Faulting Hardware from Software

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2020-09-13

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CTV

Test - Mozilla Firefox (on lab02)

Test

file:///home/dgruss/rowhammerjs/rowhammer.html

Search

320: 12
330: 9
340: 1
350: 0
360: 1
370: 2
380: 199
390: 76
400: 72
410: 231
420: 572
1250
[!] Found flip (254 != 255) at array index 340021386 when hammering indices 339881984 and 340156416

[!] Found flip (239 != 255) at array index 340022176 when hammering indices 339881984 and 340156416

[!] Found flip (191 != 255) at array index 340023138 when hammering indices 339881984 and 340156416

[!] Found flip (254 != 255) at array index 340025146 when hammering indices 339881984 and 340156416

DRAM organization

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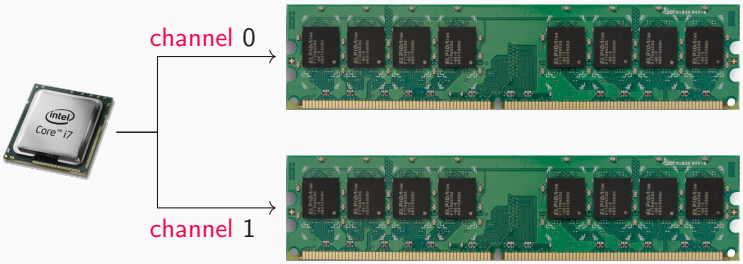
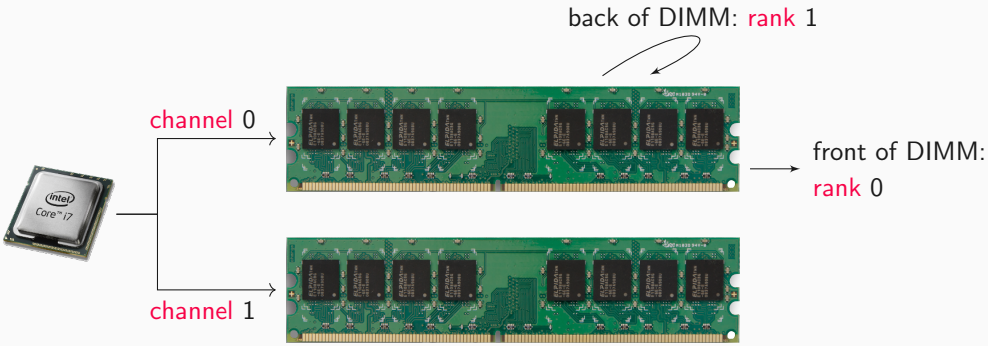


DRAM organization



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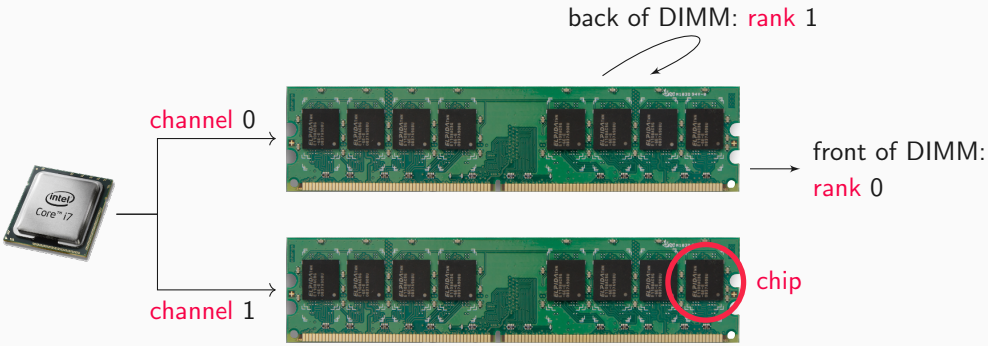
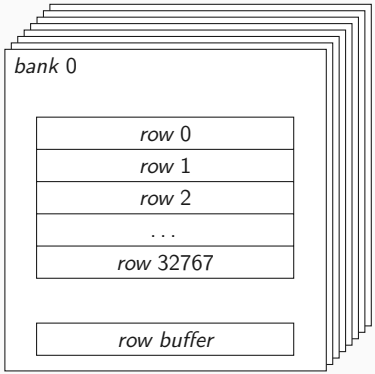


DRAM organization

chip



DRAM organization

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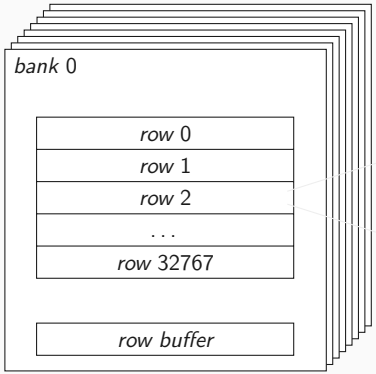
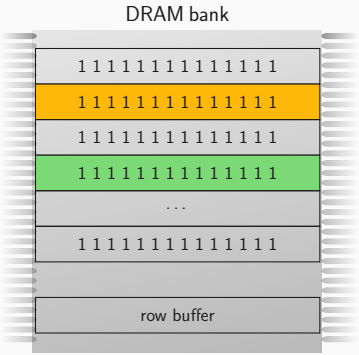
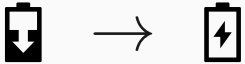
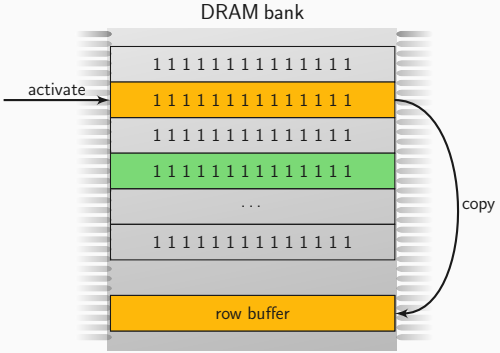
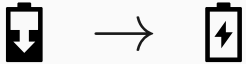


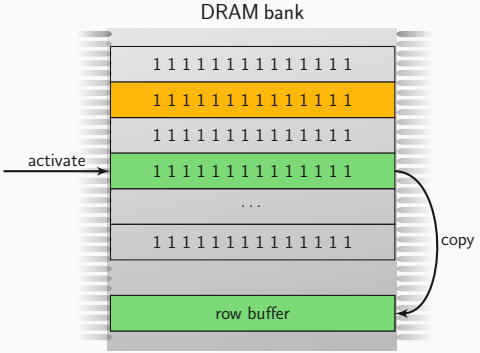
64k cells
1 capacitor,
1 transitor each

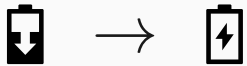

DRAM bank
1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
. . .
1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
row buffer



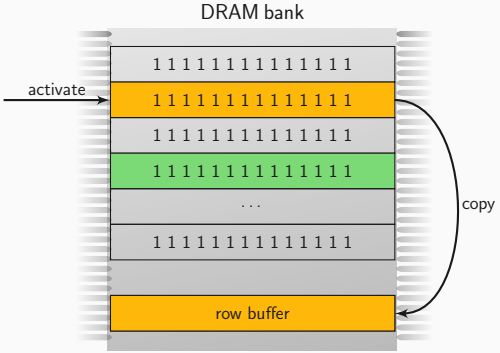

DRAM bank
activate
1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
. . .
1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
copy
row buffer

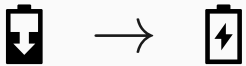






Cells leak faster upon proximate accesses $\rightarrow$ Rowhammer





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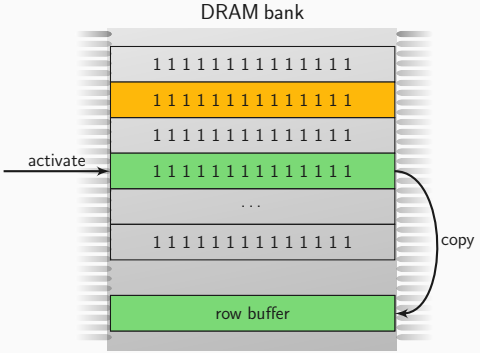

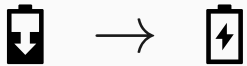

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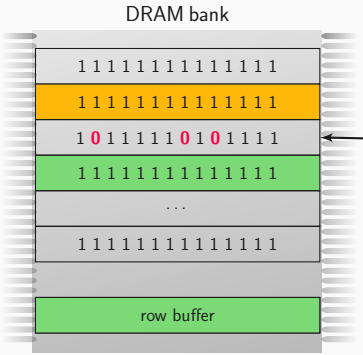
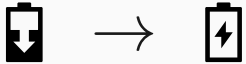


bit flips in row 2!



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DDR3

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DDR4

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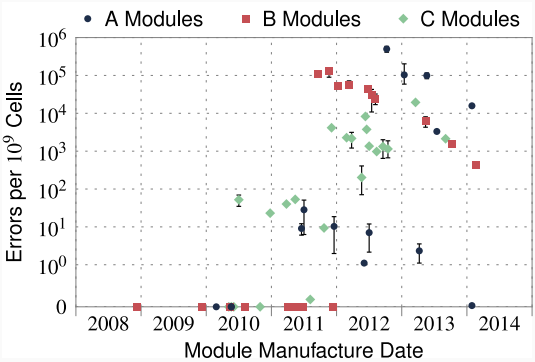
- We showed bit flips [Pes+16]
- 67% affected [Lan16]




BIT FLIPS
BIT FLIPS EVERYWHERE

Requirements

Memory accesses must be

- uncached: reach DRAM
- fast: race against the next row refresh
- targeted: reach specific row

How do we get enough uncached accesses?

- `clflush` instruction → original paper [Kim+14]

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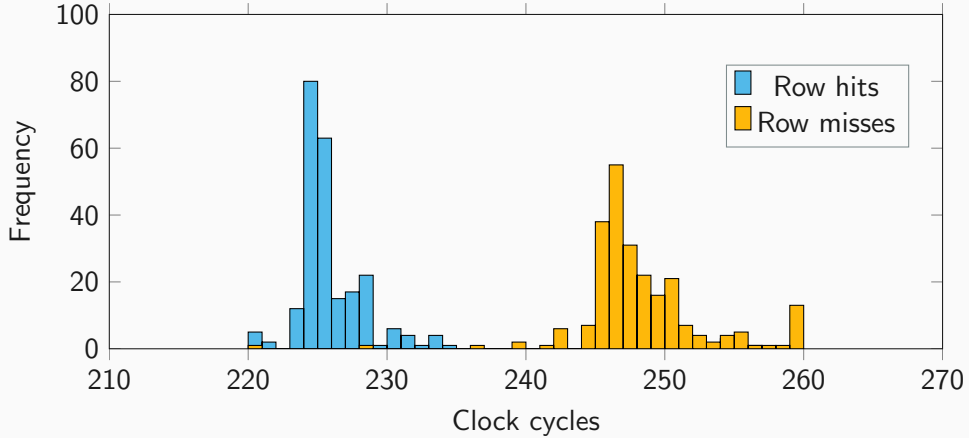
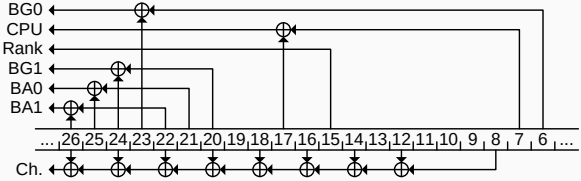
- cache eviction [GMM16; Awe+16]
- non-temporal accesses [QS16]
- uncached memory [Vee+16]

How do we target accesses?

