


Adrian Tang et al. "CLKSCREW: exposing the perils of security-oblivious energy management"

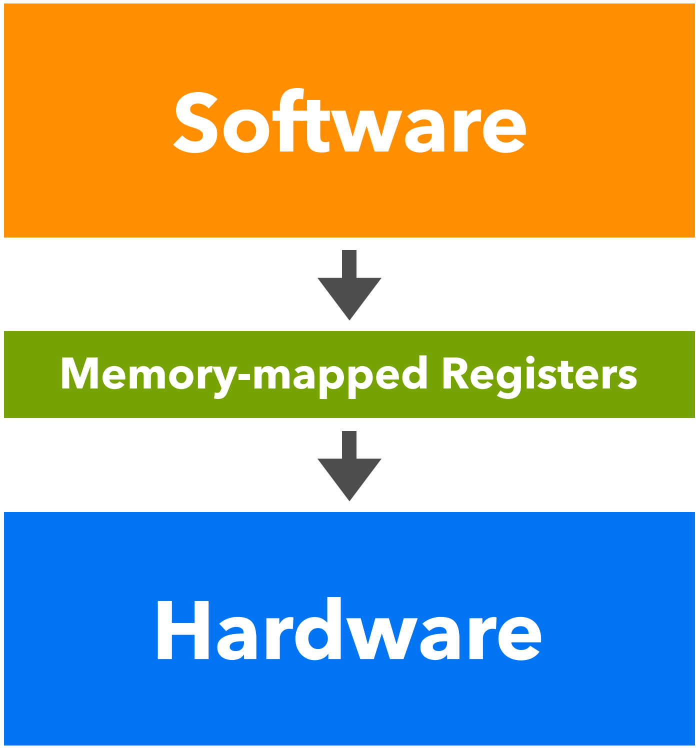
In: USENIX Security Symposium. 2017

A new class of fault attacks

https://www.youtube.com/watch?v=6Pf3pY3GxBM

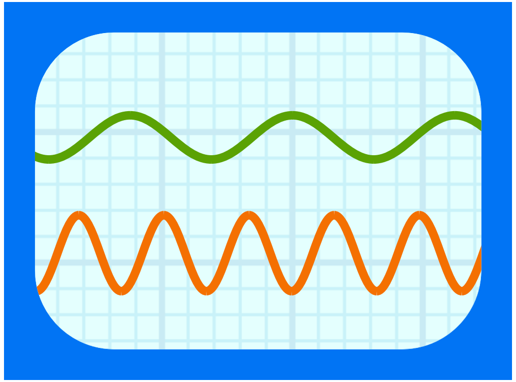


Memory Mapped Registers...



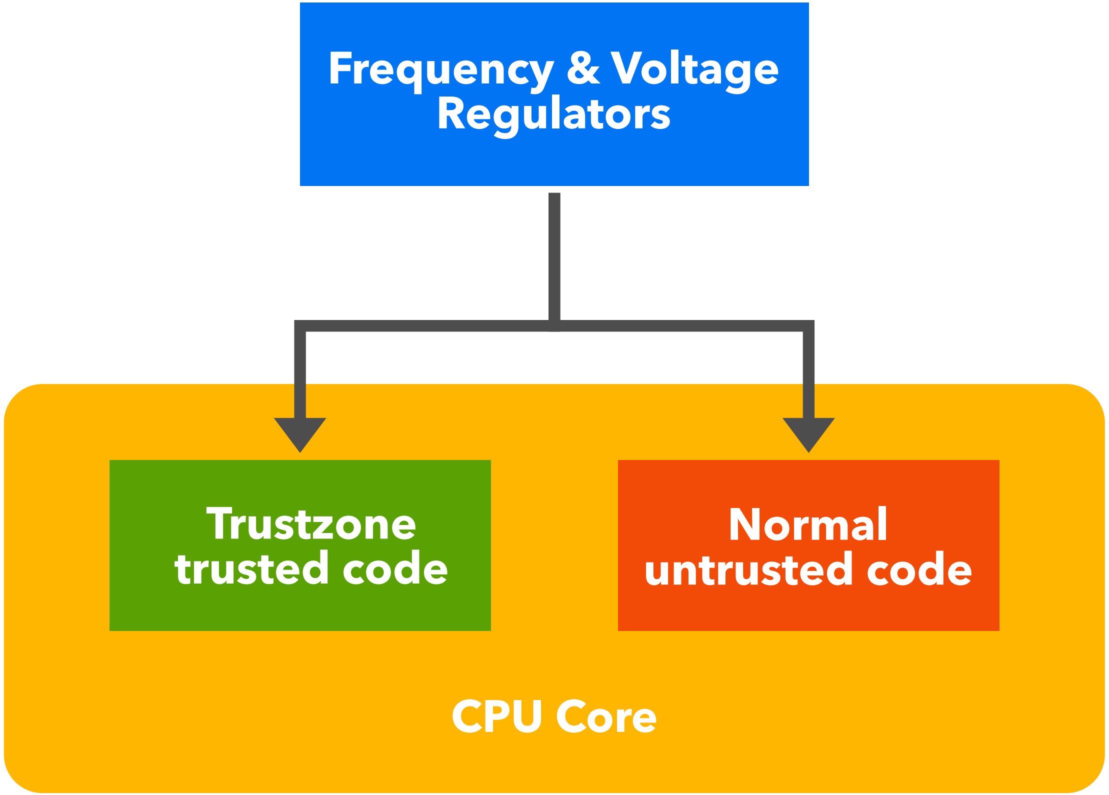
CLKscrew attack

```
add.w    (a0)+,d1
cmp.l    a0,d0
bcc.s    loop
movea.l  #$18E,a1
cmp.w    (a1),d1
bne.w    WrongChecksum
```

