Drammer: Deterministic Rowhammer Attacks on Mobile Platforms

by

A bunch of pasty faced sad sack nerds sitting in a basement want to sound cool and tough, like they've just done a tour in 'Nam. [slashdot]

Drammer: Deterministic Rowhammer Attacks on Mobile Platforms

Victor van der Veen[1], *Yanick Fratantonio*[2], *Martina Lindorfer*[2], *Daniel Gruss*[3], *Clémentine Maurice*[3], *Giovanni Vigna*[2], *Herbert Bos*[1], *Kaveh Razavi*[1], *and Cristiano Giuffrida*[1]

[1]Vrije Universiteit Amsterdam, [2]UC Santa Barbara, [3]TU Graz

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Your takeaway message of today

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Rowhammer on ARM

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Deterministic exploitation

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Rowhammer on ARM

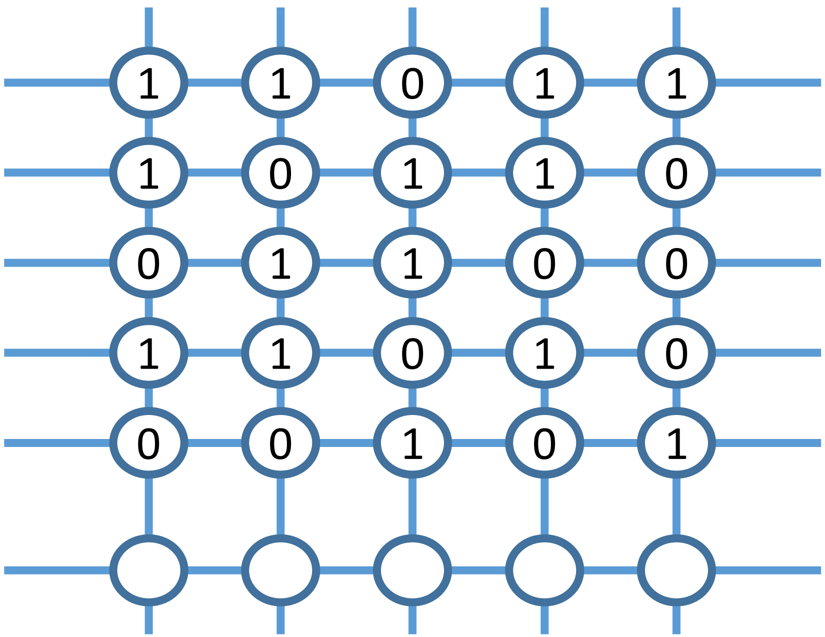
Deterministic exploitation

Works on a Google Pixel

Drammer: Deterministic **Rowhammer** Attacks on Mobile Platforms

Flipping bits in memory

DRAM hardware glitch causing disturbance errors



Aggressor row

Victim row

Aggressor row

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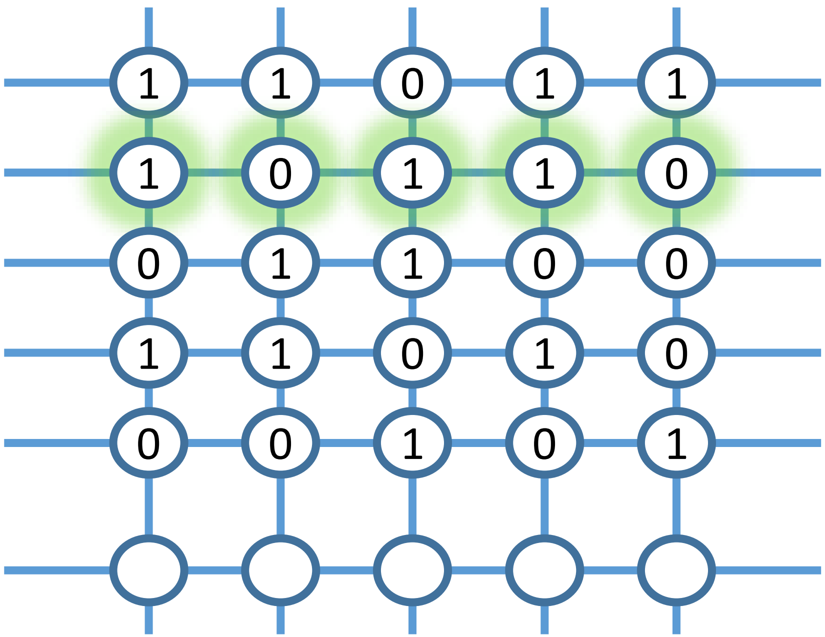

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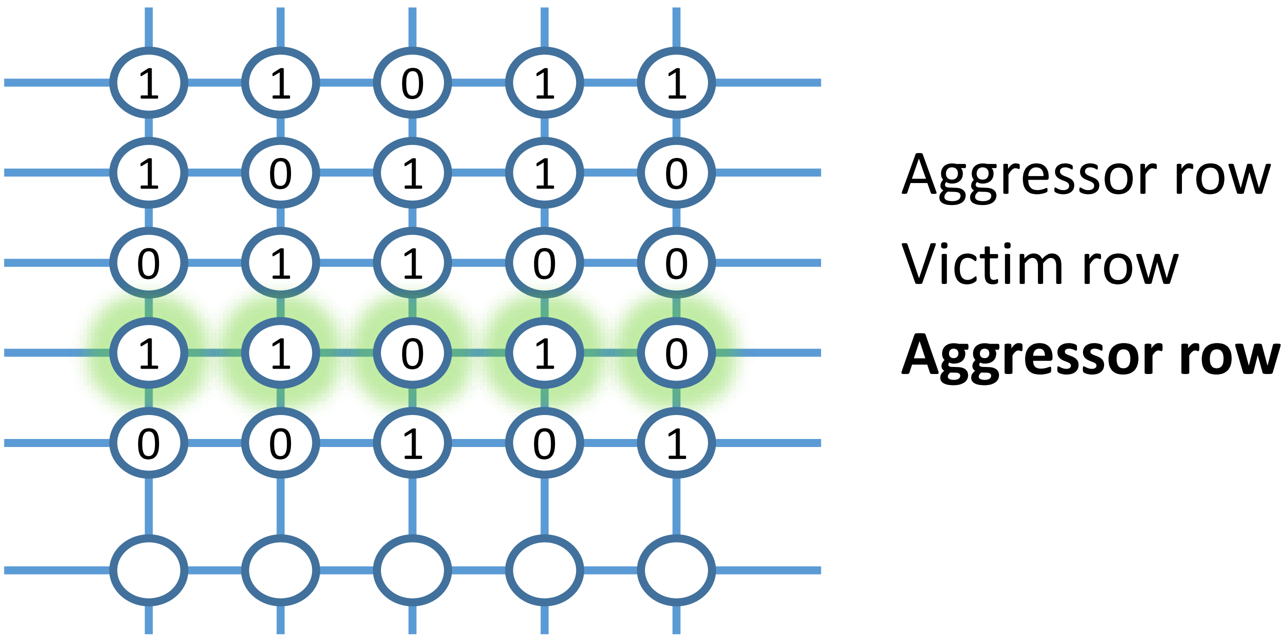

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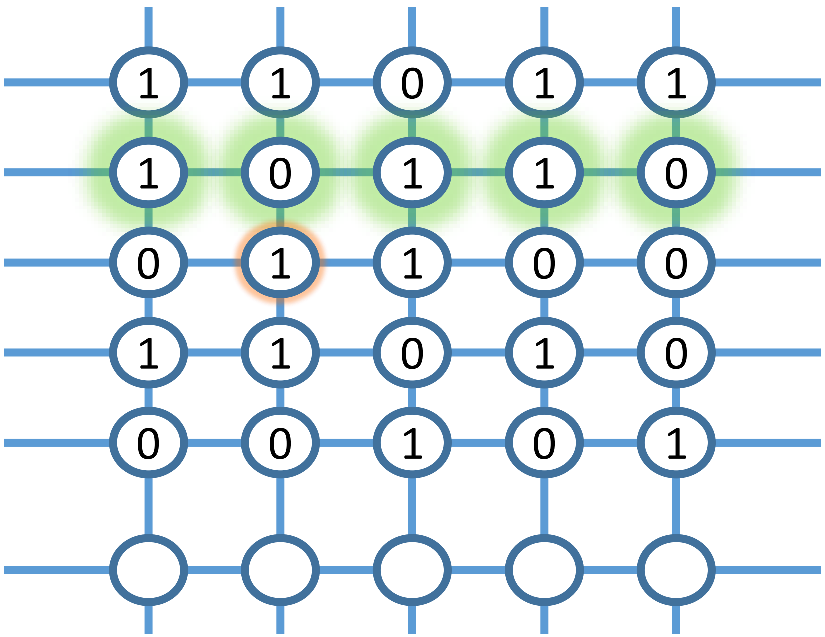

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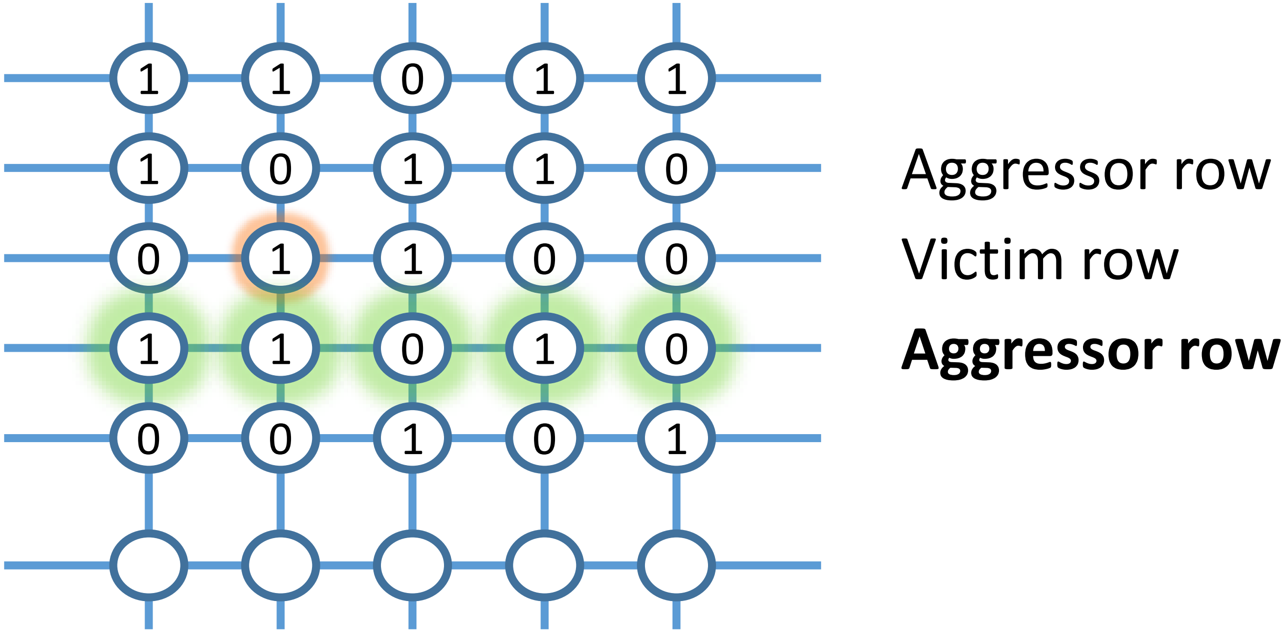

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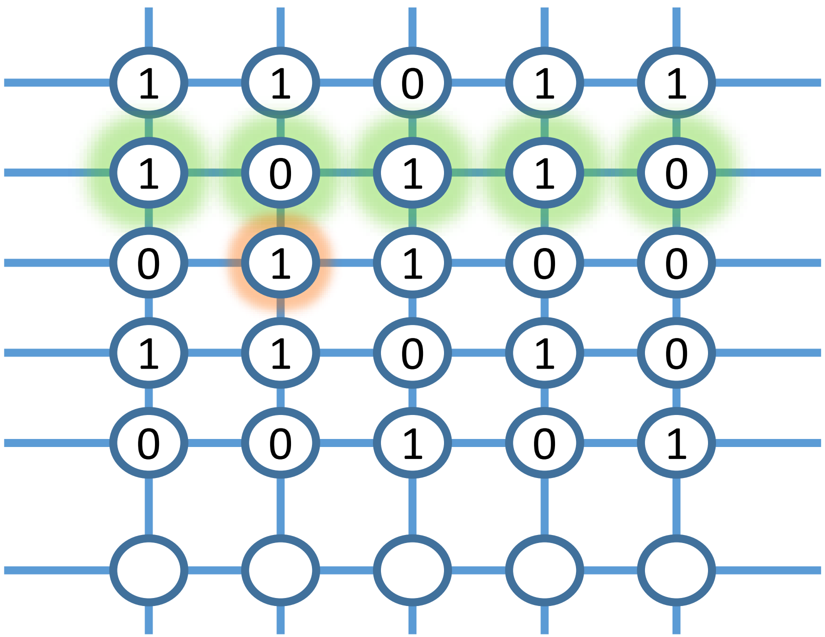

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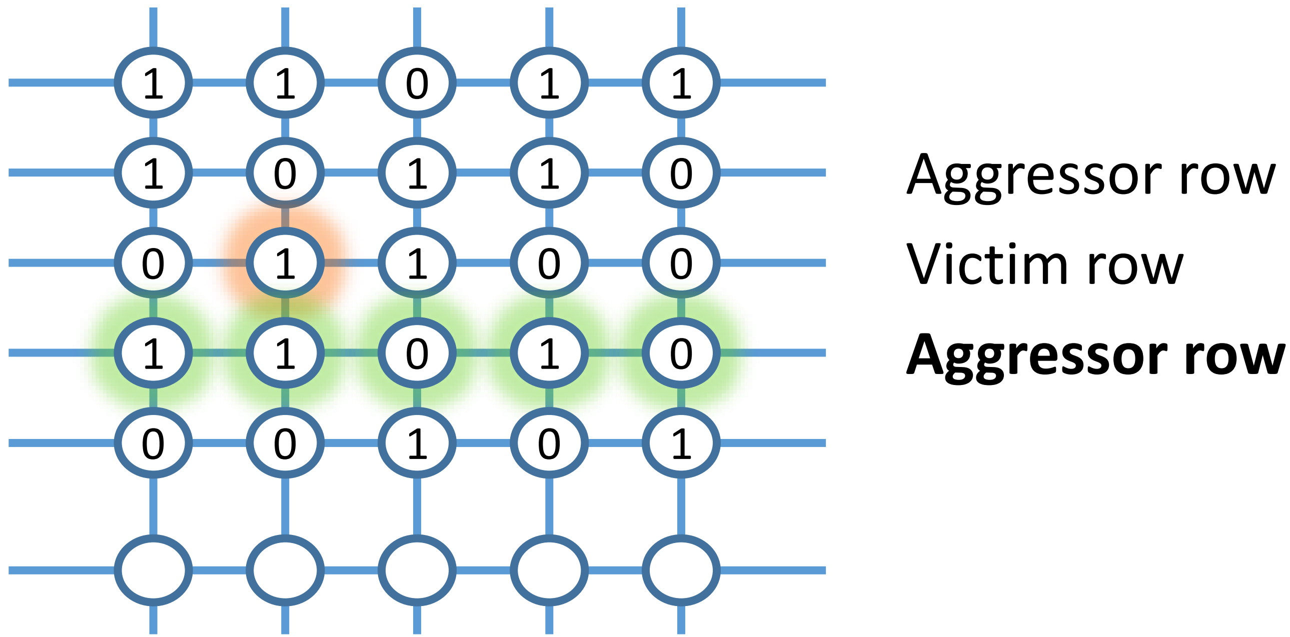

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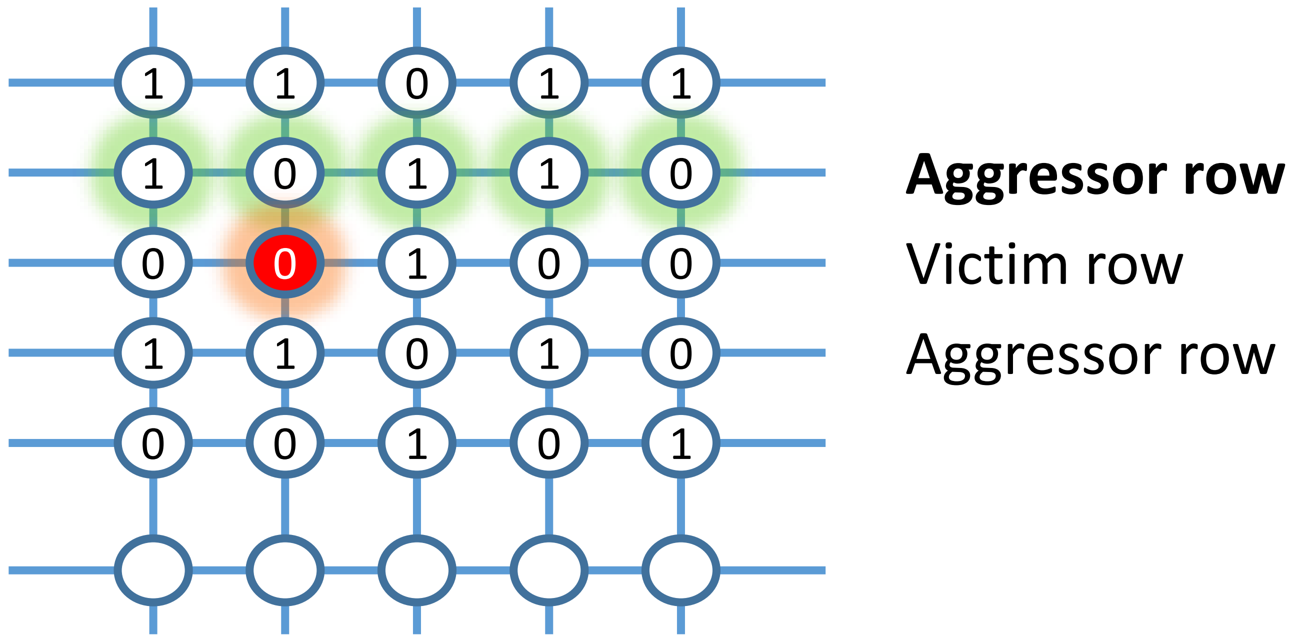

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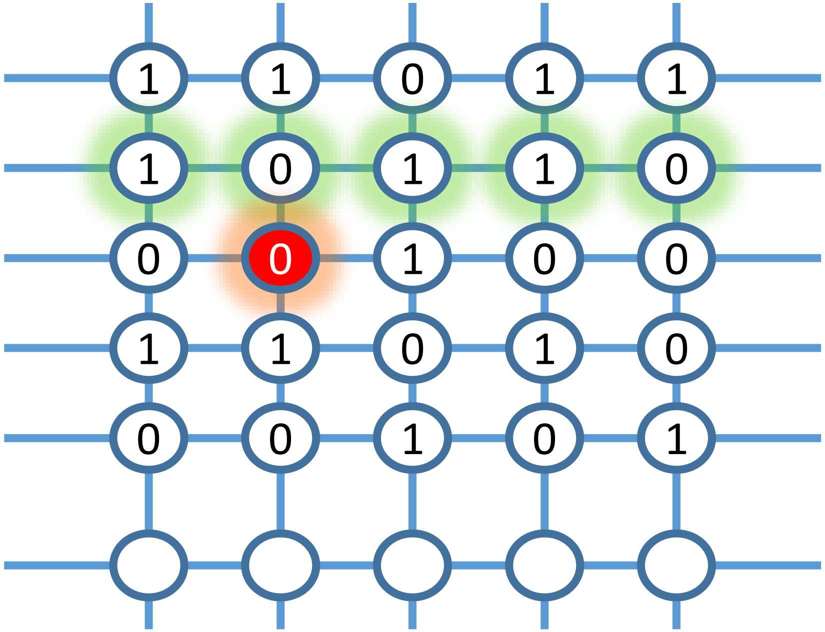

Aggressor row

Victim row

Aggressor row

- Not every bit may flip
- Once a bit flips, we can reproduce it

Overview

1. Memory Templating

   Scan memory for useful bit flips

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1. ## Memory Templating
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2. ## Land sensitive data
   Store a crucial data structure on a vulnerable page

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1. **Memory Templating**
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2. **Land sensitive data**
   Store a crucial data structure on a vulnerable page
3. **Reproduce the bit flip**
   Modify the data structure and get root acces

Overview

1. Memory Templating

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Templating

Uncached memory access

- `clflush`
- cache eviction
- non-temporal access instructions

Determining the physical addresses aggressor/victim rows

- `/proc/self/pagemap`
- 2MB huge pages (relative)

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But does it work on ARM?

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But does it work on ARM?

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None of them

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But does it work on ARM?

(and we tried)

Templating on ARM

DMA

Direct Memory Access

Android's DMA memory allocator provides everything we need:

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- Physically contiguous memory

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DMA ALLOCATED CHUNK

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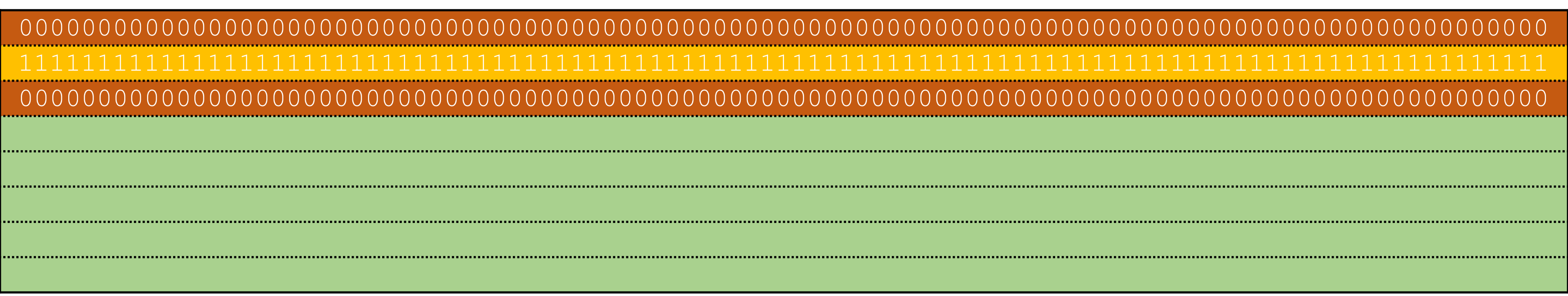

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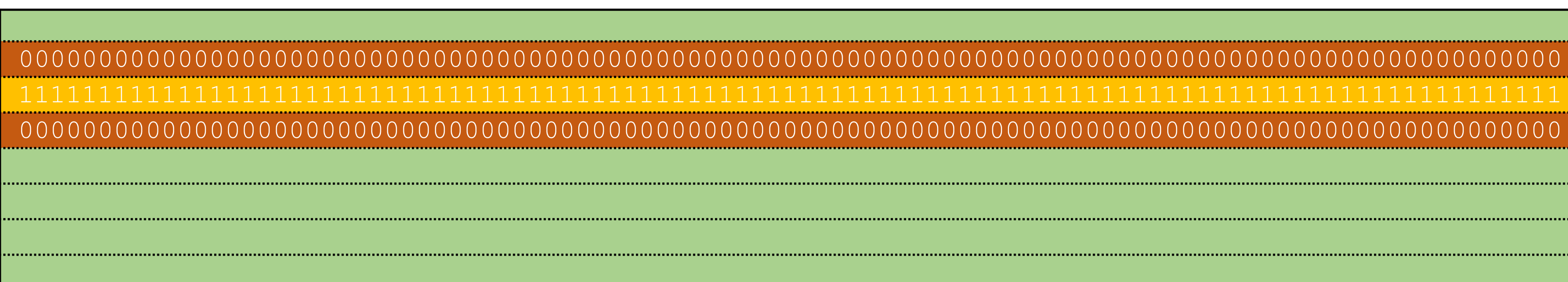

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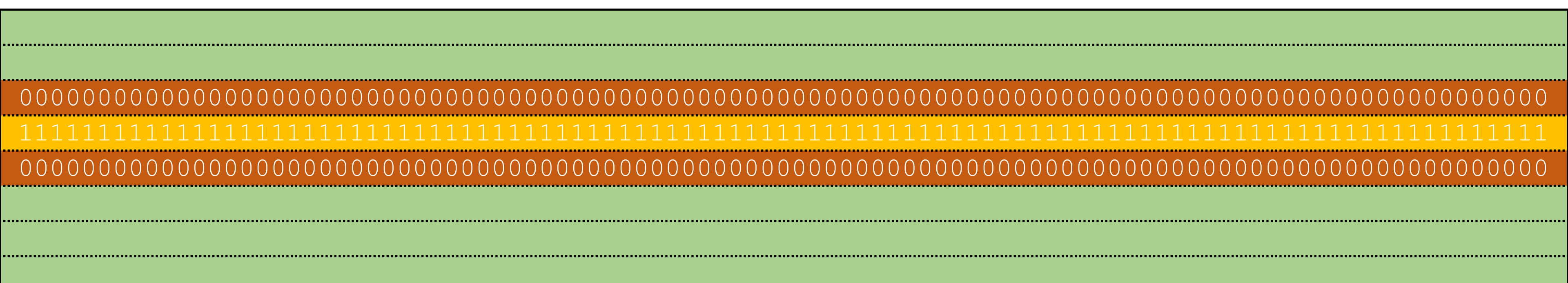

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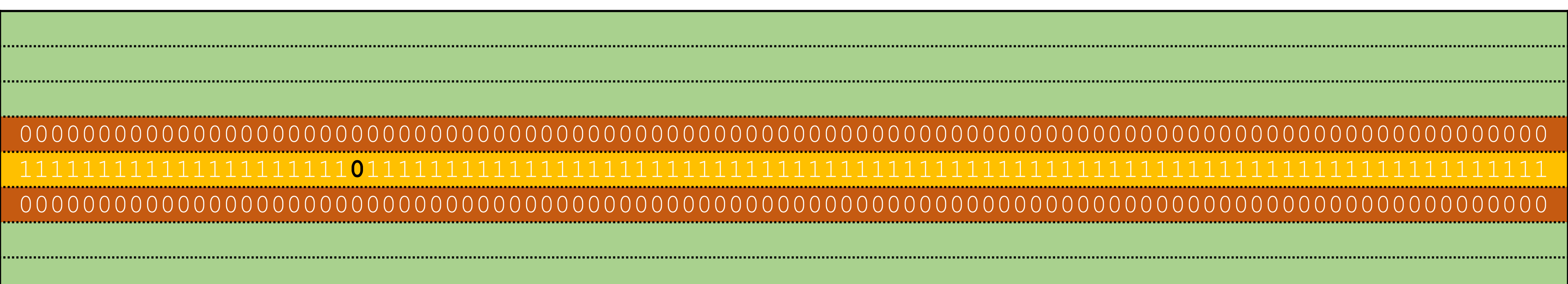

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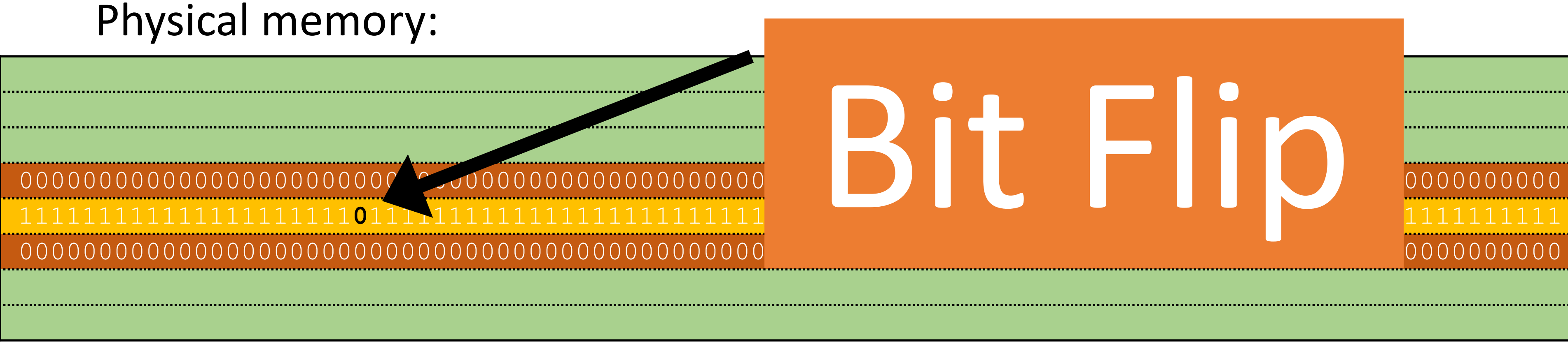

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   Scan memory for useful bit flips
2. Land a Page Table
   Store a page table on a vulnerable page

But why?

Page Tables

Mapping virtual addresses to physical addresses

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Mapping virtual addresses to physical addresses

Example lookup for input virtual address `0xb6a5717f`

1 0 1 1	0 1 1 0	1 0 1 0	0 1 0 1	0 1 1 1	0 0 0 1	0 1 1 1	1 1 1 1

Page Tables

Mapping virtual addresses to physical addresses

Example lookup for input virtual address `0xb6a5717f`

1 0 1 1	**0 1 1 0**	**1 0 1 0**	0 1 0 1	0 1 1 1	0 0 0 1	0 1 1 1	1 1 1 1

- Highest 12 bits: *level 1 table index* (*Translation Table Base Register*)

Page Tables

Mapping virtual addresses to physical addresses

Example lookup for input virtual address `0xb6a5717f`

1 0 1 1	0 1 1 0	1 0 1 0	**0 1 0 1**	**0 1 1 1**	0 0 0 1	0 1 1 1	1 1 1 1

- Highest 12 bits: *level 1 table index* (*Translation Table Base Register*)
- Middle 8 bits: *level 2 table index*

Page Tables

Mapping virtual addresses to physical addresses

Example lookup for input virtual address `0xb6a5717f`

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- Lowest 12 bits: *offset in page*

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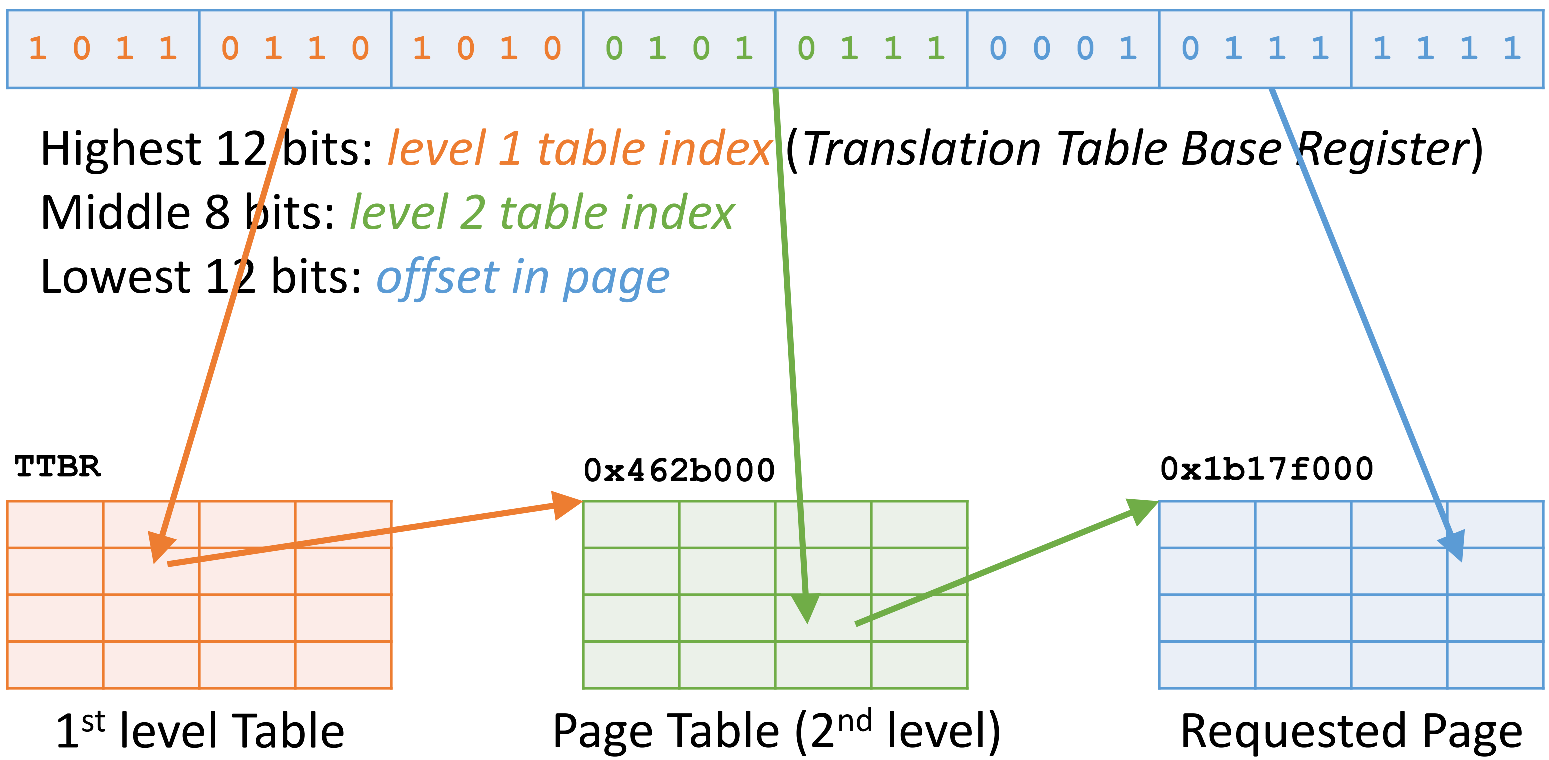

Page Table Entries

Entry in the (2nd level) Page Table

0 0 0 1	1 0 1 1	0 0 0 1	0 1 1 1	1 1 1 1	x x x x	x x x x	x x x x

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0 0 0 1	1 0 1 1	0 0 0 1	0 1 1 1	1 1 1 1	x x x x	x x x x	x x x x

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Page Table Entries

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0 0 0 1	1 0 1 1	0 0 0 1	0 1 1 1	1 1 1 1	x x x x	x x x x	x x x x

- 12 bits of *properties*
- 20 bits for the *page base address*

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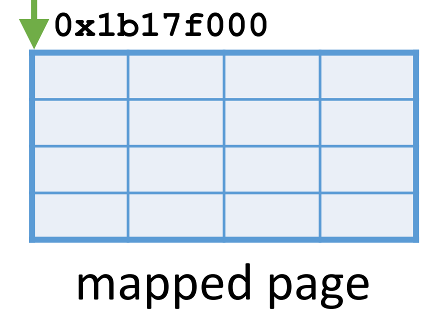
0 0 0 1	1 0 1 1	0 0 0 1	0 1 1 1	1 1 1 1	x x x x	x x x x	x x x x

`0x1b17f << 12`

- 12 bits of *properties*
- 20 bits for the *page base address*



What if we flip a bit in the entry?