Timing difference





https://github.com/IAIK/drama

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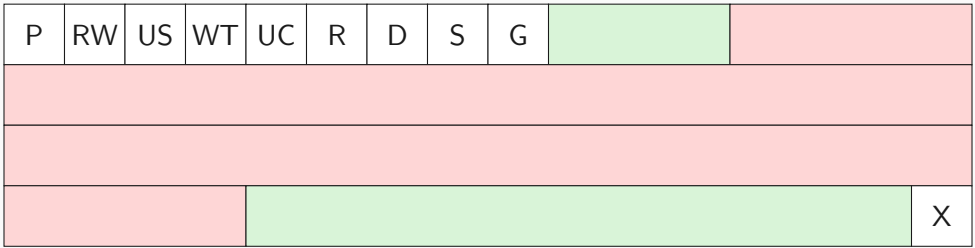
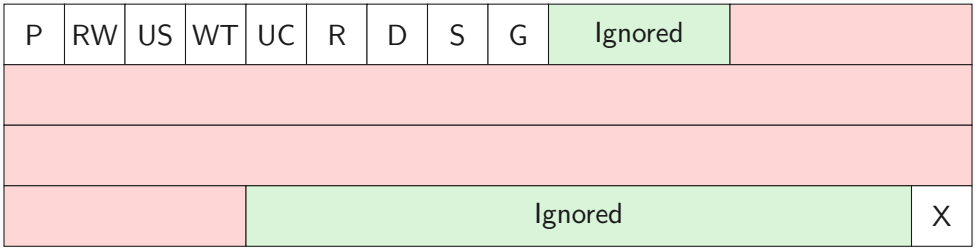
- Alternatively: Build a PUF [Ana+18]

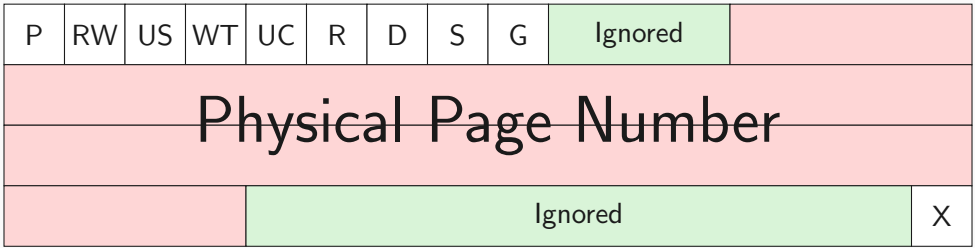
Page Table Entries

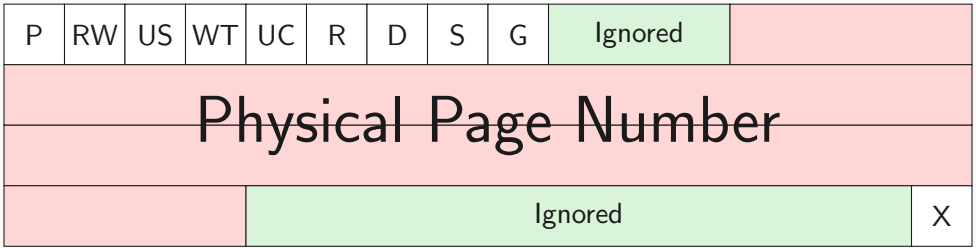


Page Table Entries



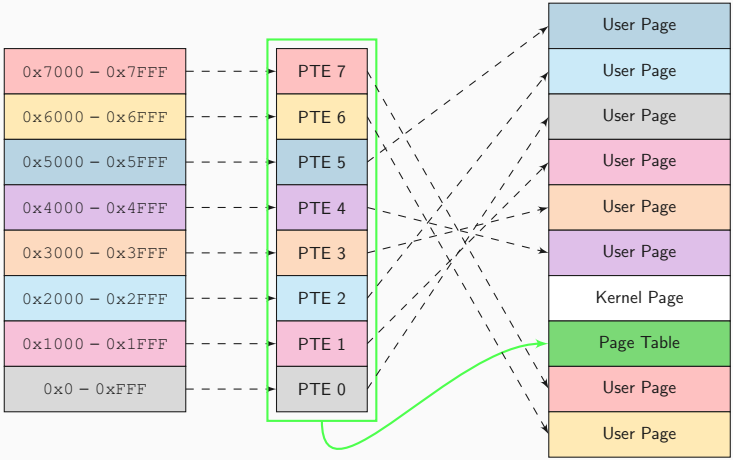
Page Table Entries

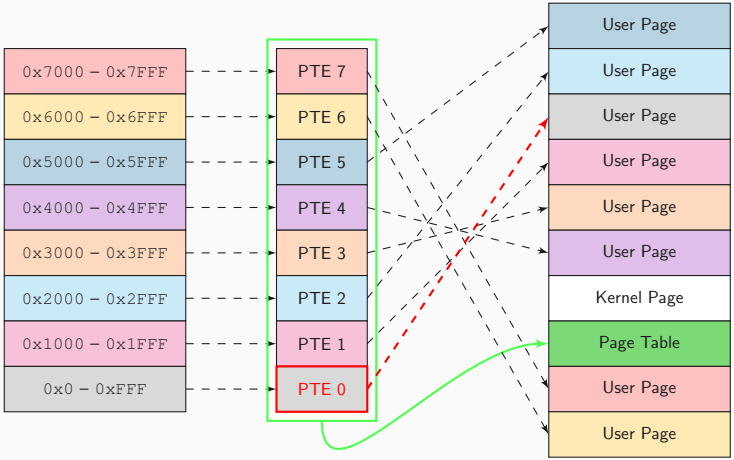




Each 4 KB page table consists of 512 such entries

Page Table Manipulation

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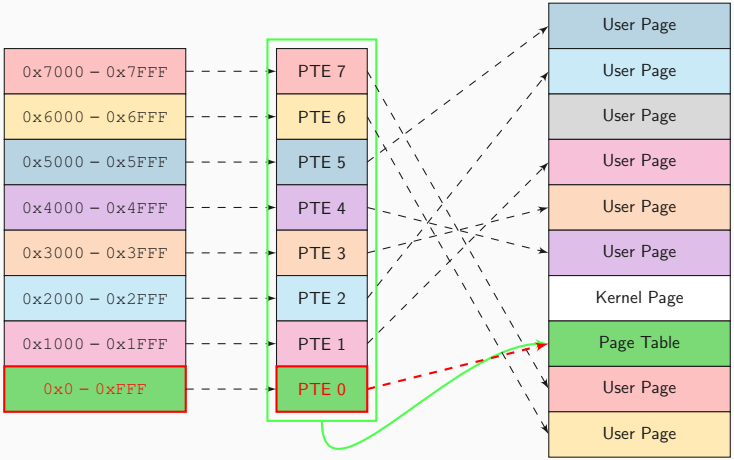
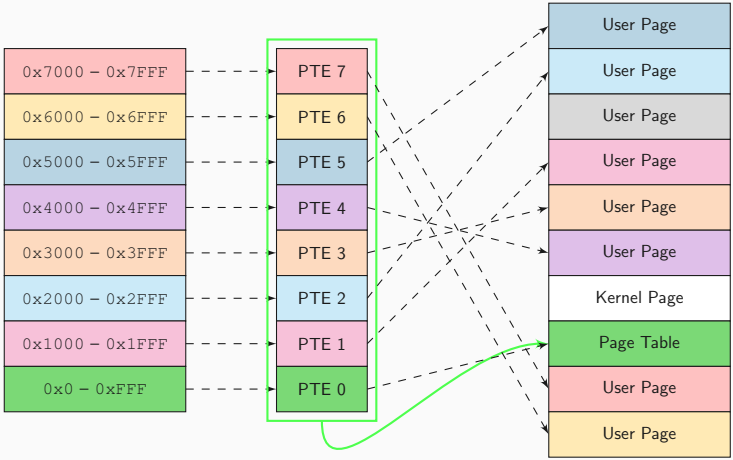
Page Table Manipulation

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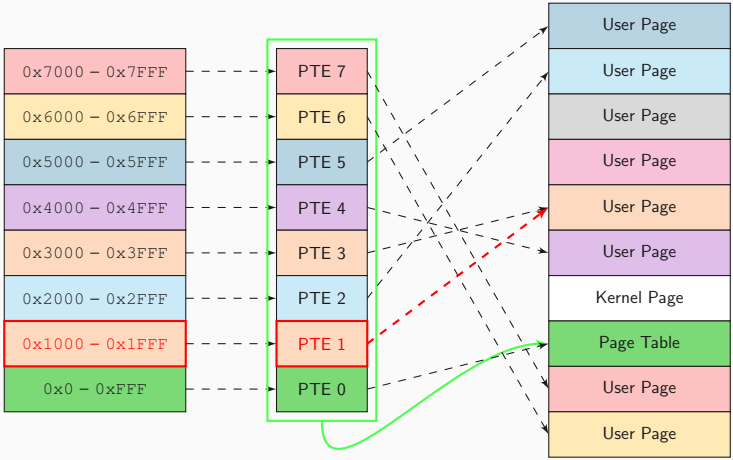
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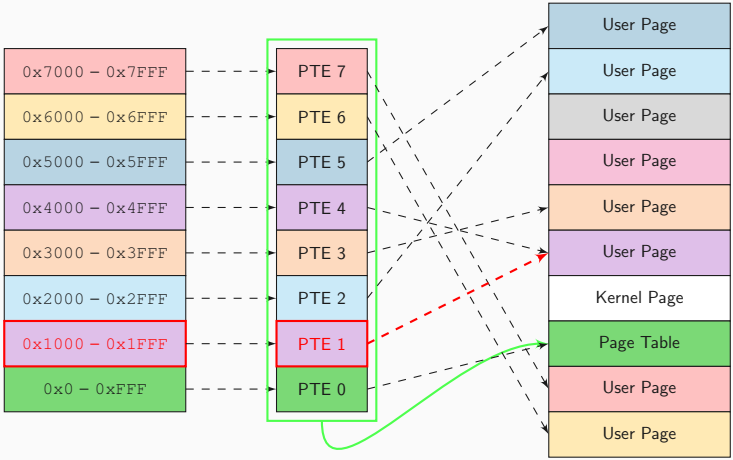