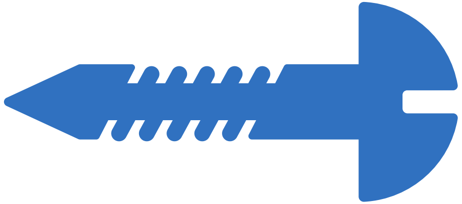


2 + 2 = 5

Memory Mapped Registers



CLKscrew - Summary

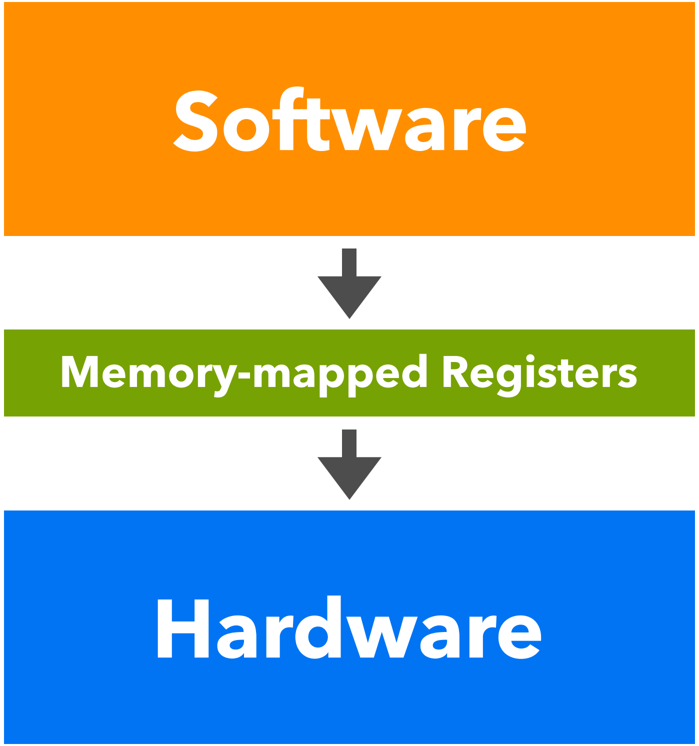


- Infer secret AES key that was stored within Trustzone
- Trick Trustzone into loading a self-signed app

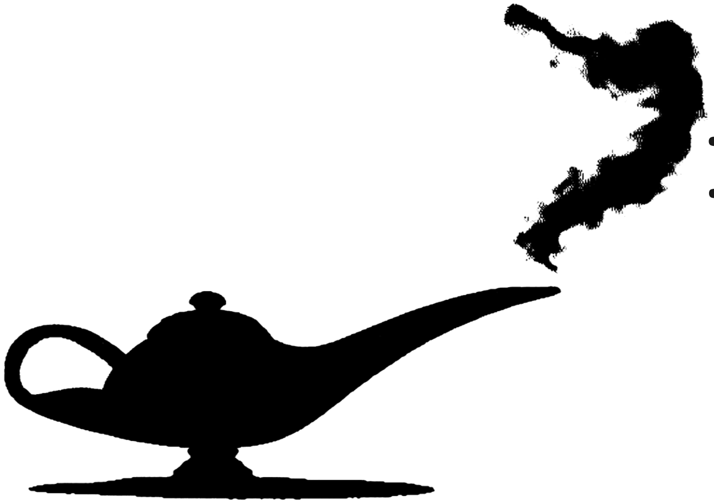
ARM

What about Intel?

Memory Mapped Registers...