Page Table Entries

Entry in the (2^{nd} level) Page Table

0 0 0 1	1 0 1 1	0 0 0 1	0 1 1 1	1 1 1 1	x x x x	x x x x	x x x x

`0x1b17f << 12`

- 12 bits of *properties*
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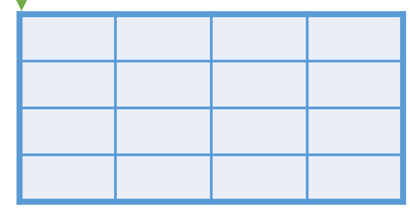
`0x1b17f000`



mapped page

0 0 0 1	1 0 1 1	0 0 0 1	0 1 1 1	1 1 1 0	x x x x	x x x x	x x x x

Rowhammer Attacks on
Page Table Entries

Entry in the (2^{nd} level) Page Table

0 0 0 1	1 0 1 1	0 0 0 1	0 1 1 1	1 1 1 1	x x x x	x x x x	x x x x

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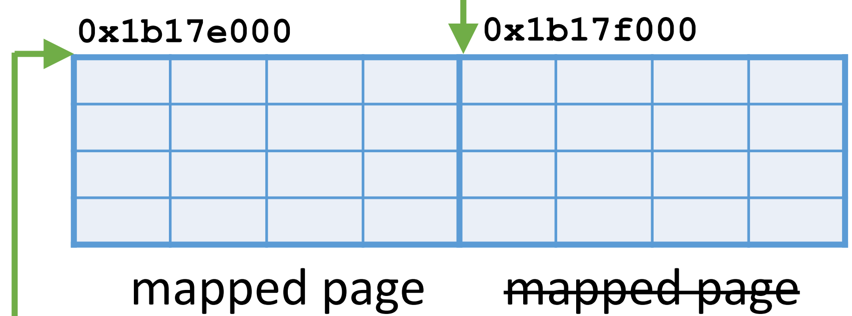

`0x1b17e << 12`

0 0 0 1	1 0 1 1	0 0 0 1	0 1 1 1	1 1 1 0	x x x x	x x x x	x x x x

Rowhammer Attacks on
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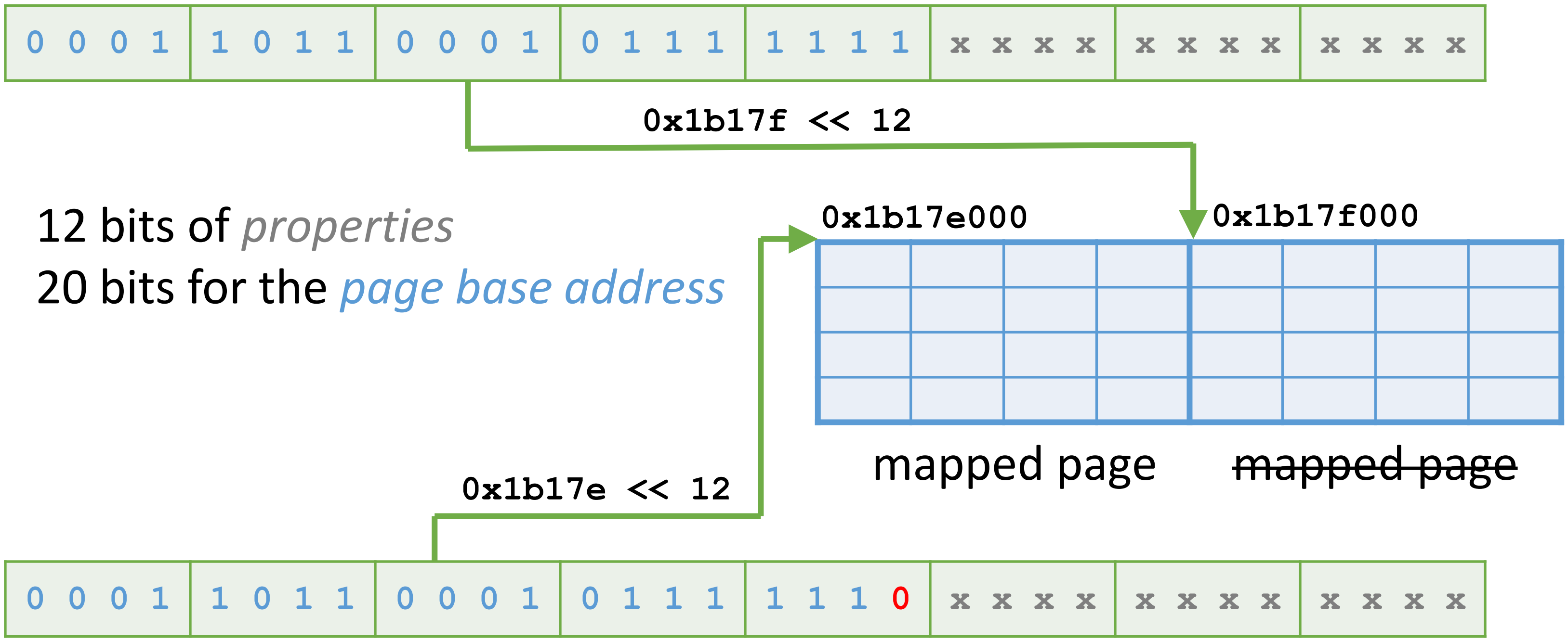

A 1-to-0 flip moves the mapping ‘to the left’

- Flip offset 0: –1 page
- Flip offset 1: –2 pages
- Flip offset 2: –4 pages
- Flip offset *n*: -2^n pages

Page Table Entries

1. Map a page 4 pages ‘away’ from its page table

Deterministic Attacks on
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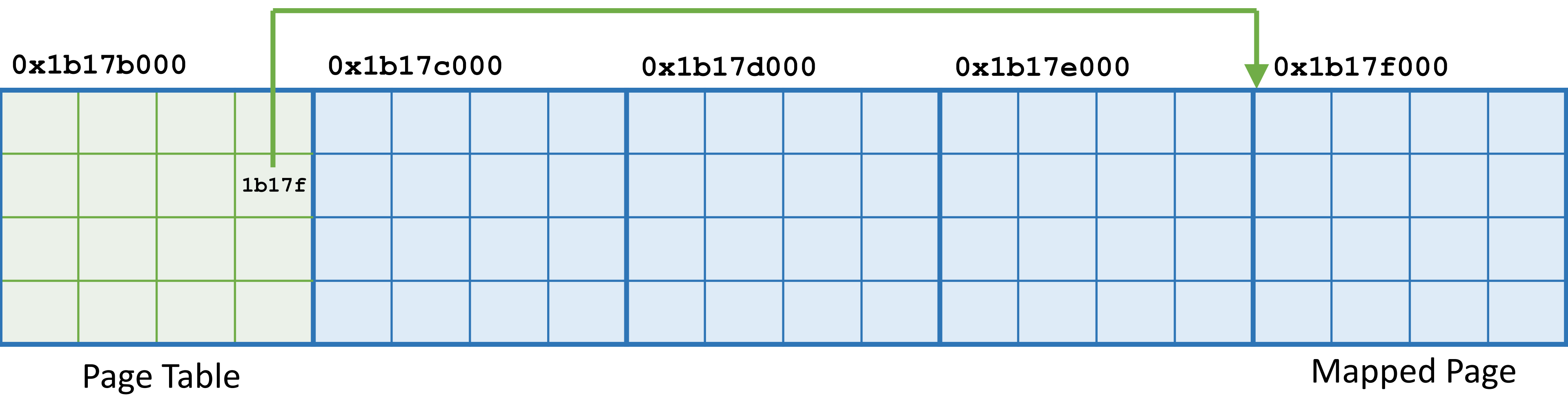

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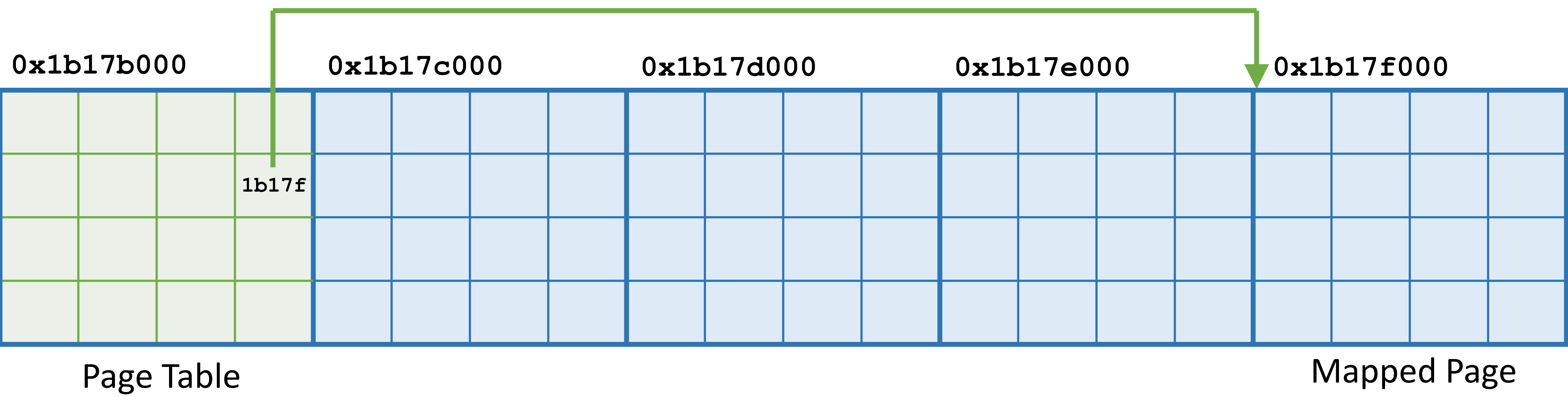


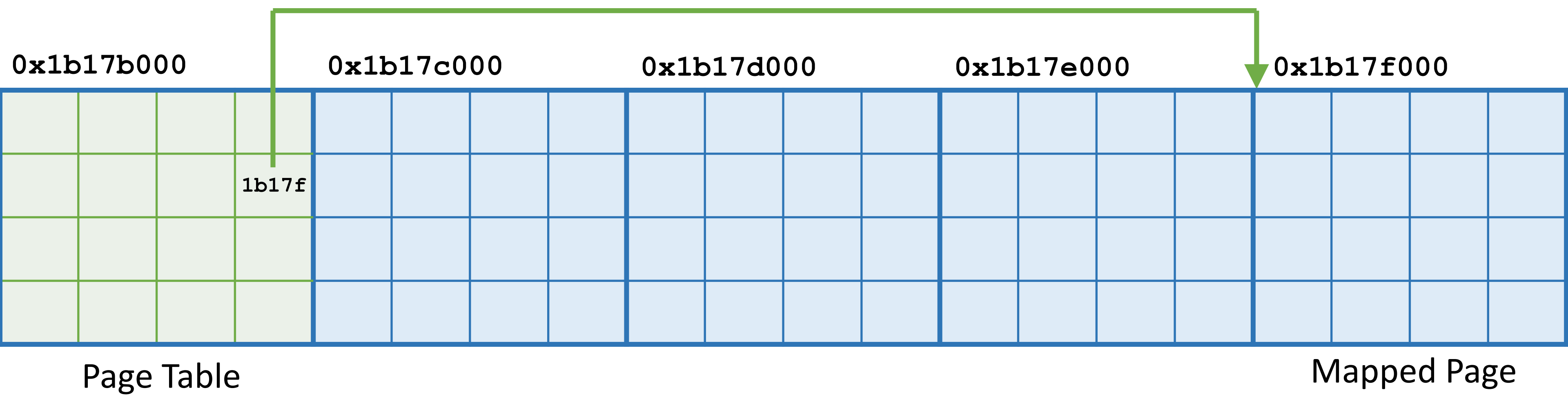
Virtual address `0xb6a57000` maps to Page Table Entry:

0 0 0 1	1 0 1 1	0 0 0 1	0 1 1 1	1 1 1 1	x x x x	x x x x	x x x x

which translates to physical page **`0x1b17f000`**

Deterministic Attacks on
Page Table Entries

1. Map a page 4 pages 'away' from its page table
2. Flip bit 2 in the page table entry



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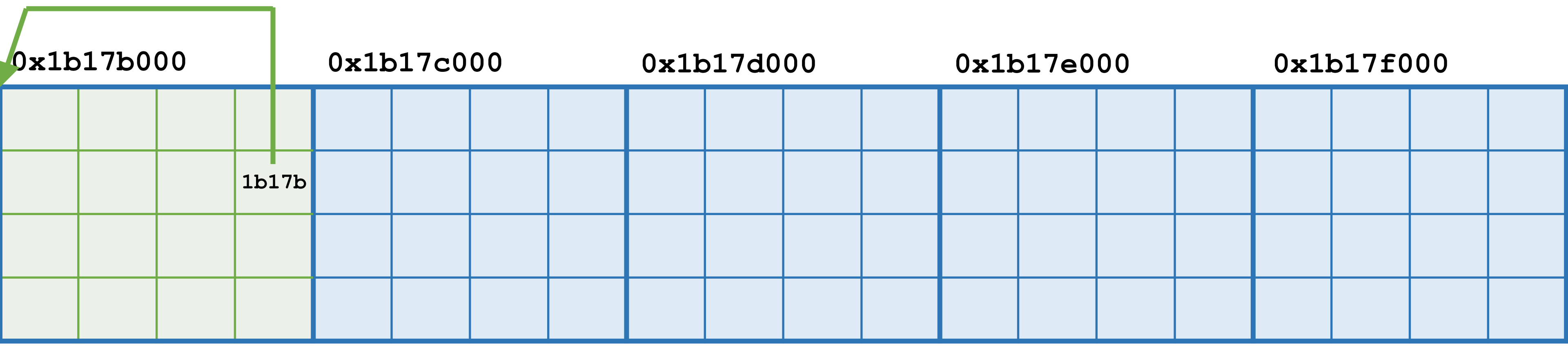


Mapped Page Table

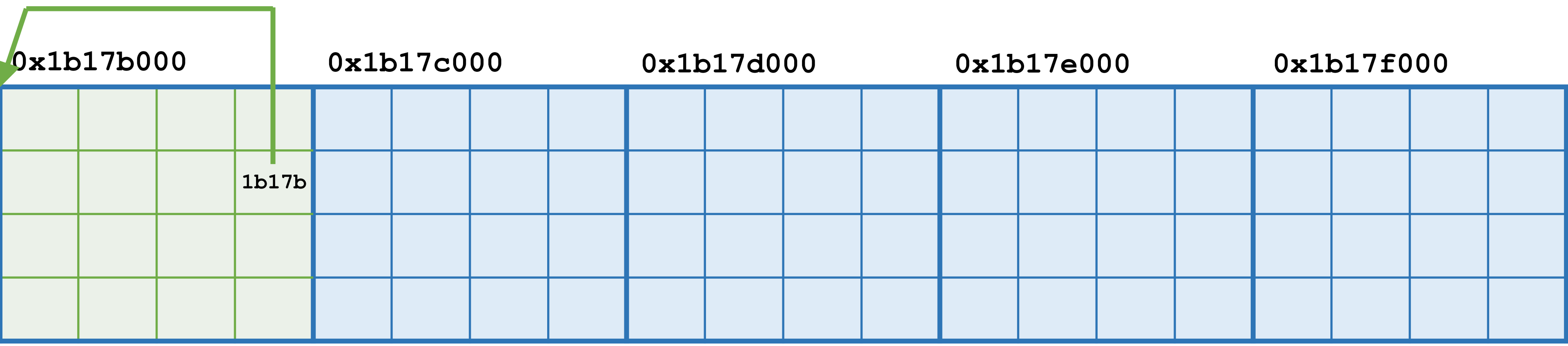
Virtual address `0xb6a57000` maps to Page Table Entry:

0 0 0 1	1 0 1 1	0 0 0 1	0 1 1 1	1 1 0 1	x x x x	x x x x	x x x x

which translates to physical page **0x1b17b000**

Deterministic Attacks on
Page Table Entries

1. Map a page 4 pages 'away' from its page table
2. Flip bit 2 in the page table entry
3. Write page table entries



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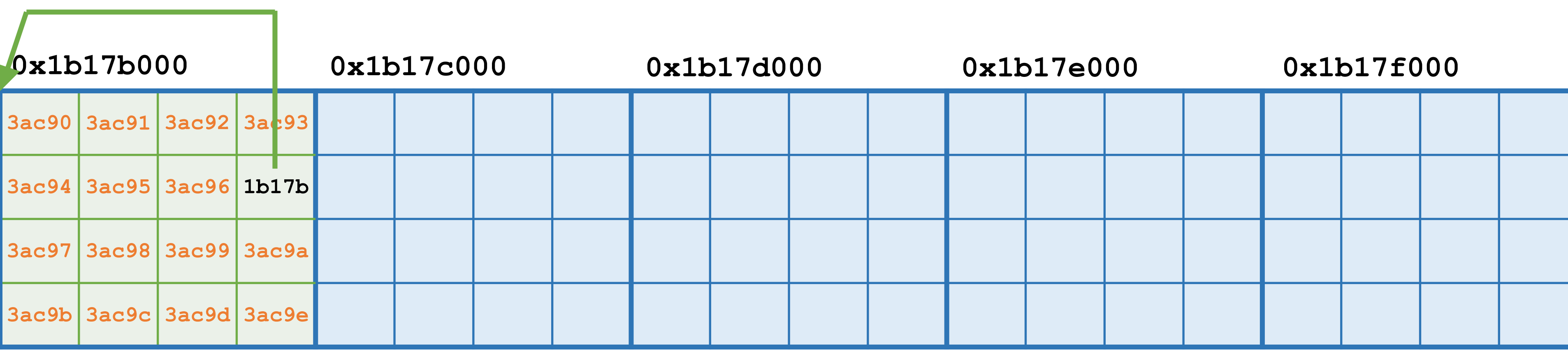

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Deterministic Attacks on
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1. Map a page 4 pages ‘away’ from its page table
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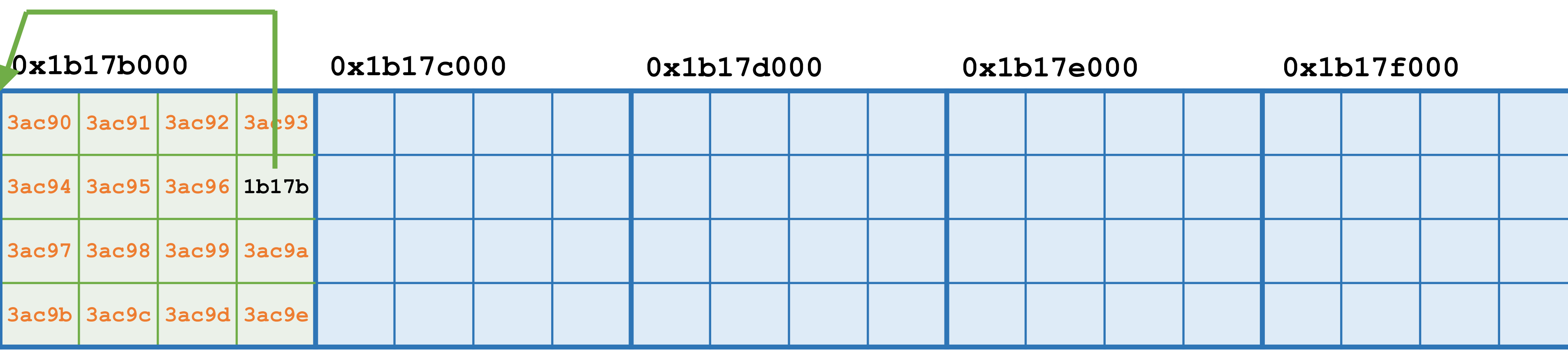
4. Read/write kernel memory



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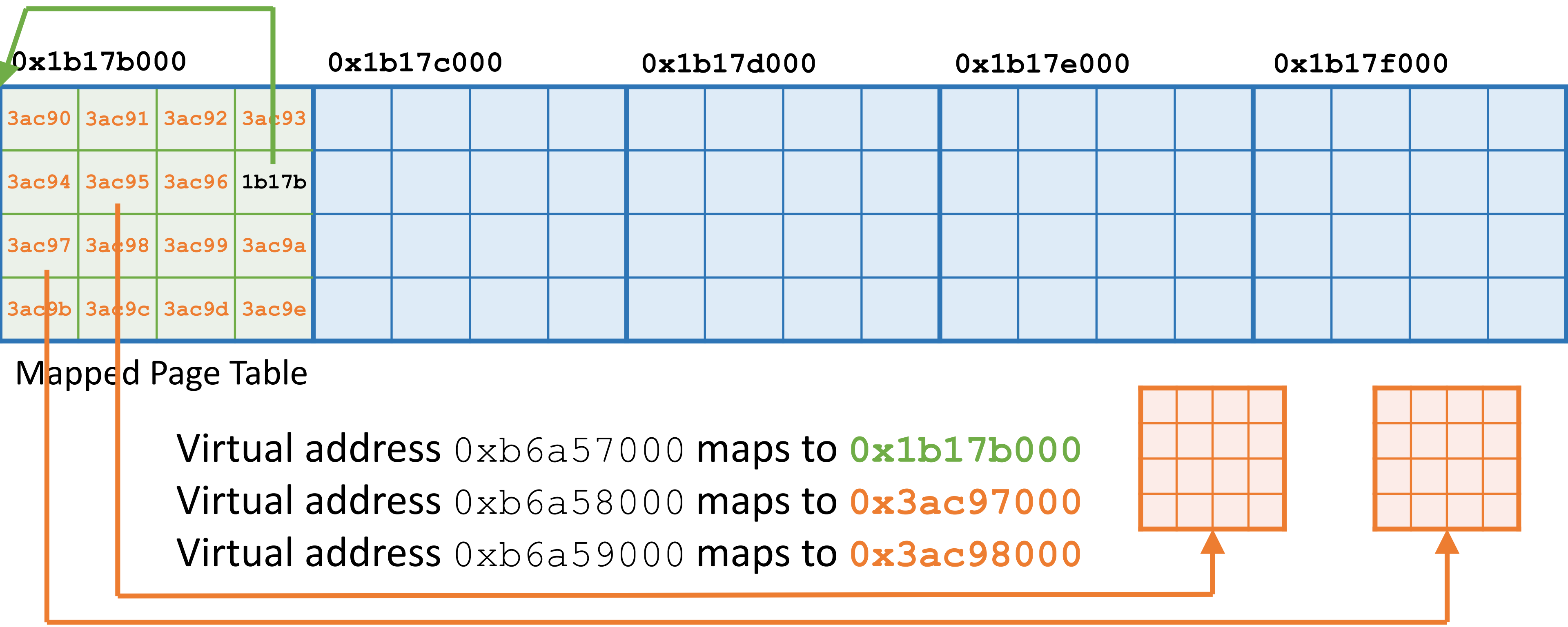

Virtual address `0xb6a57000` maps to **0x1b17b000**

Virtual address `0xb6a58000` maps to **0x3ac97000**

Virtual address `0xb6a59000` maps to **0x3ac98000**

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But how?

Landing a Page Table

- No access to `pagemap` (virtual – physical address mapping)
- No fancy memory management features (deduplication)

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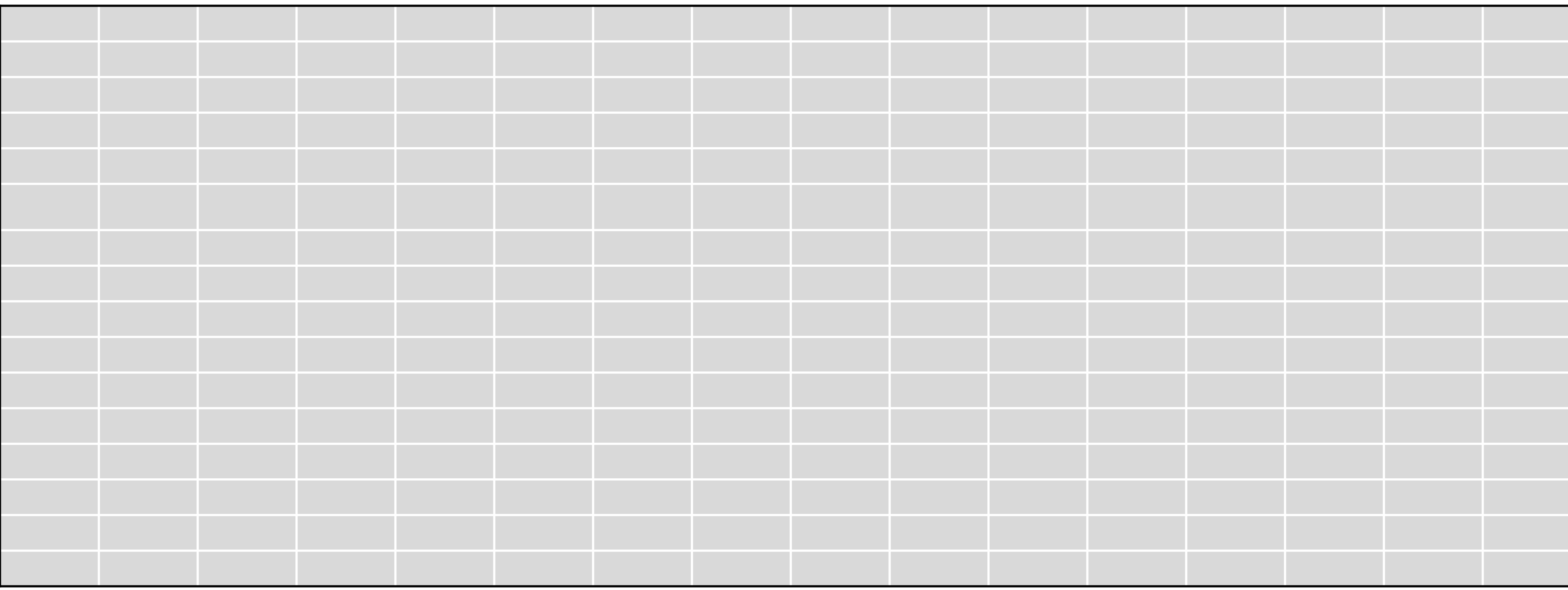

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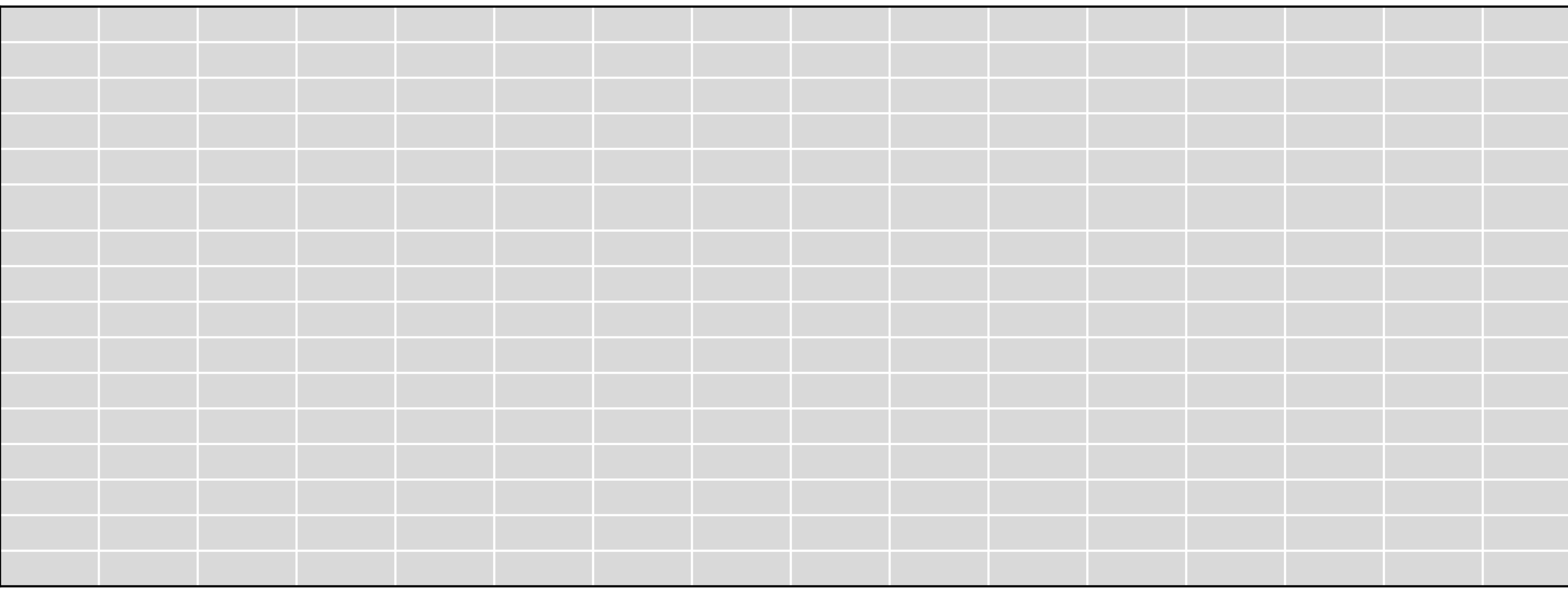

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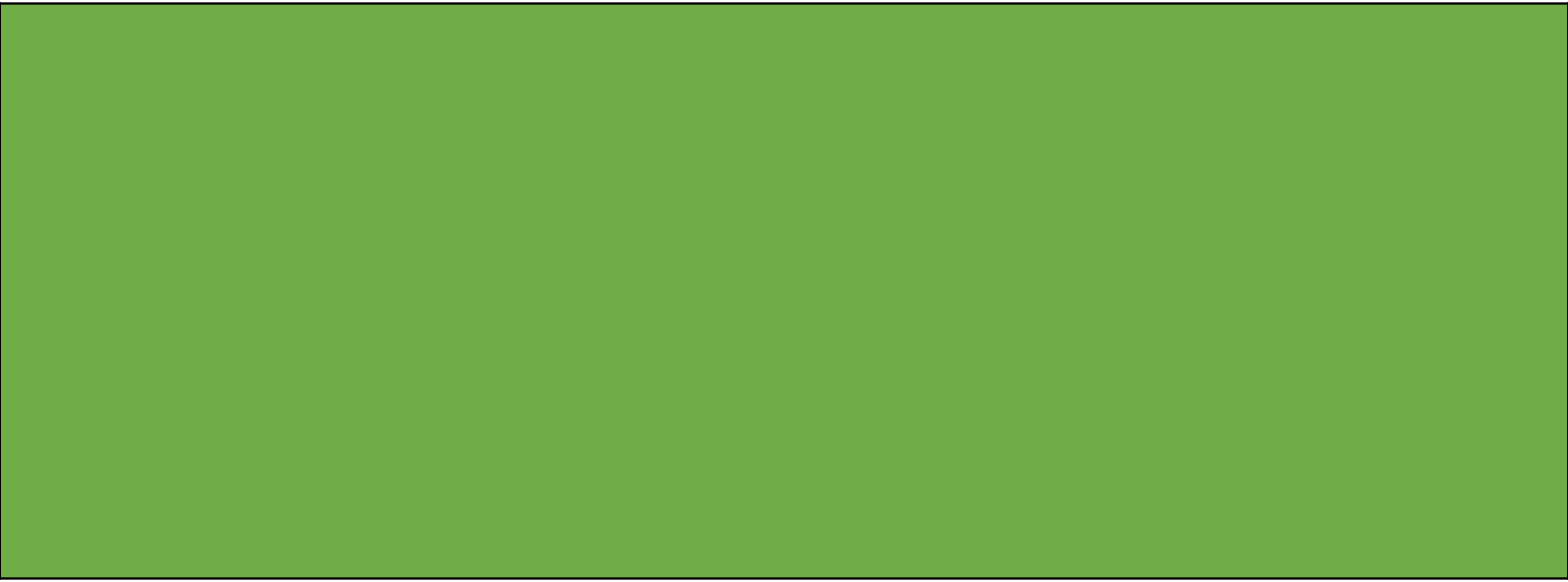