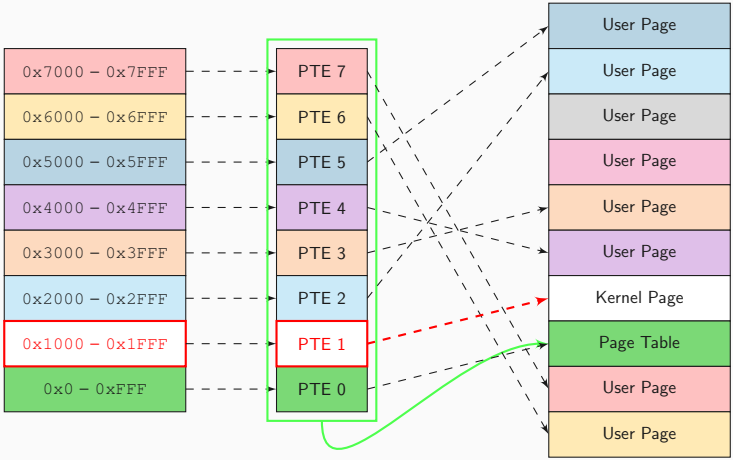
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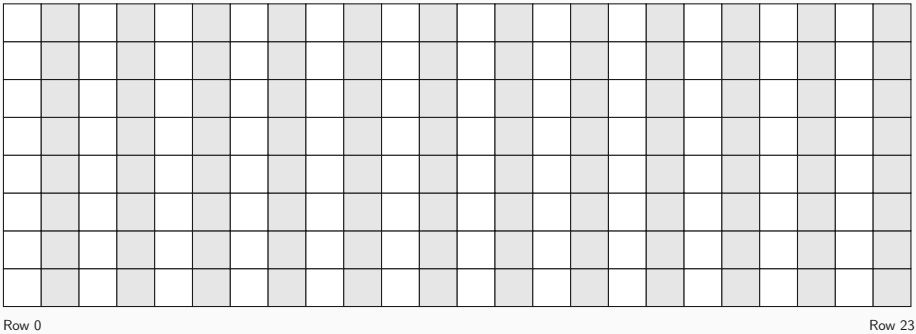
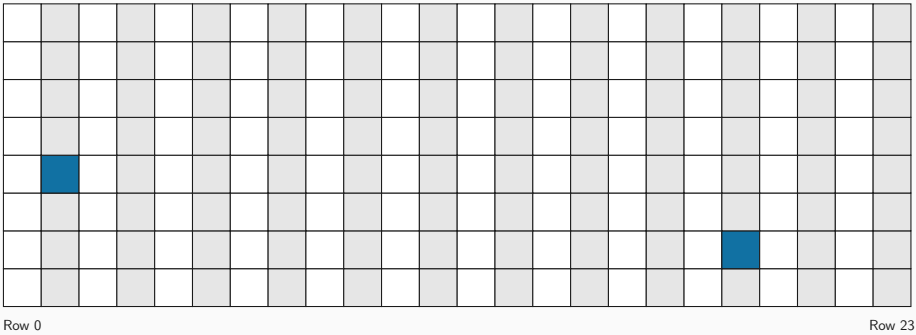


Hammering memory locations in different rows



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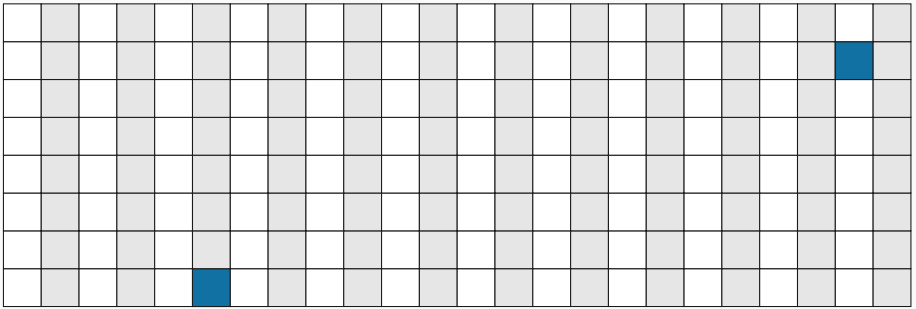

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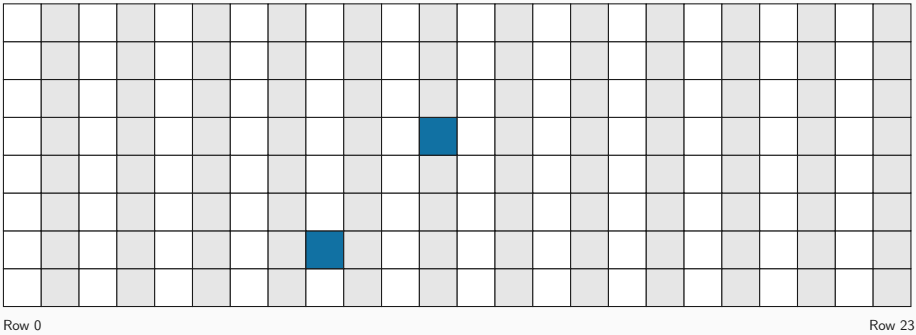

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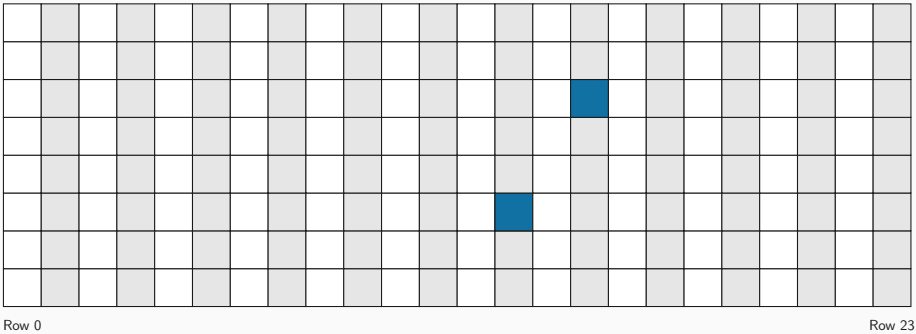

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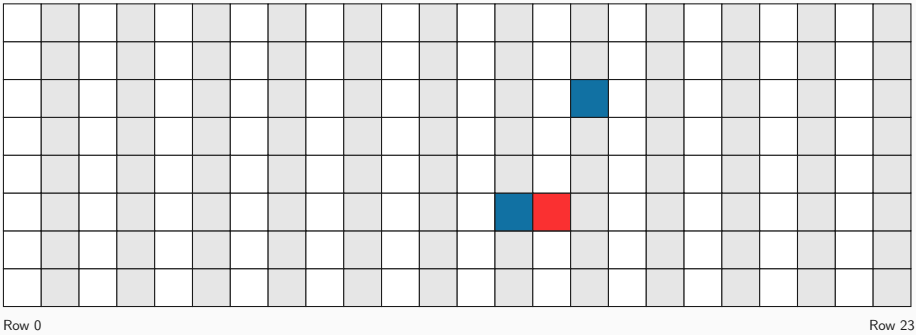

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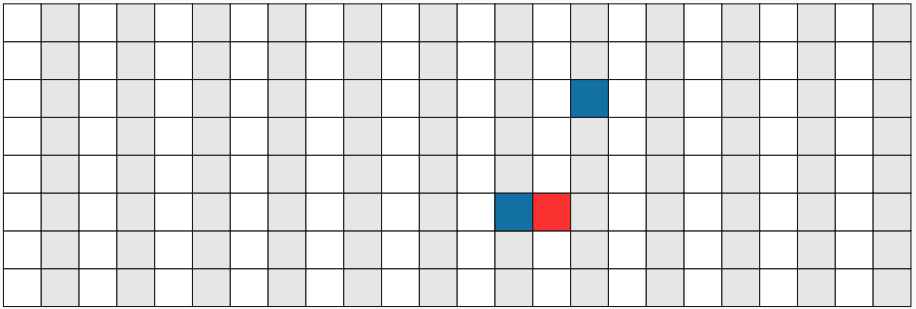
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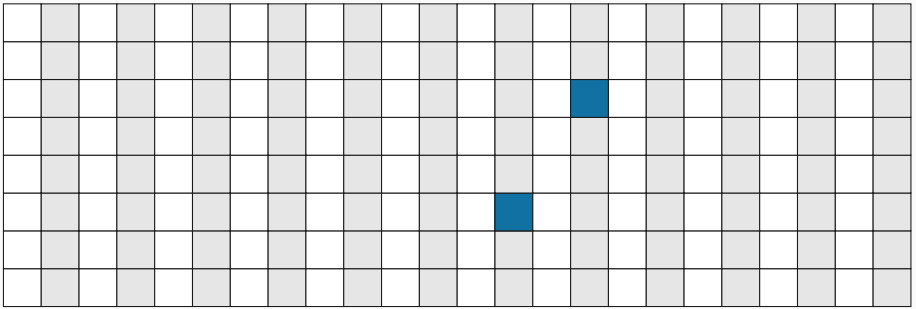
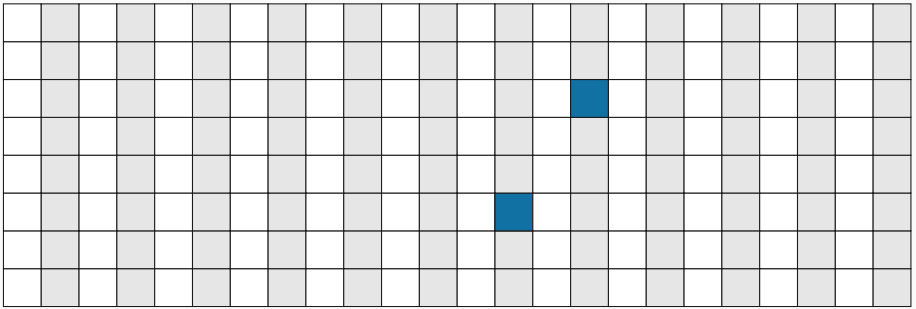
Row 23


Row 0
Row 23

Fill all remaining memory with page tables



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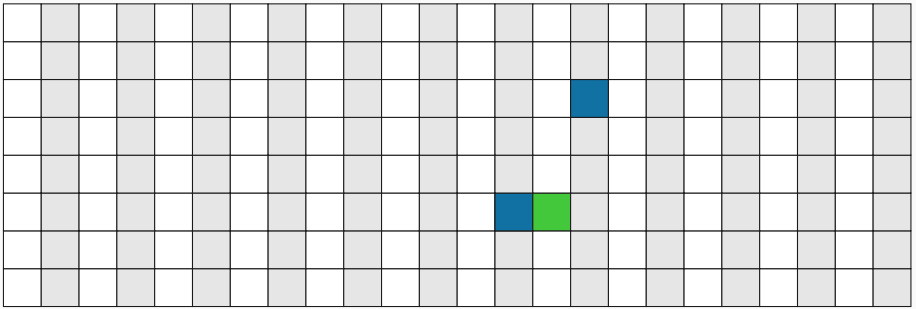