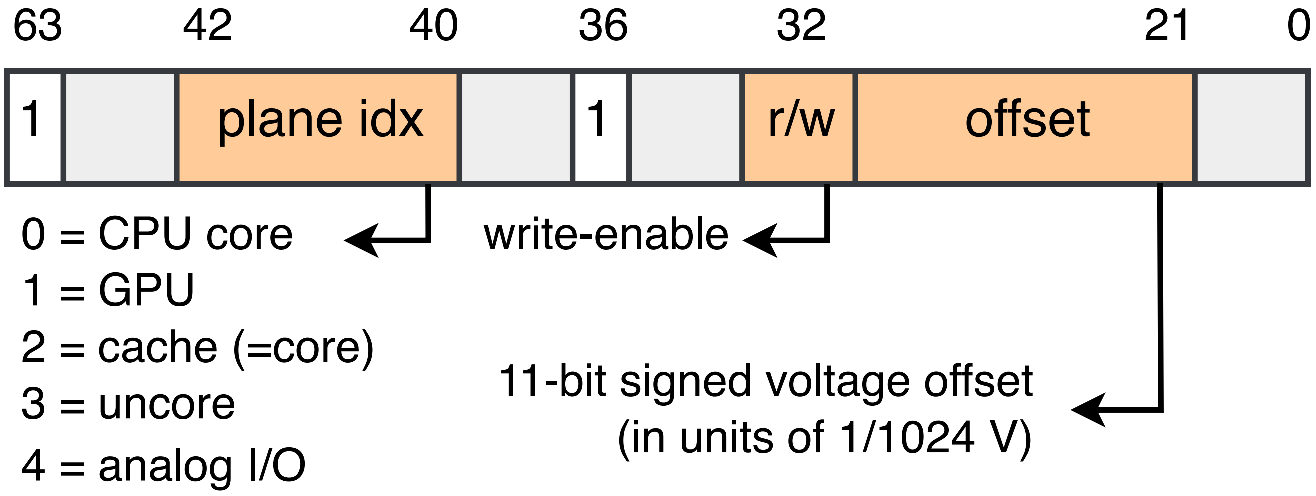


Undervolting Intel CPUs

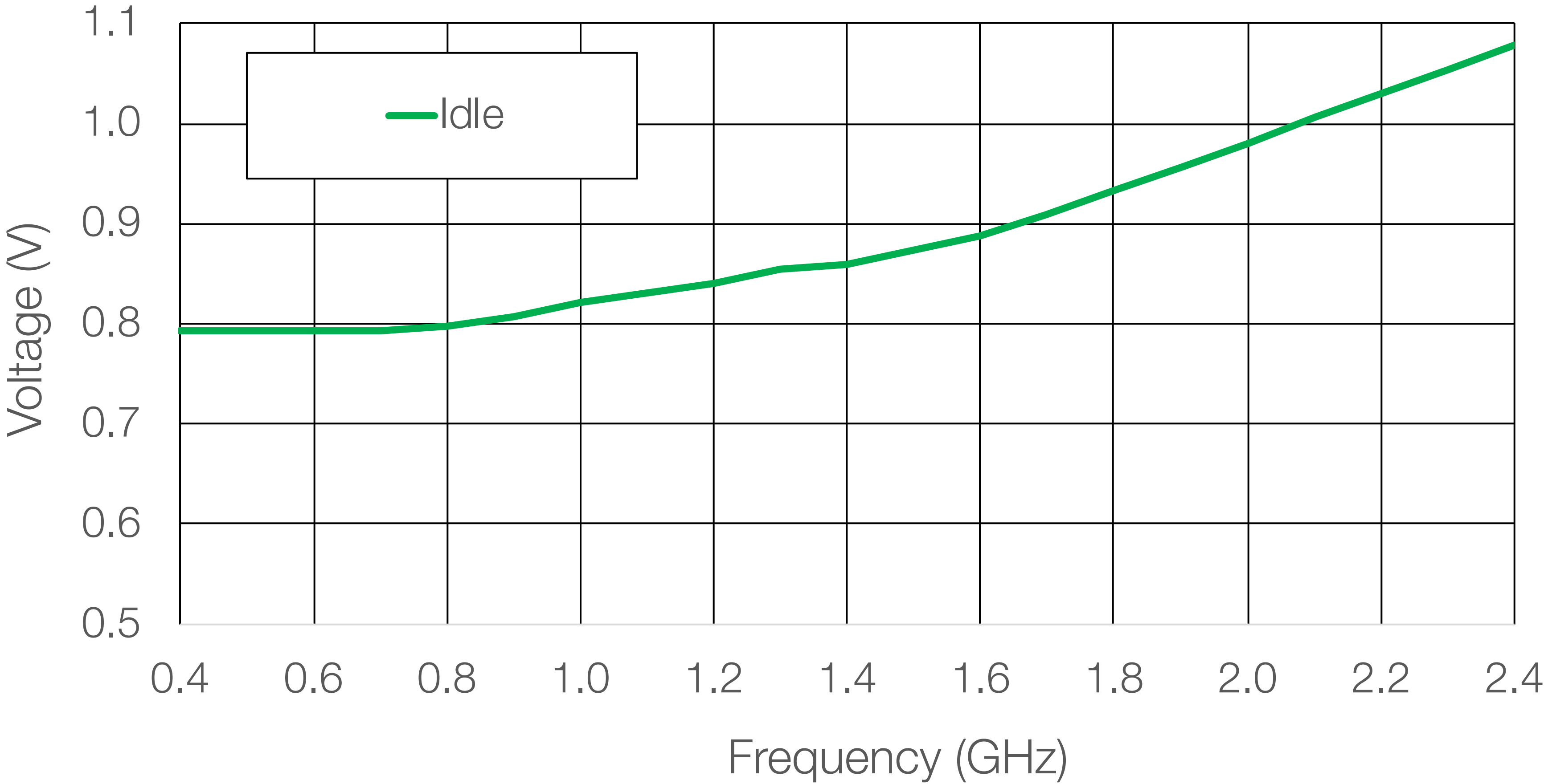


`msr 0x150`

Undervolting Intel CPUs

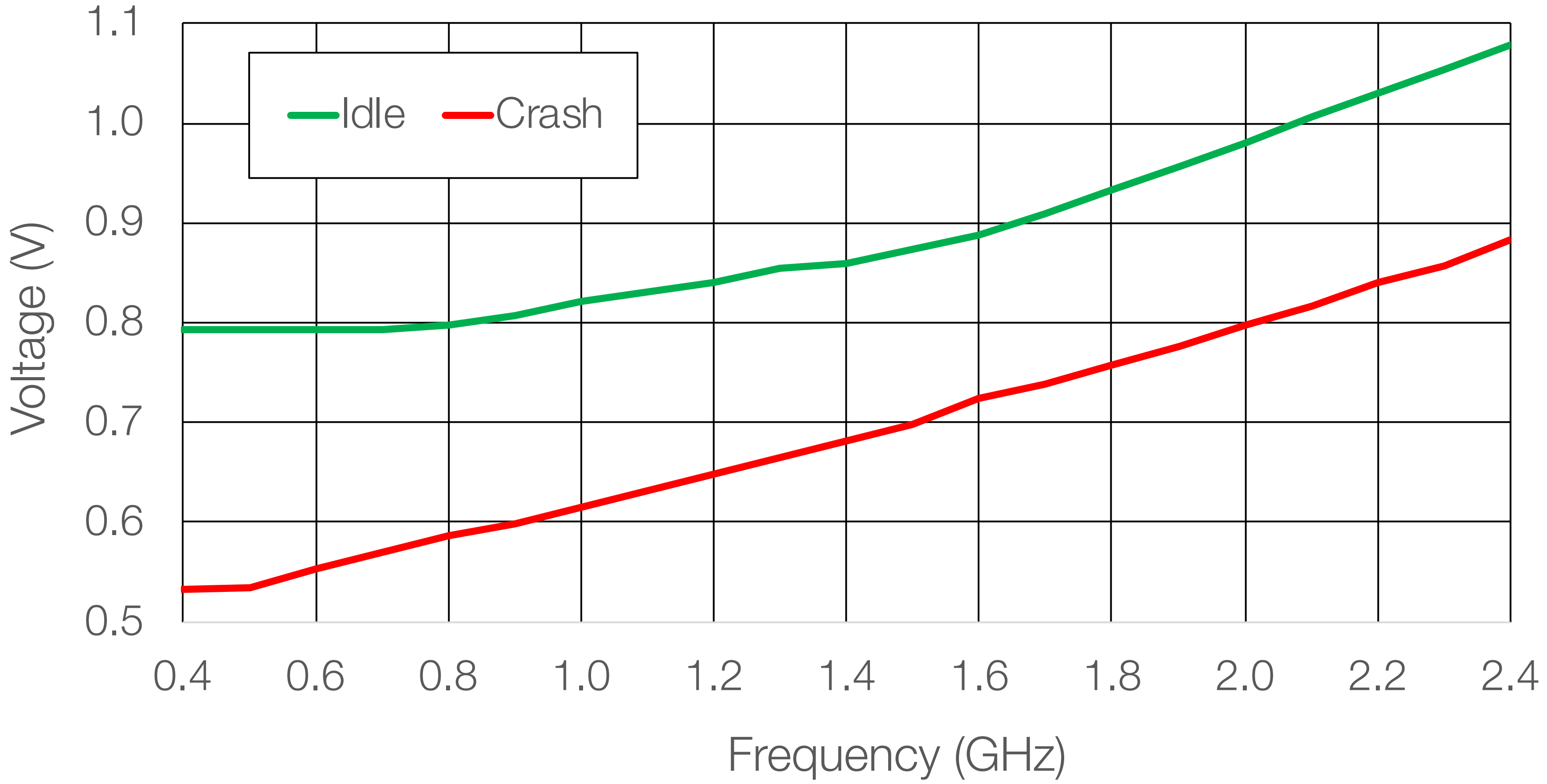


Idle voltage – Intel(R) Core(TM) i3-7100U CPU



```
bagger>
```

Idle and crash voltages – Intel(R) Core(TM) i3-7100U CPU



Can we fault it?

Will it fault?