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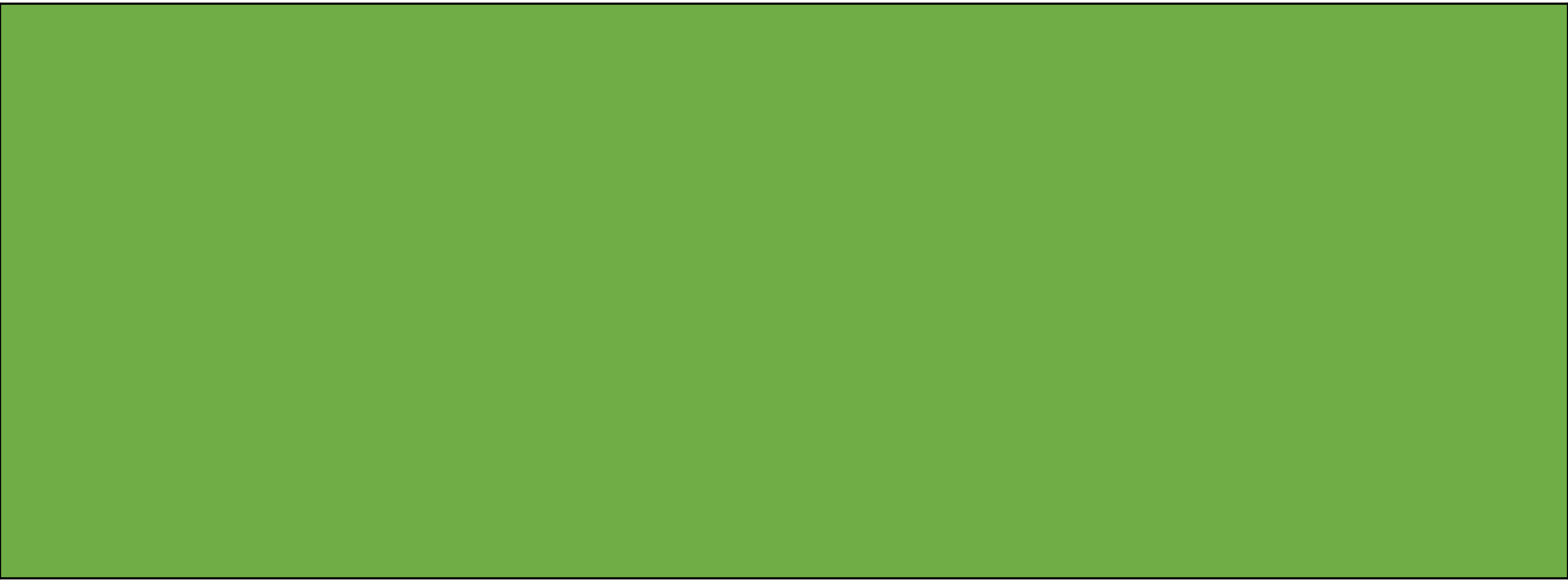

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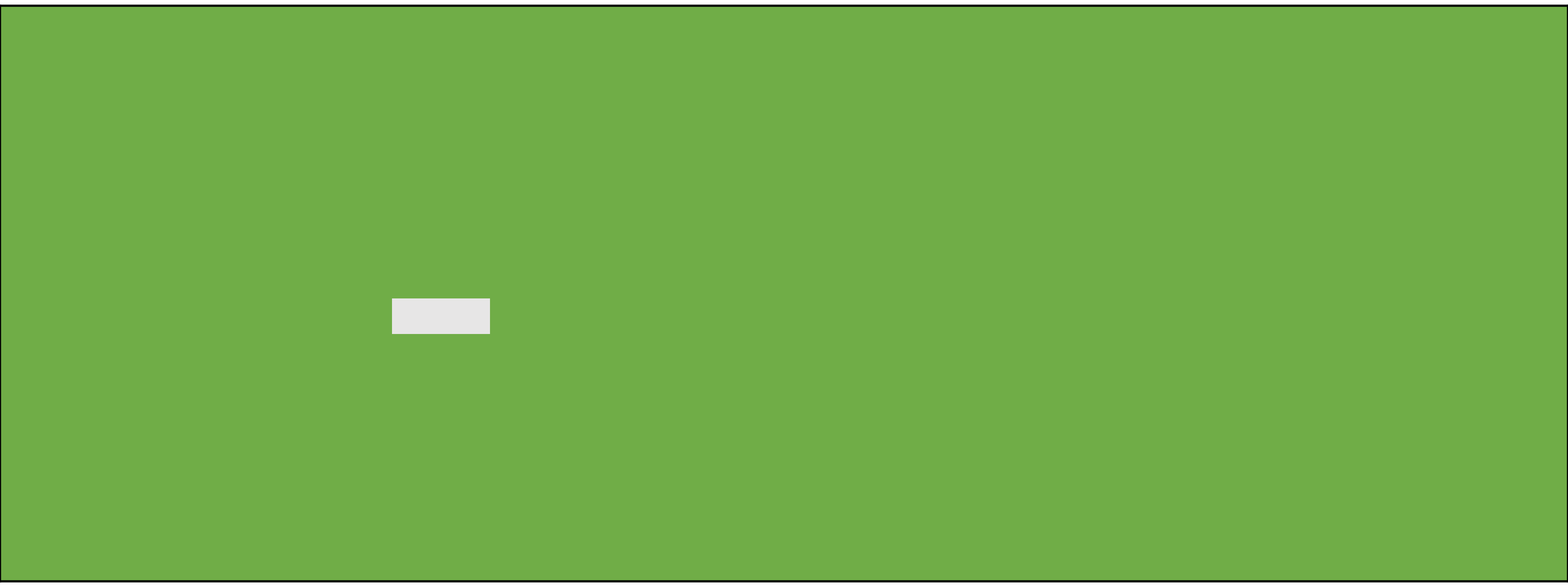

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Physical memory:

Trigger a Page Table Allocation

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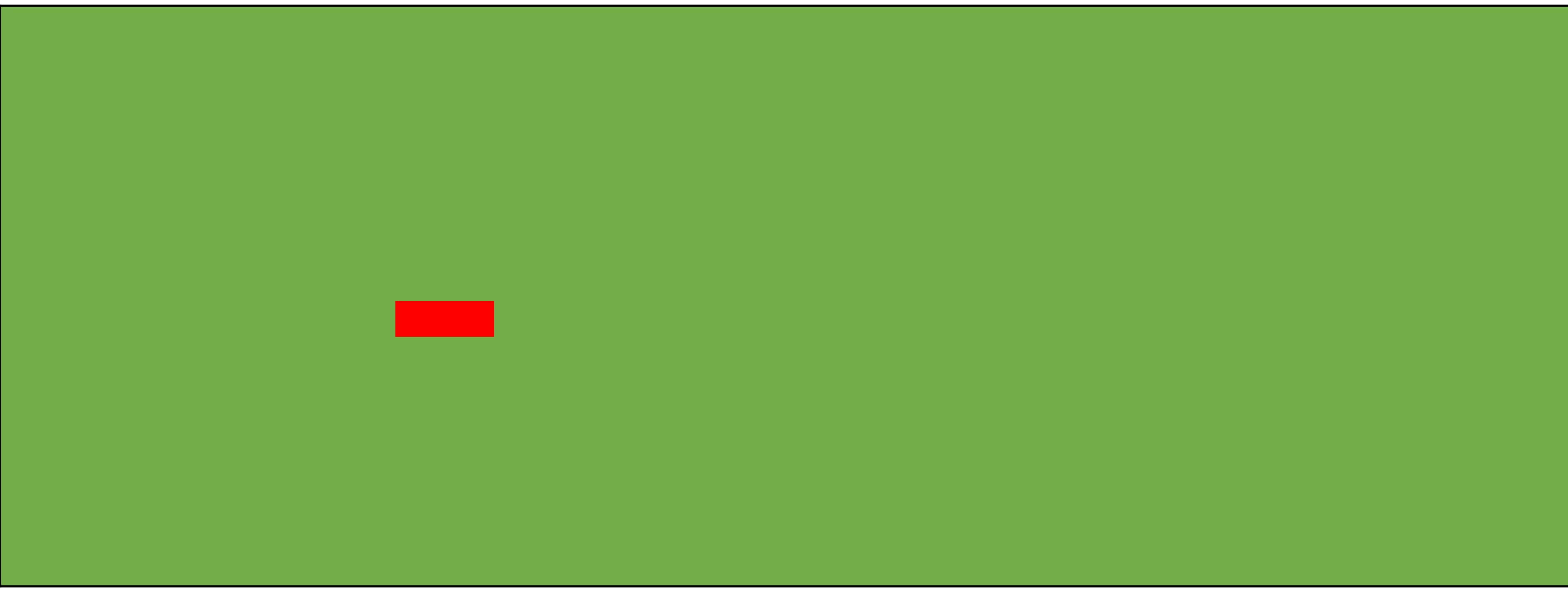
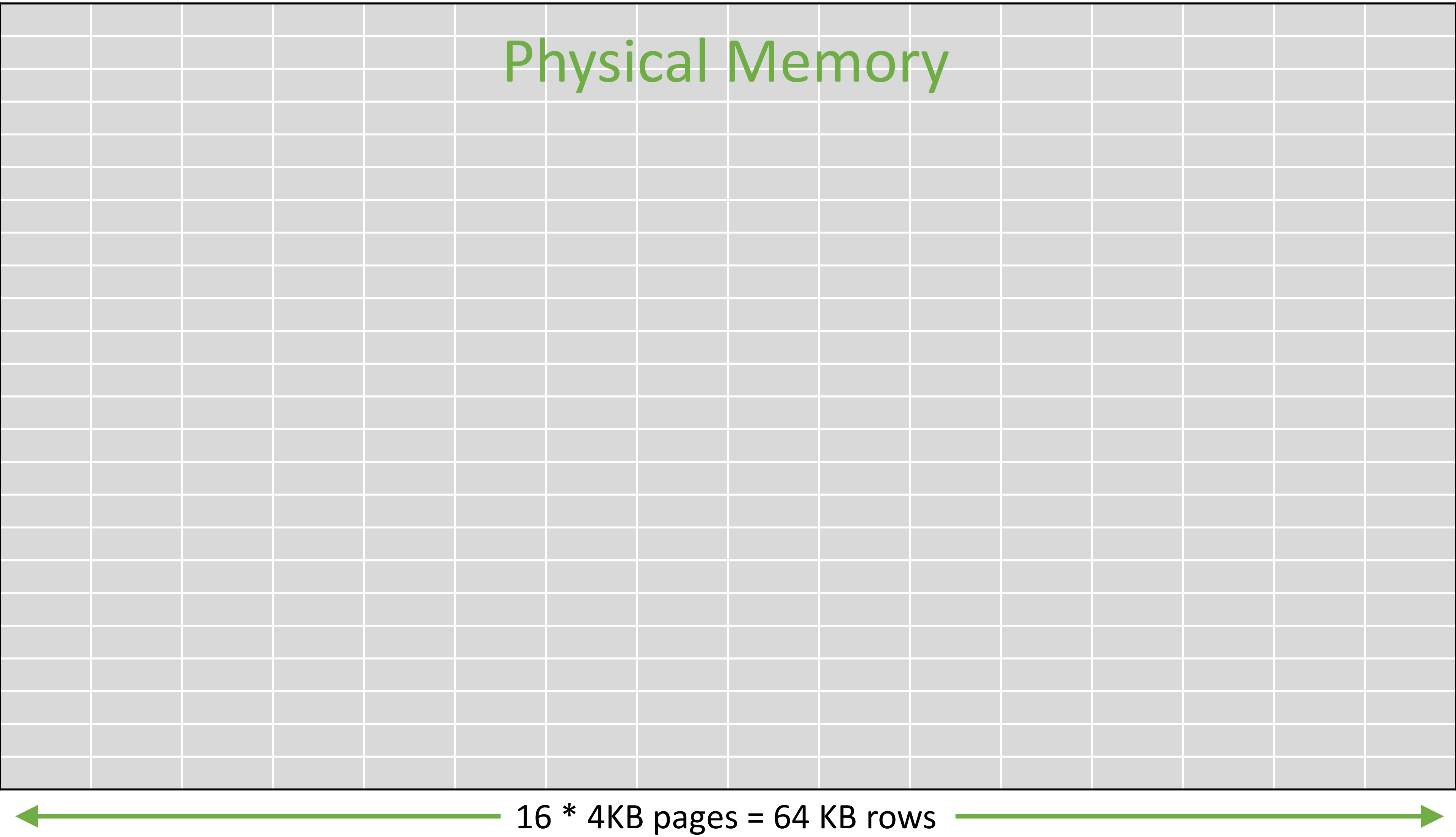


Trigger a Page Table Allocation

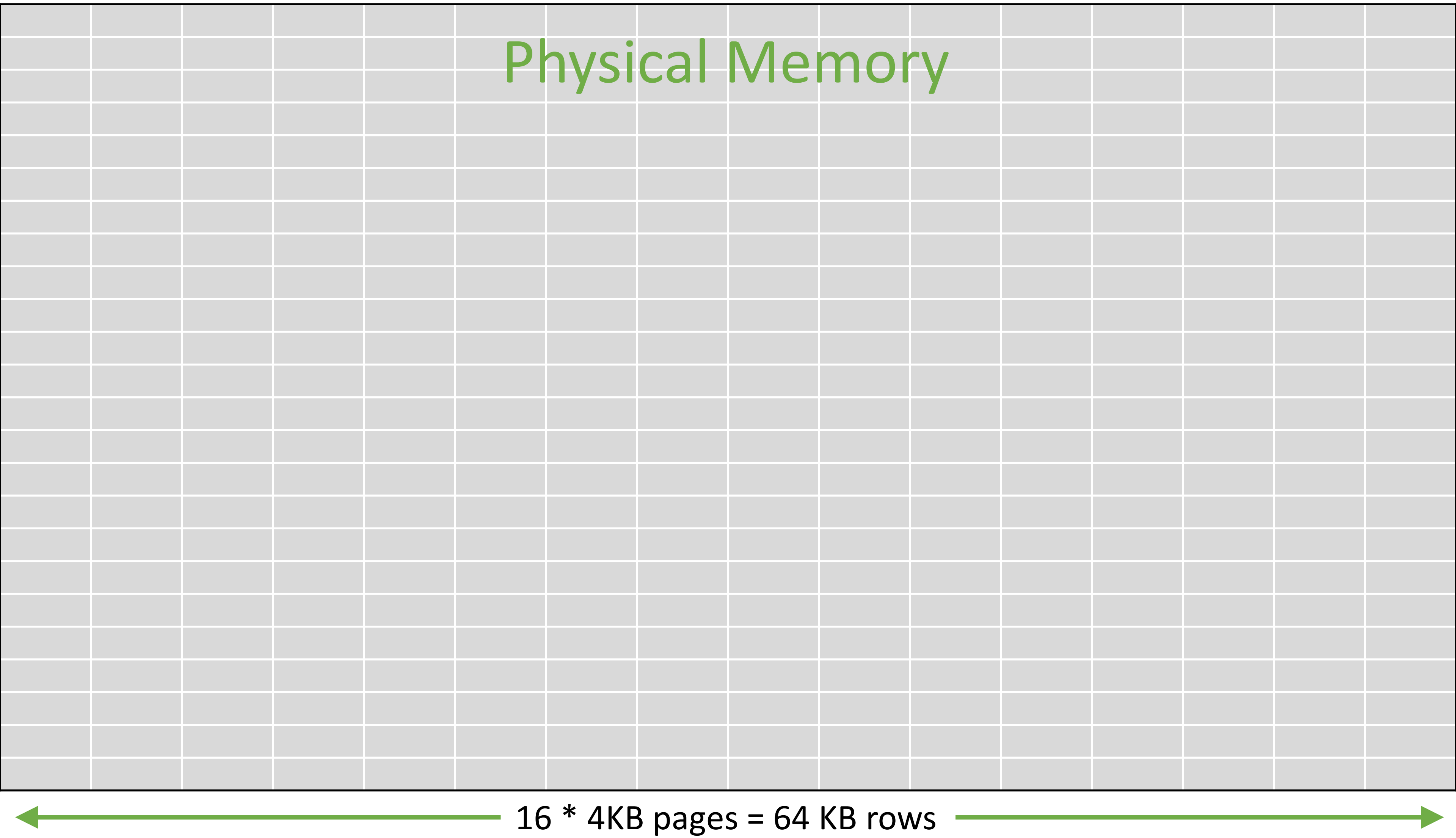
Phys Feng Shui

Exploit the predictable behavior of the Buddy Allocator



Phys Feng Shui – Buddy Allocator

Avoid fragmentation by keeping track of same-size memory chunks (*buddies*)



Phys Feng Shui – Buddy Allocator

Avoid fragmentation by keeping track of same-size memory chunks (*buddies)*

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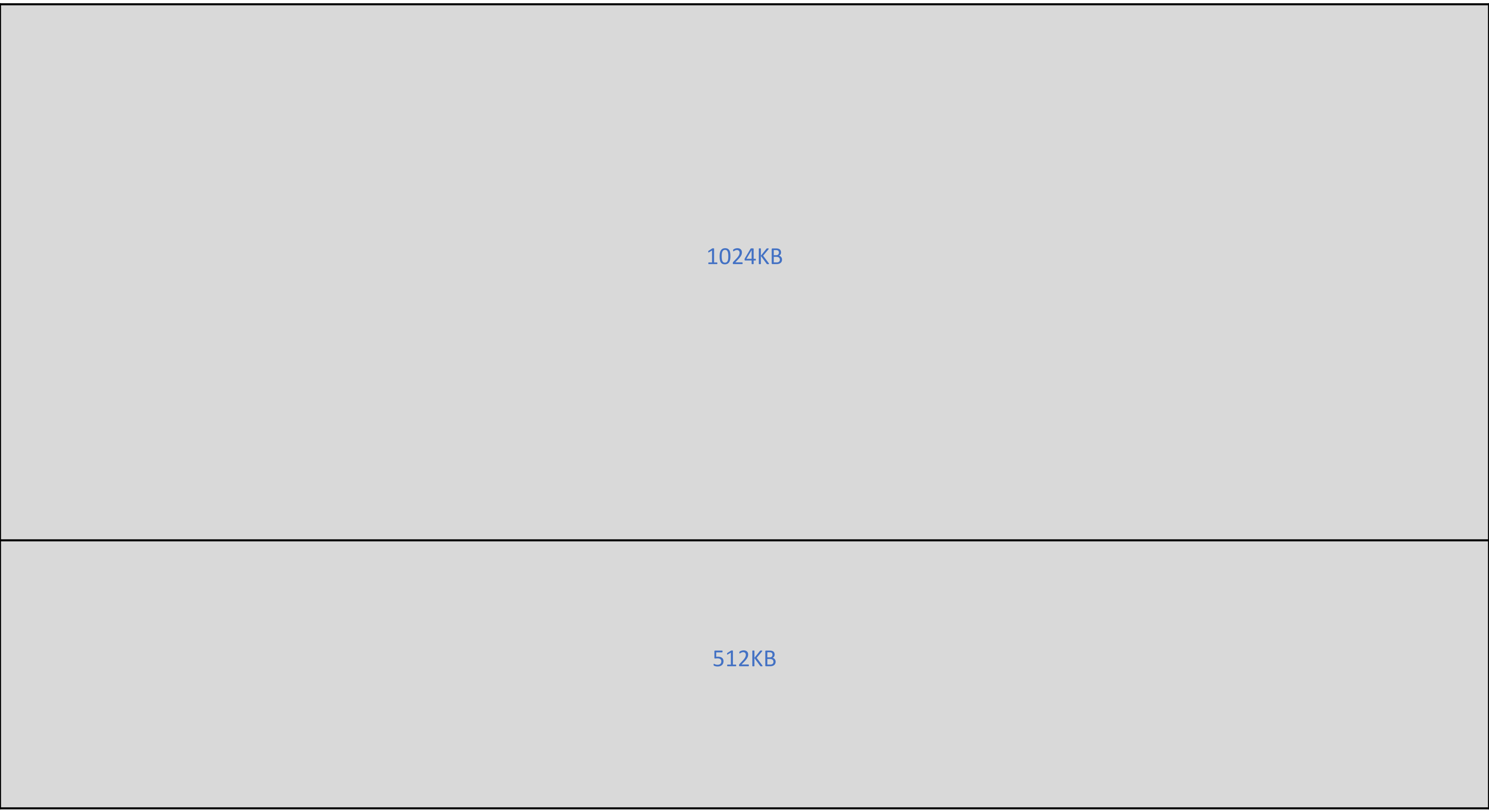

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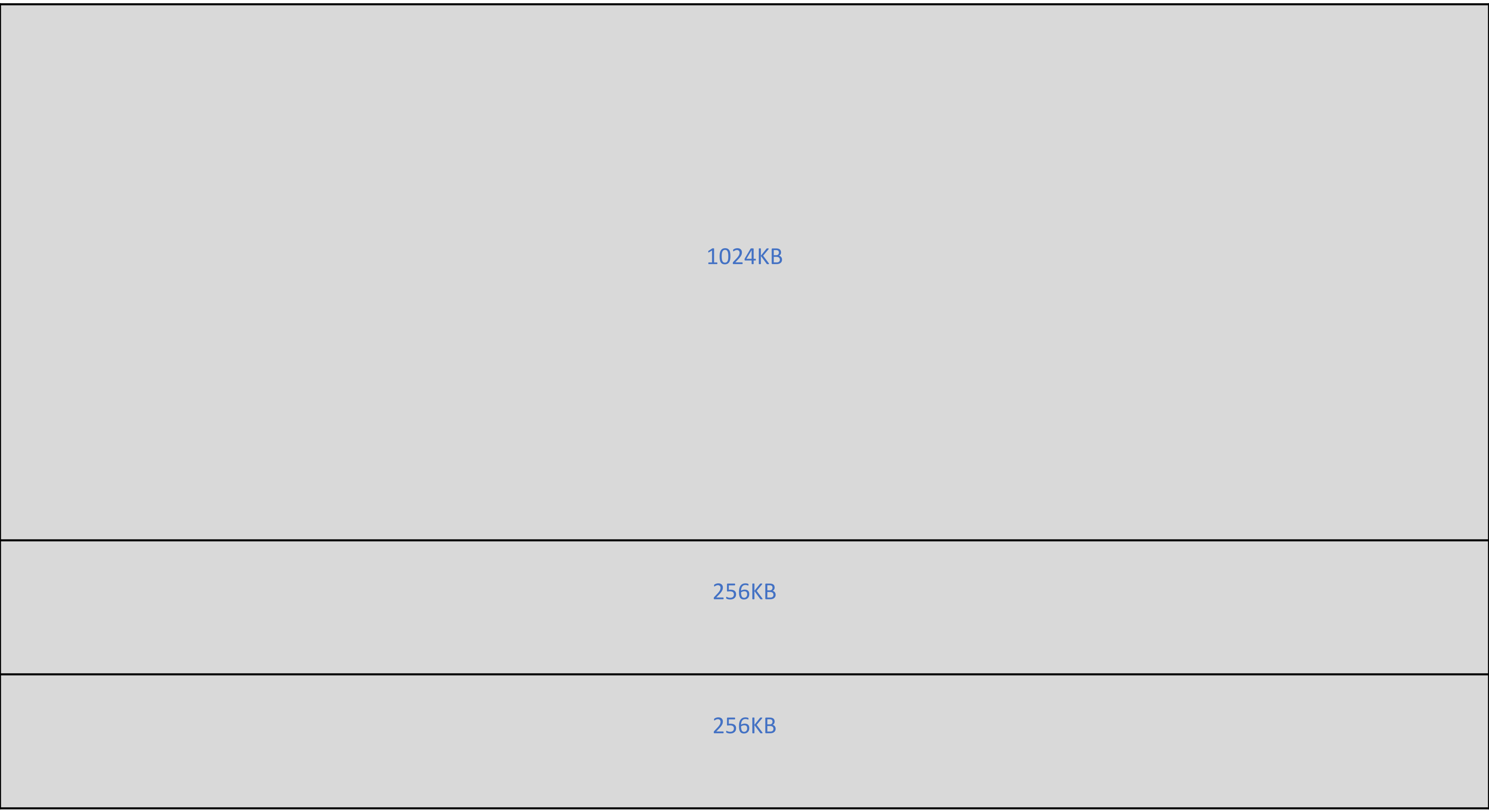

Phys Feng Shui – Buddy Allocator

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```
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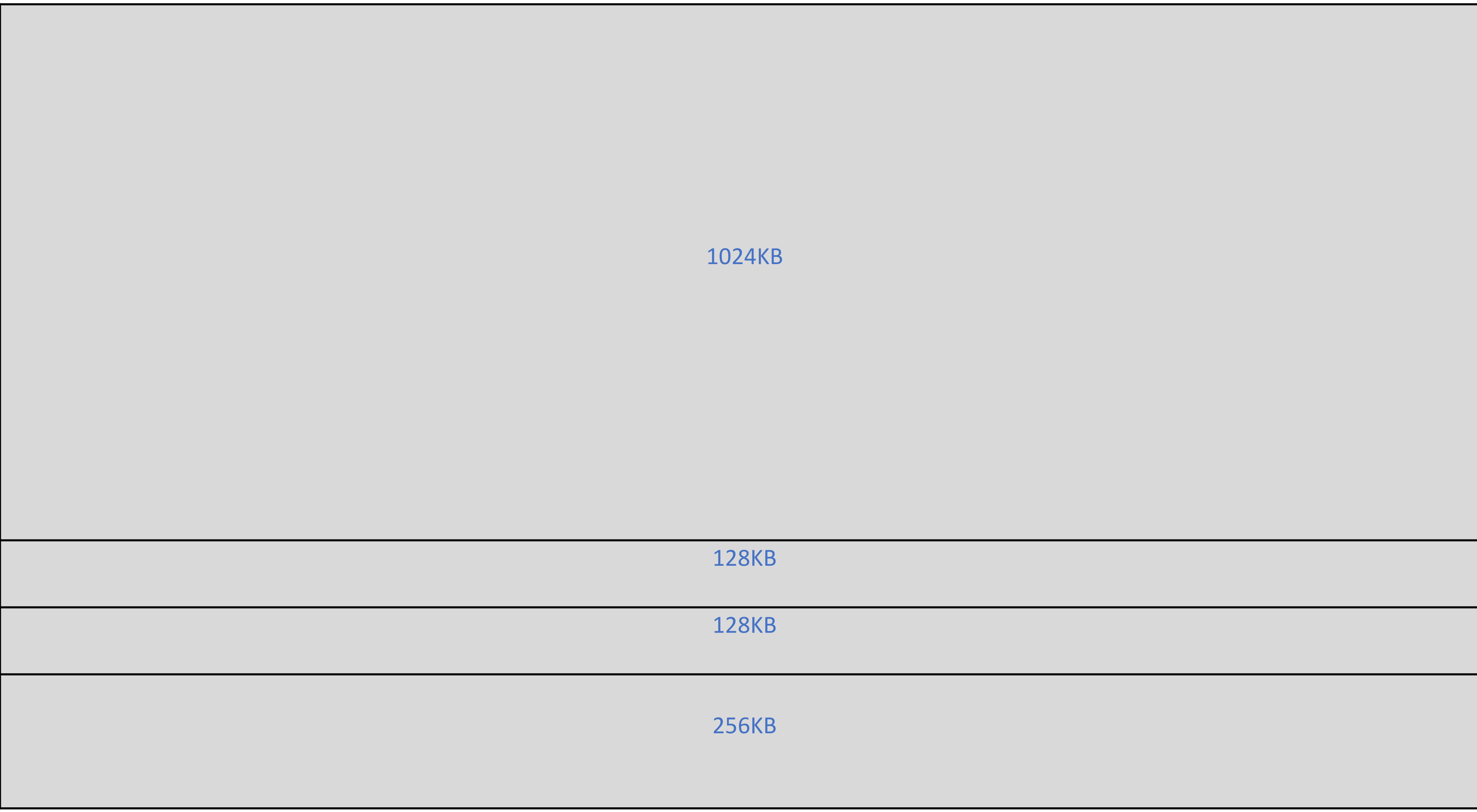

Phys Feng Shui – Buddy Allocator

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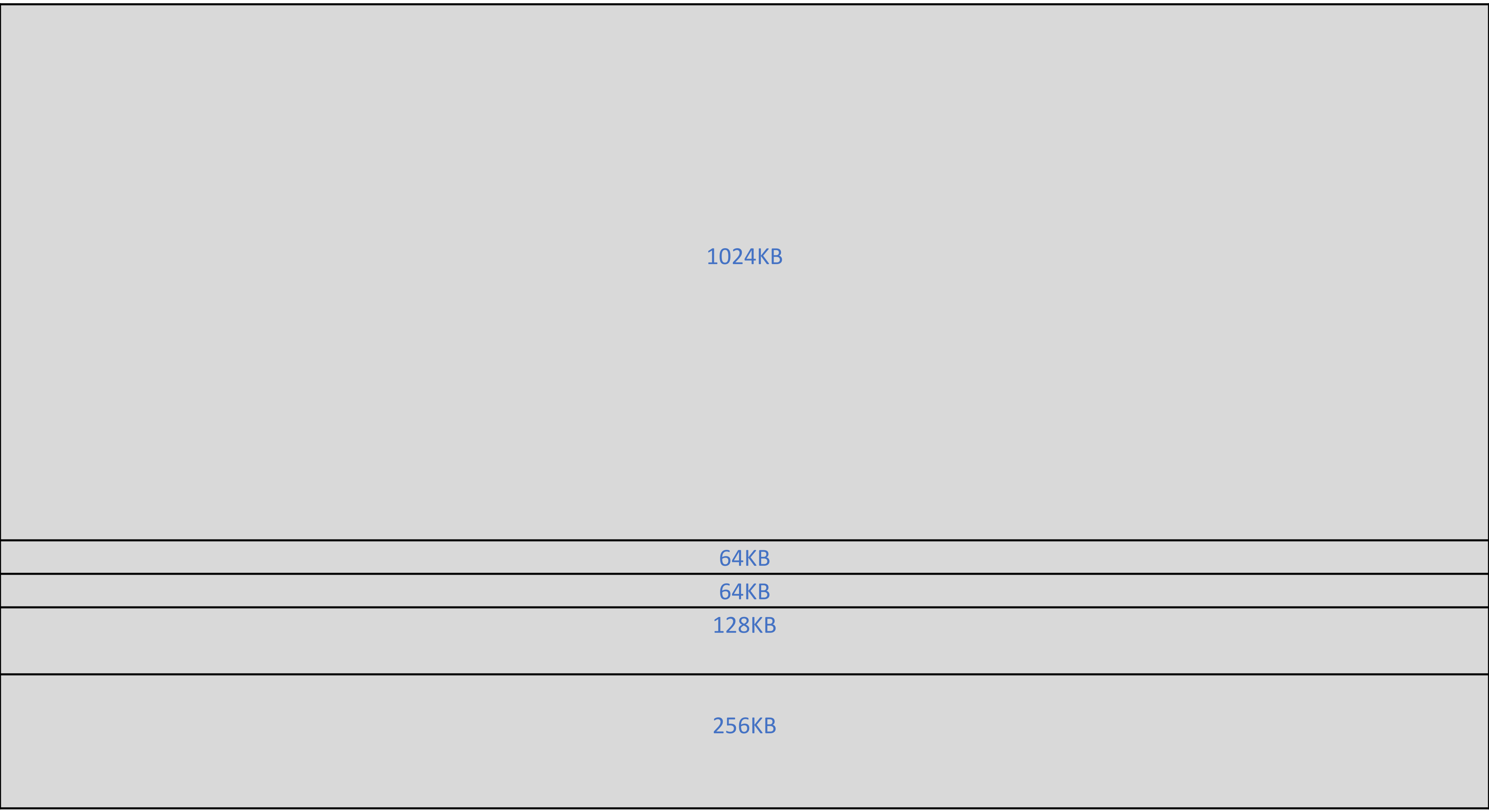