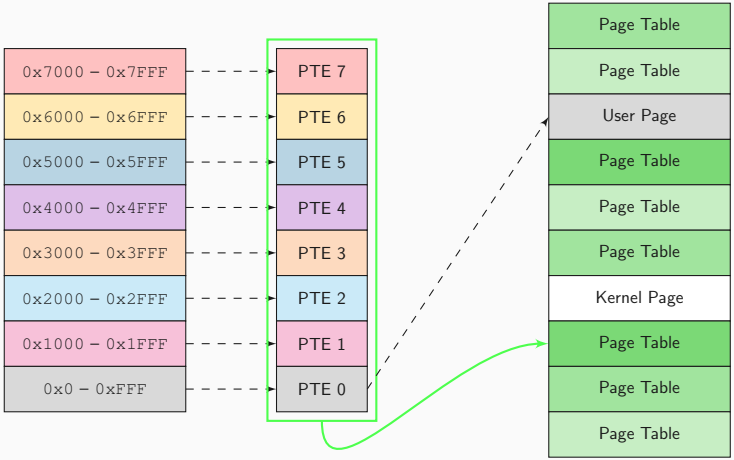
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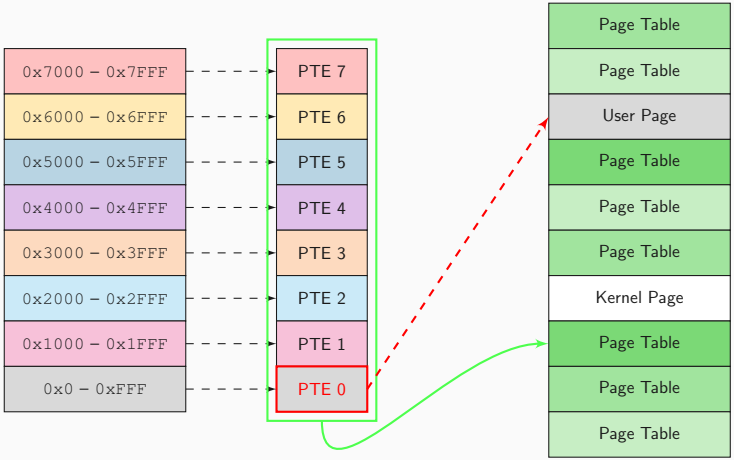
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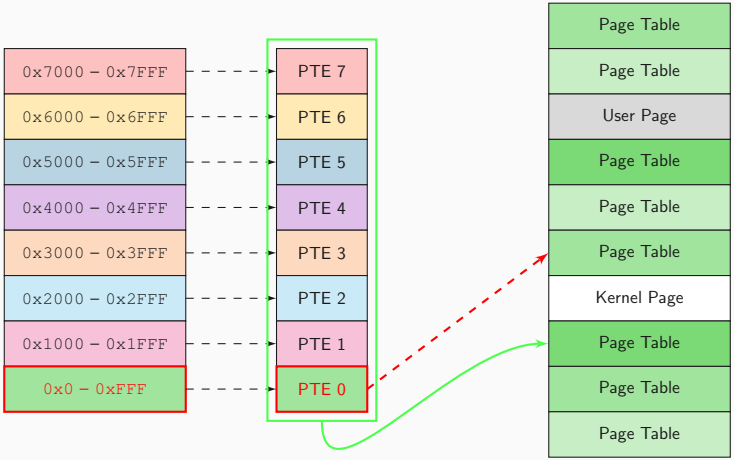
Page Table

Page Table Manipulation



Flipping Page Table PPN bits

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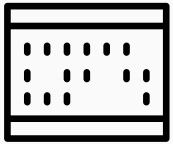
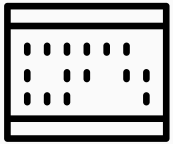


Flipping Page Table PPN bits



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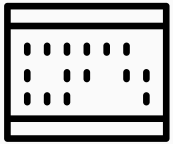
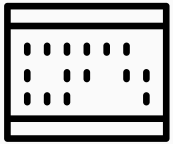


- Idea from [SD15]



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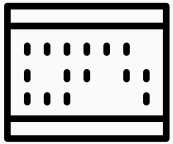

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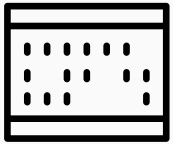

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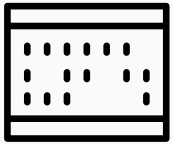
Flipping Page Table PPN bits



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- Scan entire physical memory (very fast) and:

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  - etc.
- pages are pretty unique: 32768 bits per page

- There are two different hammering techniques

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- #1: Hammer one row next to victim row and other random rows

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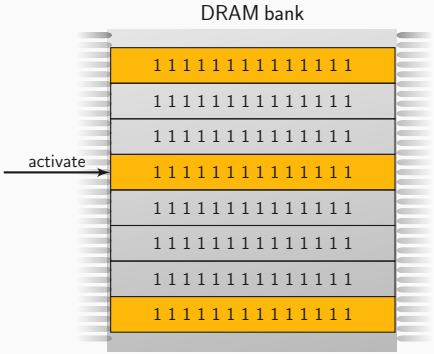
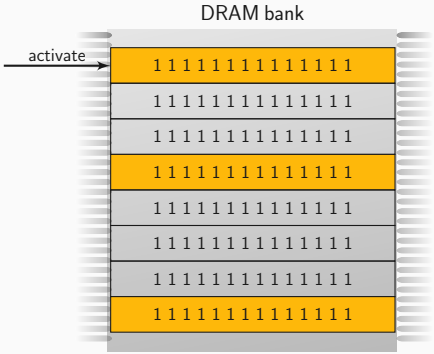
#1 - Single-sided hammering



#1 - Single-sided hammering



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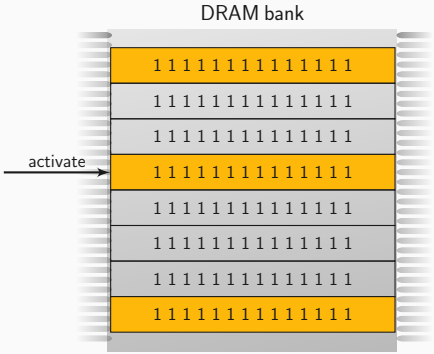

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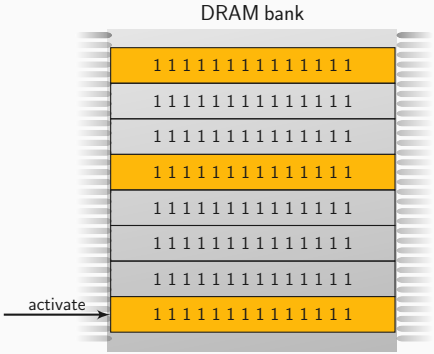

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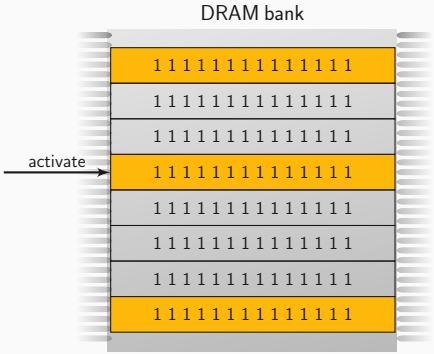

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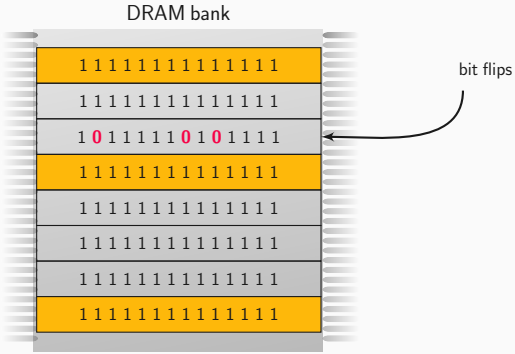
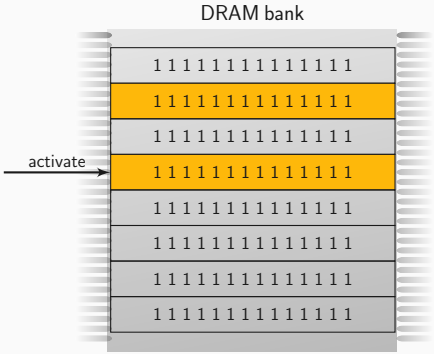


#2 - Double-sided hammering



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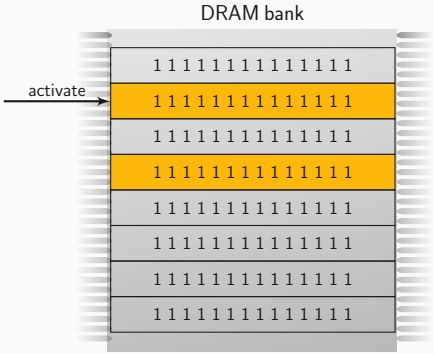

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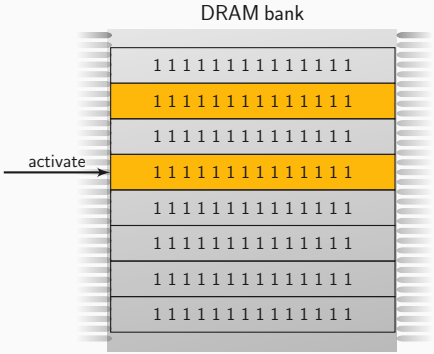

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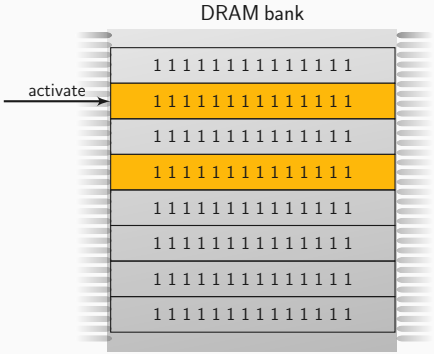

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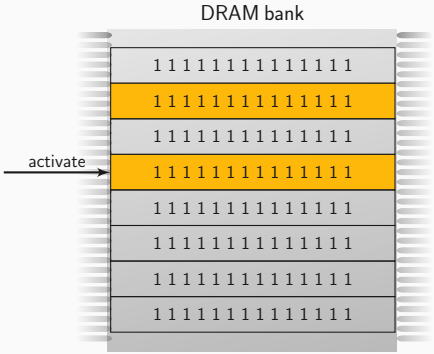

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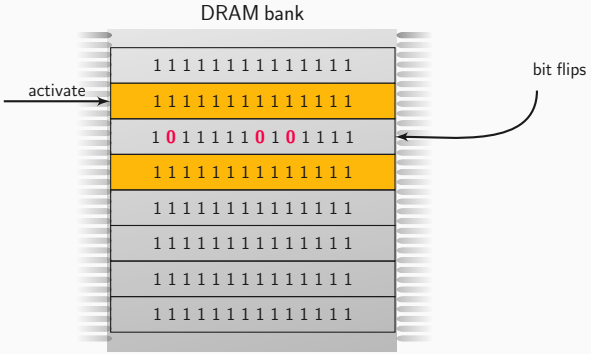
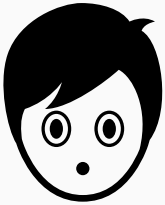


HAMMERING
TWO ROWS

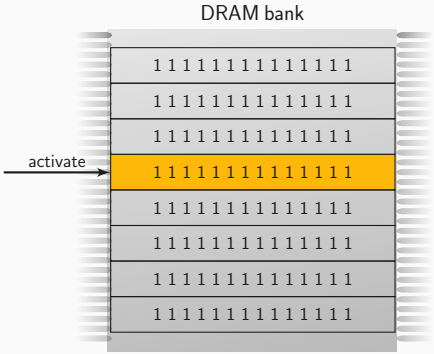
HAMMERING TWO ROWS

HAMMERING A SINGLE ROW



- There are three different hammering techniques
- #1: Hammer one row next to victim row and other random rows
- #2: Hammer two rows neighboring victim row
- #3: Hammer only one row next to victim row

#3 - One-location hammering



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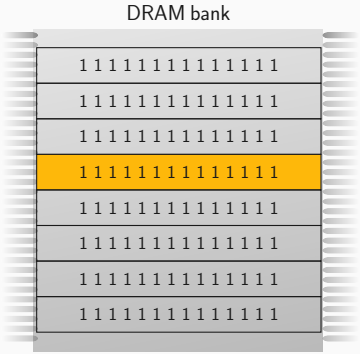

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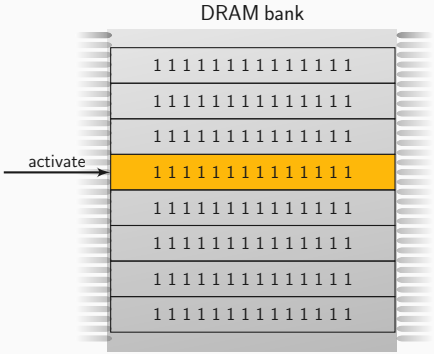