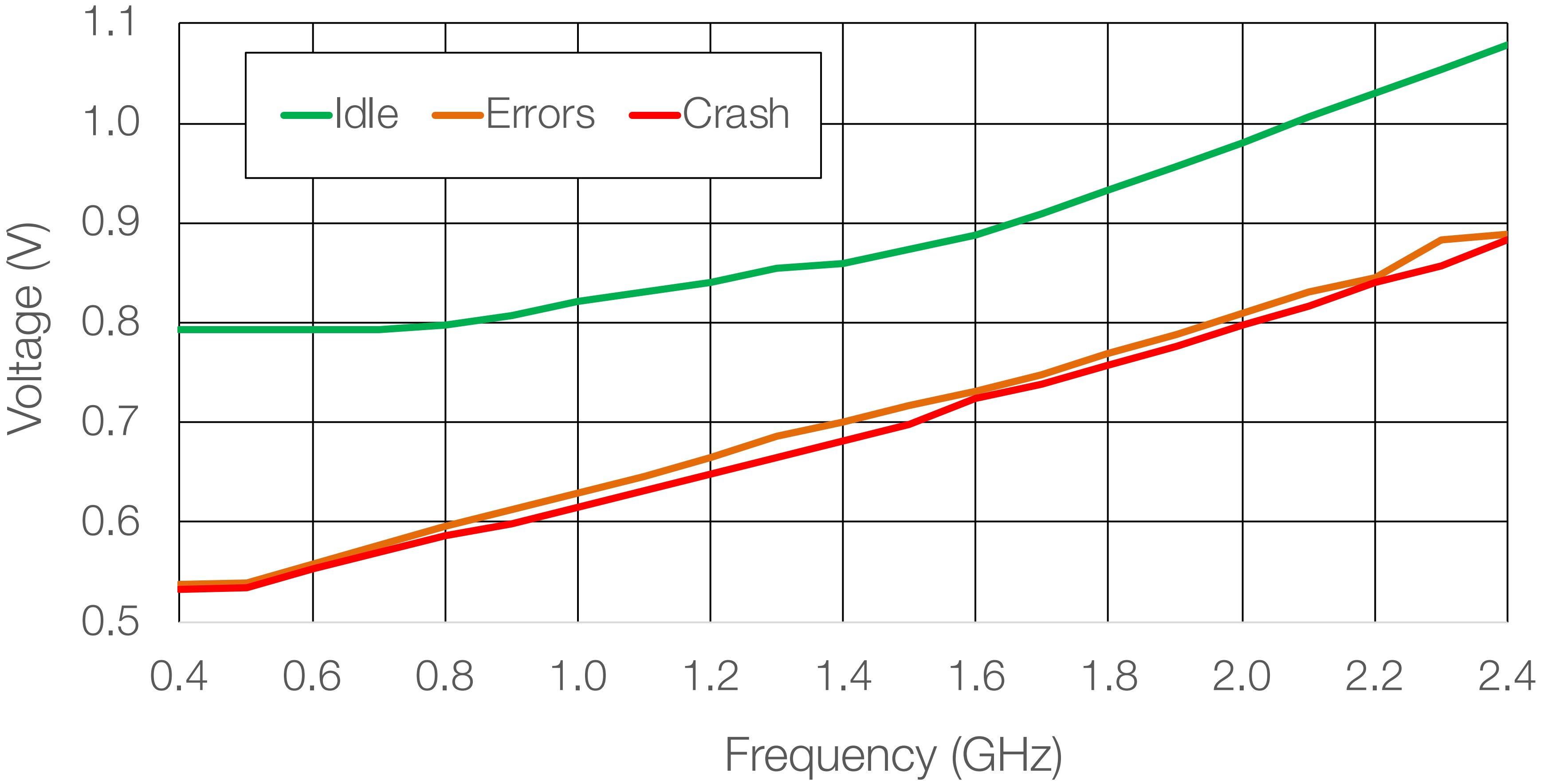
```
correct        = 7 * 3
my_value       = 7 * 3

// Start undervolting

while ( my_value == correct )
{
        my_value = 7  *  3
}

// Can we ever get here?
```

Will it fault?