Phys Feng Shui – Buddy Allocator

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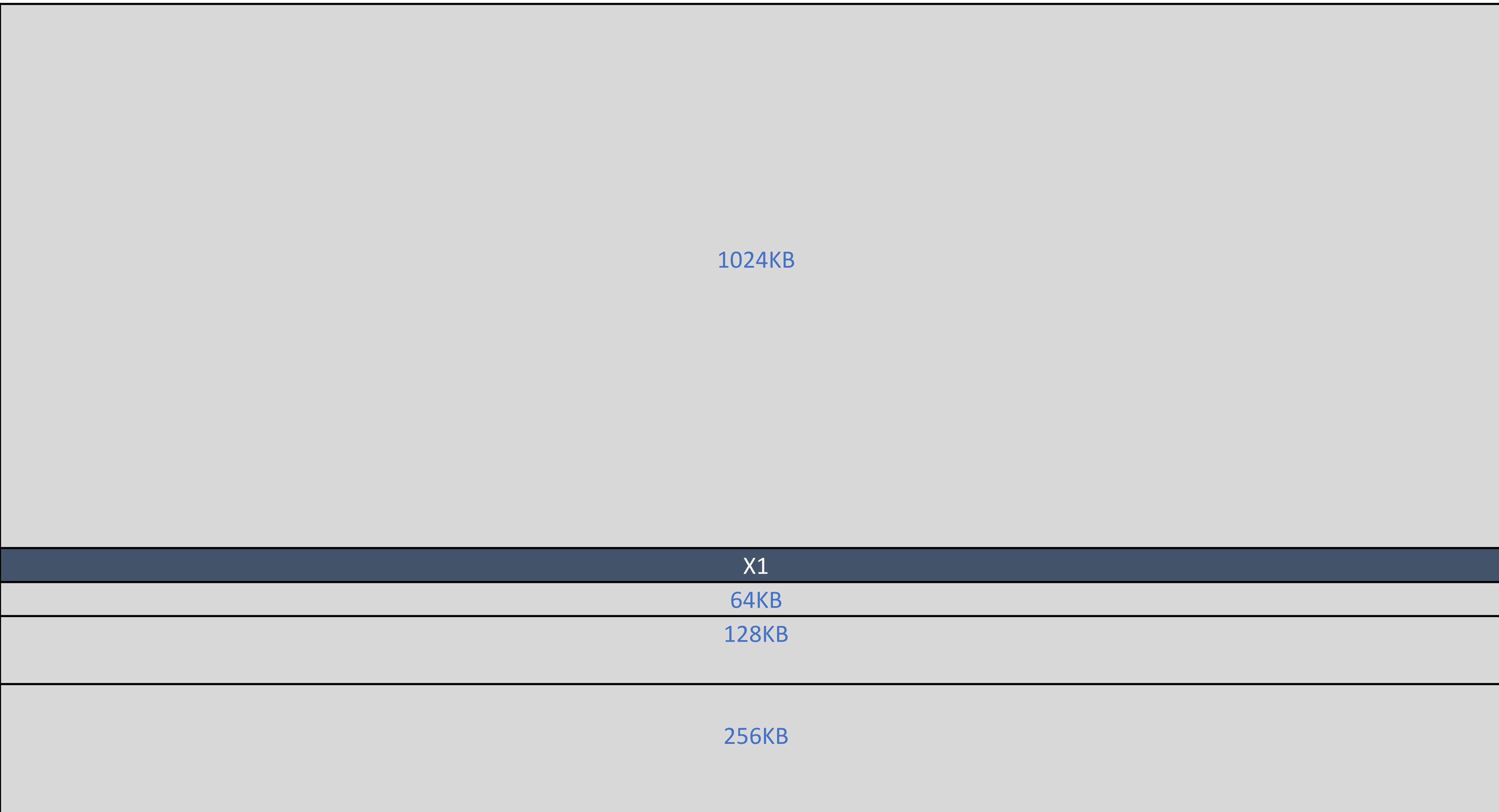
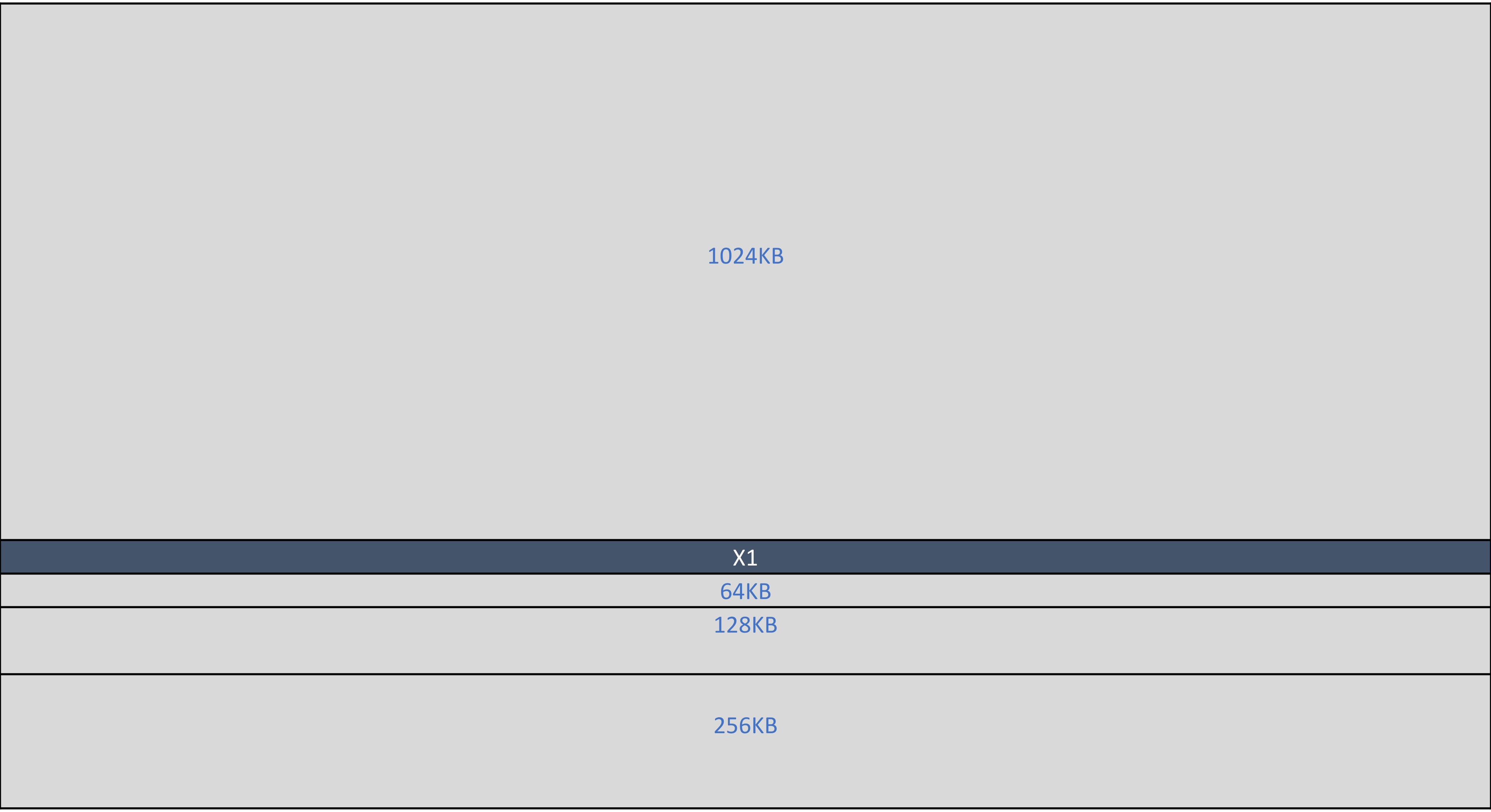


Phys Feng Shui – Buddy Allocator

Avoid fragmentation by keeping track of same-size memory chunks (*buddies)*

```
X2 = __get_free_pages(flags, 3); // get 2^3 = 8KB of memory
```



Phys Feng Shui – Buddy Allocator

Avoid fragmentation by keeping track of same-size memory chunks (*buddies)*

```
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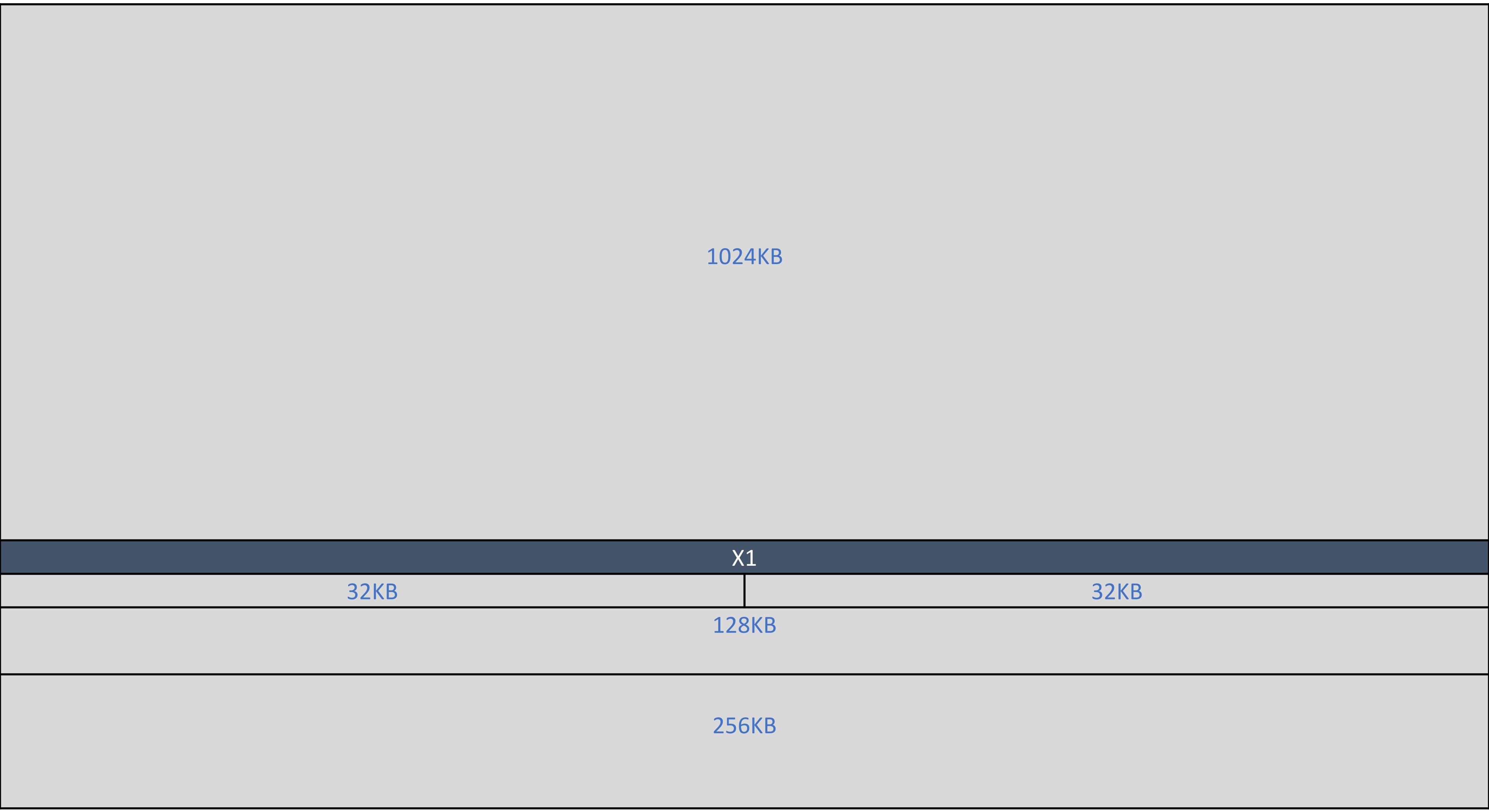

Phys Feng Shui – Buddy Allocator

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```
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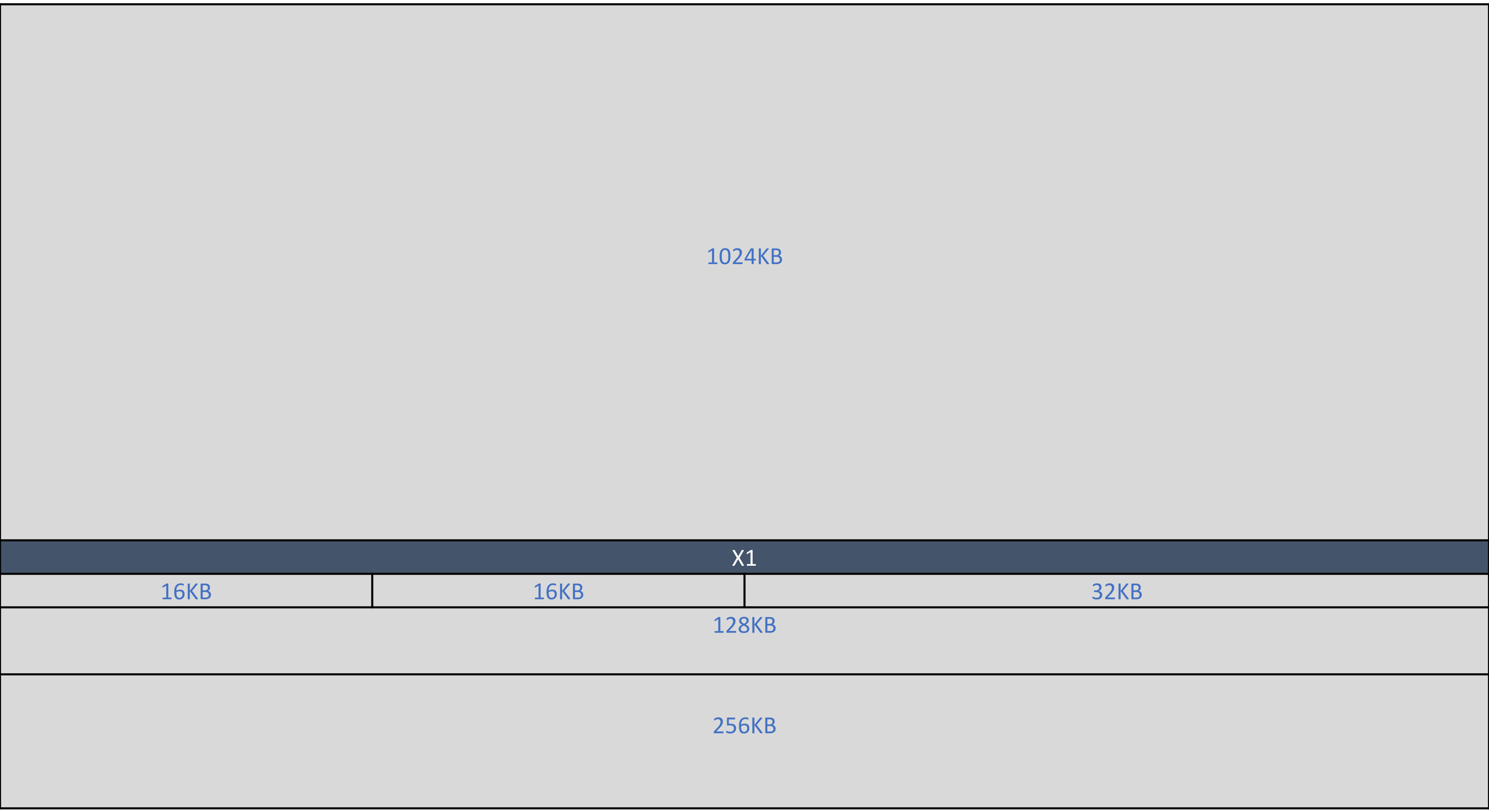

Phys Feng Shui – Buddy Allocator

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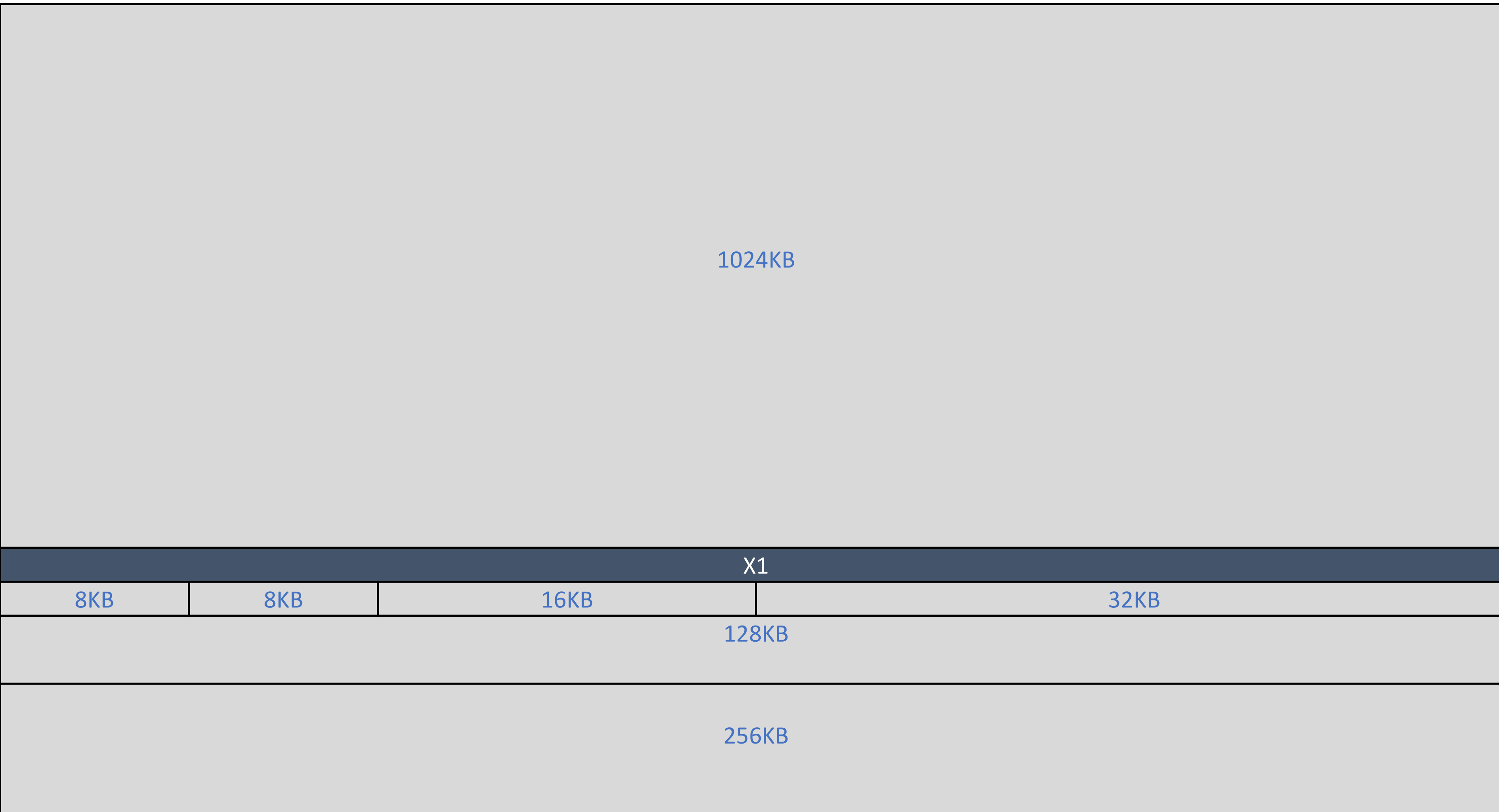
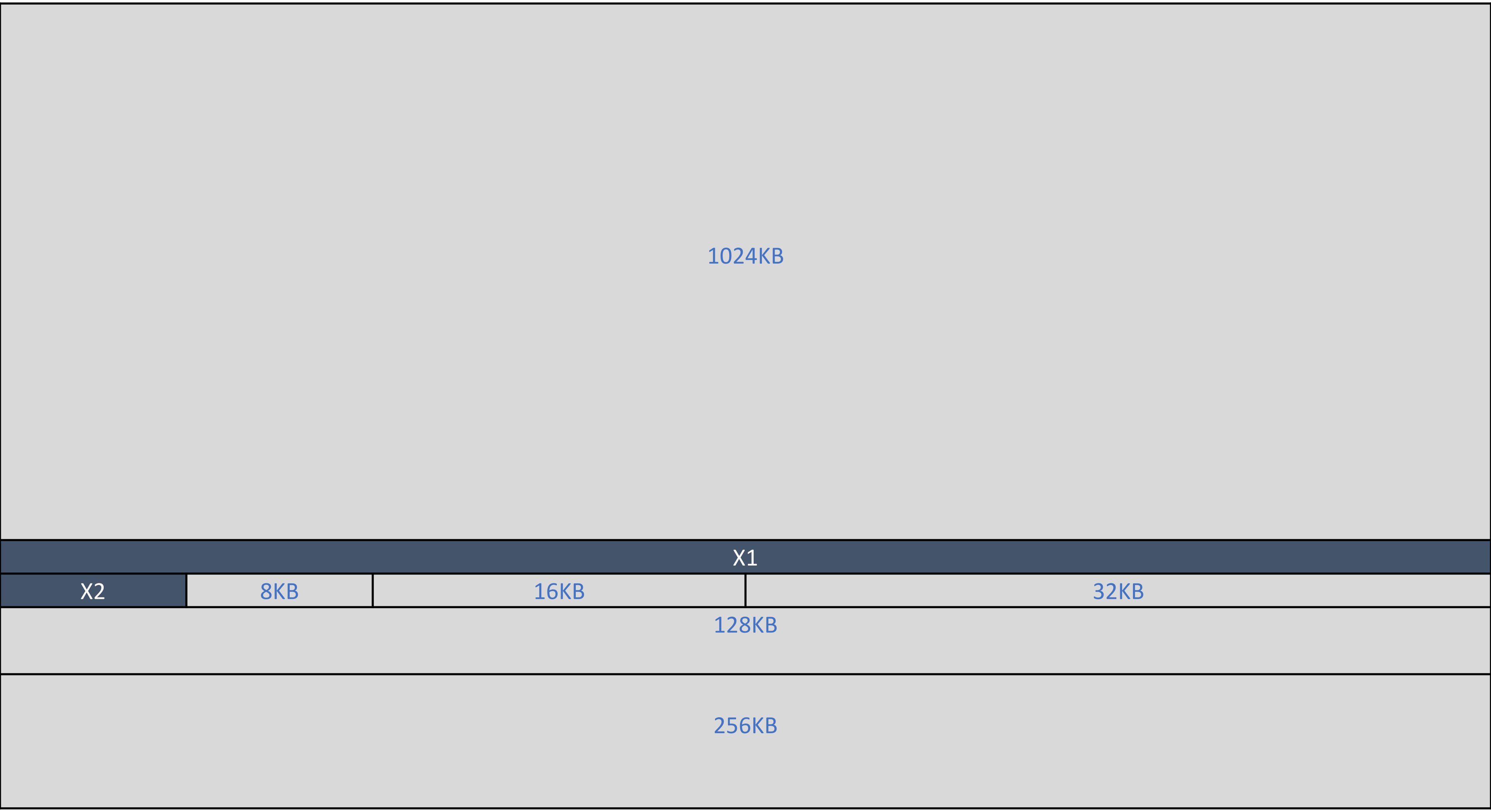


Phys Feng Shui – Buddy Allocator

Avoid fragmentation by keeping track of same-size memory chunks (*buddies)*

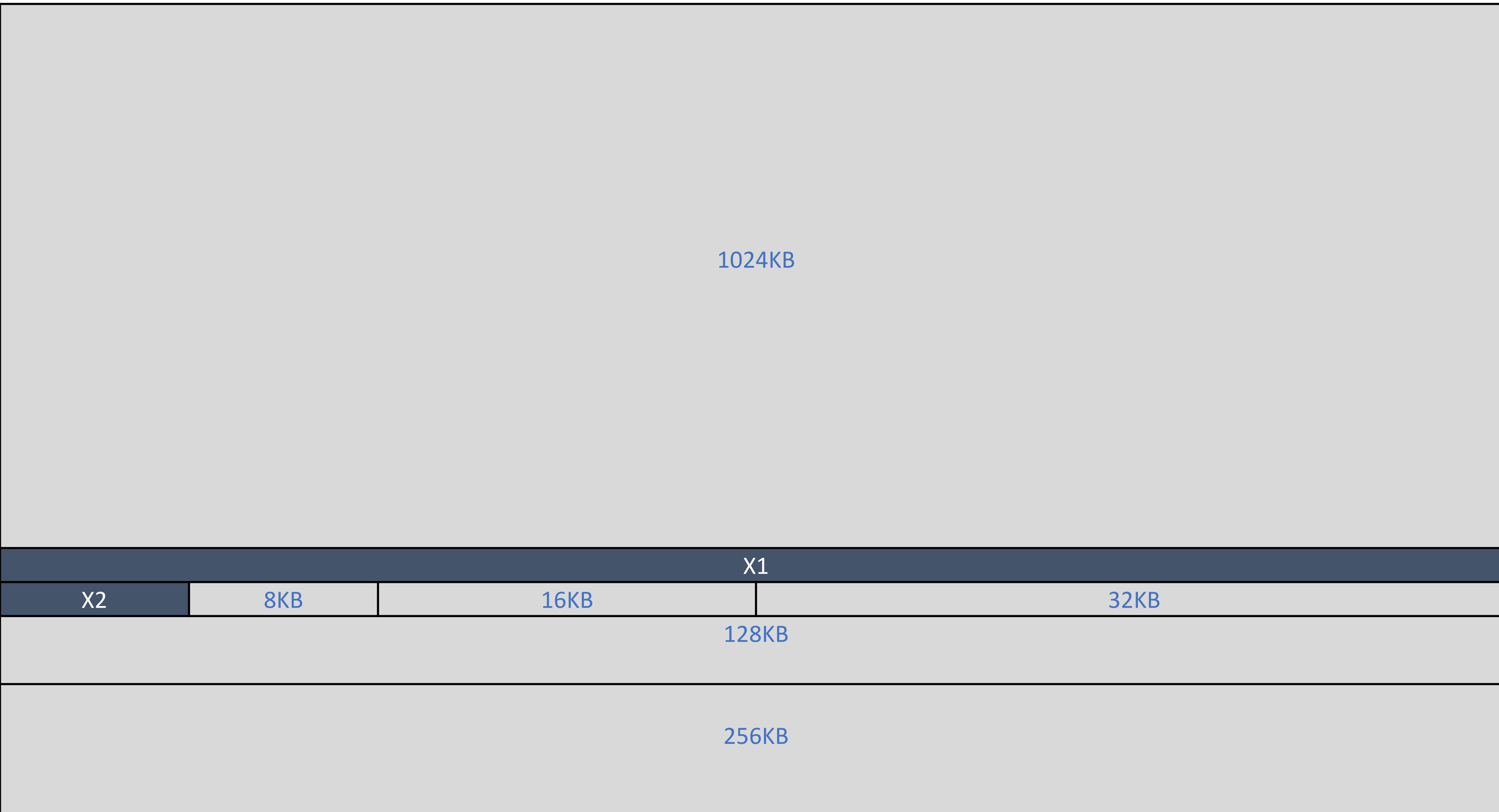
```
X2 = __get_free_pages(flags, 3); // get 2^3 = 8KB of memory
```



Phys Feng Shui – Buddy Allocator

Avoid fragmentation by keeping track of same-size memory chunks (*buddies)*

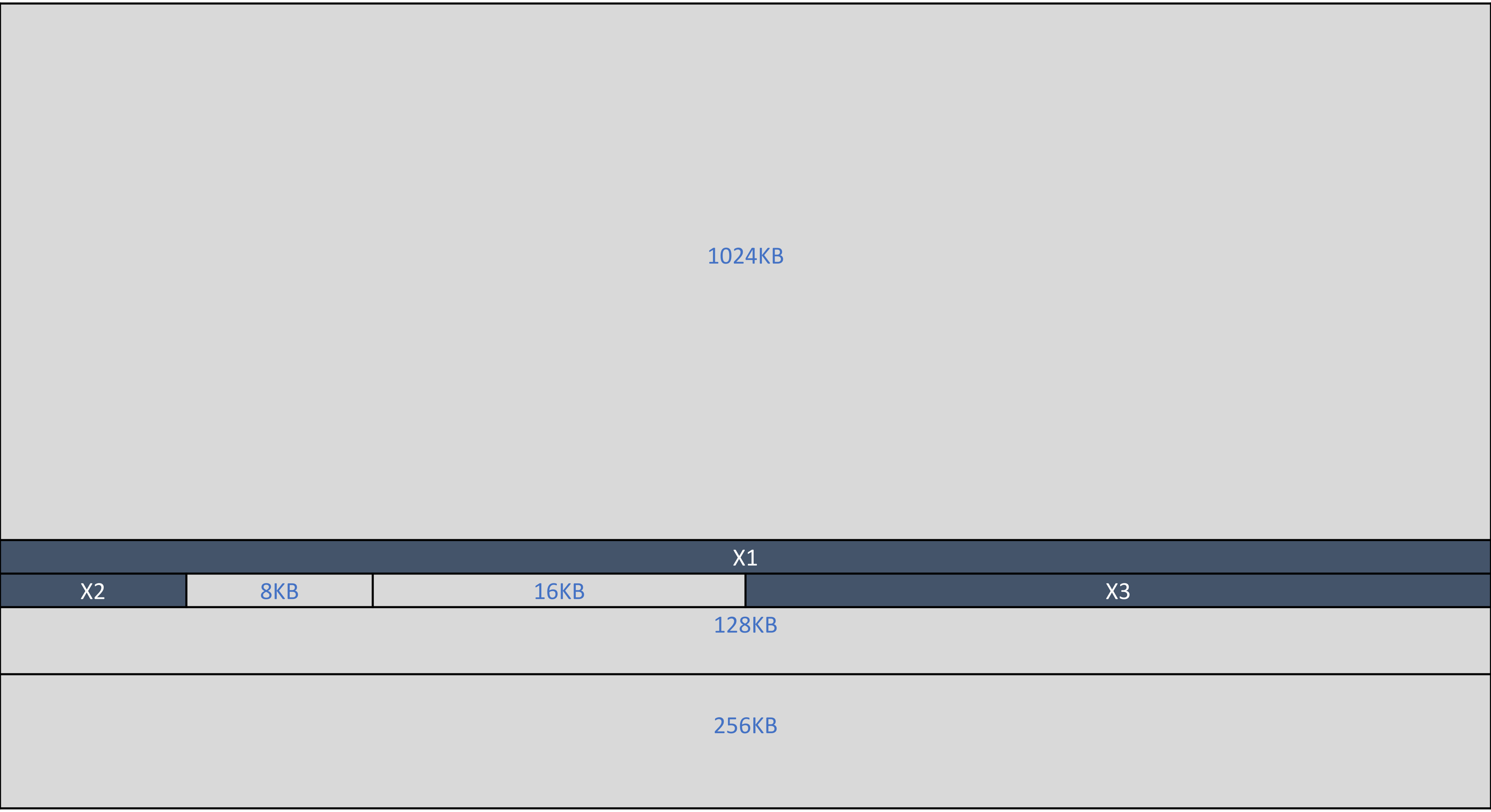
```
X3 = __get_free_pages(flags, 5); // get 2^3 = 32KB of memory
```



Phys Feng Shui – Buddy Allocator

Avoid fragmentation by keeping track of same-size memory chunks (*buddies)*

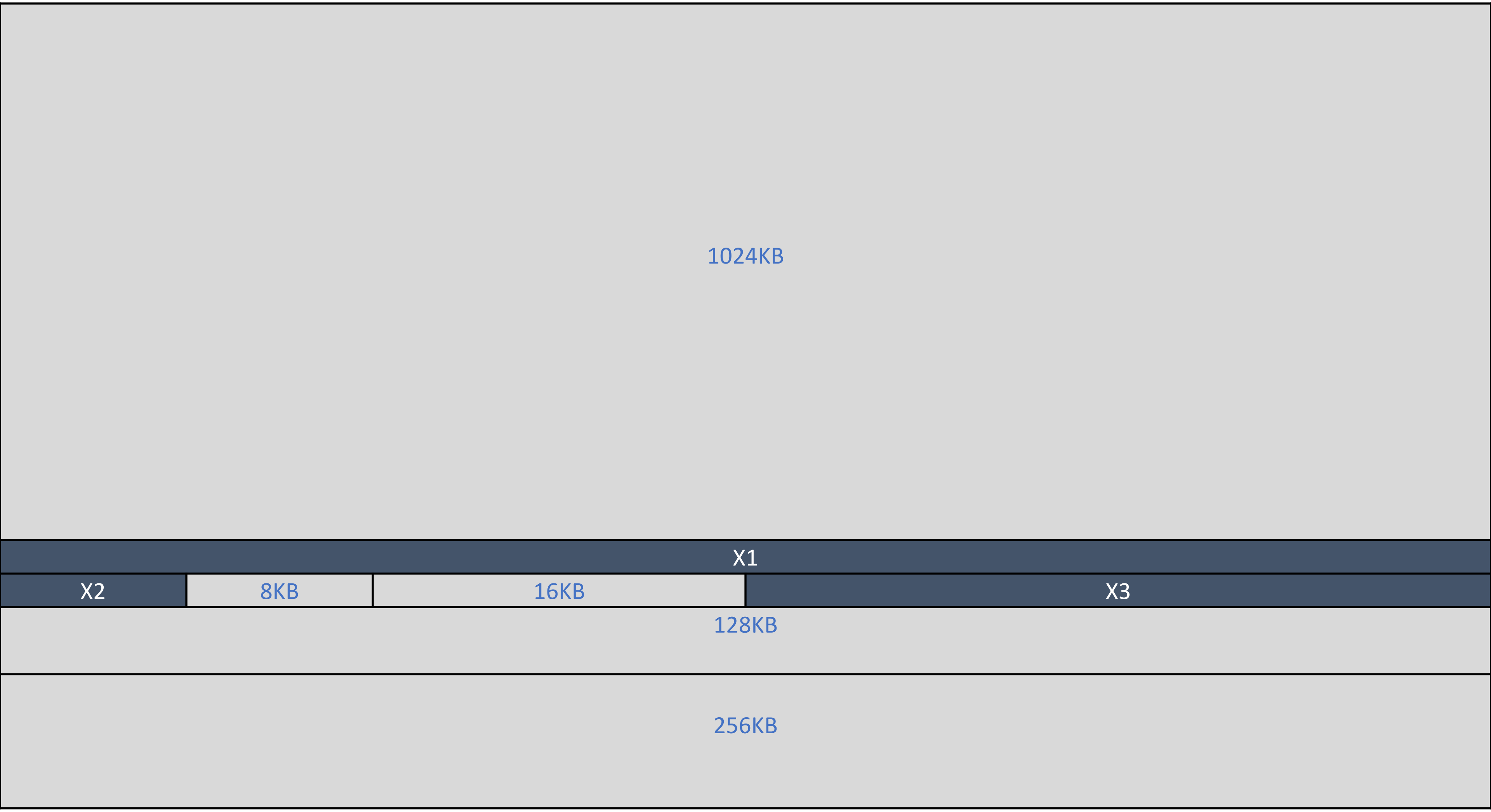
`P3 = __get_free_pages(flags, 5); // get 2^3 = 32KB of memory`



Phys Feng Shui – Buddy Allocator

Avoid fragmentation by keeping track of same-size memory chunks (*buddies)*