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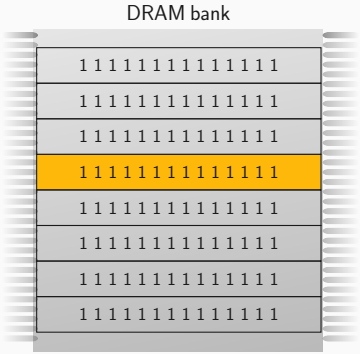

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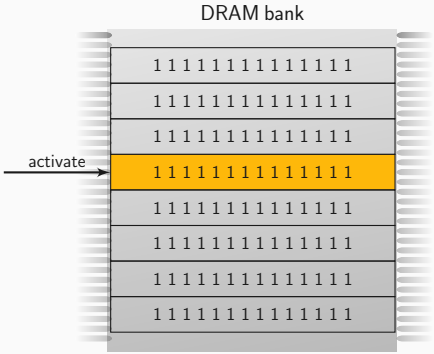

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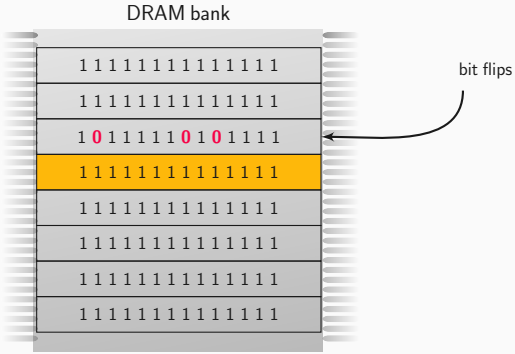
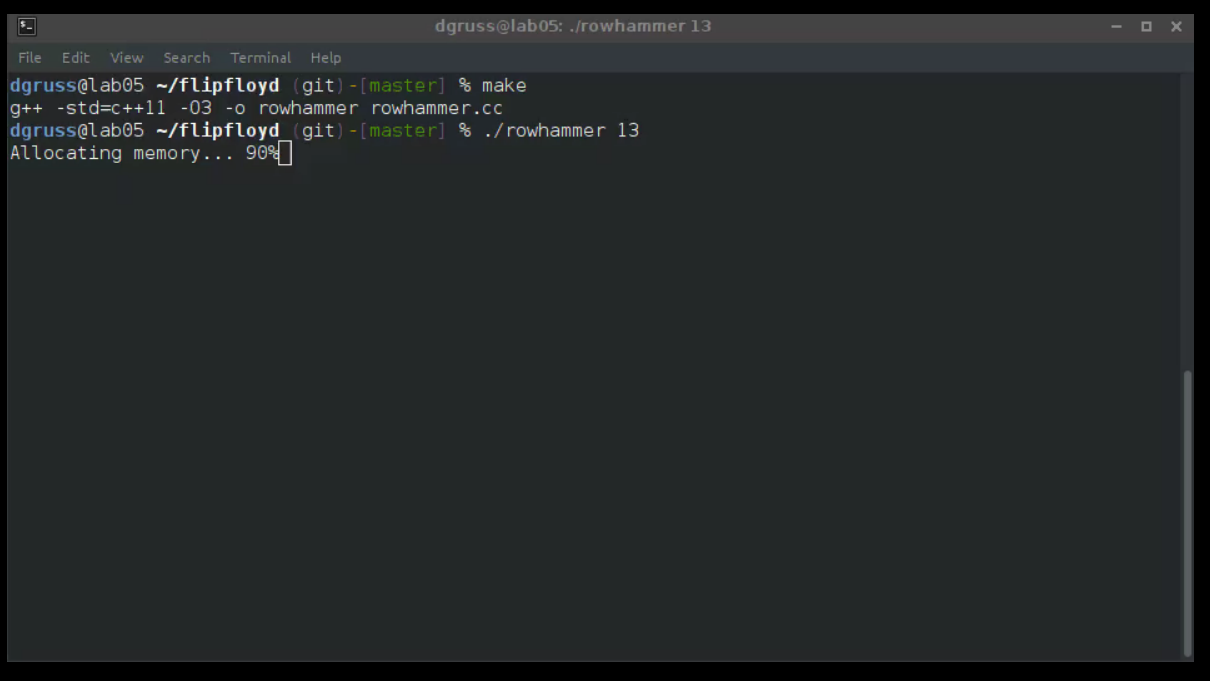
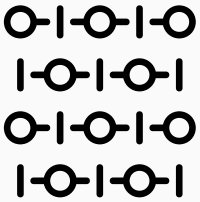
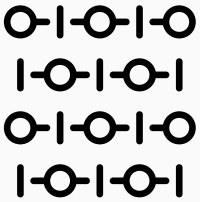


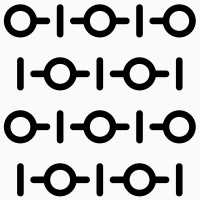

dgruss@lab05: ./rowhammer 13
File Edit View Search Terminal Help
dgruss@lab05 ~/flipfloyd (git)-[master] % make
g++ -std=c++11 -O3 -o rowhammer rowhammer.cc
dgruss@lab05 ~/flipfloyd (git)-[master] % ./rowhammer 13
Allocating memory... 90%



- **Open-page policy**: Keep row opened and buffered



- **Open-page policy**: Keep row opened and buffered
  - Low latency for subsequent accesses to same row
  - High latency for accesses to any other row



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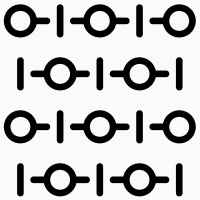

- **Open-page policy**: Keep row opened and buffered
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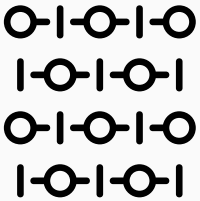
- **Close-page policy**: Immediately close row, ready to open a new row
  - Medium latency for accesses to any row



- **Open-page policy**: Keep row opened and buffered
  - Low latency for subsequent accesses to same row
  - High latency for accesses to any other row
- **Close-page policy**: Immediately close row, ready to open a new row
  - Medium latency for accesses to any row
  - Perform better on multi-core systems [Dav+11]

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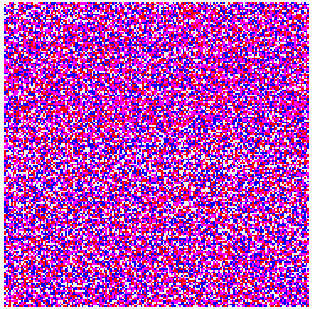
- We observed close-page policies on desktop computers

- Policies that preemptively close rows, would allow one-location hammering
- We observed close-page policies on desktop computers
- Mobile devices (e.g., laptops) seem to use mostly open-page policies

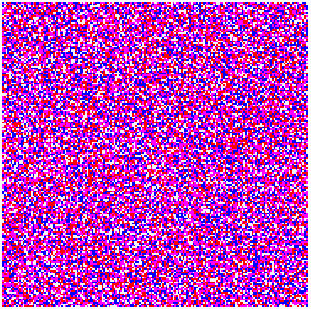
How well does it work?



Double-sided

77.0 % bit offsets

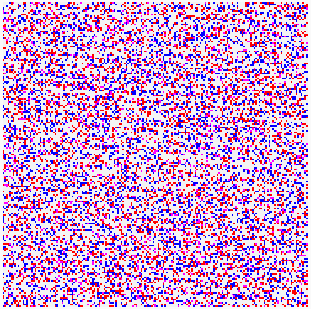
51.7 % 0→1 bit flips



Single-sided

78.5 % bit offsets

54.1 % 0→1 bit flips



One-location

36.5 % bit offsets

51.6 % 0→1 bit flips

What if we cannot target kernel pages?

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Opcode Flipping

- Many applications perform actions as root

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- They can be used by unprivileged users as well
- Implicitly: e.g., `ping` or `mount`
- Explicitly: `sudo`
- Target `sudo` (easy to exploit)


JE
HLT
0 1 1 1 0 1 0 0
1 1 1 1 0 1 0 0


JE
0 1 1 1 0 1 0 0
XORB
0 0 1 1 0 1 0 0


JE
0 1 1 1 0 1 0 0
PUSHQ
0 1 0 1 0 1 0 0


JE
0 1 1 1 0 1 0 0
<prefix>
0 1 1 0 0 1 0 0


JE
0 1 1 1 0 1 0 0
JL
0 1 1 1 1 1 0 0


JE
0 1 1 1 0 1 0 0
JO
0 1 1 1 0 0 0 0

Opcode Flipping - Conditional Jump


JE
0 1 1 1 0 1 0 0
JNE
0 1 1 1 0 1 0 1

How to get the target virtual page to the target physical location?

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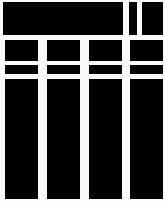
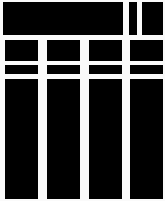
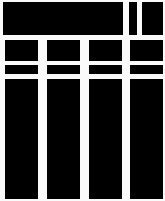
Memory Waylaying



- If a binary is loaded the first time, it is loaded to the memory



- If a binary is loaded the first time, it is loaded to the memory
- It stays in memory (in the page cache) even after execution



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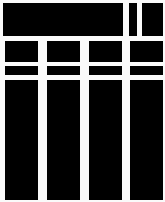
- It stays in memory (in the page cache) even after execution
- Only evicted if page cache is full

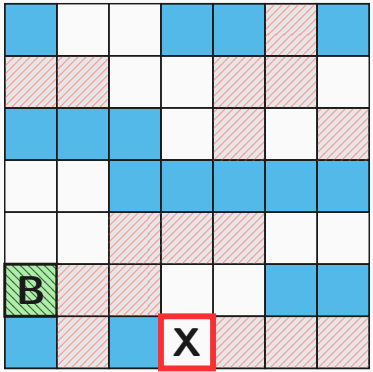


- If a binary is loaded the first time, it is loaded to the memory
- It stays in memory (in the page cache) even after execution
- Only evicted if page cache is full
- Page cache is huge - usually all unused memory

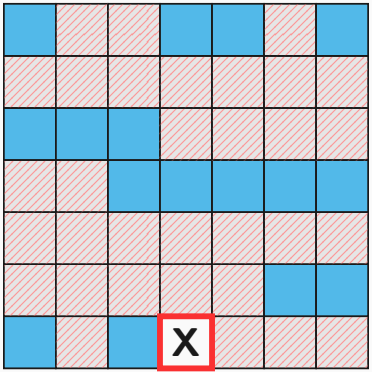
MEMORY WAYLAYING

Wait for the right moment, and then hit it with a bit flip!