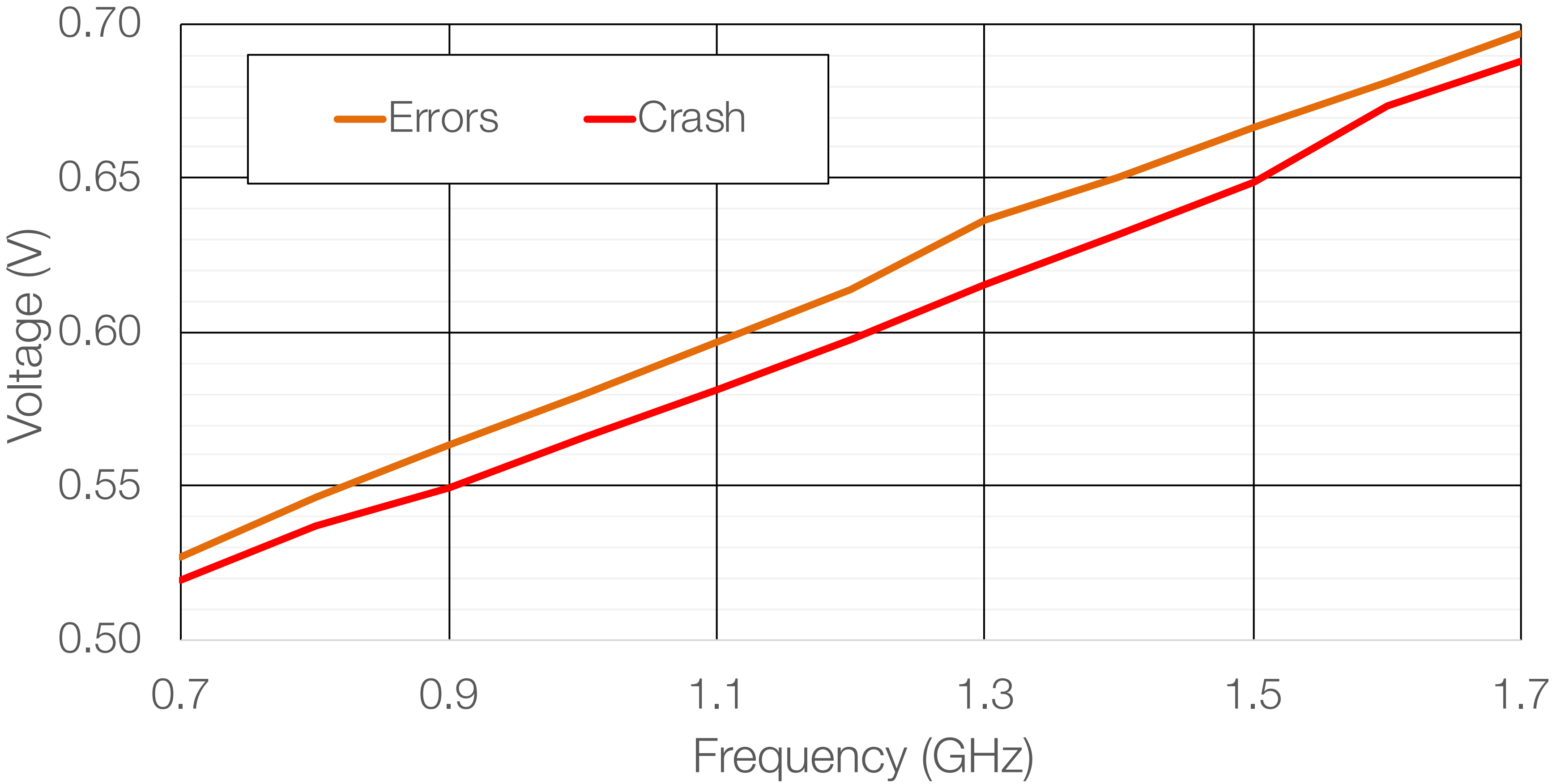
```
uint64_t multiplier = 0x1122334455667788;
uint64_t correct    = 0xdeadbeef*multiplier;
uint64_t var        = 0xdeadbeef*multiplier;

// start undervolting

while ( var == correct )
{
    var = 0xdeadbeef * multiplier;
}
// stop undervolting
// Can we ever get here?
uint64_t flipped_bits = var ^ correct;
```

```
bagger>
```