```
free_pages(X2, 3); // free X2
```



Phys Feng Shui – Buddy Allocator

Avoid fragmentation by keeping track of same-size memory chunks (*buddies)*

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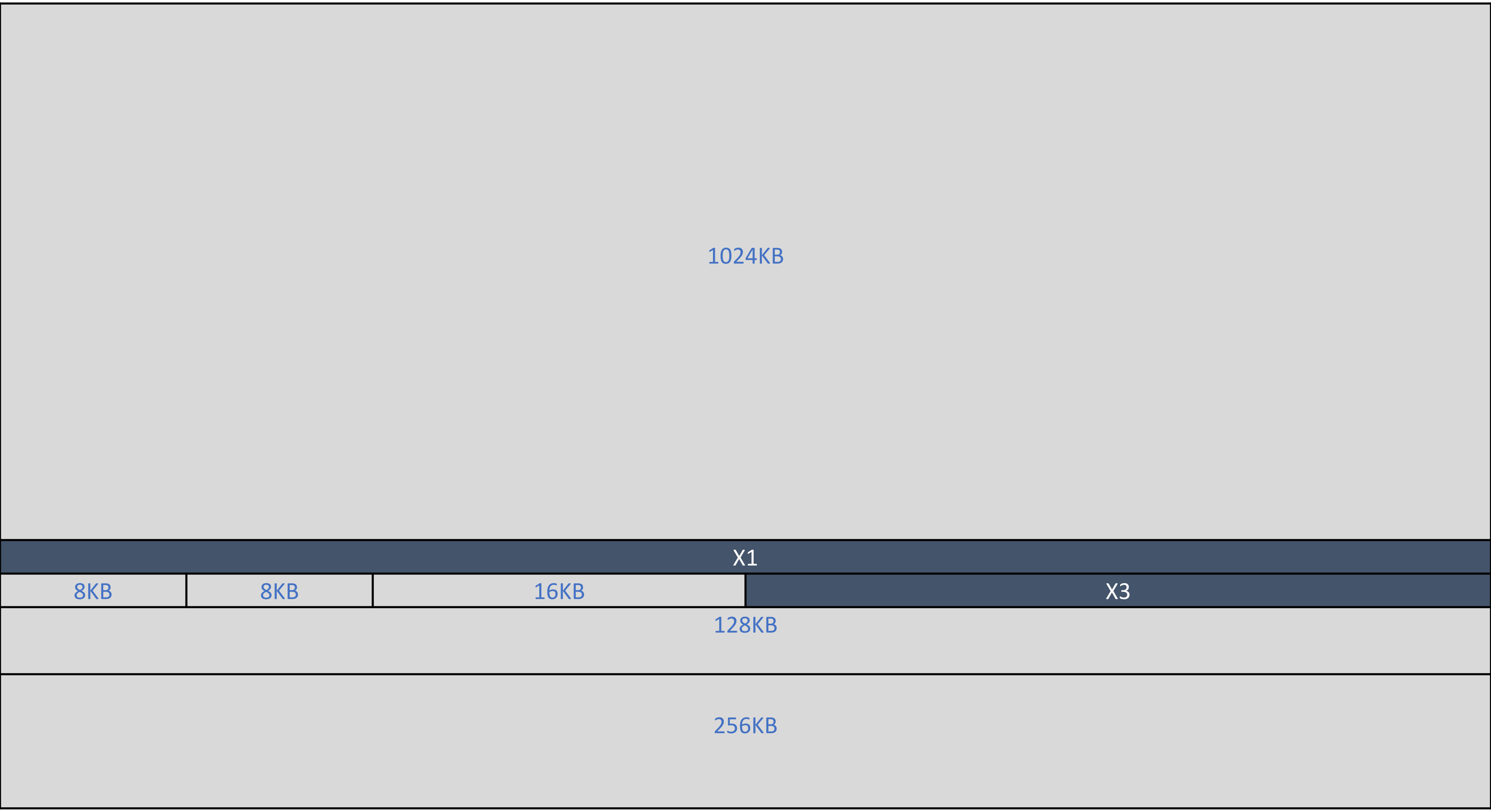

Phys Feng Shui – Buddy Allocator

Avoid fragmentation by keeping track of same-size memory chunks (*buddies)*

```
free_pages(X2, 3); // free X2
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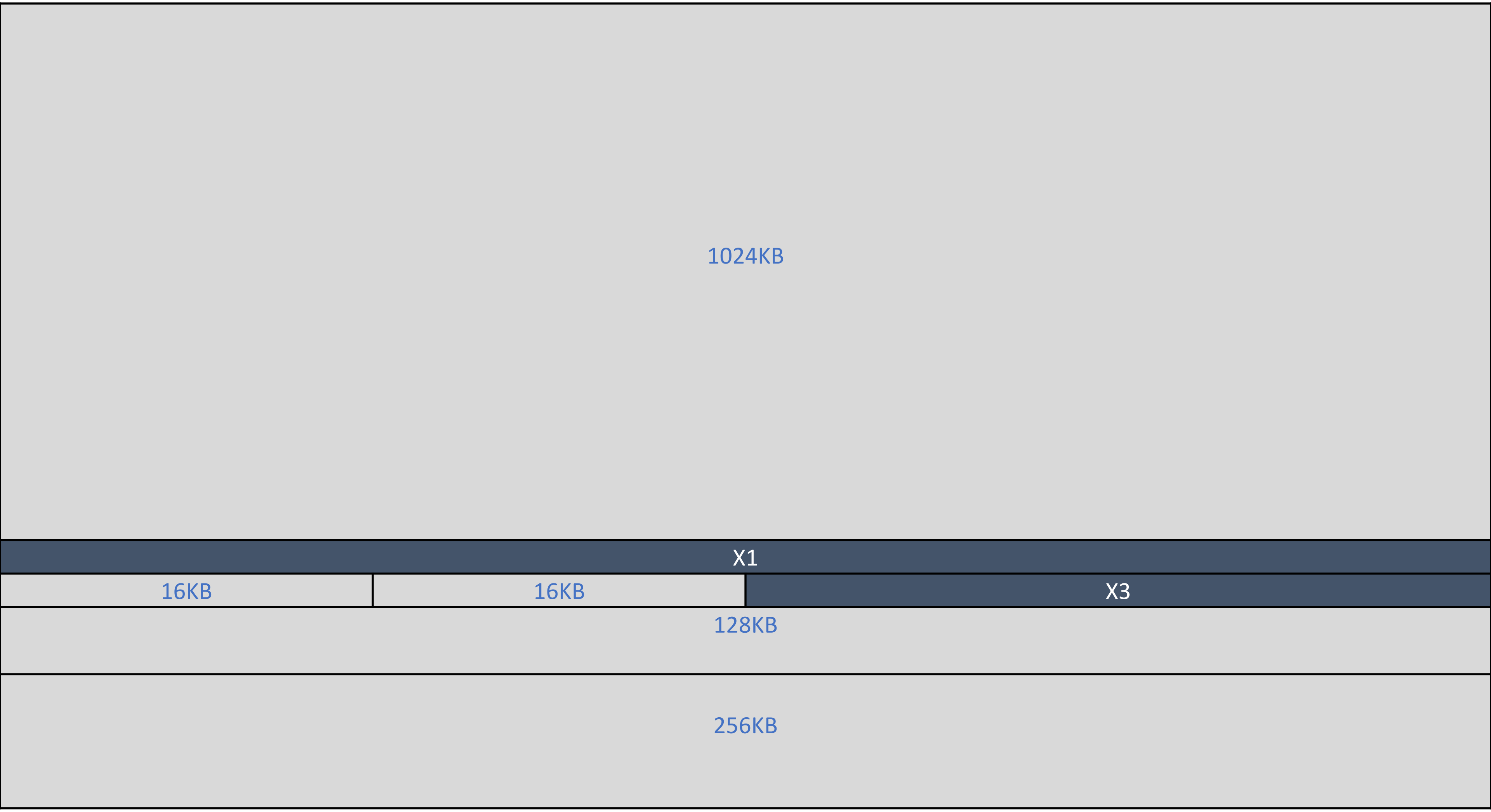
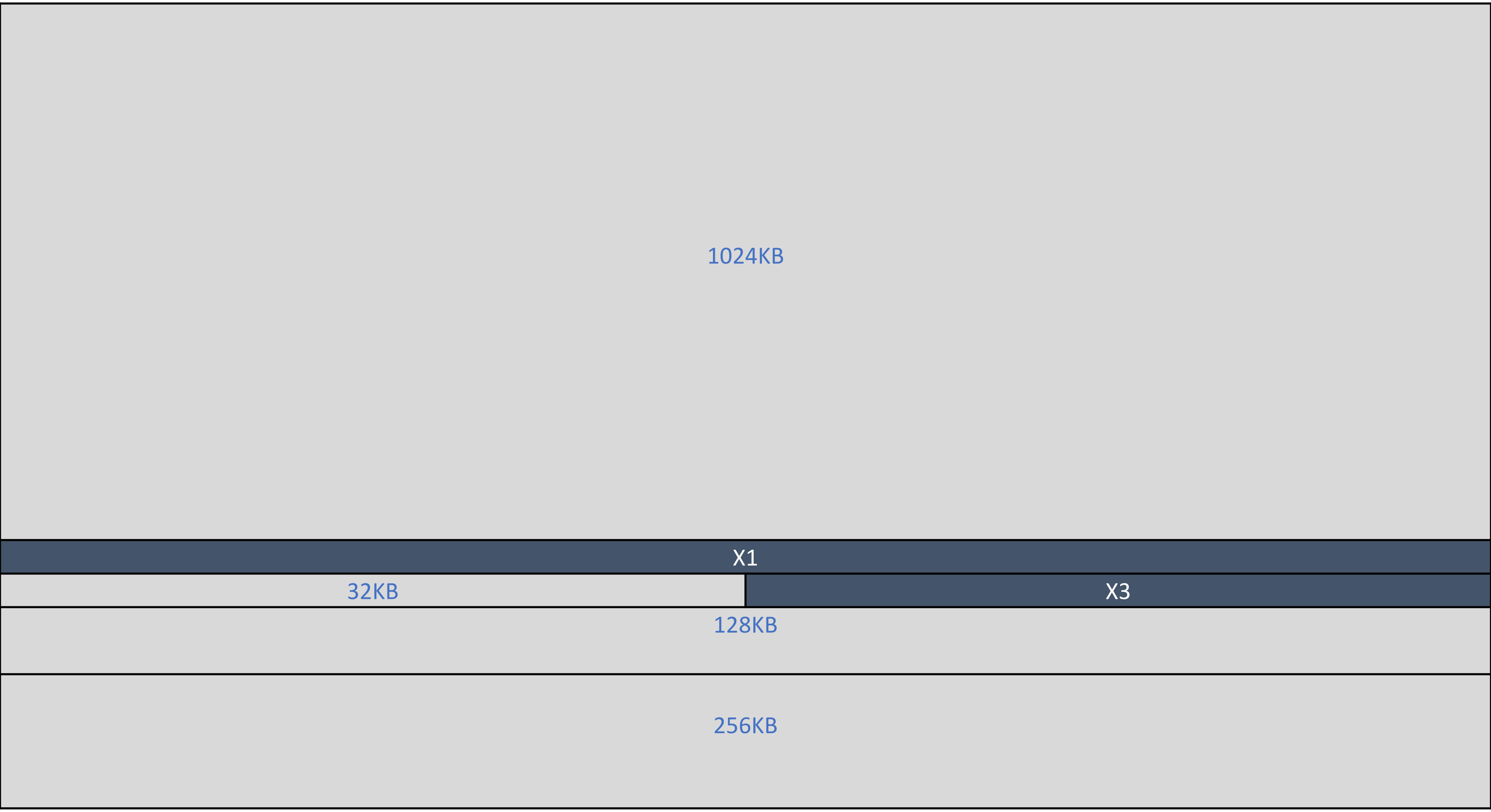


Phys Feng Shui – Buddy Allocator

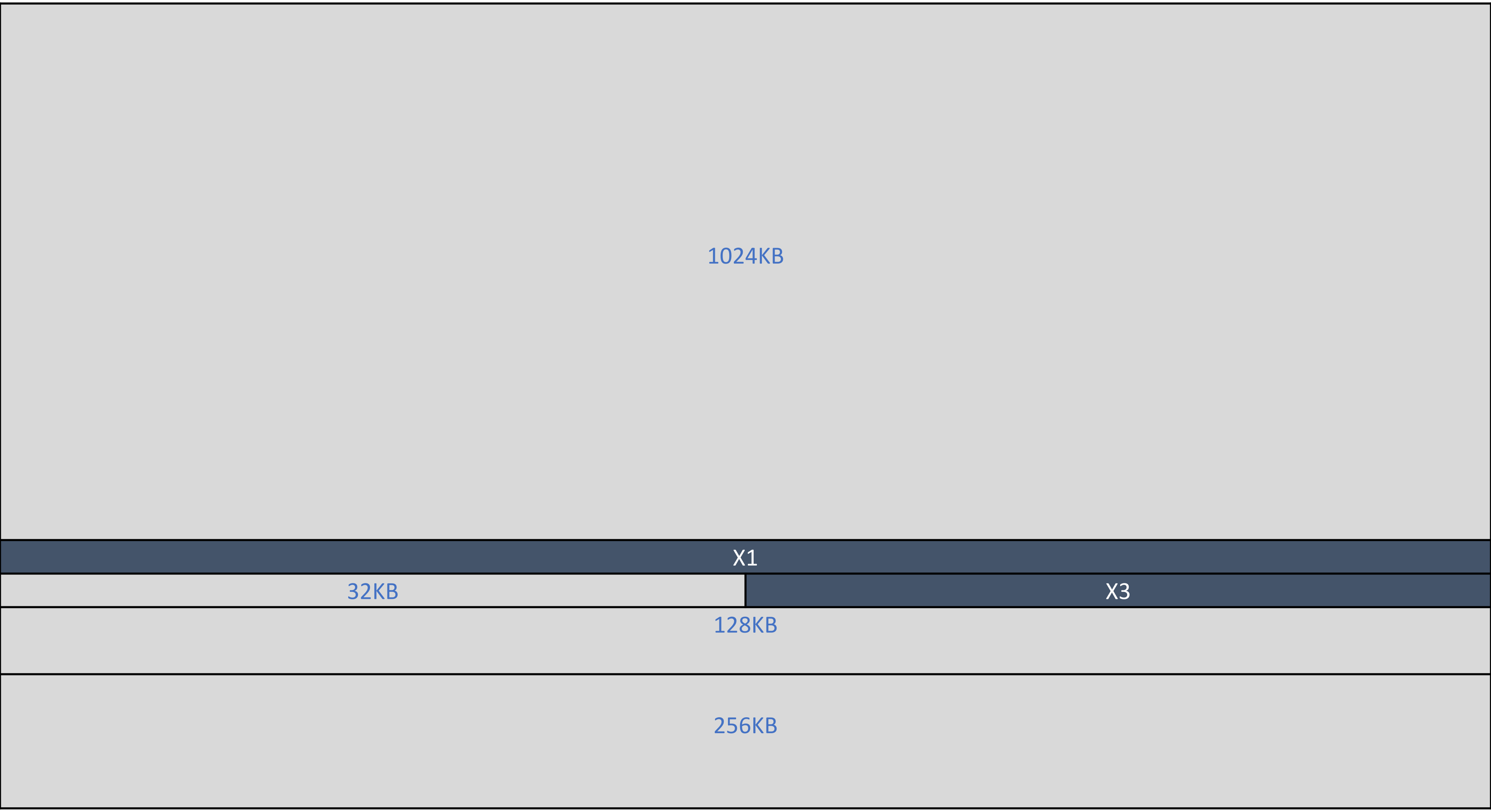
Avoid fragmentation by keeping track of same-size memory chunks (*buddies)*

```
free_pages(X2, 3); // free X2
```



Phys Feng Shui

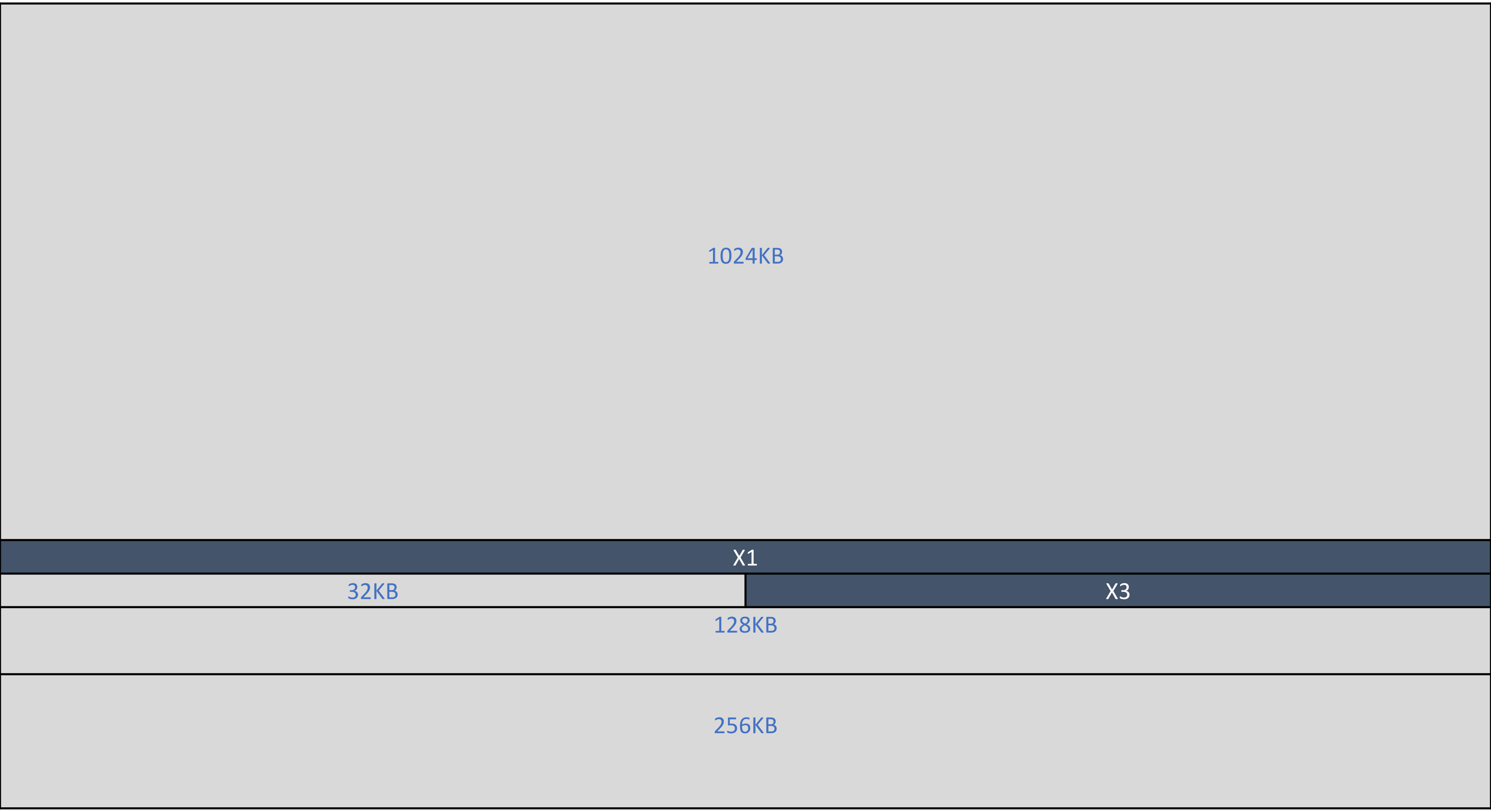
Deterministic Rowhammer exploitation in 8 steps



Phys Feng Shui step 1/8

Exhaust + Template *Large* chunks

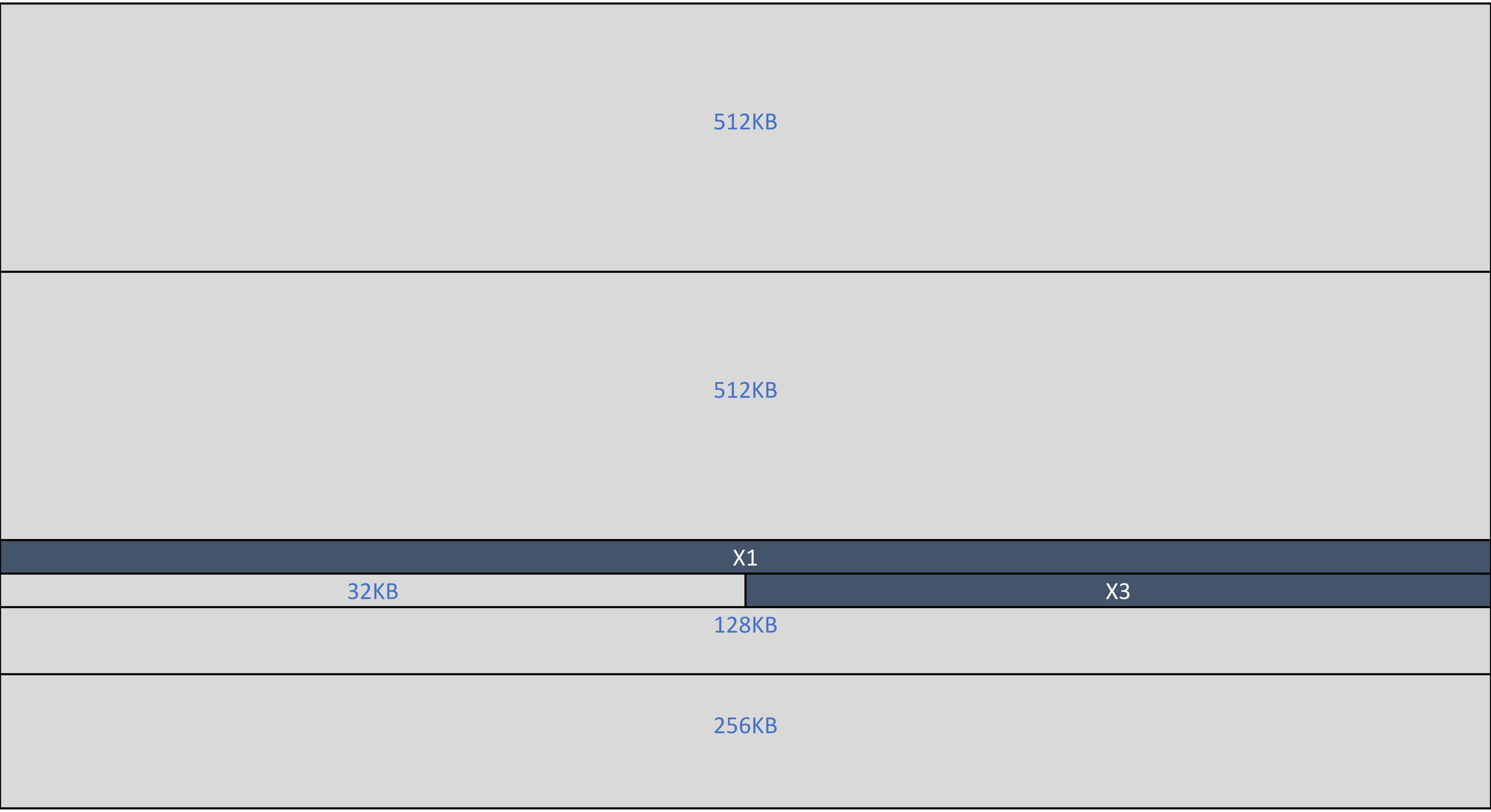
```
L1, L2, …, Ln = exhaust(L);
```



Phys Feng Shui step 1/8

Exhaust + Template *Large* chunks

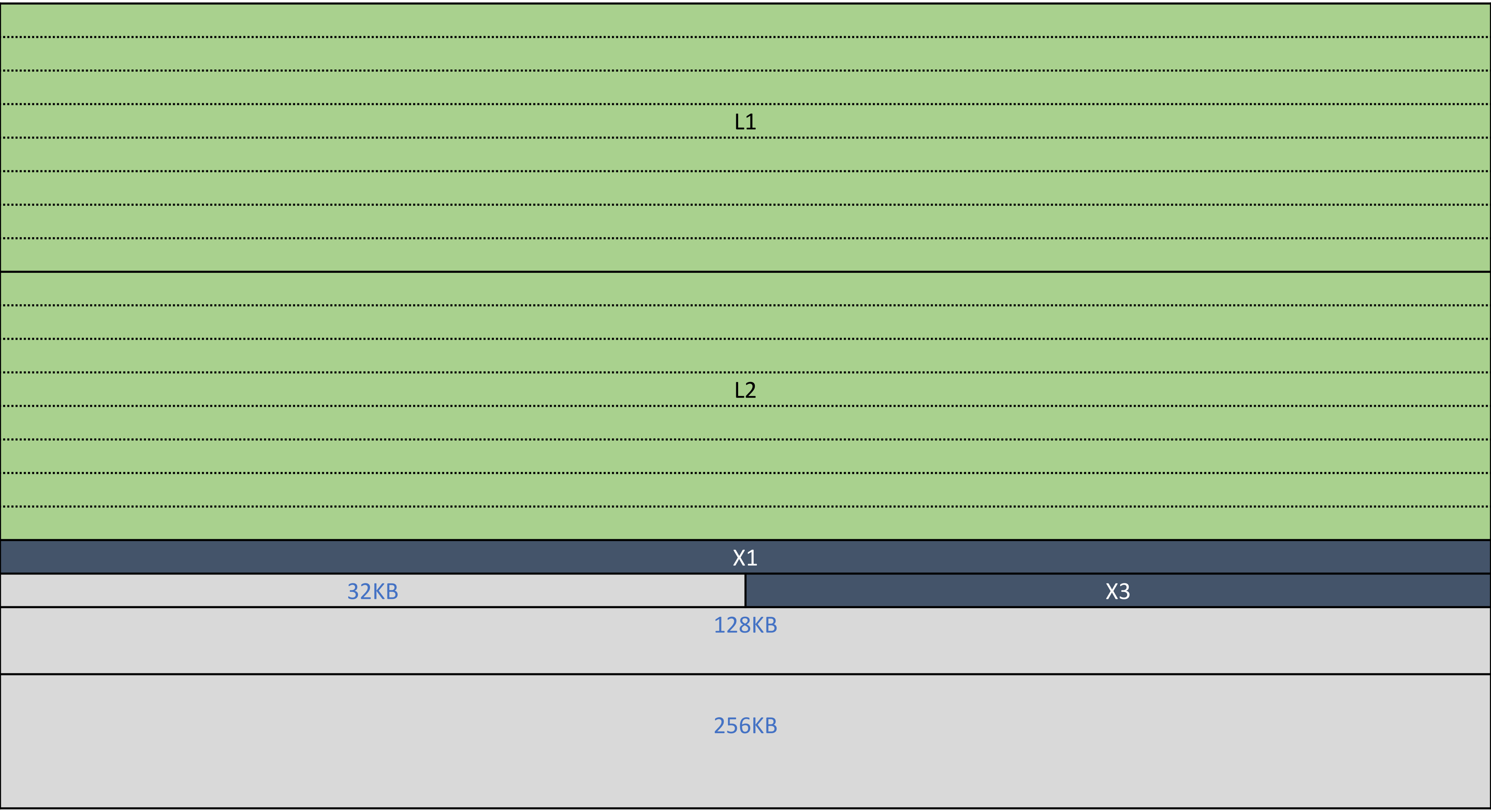
```
L1, L2, …, Ln = exhaust(9); // get all 2^9 = 512KB chunks
```



Phys Feng Shui step 1/8

Exhaust + Template *Large* chunks

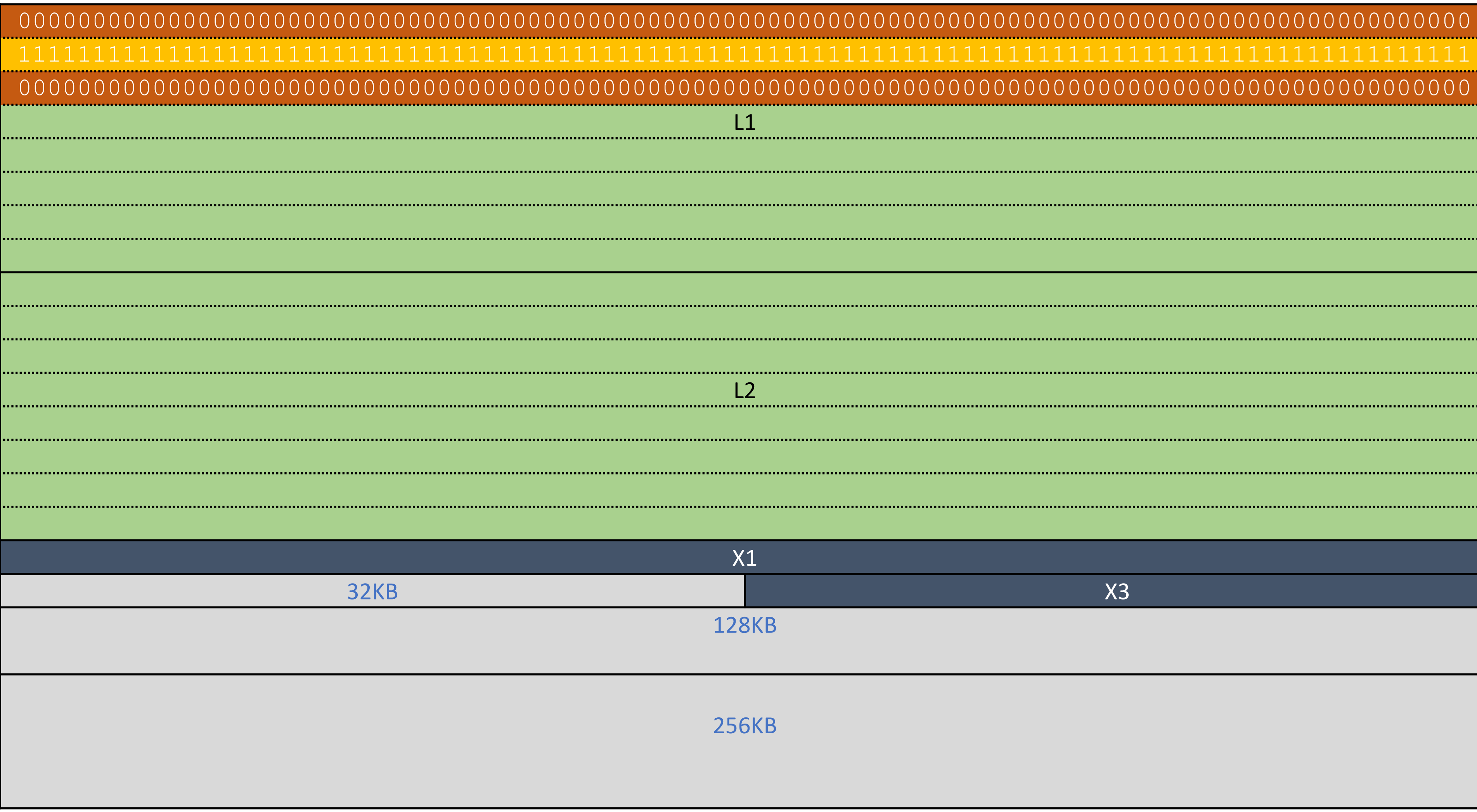
```
L1, L2, …, Ln = exhaust(L); // get all 2^9 = 512KB chunks
```



Phys Feng Shui step 1/8

Exhaust + Template *Large* chunks

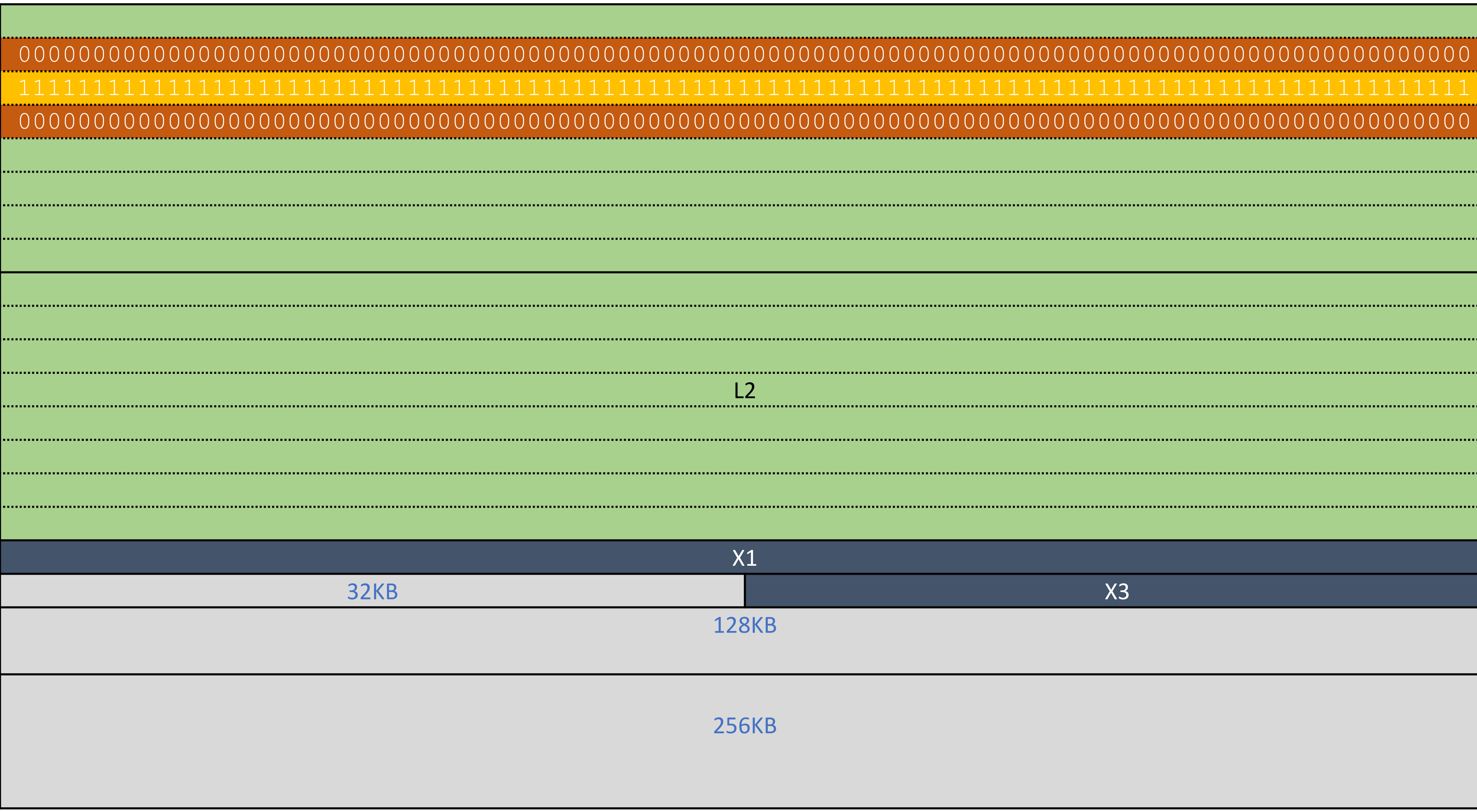
`Hammer(L1, 2);` `// hammer row 2 of chunk L1`