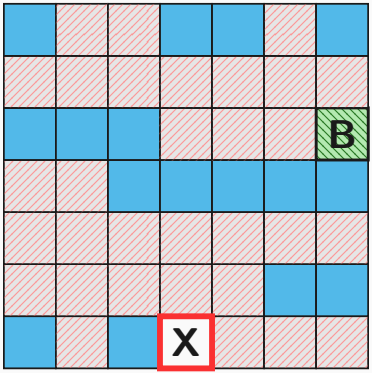
(1) Start



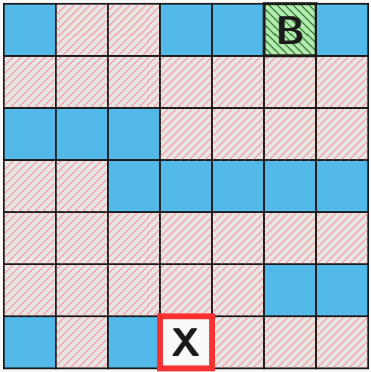
(2) Evict Page Cache



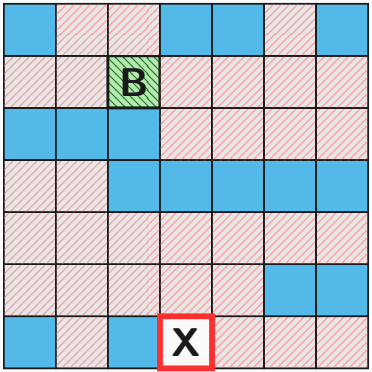
(3) Access Binary



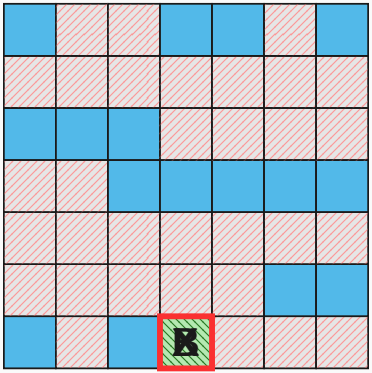
(4) Evict + Access



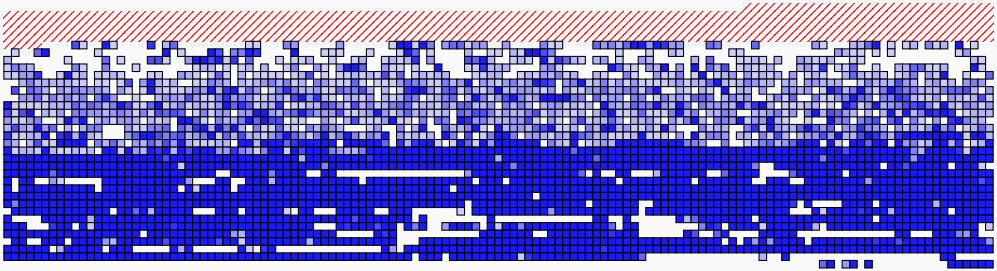
(5) Evict + Access



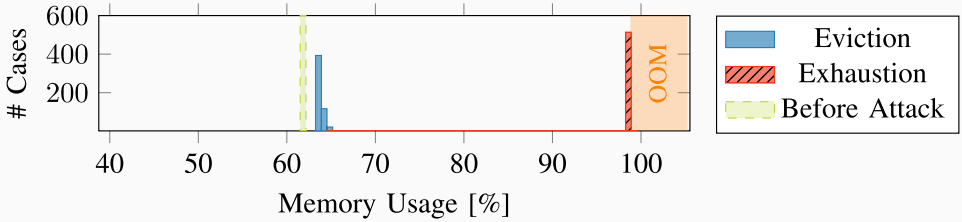
(6) Stop if target reached



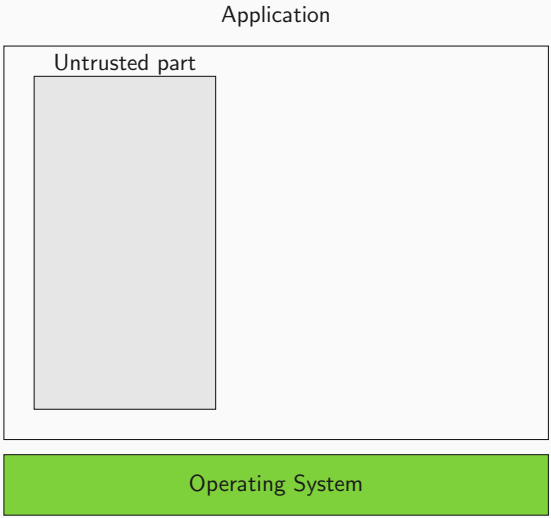
- New pages cover most of the physical memory

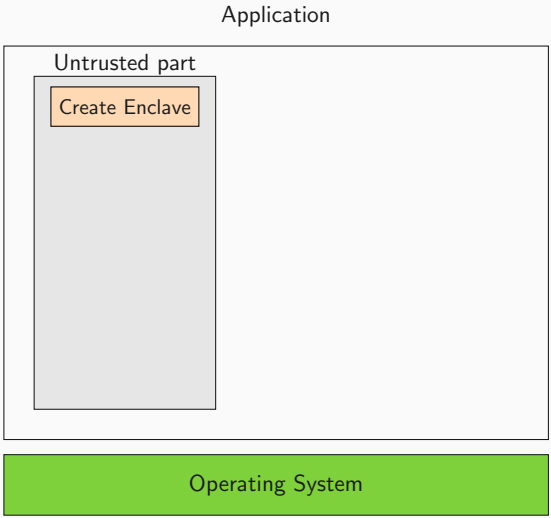


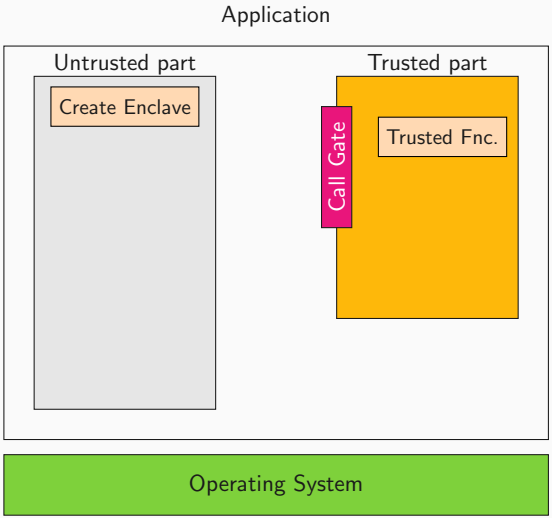
- Great advantage over memory massaging: only negligible memory footprint

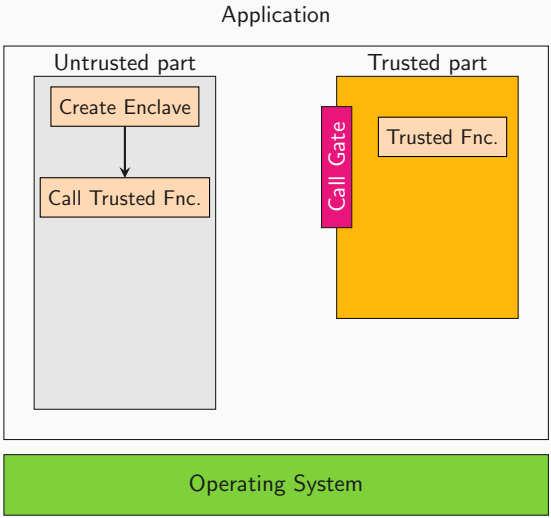


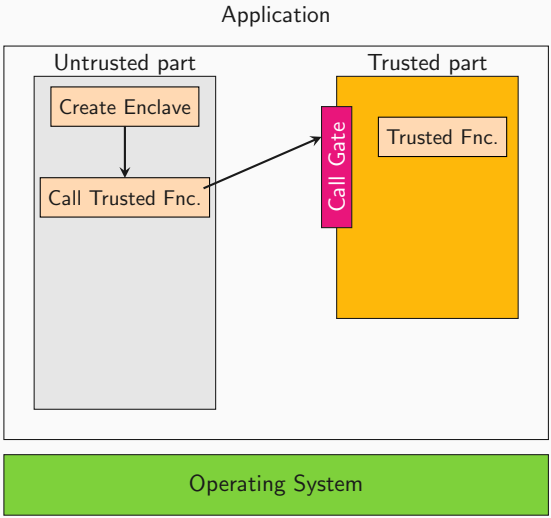
Rowhammer + SGX = Cheap Denial of Service

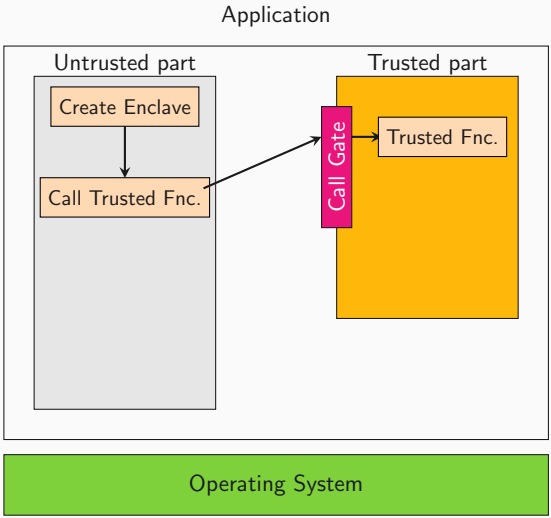

Application
Untrusted part
Operating System


Application
Untrusted part
Create Enclave
Operating System


Application
Untrusted part
Create Enclave
Trusted part
Call Gate
Trusted Fnc.
Operating System


Application
Untrusted part
Create Enclave
Call Trusted Fnc.
Trusted part
Call Gate
Trusted Fnc.
Operating System


Application
Untrusted part
Trusted part
Create Enclave
Call Trusted Fnc.
Call Gate
Trusted Fnc.
Operating System


Application
Untrusted part
Trusted part
Create Enclave
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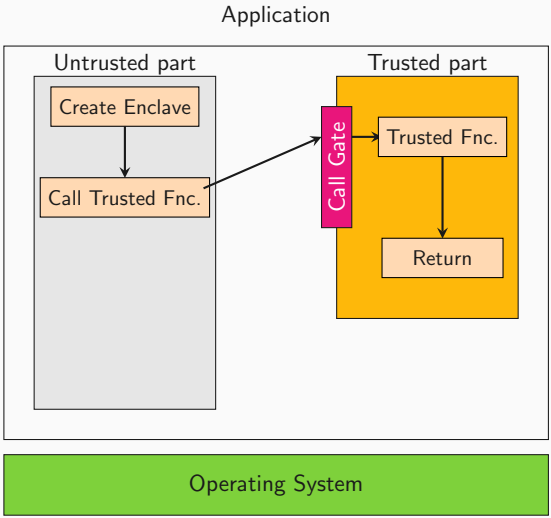
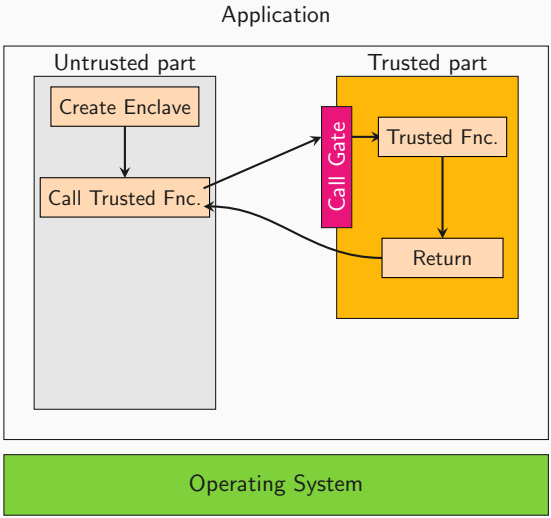
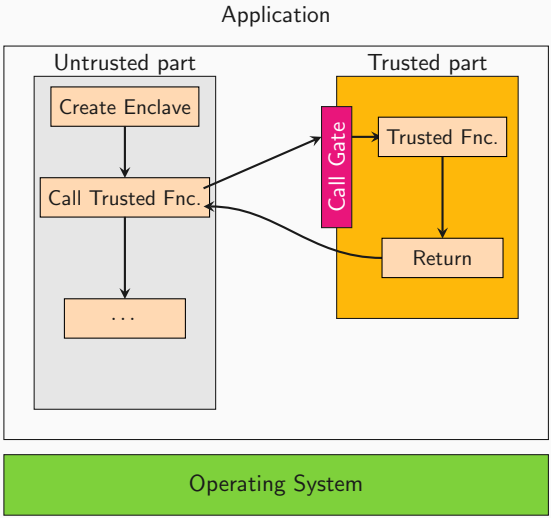
Operating System