Idle, error and crash voltages – Intel(R) Core(TM) i3-7100U CPU



Error and crash voltages – Intel(R) Core(TM) i3-7100U CPU



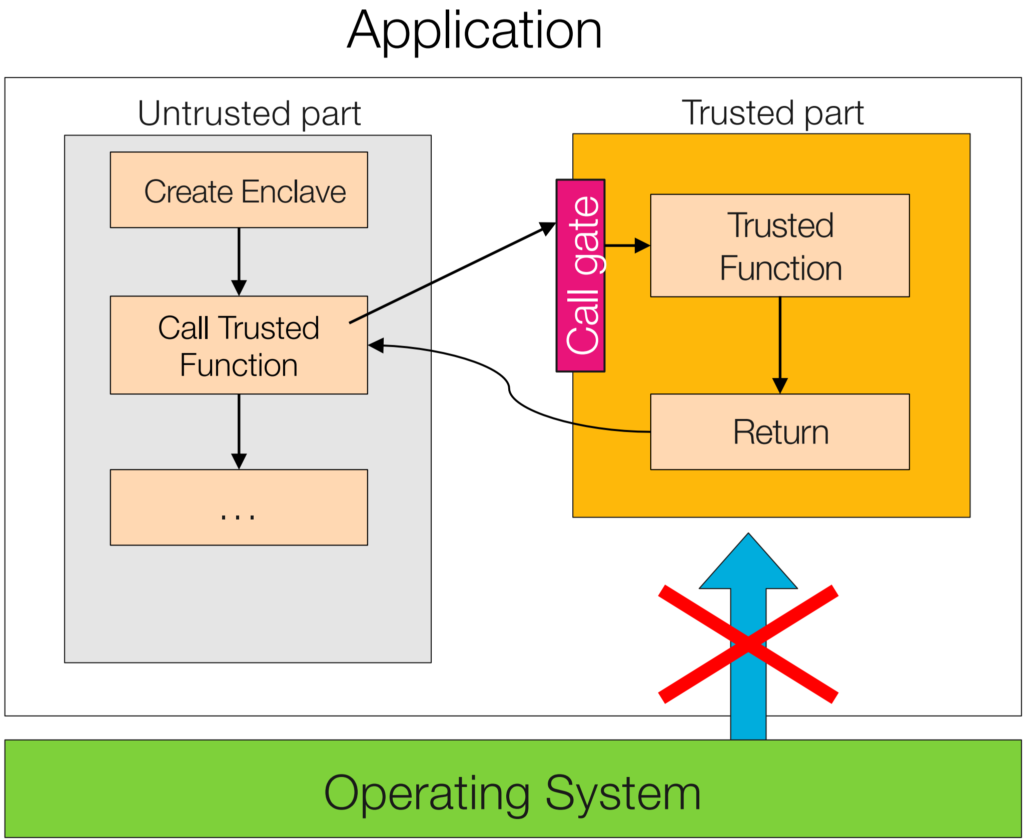
Carmen Crincoli, but Fhqwhgads
@CarmenCrincoli

"Plundervolt" sure does have a catchy name and logo for an exploit that... <checks notes> ...requires you to be running as root already.

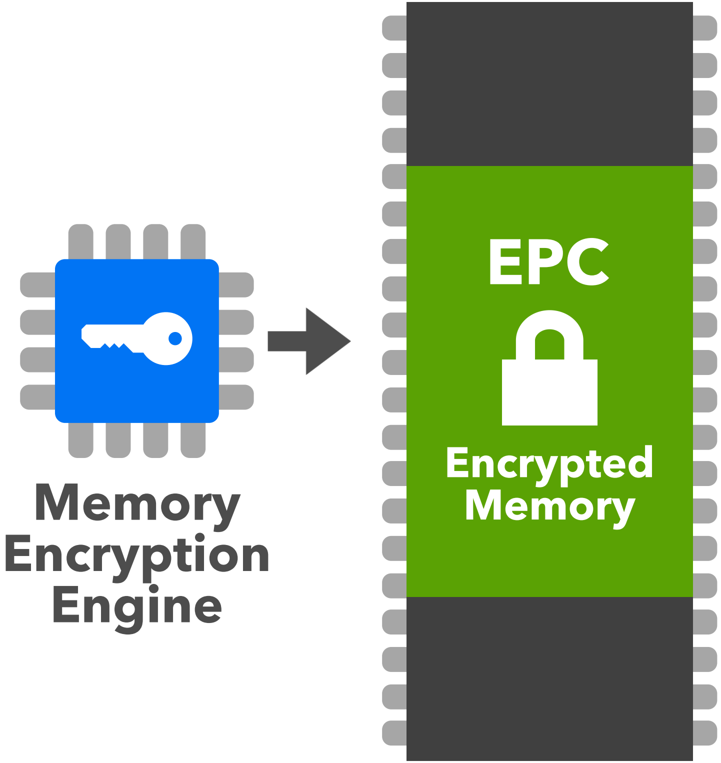
1:59 AM · Dec 11, 2019 · Twitter Web App

Let's meet SGX

SGX


Application
Untrusted part
Trusted part
Create Enclave
Call Trusted Function
. . .
Call gate
Trusted Function
Return
Operating System

Physical Memory



We can bypass the SGX integrity checks!

Larry Osterman
@osterman

Replying to @CarmenCrincoli and @MT6572A

Since the threat model for SGX assumes that the attacker has root access (and I believe also has physical control over the hardware), this is actually a bigger deal than you make it out to be.