Phys Feng Shui step 1/8

Exhaust + Template *Large* chunks

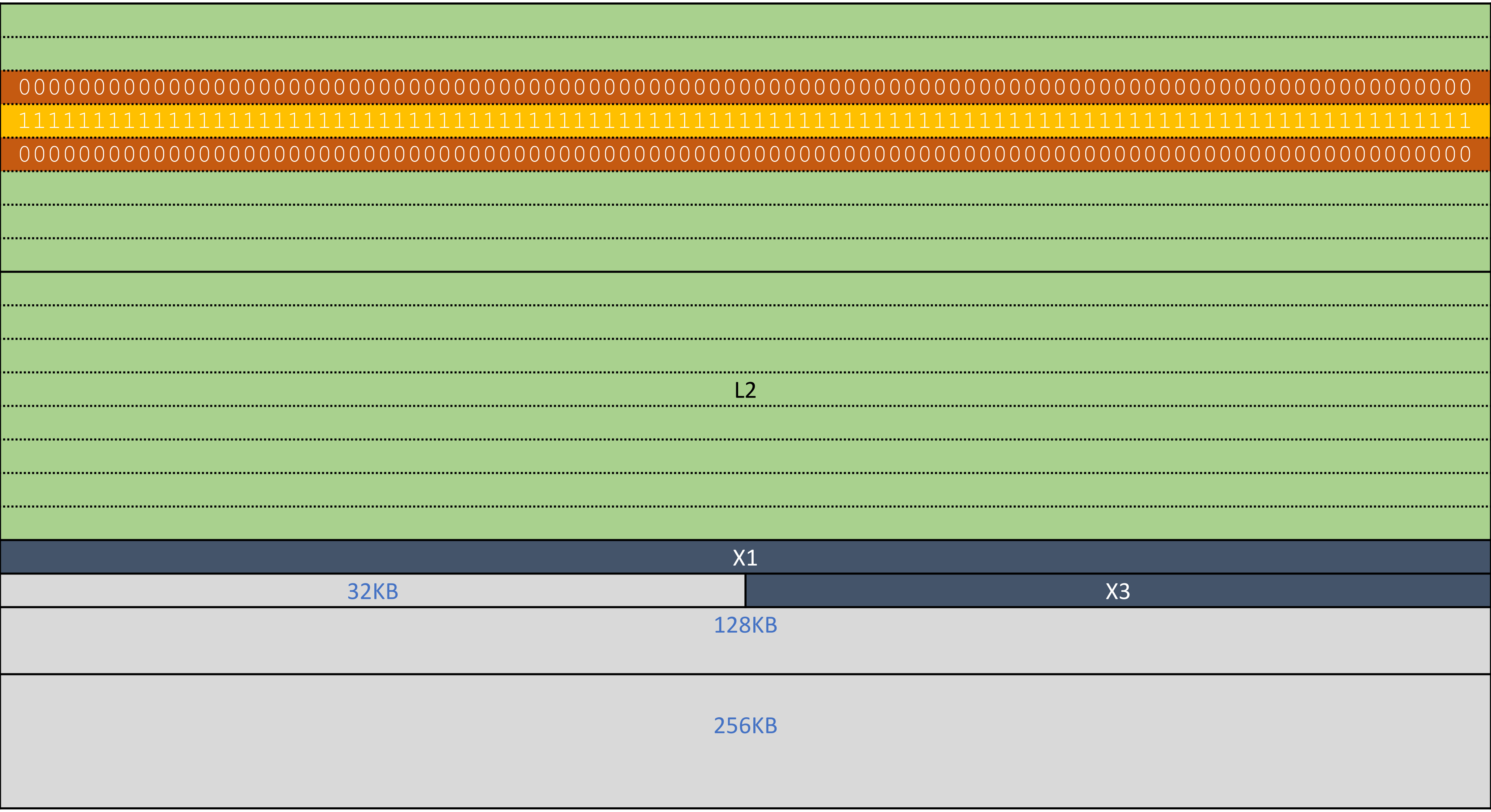
`Hammer(L1, 3);` `// hammer row 3 of chunk L1`



Phys Feng Shui step 1/8

Exhaust + Template *Large* chunks

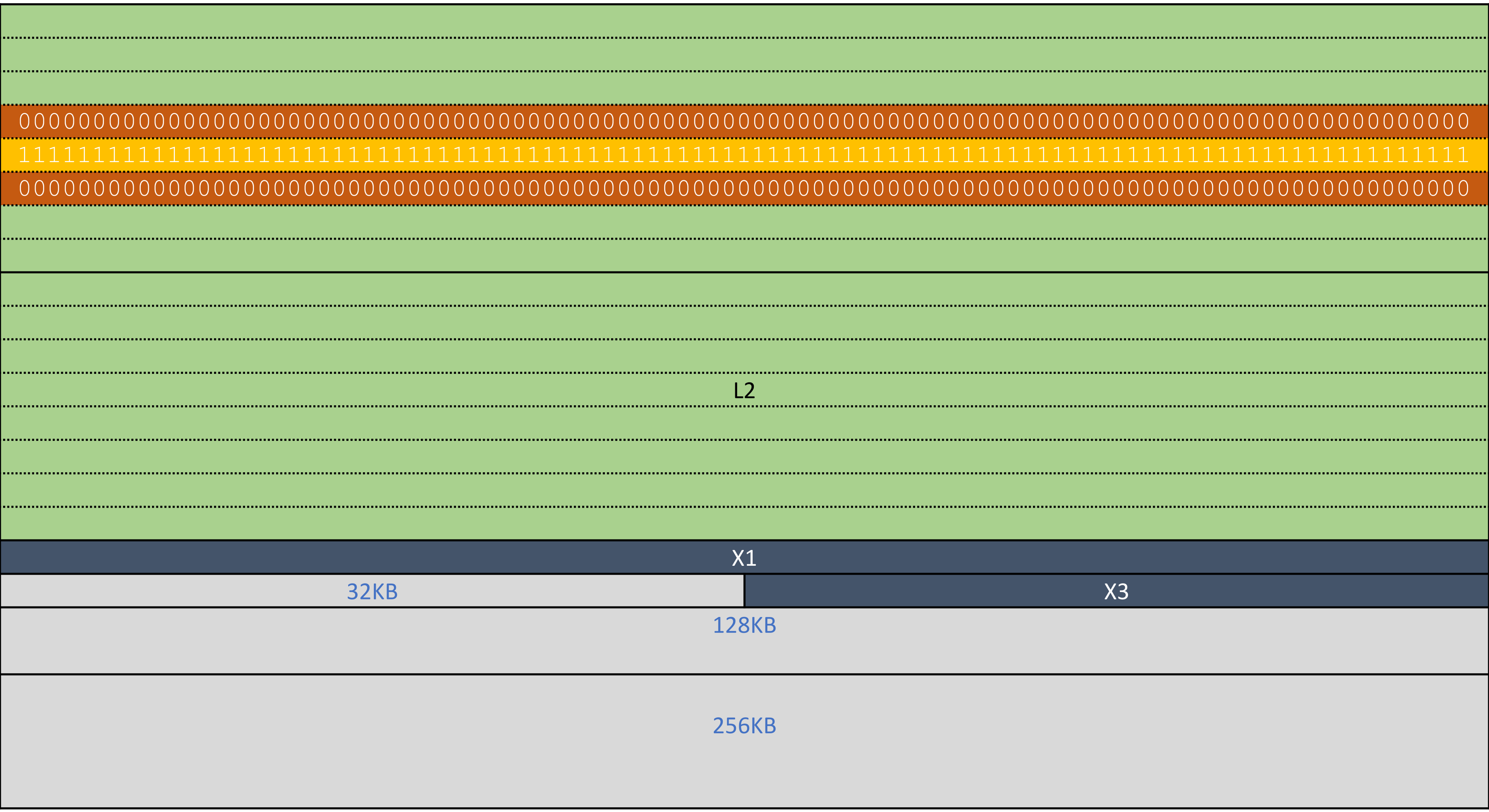
```
Hammer(L1, 4); // hammer row 4 of chunk L1
```



Phys Feng Shui step 1/8

Exhaust + Template *Large* chunks

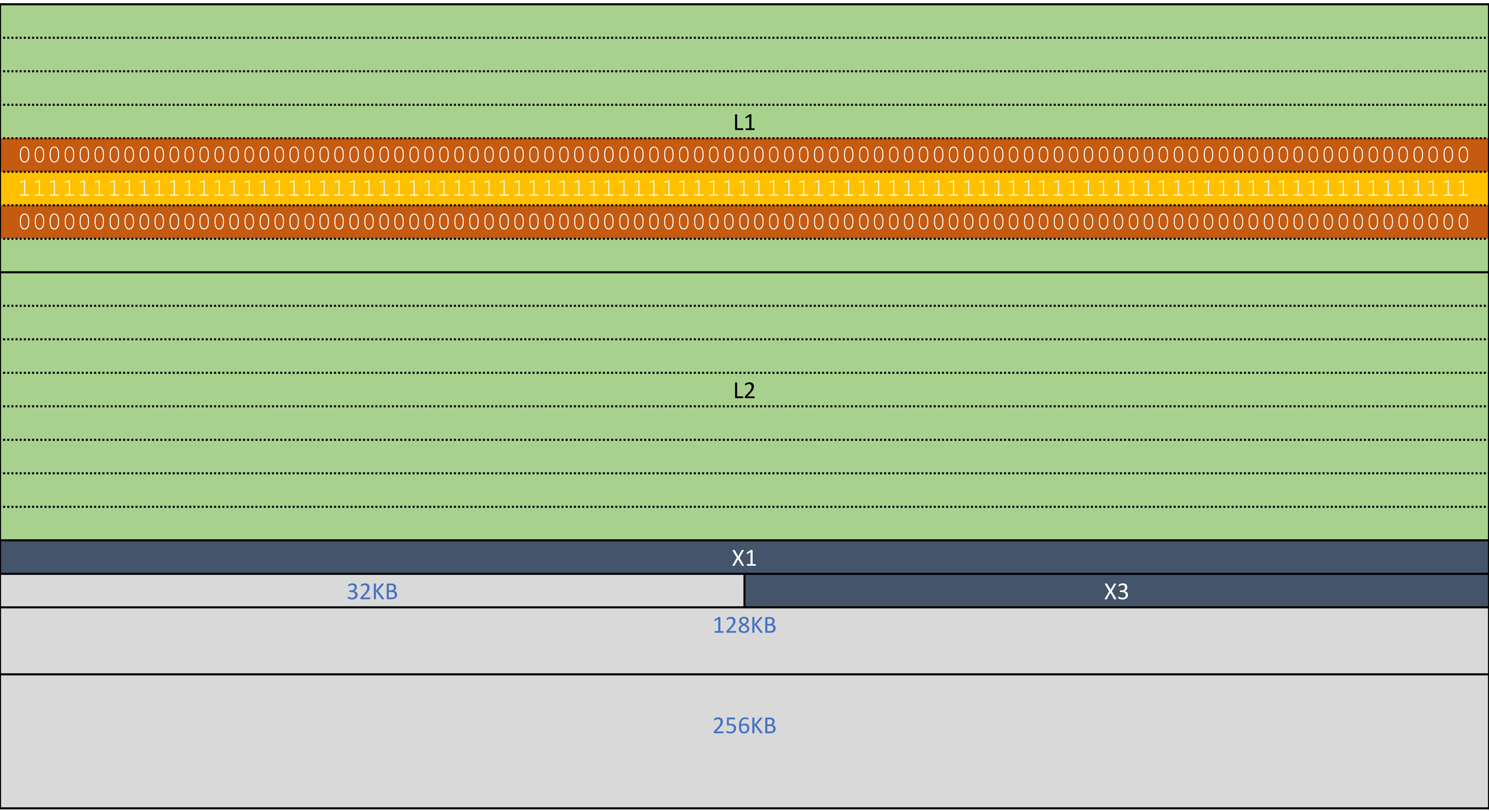
`Hammer(L1, 5);` `// hammer row 5 of chunk L1`



Phys Feng Shui step 1/8

Exhaust + Template *Large* chunks

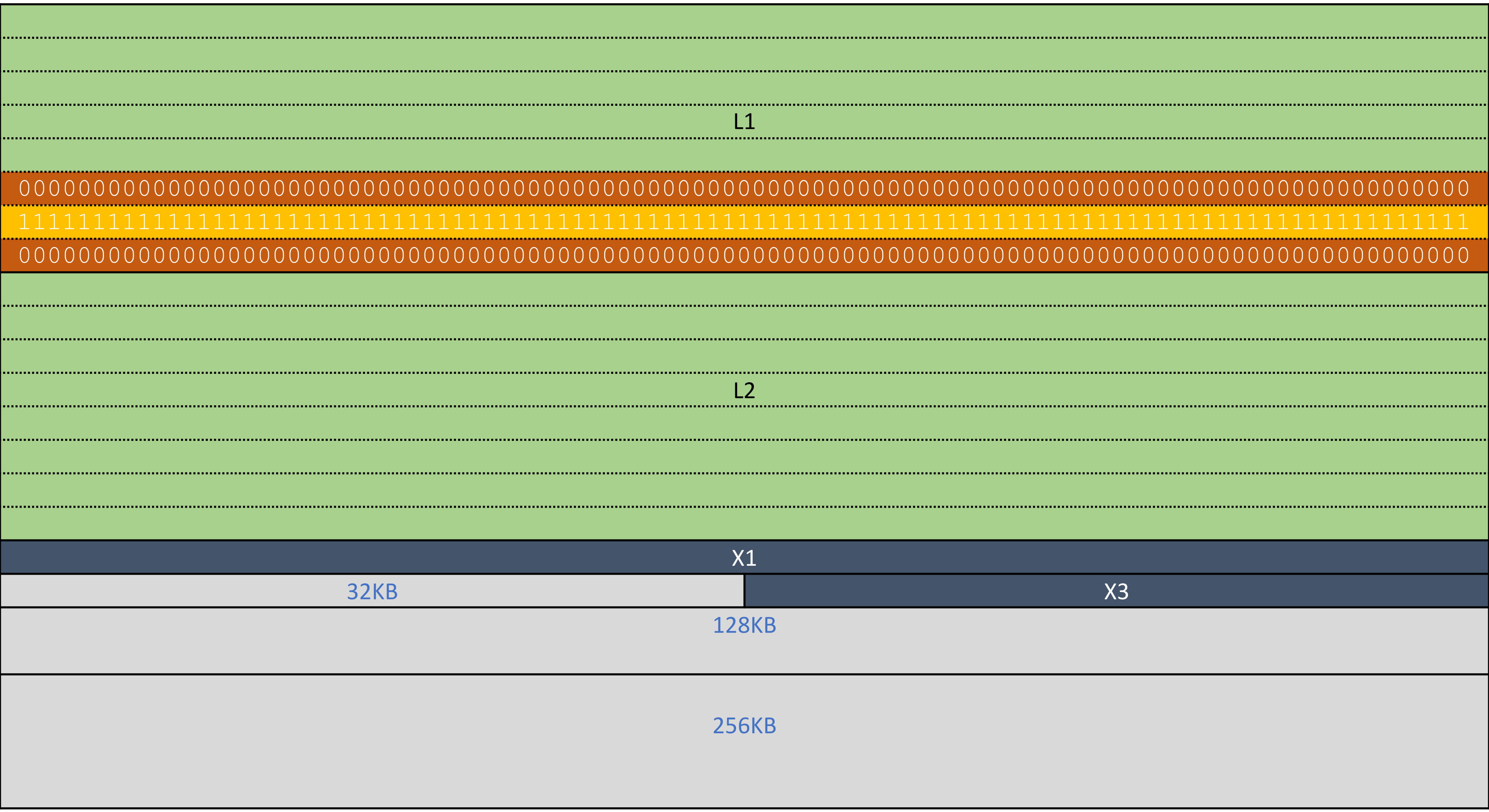
```
Hammer(L1, 6); // hammer row 6 of chunk L1
```



Phys Feng Shui step 1/8

Exhaust + Template *Large* chunks

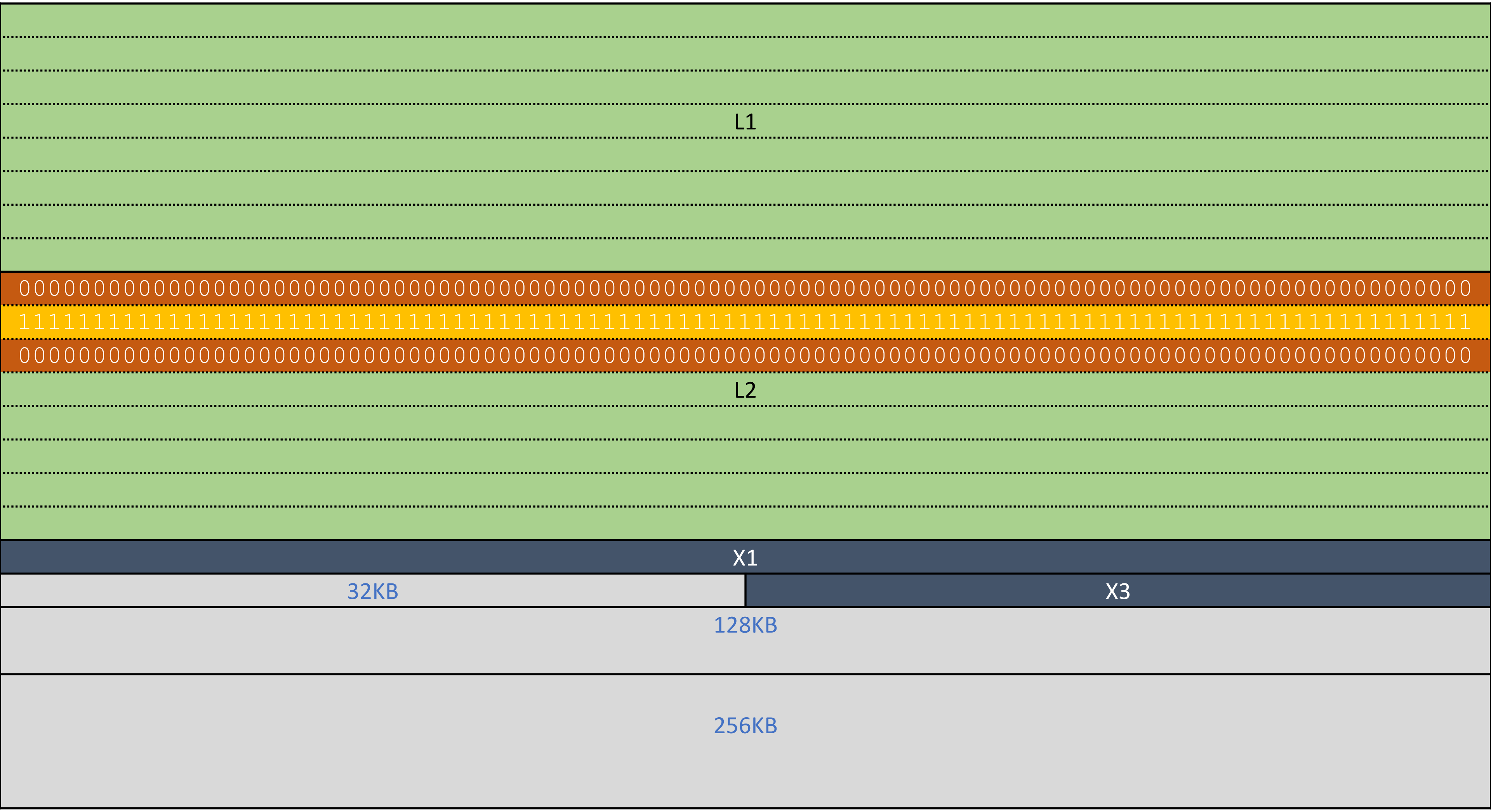
```
Hammer(L1, 7); // hammer row 7 of chunk L1
```



Phys Feng Shui step 1/8

Exhaust + Template *Large* chunks

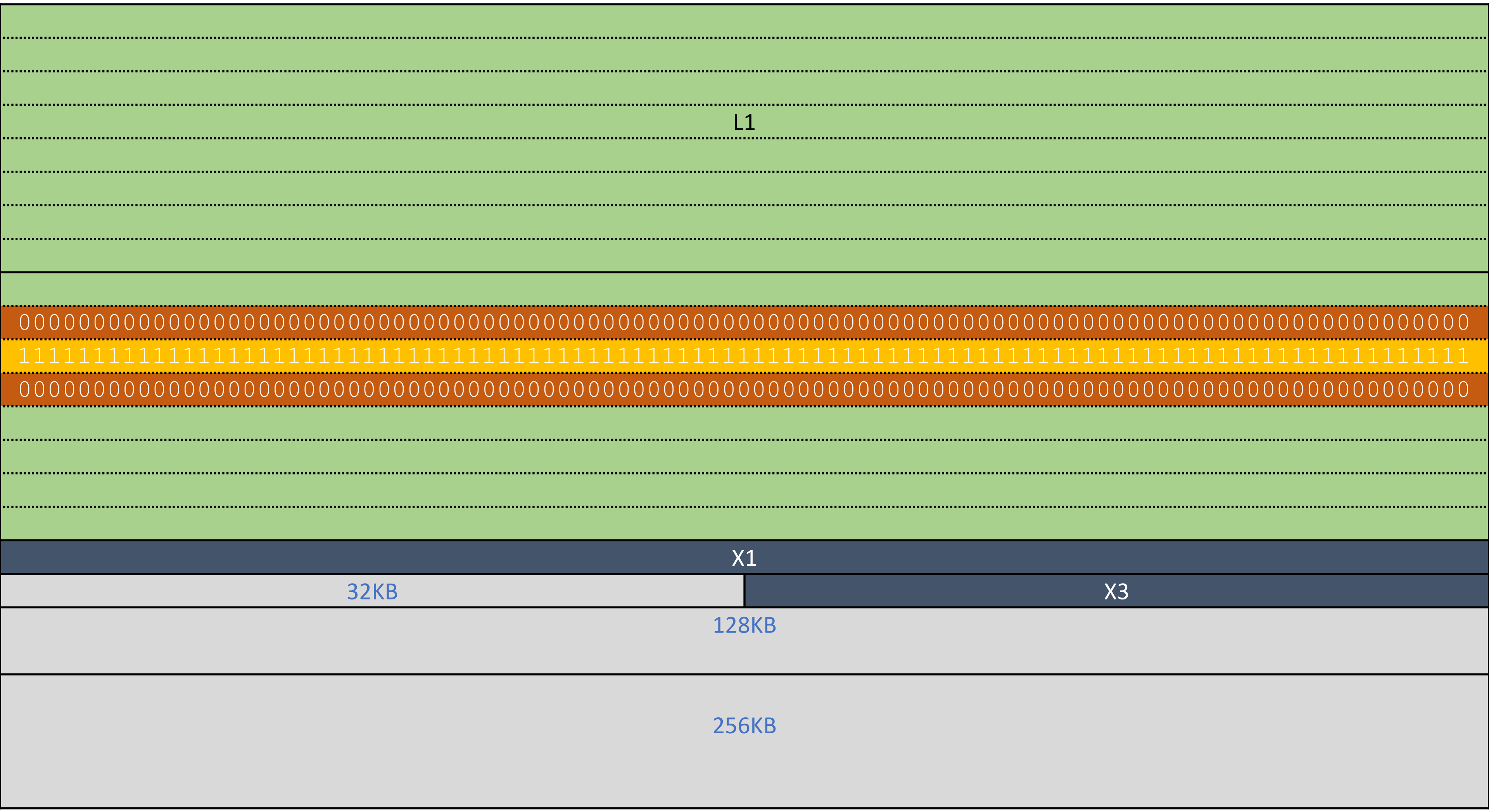
```
Hammer(L2, 2); // hammer row 2 of chunk L2
```



Phys Feng Shui step 1/8

Exhaust + Template *Large* chunks

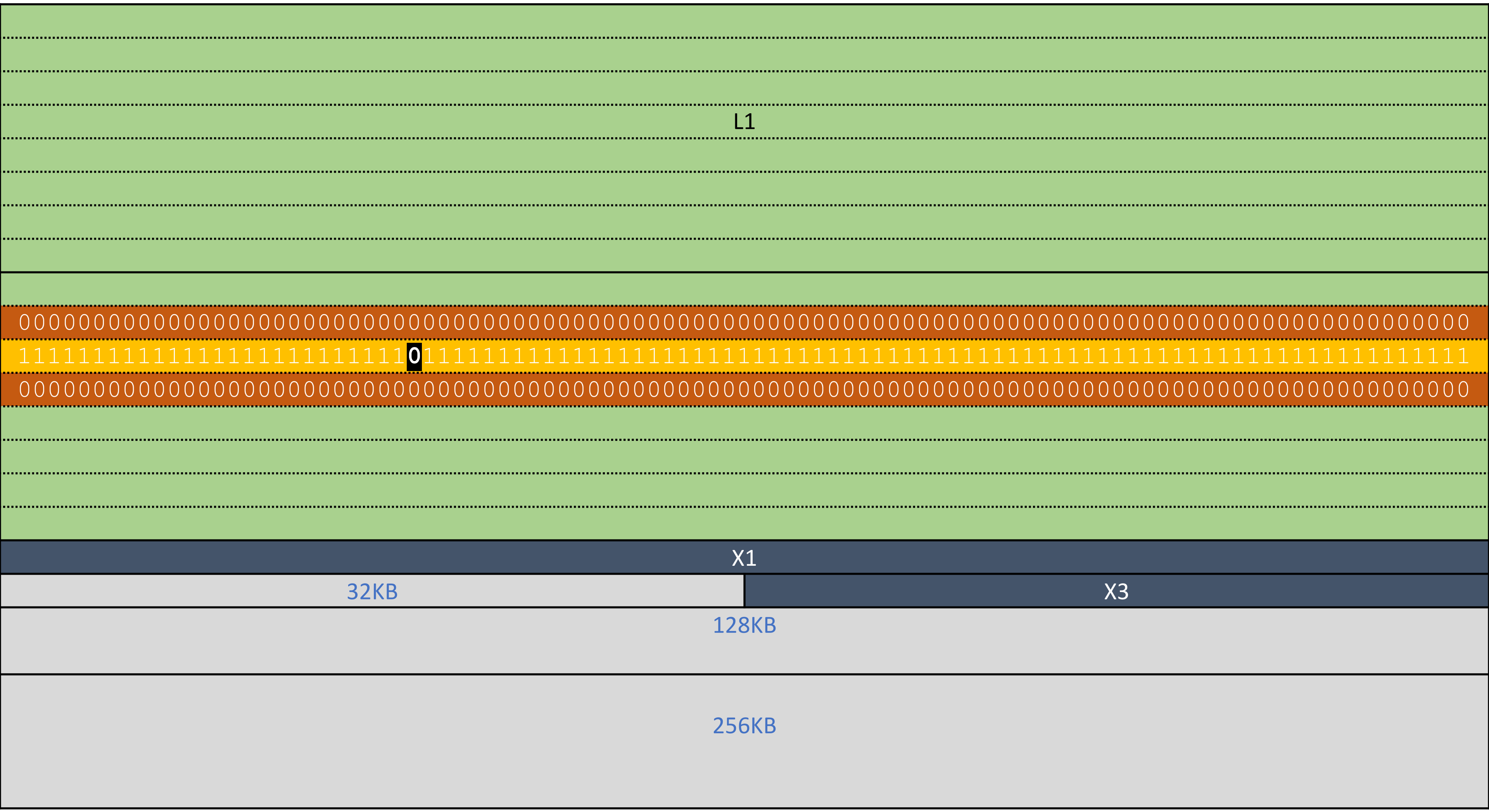
```
Hammer(L2, 3); // hammer row 3 of chunk L2
```



Phys Feng Shui step 1/8

Exhaust + Template *Large* chunks

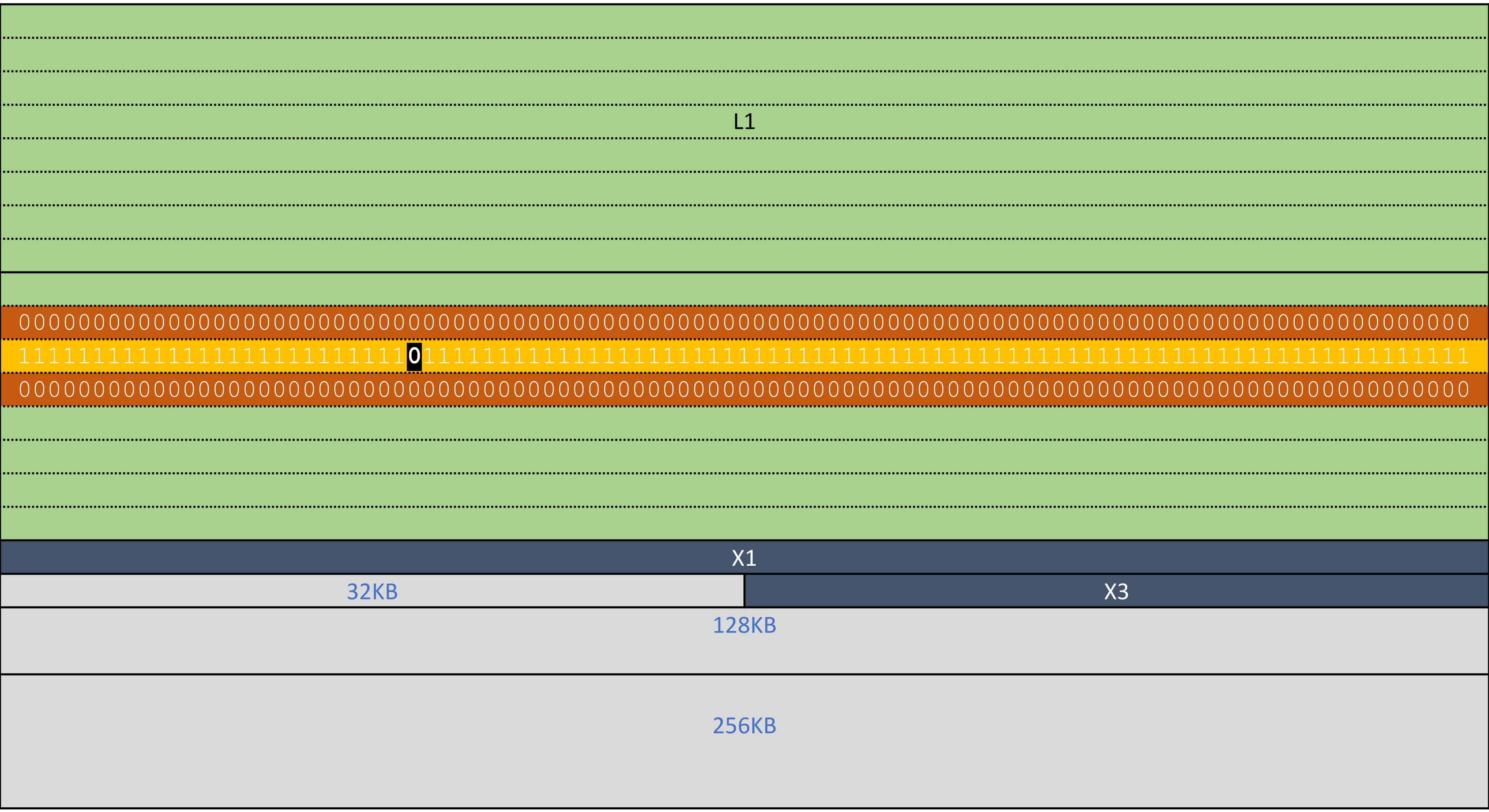
`“exploitable flip found in page 5 of virtual row 3 of L2!”`



Phys Feng Shui step 2/8

Exhaust *Medium-sized* chunks

```
_M1, _M2, …, _Mn = exhaust(6); // get all 2^6 = 64KB chunks
```



Phys Feng Shui step 2/8

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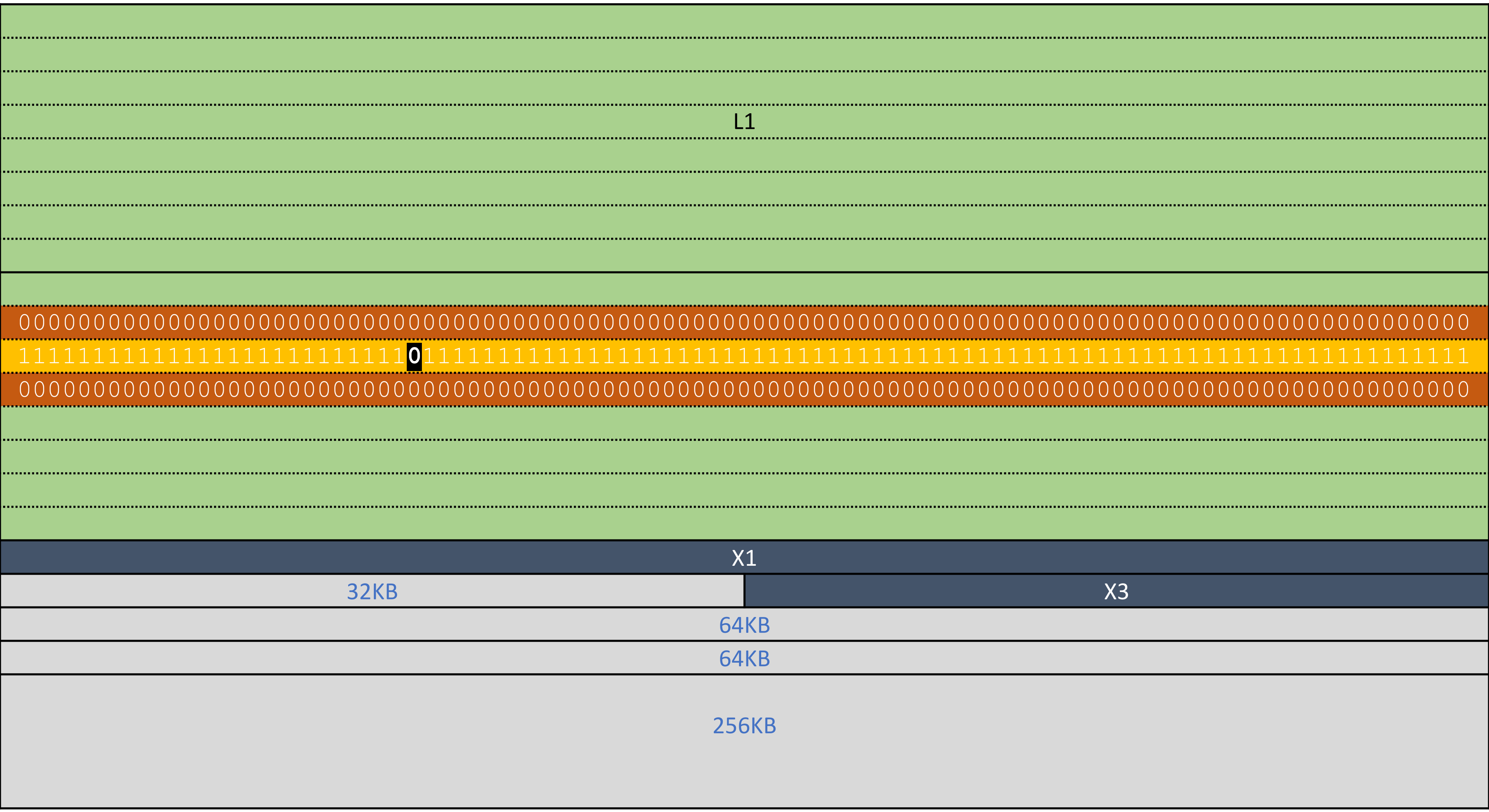