Application
Untrusted part
Trusted part
Create Enclave
Call Trusted Fnc.
Call Gate
Trusted Fnc.
Return
Operating System


Application
Untrusted part
Trusted part
Create Enclave
Call Trusted Fnc.
Call Gate
Trusted Fnc.
Return
Operating System


Application
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Create Enclave
Call Trusted Fnc.
...
Call Gate
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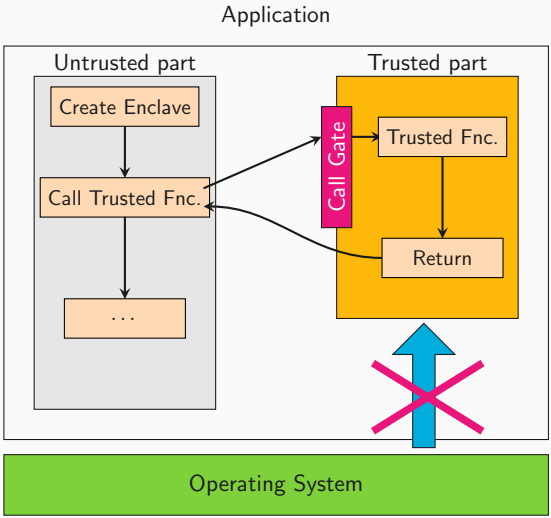
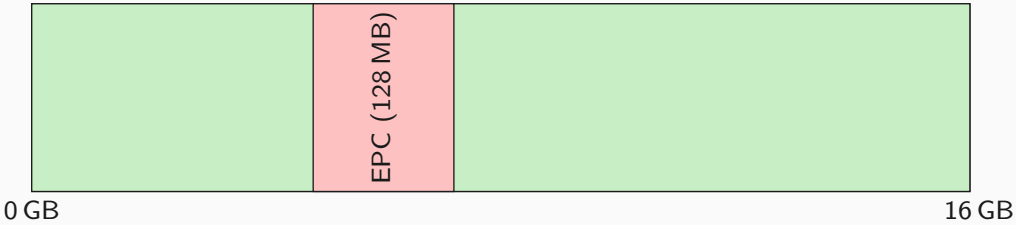
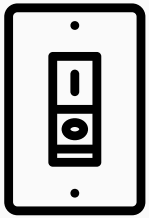
Return
Operating System


Application
Untrusted part
Trusted part
Create Enclave
Call Trusted Fnc.
...
Call Gate
Trusted Fnc.
Return
Operating System

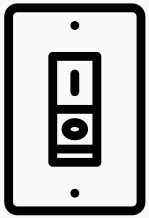

0 GB
16 GB


EPC (128 MB)
0 GB
16 GB

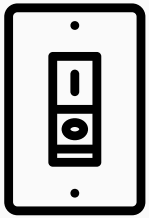


- What happens if a bit flips in the EPC?

Bit Flips in the EPC



- What happens if a bit flips in the EPC?
- Integrity check will fail!



- What happens if a bit flips in the EPC?
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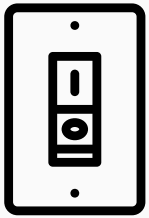
→ Locks up the memory controller



- What happens if a bit flips in the EPC?
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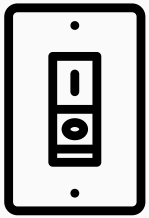
→ Not a single further memory access!



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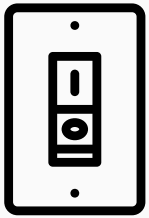
→ Not a single further memory access!

→ System halts immediately



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→ Not a single further memory access!

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SOUNDS UNSAFE?
IT IS UNSAFE!
imgflip.com

- If a malicious enclave induces a bit flip, ...

- If a malicious enclave induces a bit flip, ...
- ...the entire machine halts

- If a malicious enclave induces a bit flip, ...
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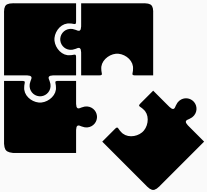
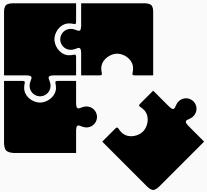
- ...including co-located tenants

- If a malicious enclave induces a bit flip, ...
- ...the entire machine halts
- ...including co-located tenants
- Denial-of-Service Attacks in the Cloud [Gru+18; Jan+17]

SGX + One-location Hammering + Opcode Flipping = Undetectable Exploit

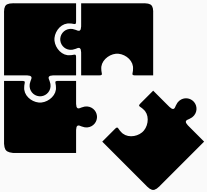


- SGX protects software from malicious environments



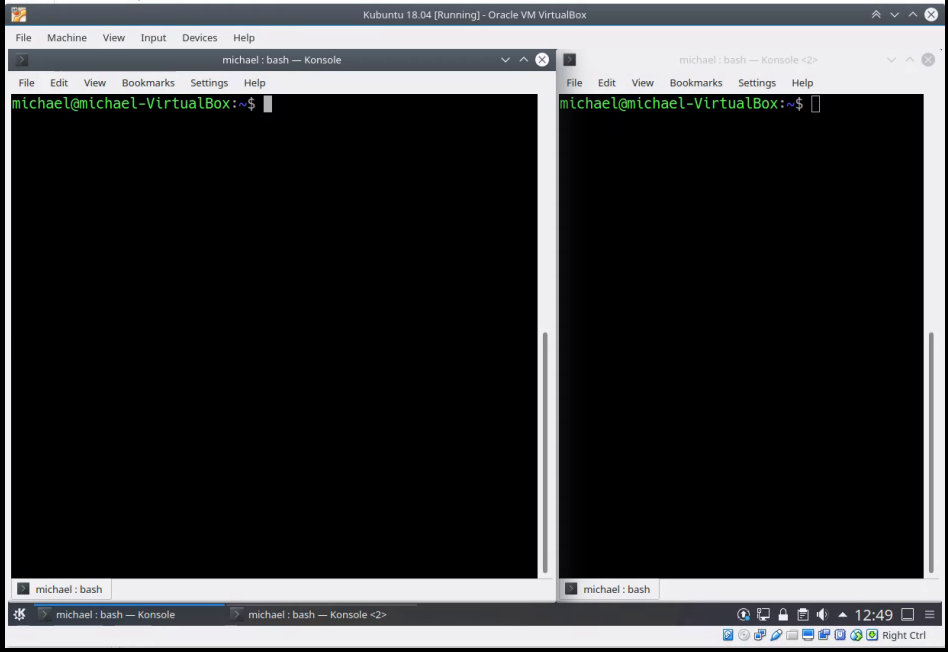
- SGX protects software from malicious environments
- Thwarts static and dynamic (= performance counters) analysis

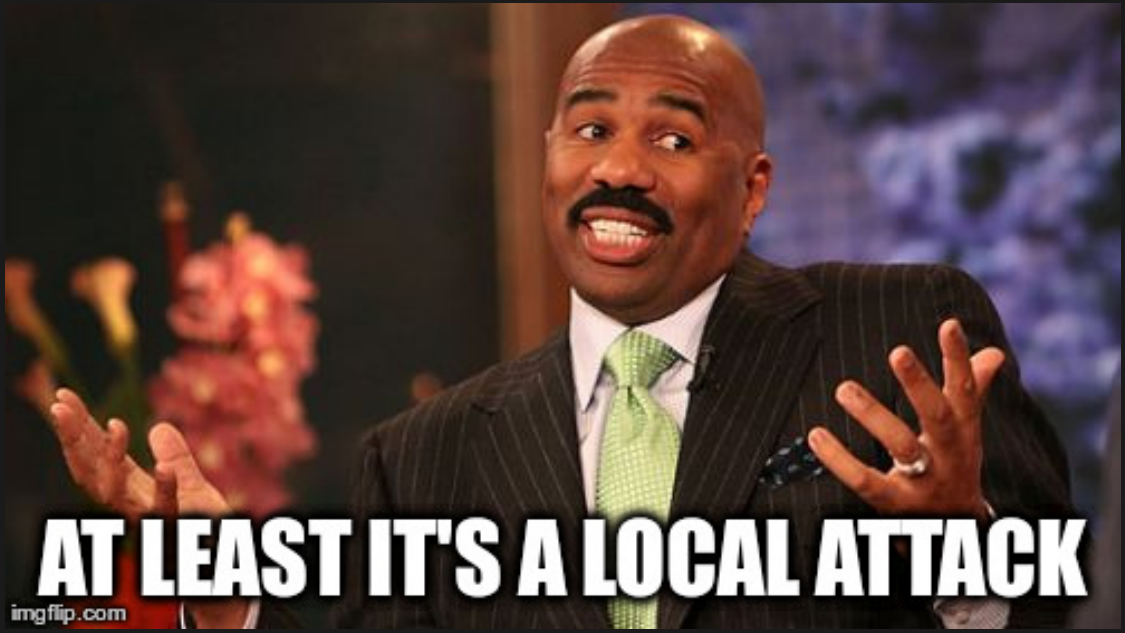
(Ab)using SGX Protection



- SGX protects software from malicious environments
- Thwarts static and dynamic (= performance counters) analysis
- Hammering from SGX defeats countermeasures relying on this


STEALTH LEVEL: EXPERT


Kubuntu 18.04 [Running] - Oracle VM VirtualBox
File Machine View Input Devices Help
michael : bash — Konsole
File Edit View Bookmarks Settings Help
michael@michael-VirtualBox:~$
michael : bash — Konsole <2>
File Edit View Bookmarks Settings Help
michael@michael-VirtualBox:~$
michael : bash
michael : bash
michael : bash — Konsole
michael : bash — Konsole <2>
12:49
Right Ctrl


AT LEAST IT'S A LOCAL ATTACK
imgflip.com

Just comparing some performance numbers...