2:07 AM · Dec 11, 2019 · Twitter Web App

	A	B	C	D	E
1	Operand 1	Operand2	xor answer	undervolting	temperature
5525	0x9e2d4a	0x0024	ffffffffe0000000	-272	+36.0C
5526	0x9e2d51	0x0024	ffffffffe0000000	-272	+36.0C
5527	0x9eb497	0x0024	ffffffffe0000000	-272	+37.0C
5528	0x9eb49e	0x0024	ffffffffe0000000	-272	+36.0C
5529	0x9f3bf2	0x0024	ffffffffe0000000	-272	+37.0C
5530	0x9f3c15	0x0024	ffffffffe0000000	-272	+37.0C
5531	0x9f3c23	0x0024	ffffffffe0000000	-272	+37.0C
5532	0x9f3c2a	0x0024	ffffffffe0000000	-272	+37.0C
5533	0x9f3c5b	0x0024	ffffffffe0000000	-272	+37.0C
5534	0xa04b2d	0x0024	0000000002000000	-272	+37.0C
5535	0xa0d2f1	0x0024	0000000002000000	-272	+37.0C
5536	0xa0d306	0x0024	0000000002000000	-272	+37.0C
5537	0xa269cd	0x0024	0000000002000000	-272	+37.0C
5538	0xa269fe	0x0024	0000000002000000	-272	+36.0C
5539	0xa61e0e	0x0024	0000000010000000	-272	+37.0C
5540	0xa61e38	0x0024	0000000010000000	-272	+37.0C
5541	0xa61e3f	0x0024	0000000010000000	-272	+36.0C
5542	0xa61e46	0x0024	0000000010000000	-272	+36.0C
5543	0xa72d34	0x0024	0000000010000000	-272	+36.0C
5544	0xa72d5e	0x0024	0000000010000000	-272	+36.0C
5545	0xa8c3ae	0x0024	0000000002000000	-272	+37.0C
5546	0xa94b25	0x0024	0000000001000000	-272	+37.0C
5547	0xa9d2b1	0x0024	0000000001000000	-272	+37.0C
5548	0xaa59fe	0x0024	0000000001000000	-272	+37.0C
5549	0xaa5a0c	0x0024	0000000001000000	-272	+37.0C
5550	0xaa5a13	0x0024	0000000001000000	-272	+37.0C
5551	0xaa5a21	0x0024	0000000001000000	-272	+37.0C

Faulted Multiplications

`1st_operand * 2nd_operand = result`

Smallest

0x89af

Smallest

0x1

Smallest

0x200000

0x80000 * 0x4

Multiplication faults – the order matters

`1st_operand * 2nd_operand = result`

`0x80000 * 0x4 = 0x200000` ✓

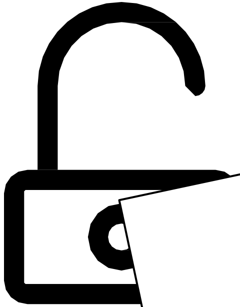
`0x4 * 0x80000 = 0x200000` ✗

Multiplication faults

Operand 1	Operand 2	Flipped Bits
0xacff13	0x00ee	0x000000003e000000
0xa7fccc	0x0335	0x0000000010000000
0x9fff4f	0x00b2	0x0000000020000000
0x2bffc0	0x0008	0x0000000001000000
0x0b7a04	0x0087	0x0000000004000000
0x080004	0x0008	0xfffffffff0000000
0x0022b2	0x6c3a	0x0000000000000700

You promised plundering...

RSA Basics



- Public Key Cryptography
- Untrusted channel
- Encry

d,p,q

Many RSA implementations use the Chinese Remainder Theorem optimisation

RSA decryption

```
// Start undervolting
uint8_t rsa_dec_ecall(int iterations)
{
    //Waitforfirstfault
    trigger_fault(iterations);

    //Actualdecryption
    ippsRSA_Decrypt(ct,dec,pPrv,scratchBuffer);
}
// Stop undervolting
```

```
bagger> dog Enclave/encl
```

And the pillaging...?

AES-NI (New Instructions)

Instruction	Description
AESENC	Perform one round of an AES enc
AESENCLAST	Perform the l
AESDEC	
	w
	eneration
	n AES Inverse Mix Columns
DQ	Carryless multiply (CLMUL)

AES can be attacked if you get a fault in the 8^{th} round.

AES New Instructions - inside SGX

```
// Start undervolting

do
{
            plaintext= <randomlygenerated>;
            result1=aes128_encryption(plaintext);
            result2=aes128_encryption(plaintext);

} while(result1 == result2)

// Stop undervolting
```

```
bagger> sudo ./aes-encrypt 100000 -262
```

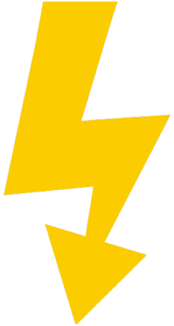
Hold tight...

But what about memory corruption?

```
struct_foo_t *foo = &arr[offset];
foo->foo = enclave_secret;
```

But what about memory corruption?

```
foo = arr + offset
```



```
0x24
```

```
Creating enclave...
==== Victim Enclave ====
[pt.c] /dev/sgx-step opened!
Enclave Base:   0x7f001a000000
```

Voltage
0.584V

Undervolting
-235mV

Summary

- A new type of attack against Intel
- Breaks the integrity of SGX
- Within SGX
    - Retrieve keys using AES-NI
    - Retrieve RSA key
    - Induce memory corruption in bug free
    - Make enclave write secrets to untrusted memory

Voltage
0.594V

Undervolting
-240mV

Kit Murdock, David Oswald, Flavio D. Garcia,
Jo Van Bulck, Daniel Gruss, and Frank Piessens.

"Plundervolt: Software-based Fault Injection Attacks against Intel SGX".
In S&P 2020

Acknowledgements

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PLUNDER VOLT

Thank you