Phys Feng Shui step 2/8

Exhaust *Medium-sized* chunks

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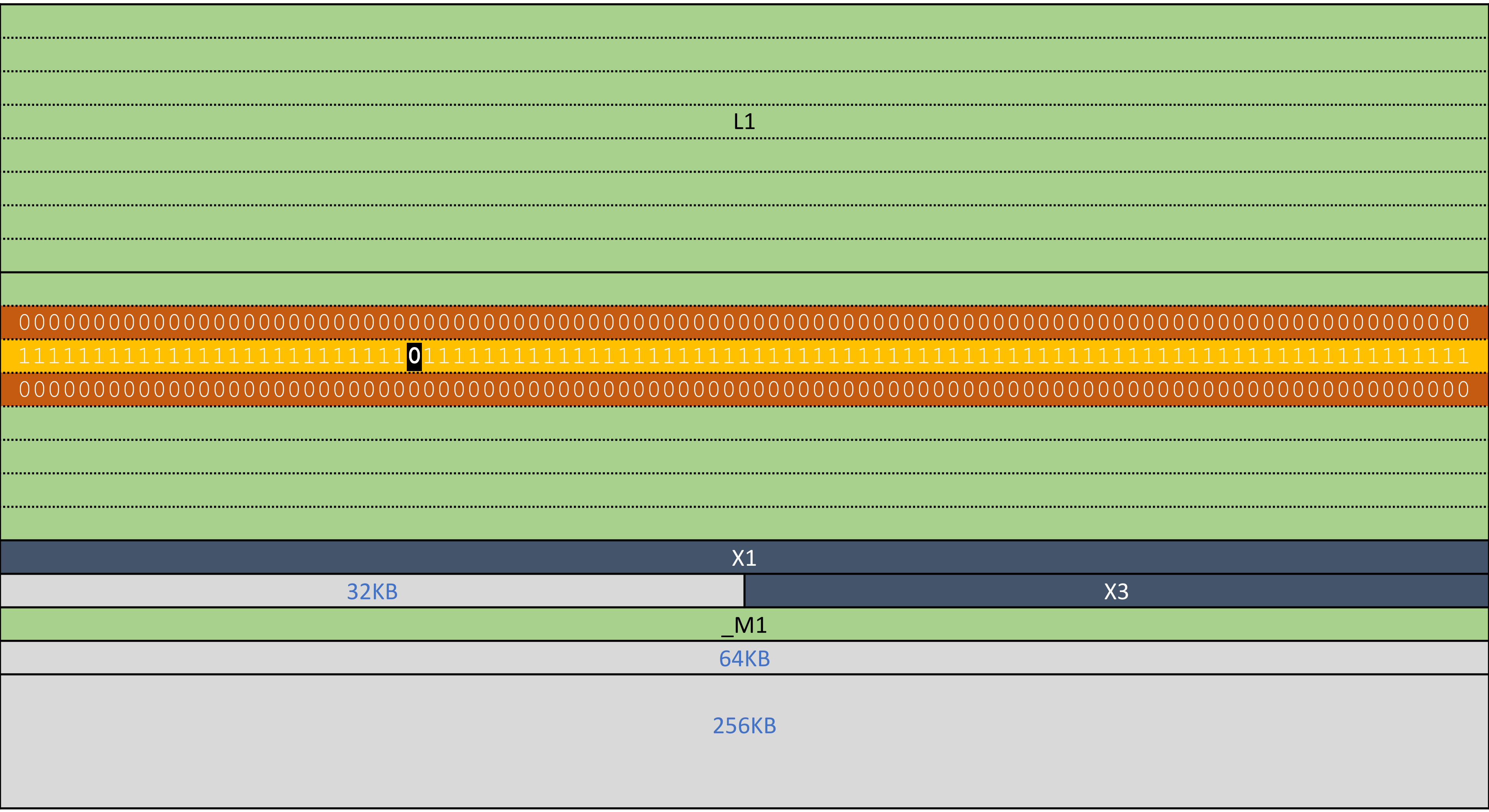

Phys Feng Shui step 2/8

Exhaust *Medium-sized* chunks

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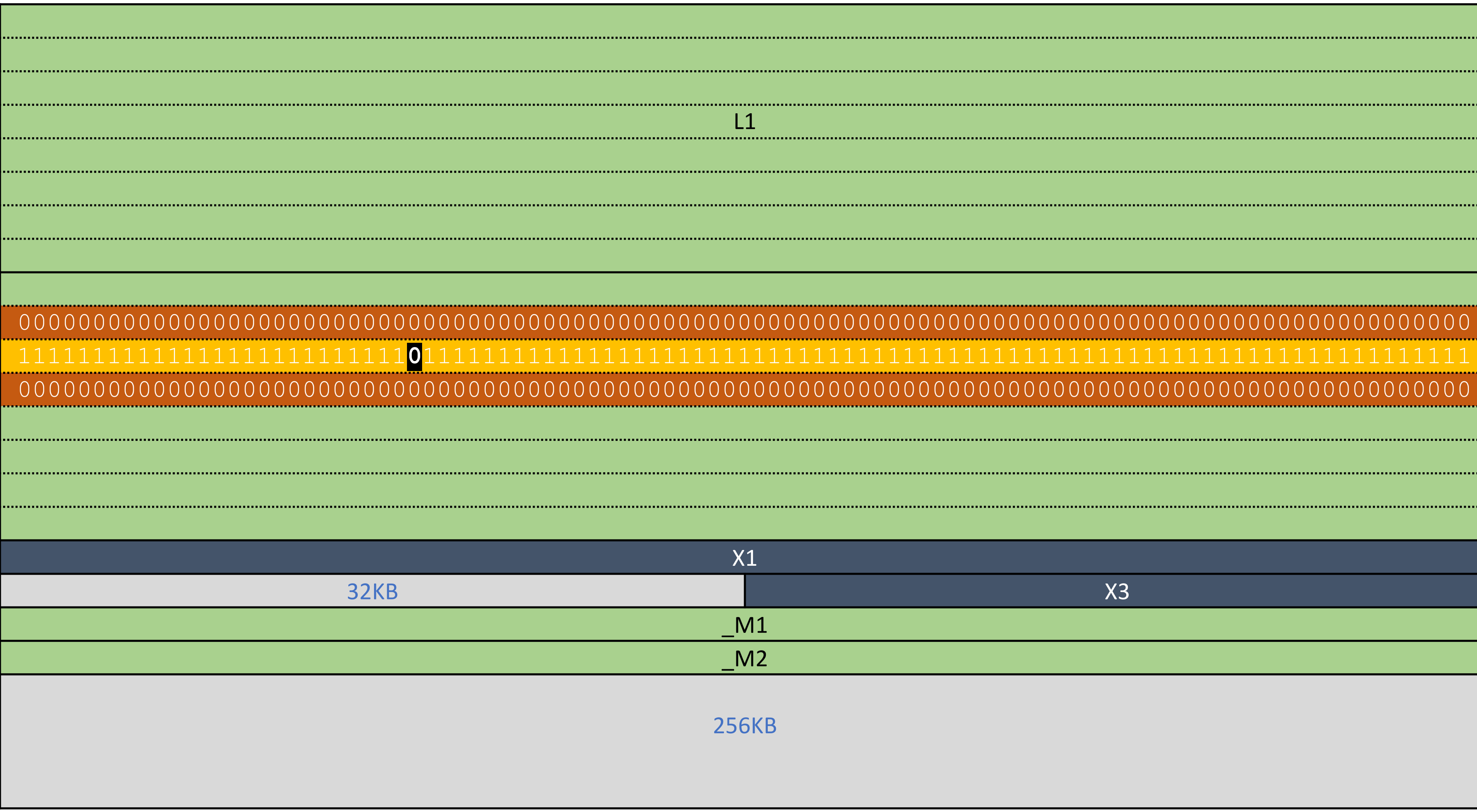

Phys Feng Shui step 2/8

Exhaust *Medium-sized* chunks

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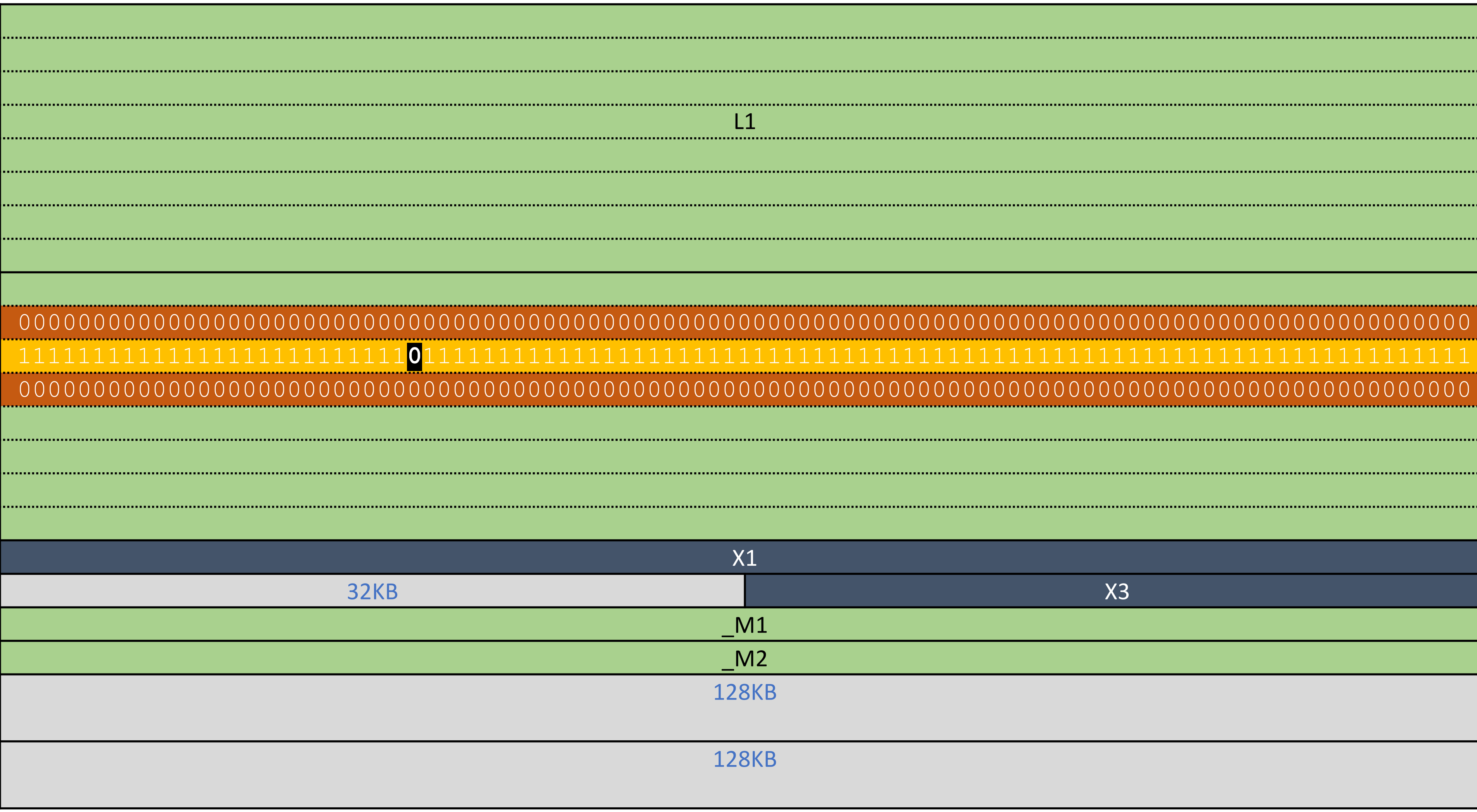

Phys Feng Shui step 2/8

Exhaust *Medium-sized* chunks

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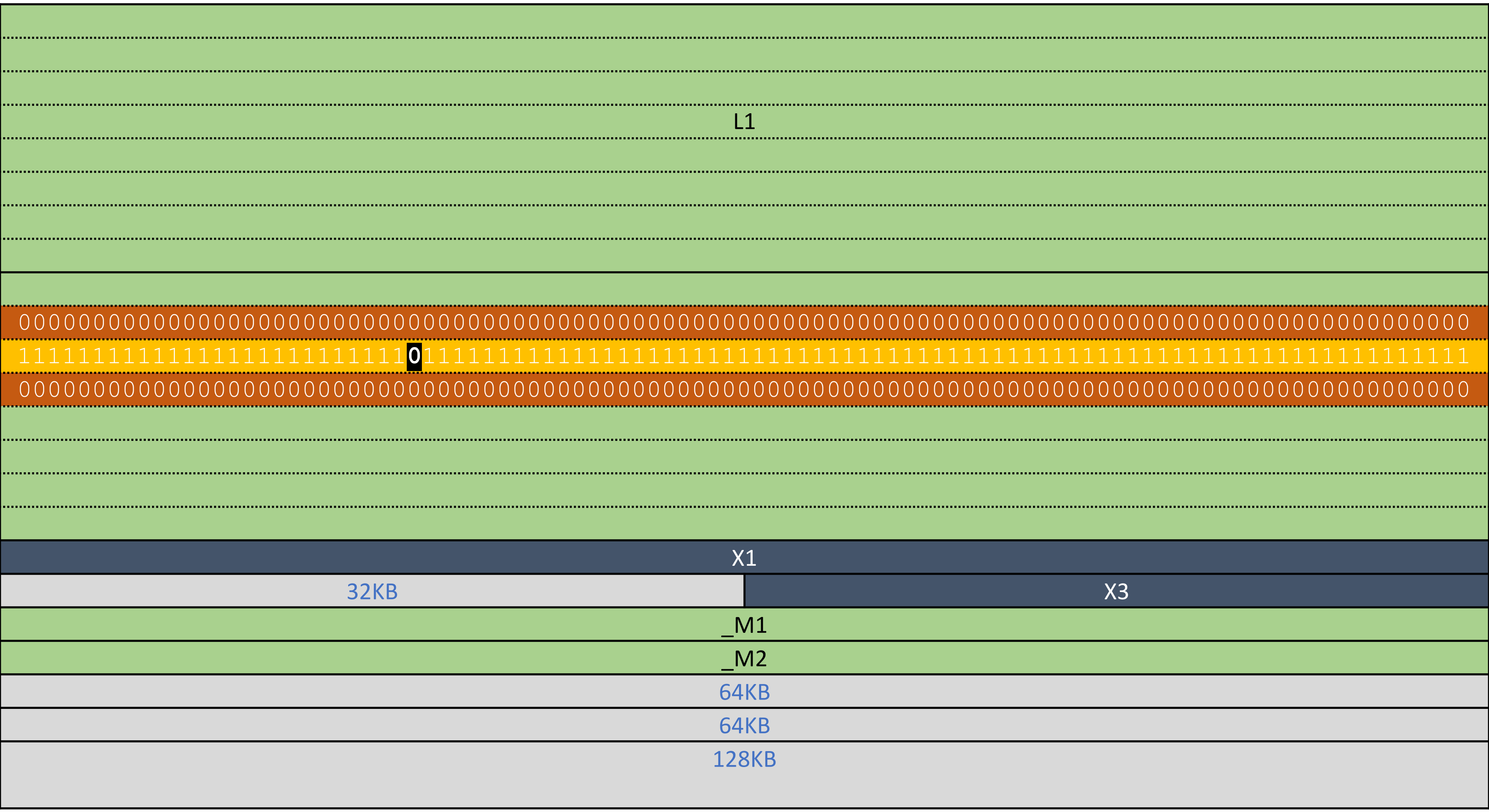

Phys Feng Shui step 2/8

Exhaust *Medium-sized* chunks

```
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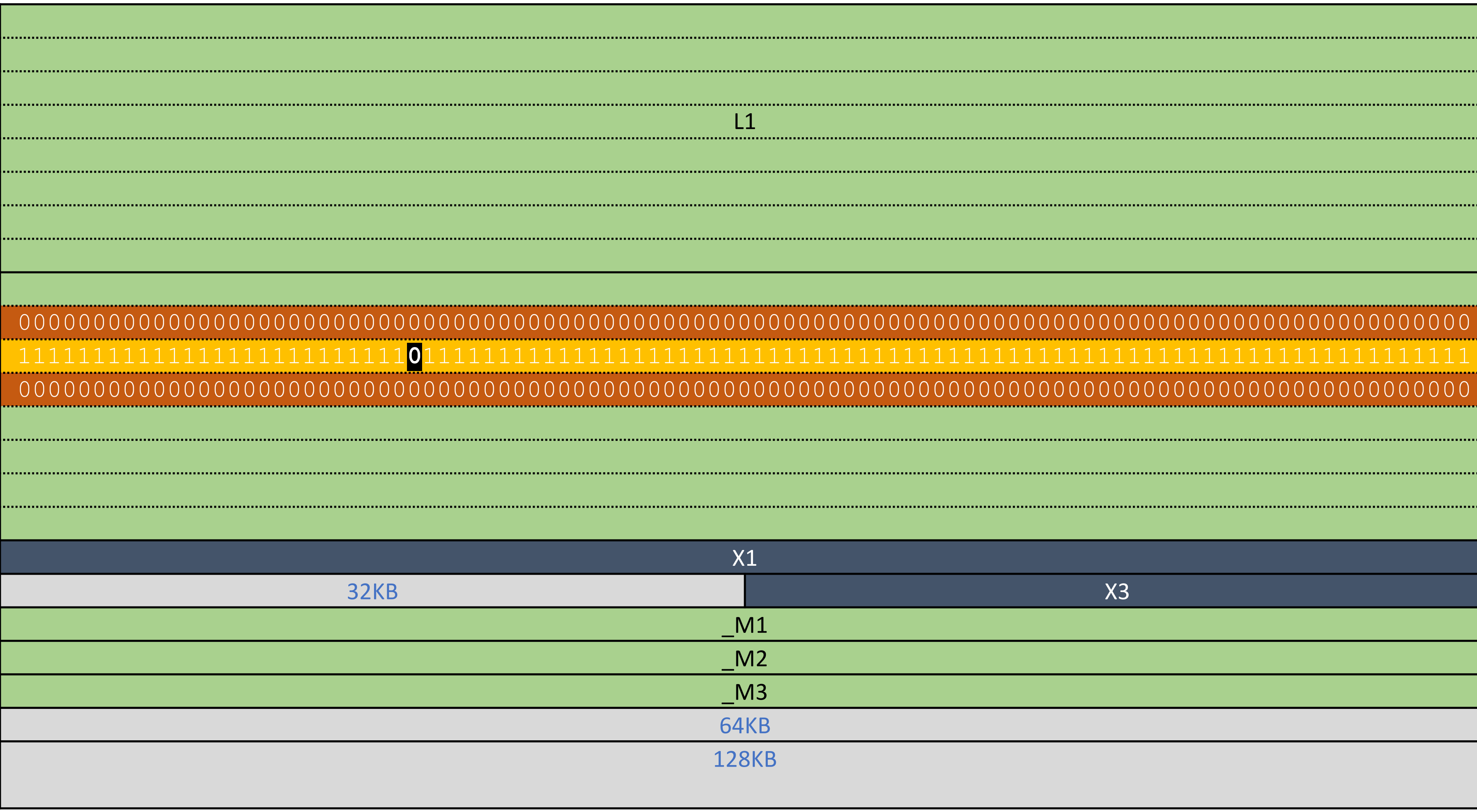

Phys Feng Shui step 2/8

Exhaust *Medium-sized* chunks

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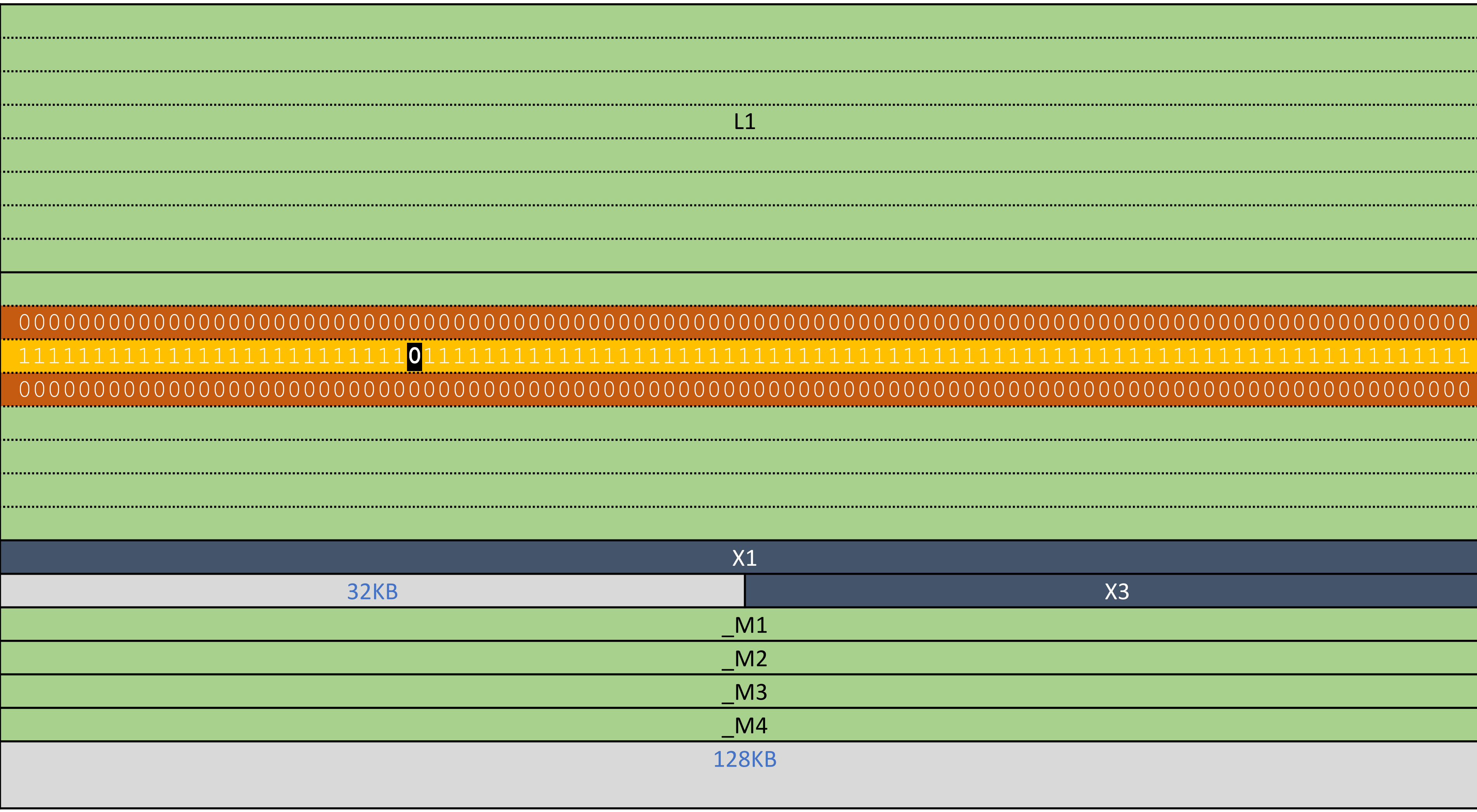

Phys Feng Shui step 2/8

Exhaust *Medium-sized* chunks

```
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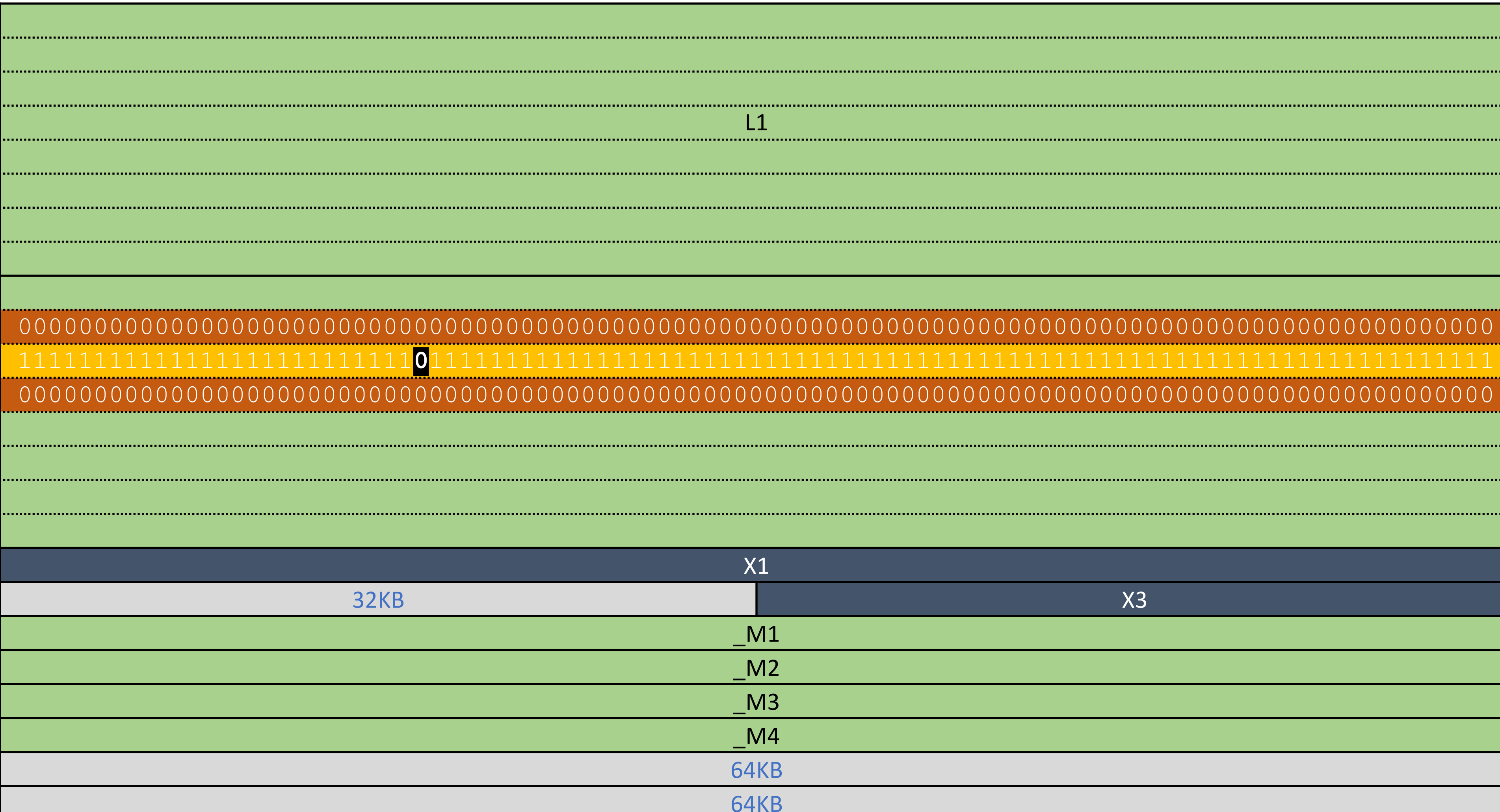