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- $\geq$ 43 000 hammering attempts (within 64 ms) for a bit flip [GMM16]

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$=$ 671 875 accesses per second

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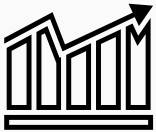

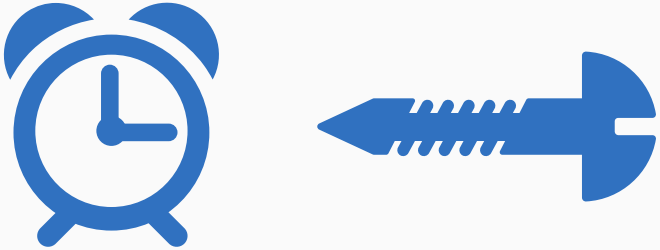

- RMClock

- RMClock
- Throttlestop

- RMClock
- Throttlestop
- linux-intel-undervolt

- RMClock
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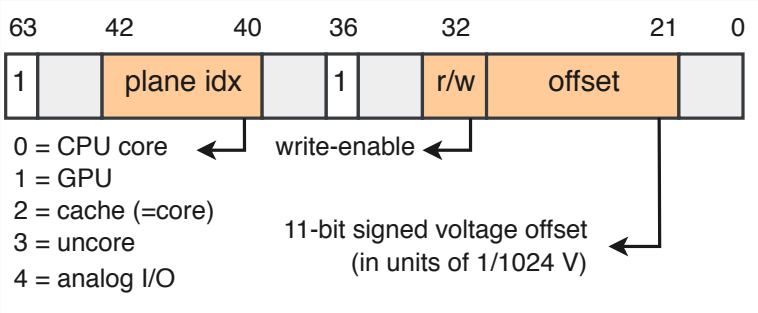
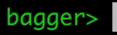
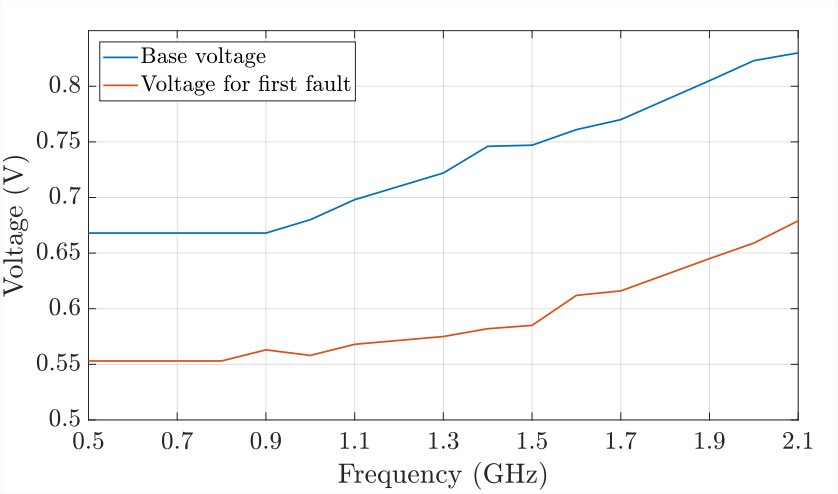
- Adrian Tang's PhD dissertation


63
42
40
36
32
21
0
1
plane idx
1
r/w
offset
0 = CPU core
1 = GPU
2 = cache (=core)
3 = uncore
4 = analog I/O
write-enable
11-bit signed voltage offset
(in units of 1/1024 V)

Will it fault?

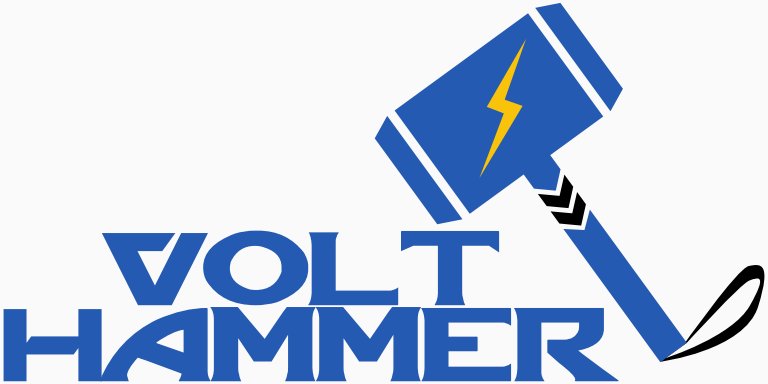
```
uint64_t multiplier = 0x1122334455667788;
uint64_t correct    = 0xdeadbeef * multiplier;
uint64_t var        = 0xdeadbeef * multiplier;

while (var == correct)
{
    var = 0xdeadbeef * multiplier;
}
            uint64_t flipped_bits = var ^ correct;
```


bagger>


Base voltage
Voltage for first fault
Voltage (V)
0.8
0.75
0.7
0.65
0.6
0.55
0.5
0.5
0.7
0.9
1.1
1.3
1.5
1.7
1.9
2.1
Frequency (GHz)

Aristotle Tzafalias
@Aristot73

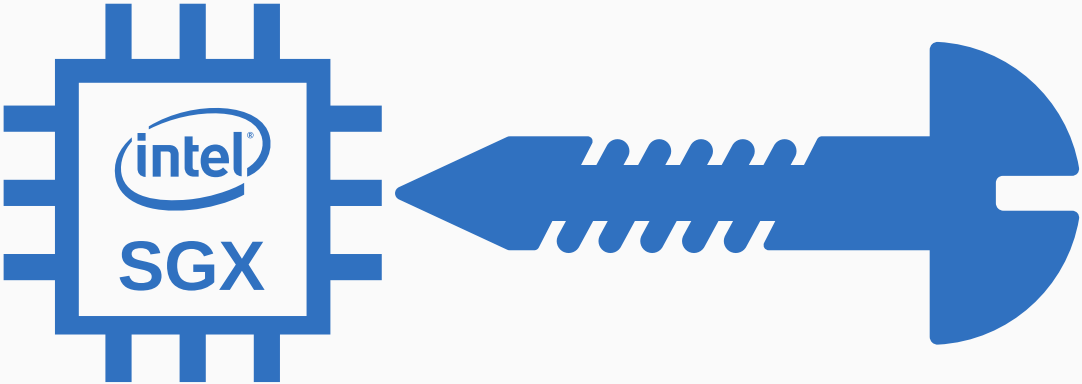
thesis: given a cool name, researchers will be able to find a new vulnerability to match it, in a finite period of time; cool name-logo combination requirements have no measurable effect on aforementioned period.


VOLT
HAMMER

What about the integrity-protected SGX EPC?

[Userspace] Voltage: -261 mV

```
[Enclave] Multiplying 0xdeadbeef 0x1122334455667788
[Enclave] Multiply_it. result: 0.
```


intel
SGX

- Public Key Crypto
- Encrypt/Sign messages
- Untrusted channel
- Encrypt/Verify messages with public key
- Decrypt/Sign messages with private key

$$n = \mathrm{p} \times q$$

$$S = H^{d} \bmod n$$

$$n = \mathrm{p} \times q$$

$$S = H^{d} \bmod n$$

$$d_p = d \bmod p - 1$$

$$d_q = d \bmod q - 1$$

$$s_1 = H^{d_p} \bmod p$$

$$s_2 = H^{d_q} \bmod q$$

$$n = \mathrm{p} \times q$$

$$S = ((q^{-1} \bmod p)(s_1 - s_2) \bmod p) \times q + s_2$$

$$d_p = d \bmod p - 1$$

$$d_q = d \bmod q - 1$$

$$s_1 = H^{d_p} \bmod p$$

$$s_2 = H^{d_q} \bmod q$$

$$n = \mathrm{p} \times q$$

$$S = ((q^{-1} \bmod p)(s_1 - s_2) \bmod p) \times q + s_2$$

$$d_p = d \bmod p - 1$$

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$$s_2 = H^{d_q} \bmod q$$

$$n = \mathrm{p} \times q$$

$$S = ((q^{-1} \bmod p)(s_1 - s_2) \bmod p) \times q + s_2$$

$$S' = ((q^{-1} \bmod p)(s_1 - s_2) \bmod p) \times q + s_2$$

$$n = p \times q$$

$$S = \left(\boxed{\text{something}} \right) \times q + s_2$$

$$S' = \left(\boxed{\text{something else}} \right) \times q + s_2$$

$$n = \mathrm{p} \times q$$

$$S = (\text{something}) \times q + s_2$$

$$S' = (\text{something else}) \times q + s_2$$

$$S - S' = \text{something} \times q$$

$$n = p \times q$$

$$S = (\text{something}) \times q + s_2$$

$$S' = (\text{something else}) \times q + s_2$$

$$S - S' = \text{something} \times q$$

$$q = \gcd(S - S', n)$$

RSA decryption

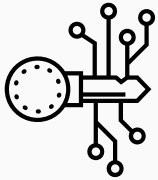
```
uint8_t rsa_dec_ecall(int iterations)
{
    // Wait for first fault
    trigger_fault(iterations);

    // Actual decryption
    ippsRSA_Decrypt(ct, dec, pPrv, scratchBuffer);
}
```

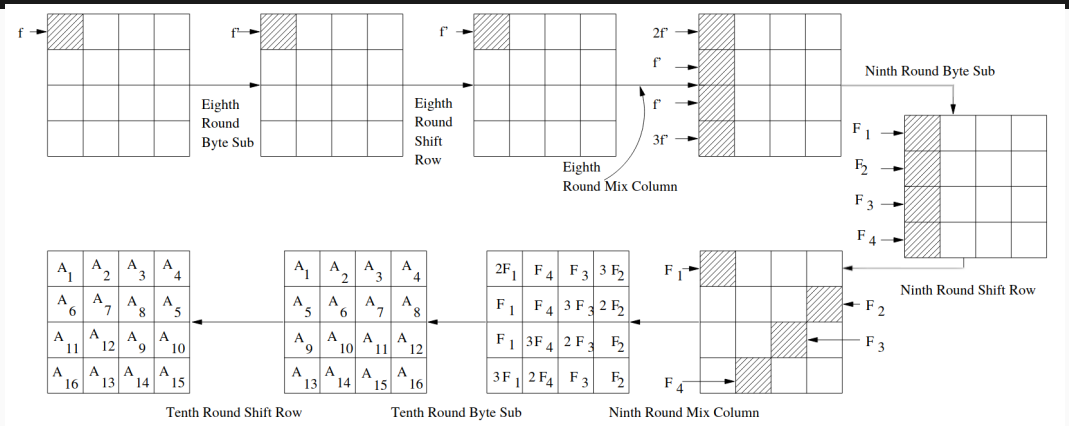
```
bagger> dog Enclave/encl
```


MUFARSA
My Undervolting
Fault Attack on RSA
imgflip.com

WHAT ELSE CAN WE BREAK?!



- Symmetric Key Crypto
- Encrypt messages for transfer over public channel
- Encrypt data for (untrusted) storage
- 4×4 byte state
- 10 rounds: S-Box, ShiftRows, MixColumns, AddRoundKey



Michael Tunstall et al. Differential Fault Analysis of the Advanced Encryption Standard Using a Single Fault. In: International Workshop on Information Security Theory and Practices. 2011 [TMA11]

AES-NI (New Instructions)

Instruction	Description
`AESENC`	Perform one round of an AES encryption flow
`AESENCLAST`	Perform the last round of an AES encryption flow
`AESDEC`	Perform one round of an AES decryption flow
`AESDECLAST`	Perform the last round of an AES decryption flow
`AESKEYGENASSIST`	Assist in AES round key generation
`AESIMC`	Assist in AES Inverse Mix Columns
`PCLMULQDQ`	Carryless multiply (CLMUL)

```
do
{
        i++;
        plaintext = <randomly generated>

        result1 = aes128_enc(plaintext);
        result2 = aes128_enc(plaintext);
} while (vec_equal_128(result1,result2) && i<iterations);
```

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


CRYPTO
VAULT
SCREW
HAMMER

But what about memory corruption?

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

But what about memory corruption?

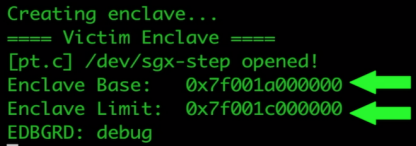
```
struct_foo_t *foo = &arr[offset];
foo->foo = encrypted_secret;
```

But what about memory corruption?


```
foo = arr + offset * 0x24
```

But what about memory corruption?

```
foo = arr + offset * 0x24
```



Voltage
0.584V

Undervolting
-235mV

- Should be related to undervolting

- Should be related to undervolting
- From protected TEE vaults

- Should be related to undervolting
- From protected TEE vaults
- Steal

- Should be related to undervolting
- From protected TEE vaults
- Steal, corrupt

- Should be related to undervolting
- From protected TEE vaults
- Steal, corrupt, plunder, ...


PLUNDER
VOLT

Faulting Hardware from Software

Daniel Gruss

2020-09-13

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