Phys Feng Shui step 2/8

Exhaust *Medium-sized* chunks

```
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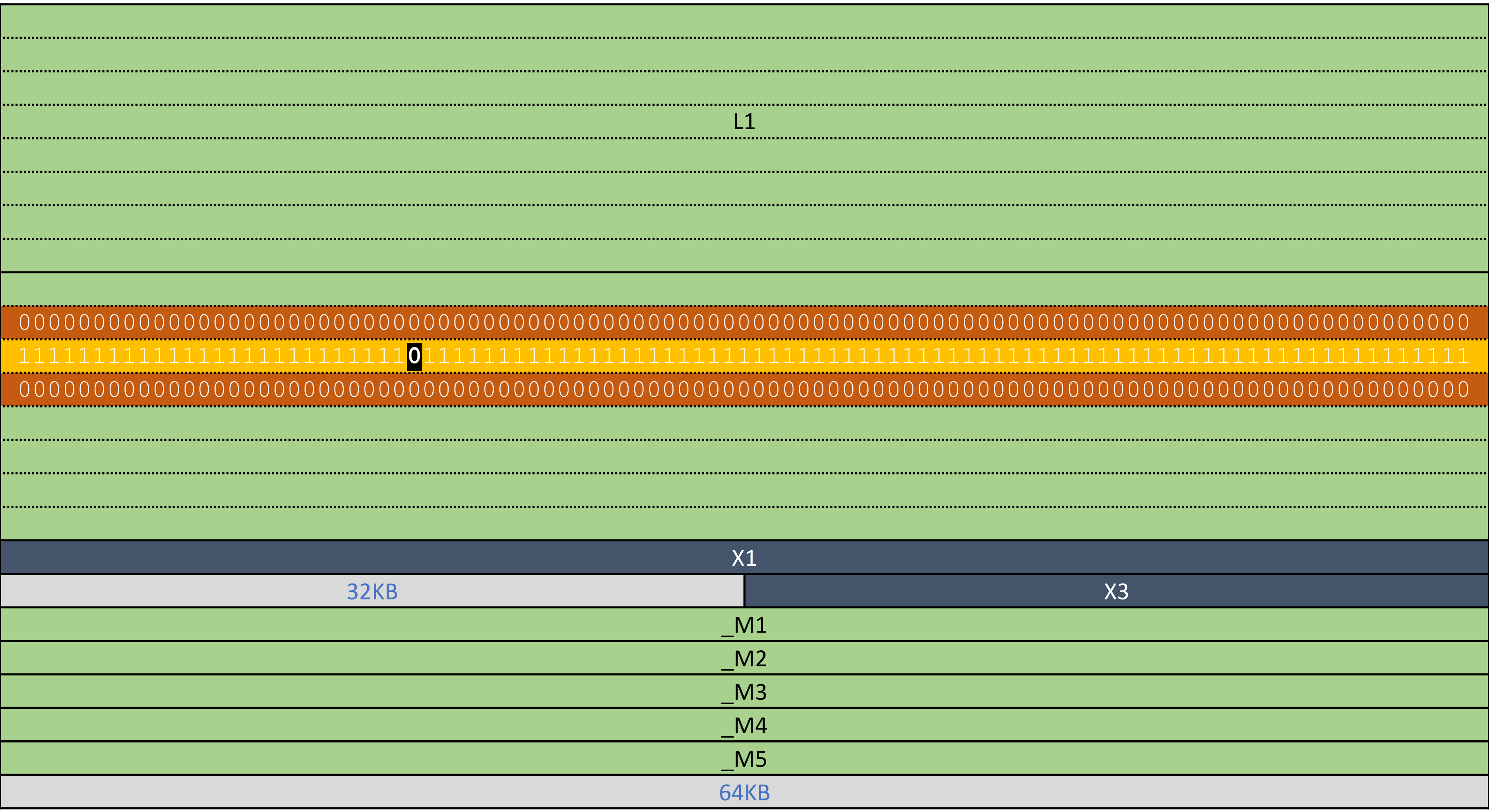
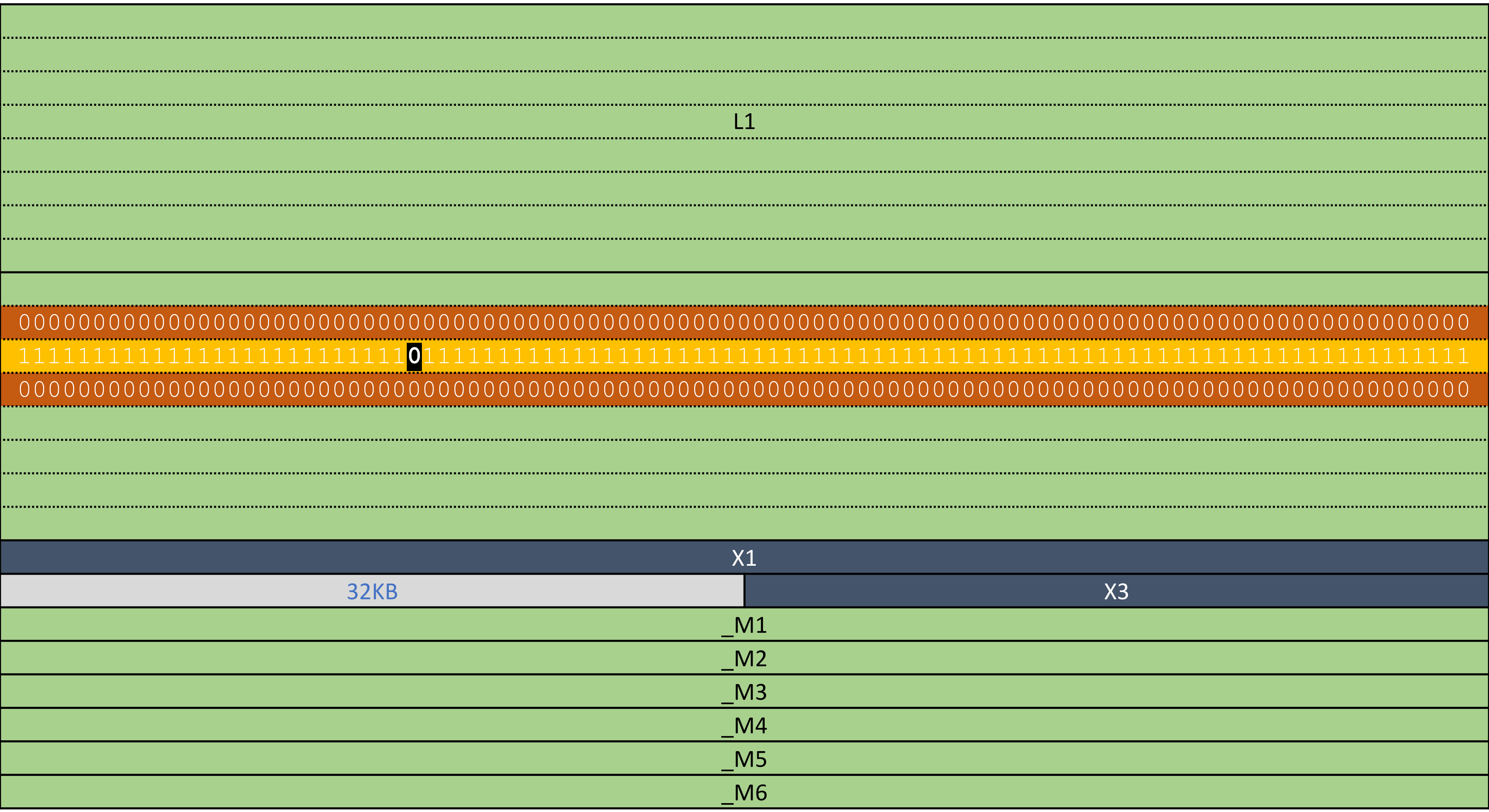


Phys Feng Shui step 2/8

Exhaust *Medium-sized* chunks

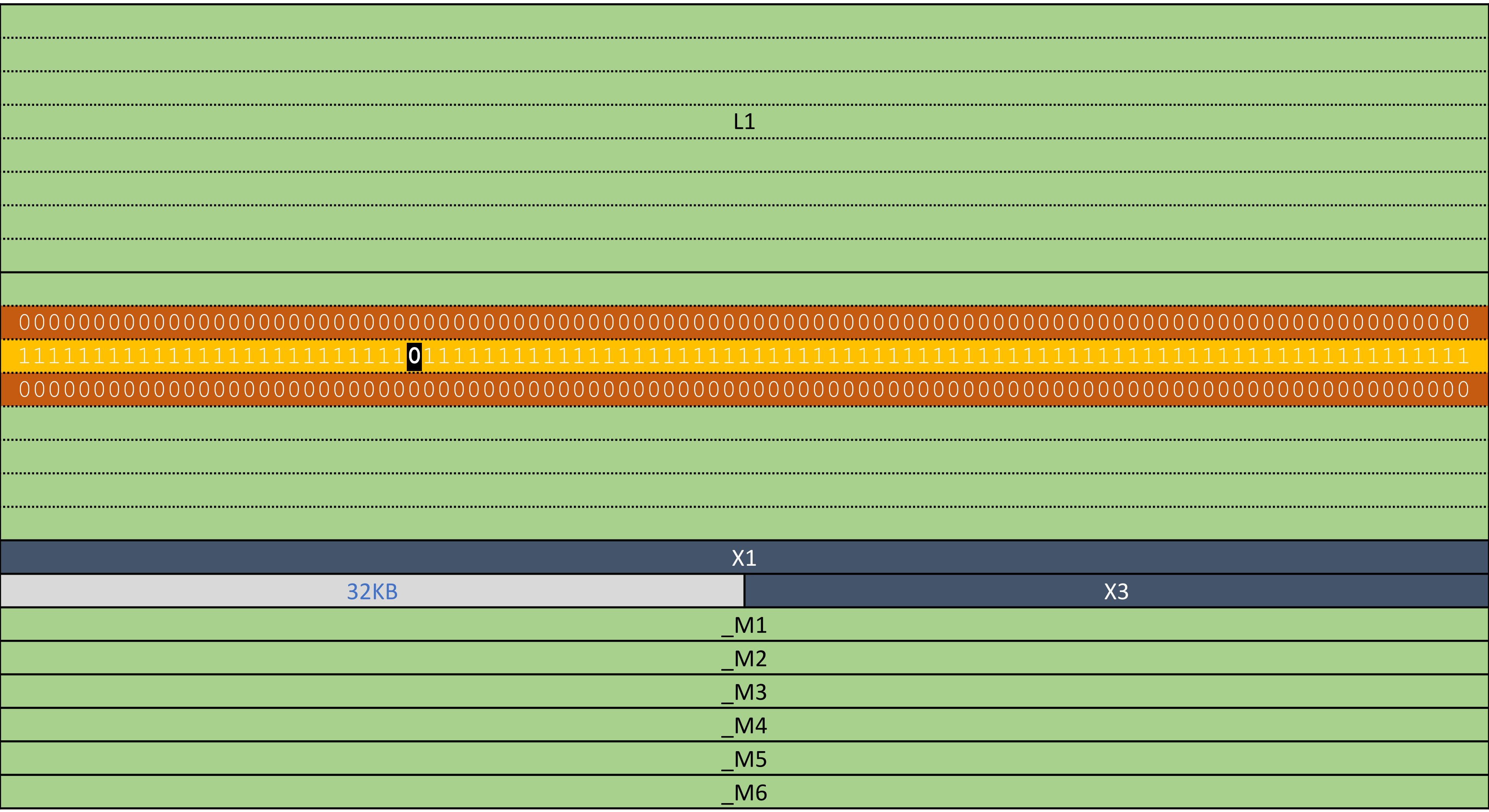
```
_M1, _M2, …, _Mn = exhaust(6); // get all 2^6 = 64KB chunks
```



Phys Feng Shui step 3/8

Release *Large* chunk with vulnerable page

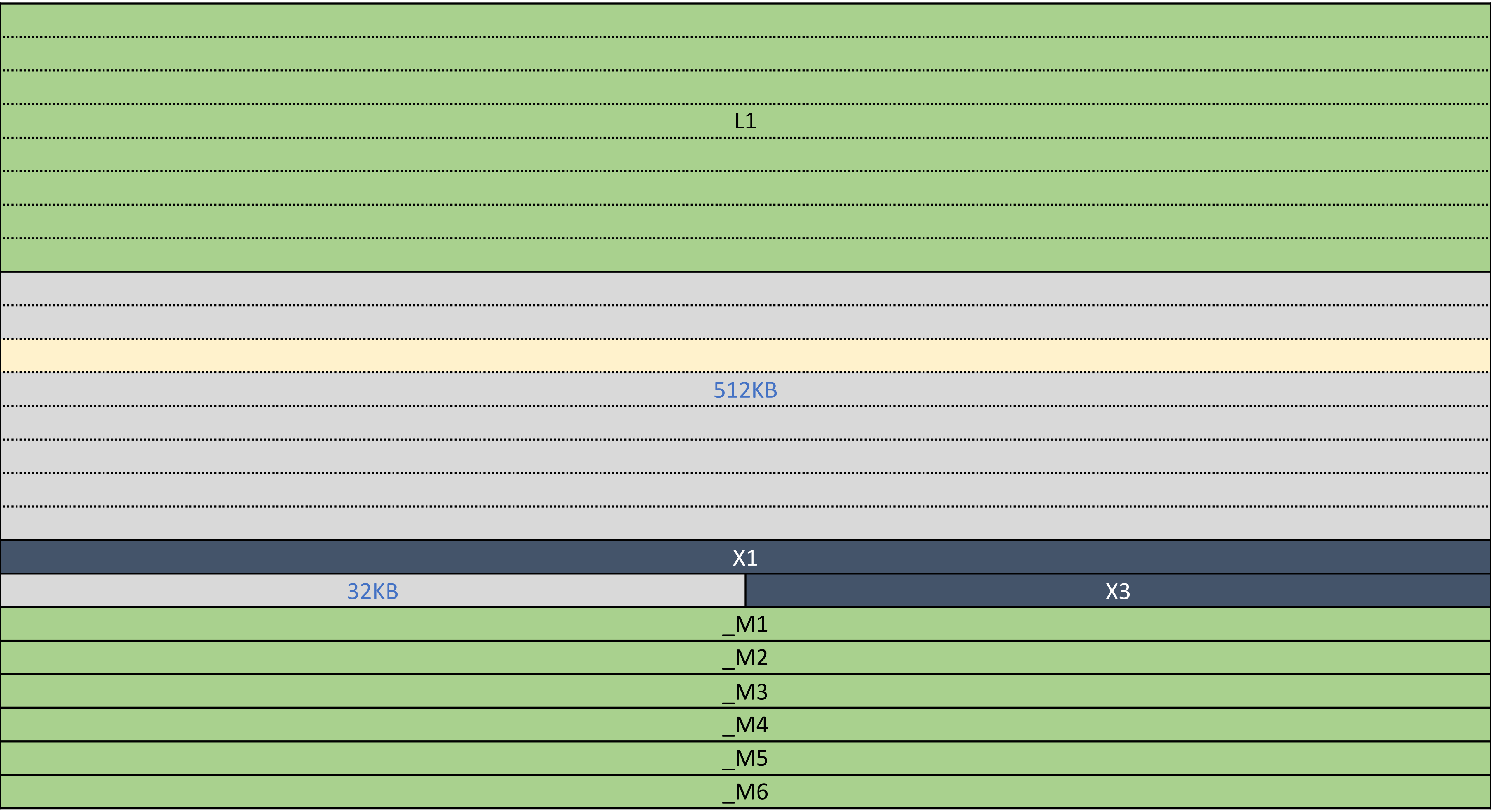
```
Release(L2); // L chunk with vulnerable page
```



Phys Feng Shui step 4/8

Exhaust *Medium-sized* chunks (again)

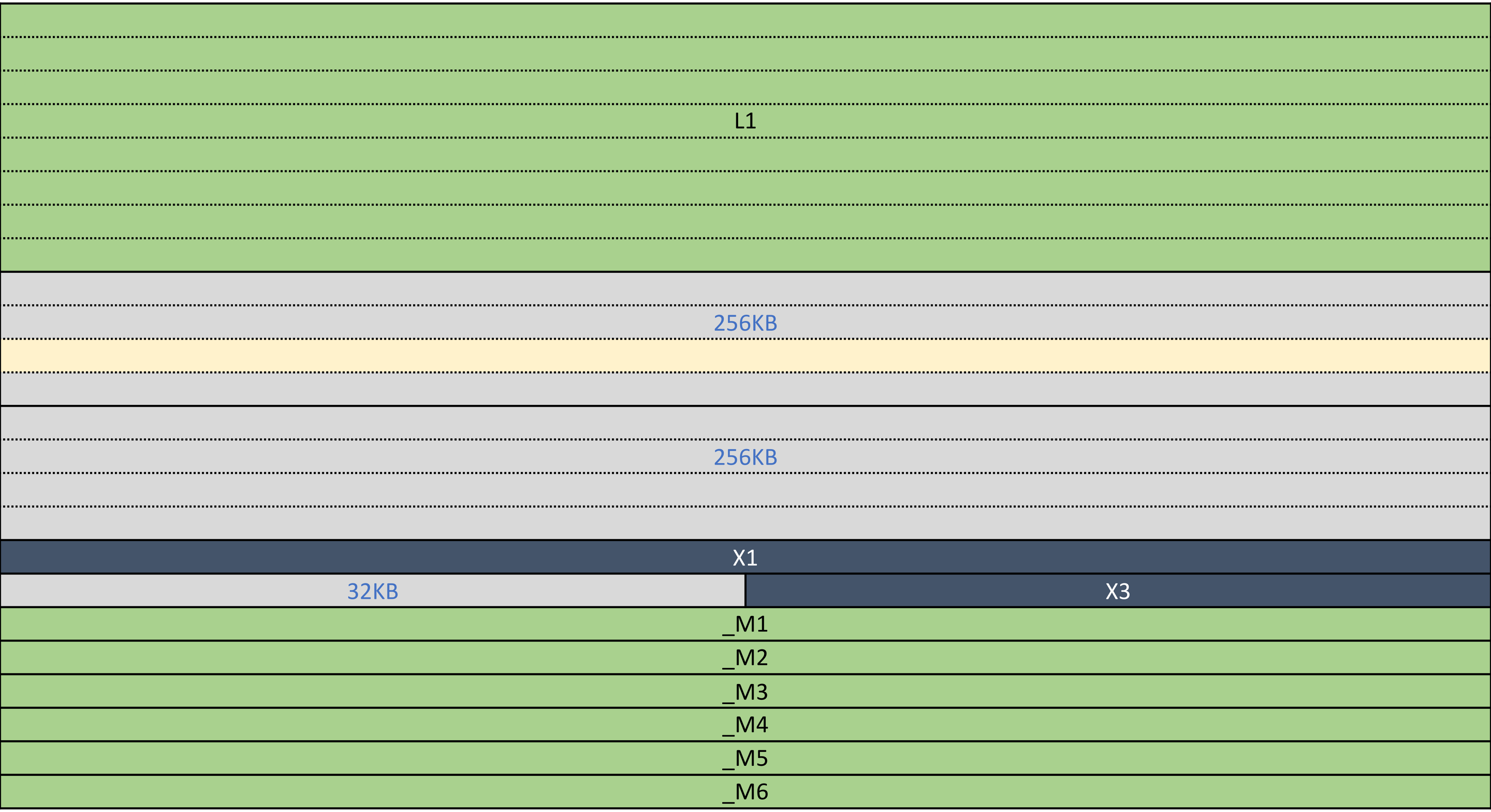
```
M1, M2, …, Mn = exhaust(6); // get all 2^6 = 64KB chunks
```



Phys Feng Shui step 4/8

Exhaust *Medium-sized* chunks (again)

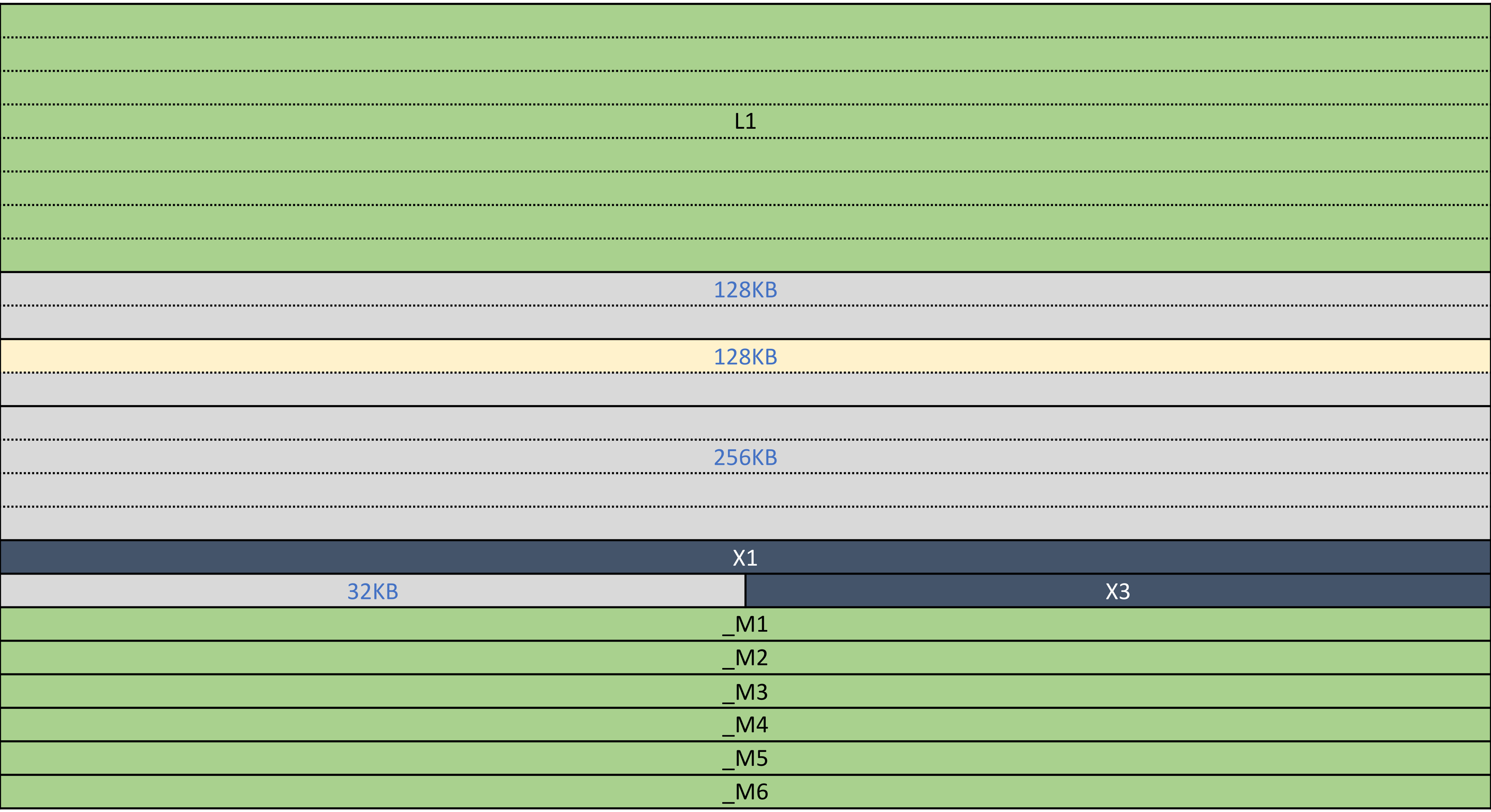
```
M1, M2, …, Mn = exhaust(6); // get all 2^6 = 64KB chunks
```



Phys Feng Shui step 4/8

Exhaust *Medium-sized* chunks (again)

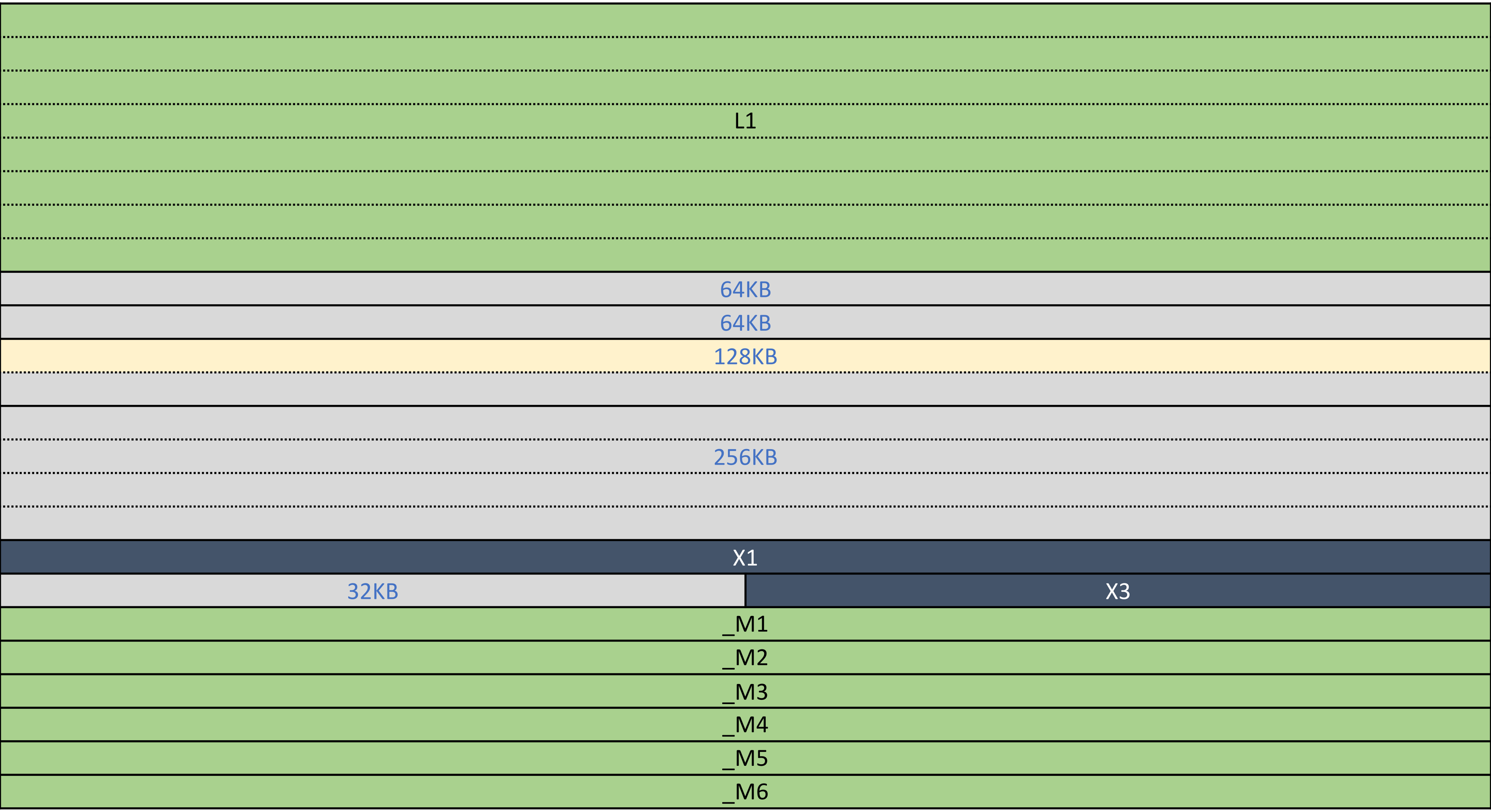
```
M1, M2, …, Mn = exhaust(6); // get all 2^6 = 64KB chunks
```



Phys Feng Shui step 4/8

Exhaust *Medium-sized* chunks (again)

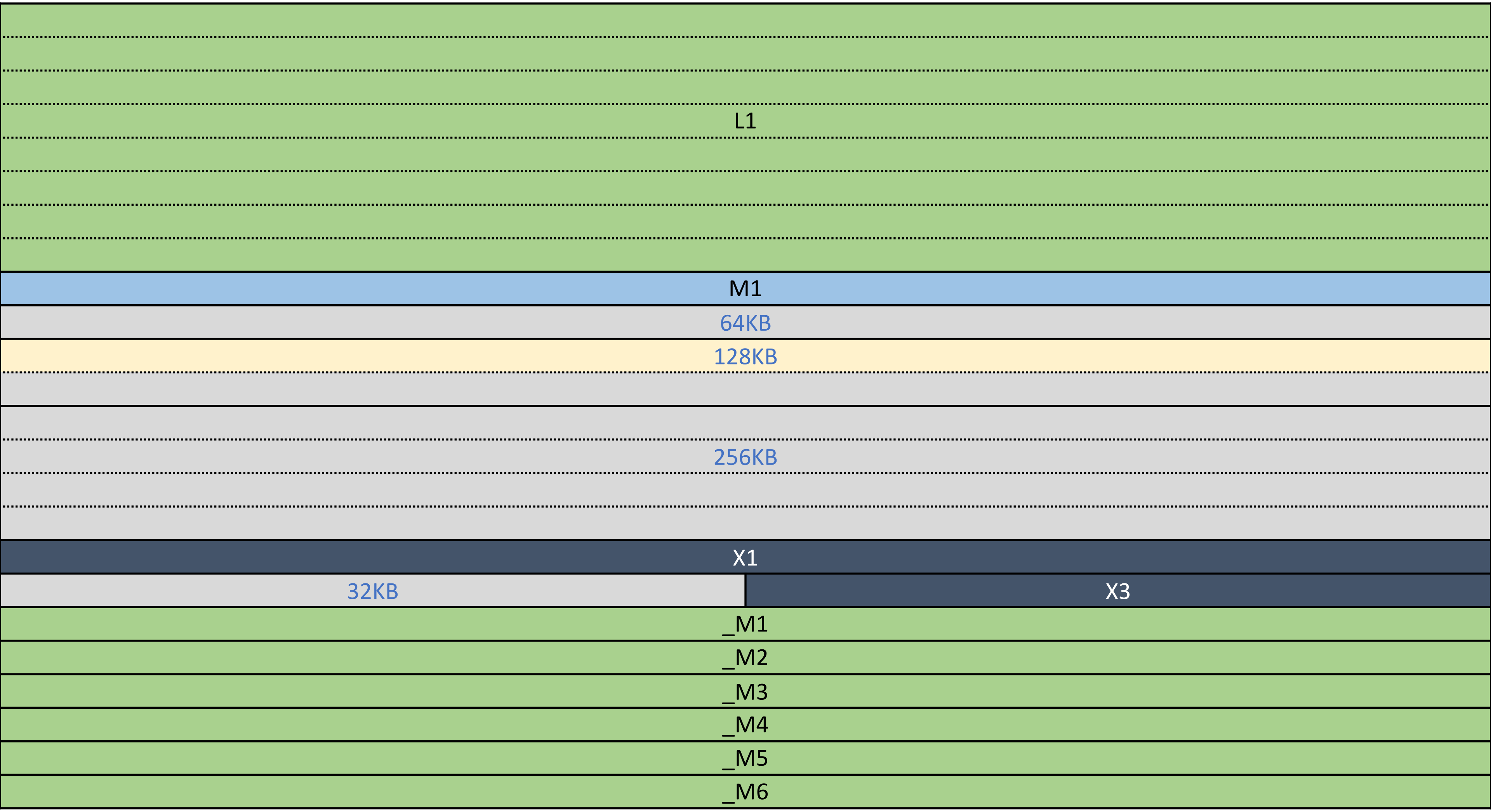
```
M1, M2, …, Mn = exhaust(6); // get all 2^6 = 64KB chunks
```



Phys Feng Shui step 4/8

Exhaust *Medium-sized* chunks (again)

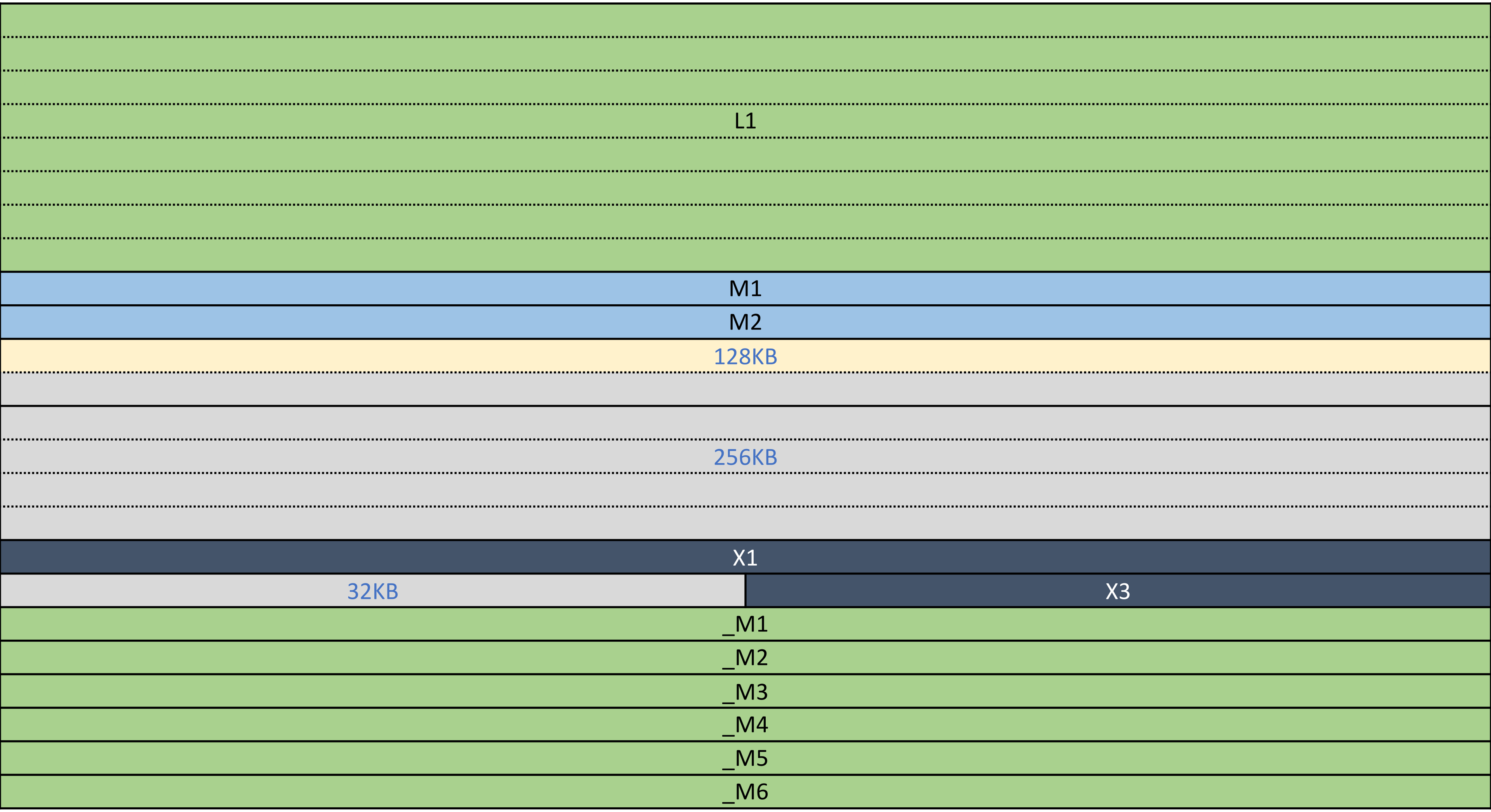
```
M1, M2, …, Mn = exhaust(6); // get all 2^6 = 64KB chunks
```



Phys Feng Shui step 4/8

Exhaust *Medium-sized* chunks (again)

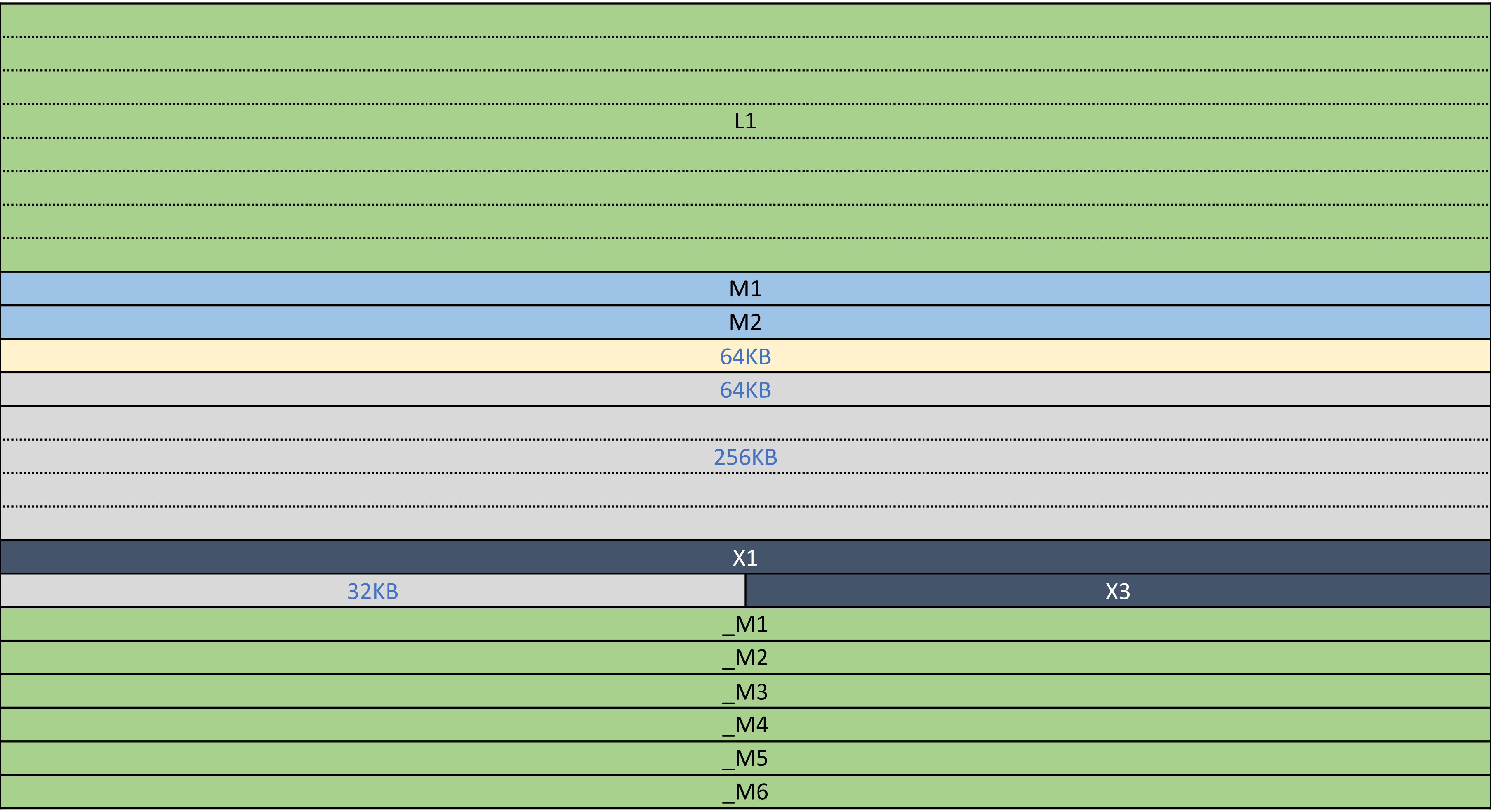
```
M1, M2, …, Mn = exhaust(6); // get all 2^6 = 64KB chunks
```



Phys Feng Shui step 4/8

Exhaust *Medium-sized* chunks (again)

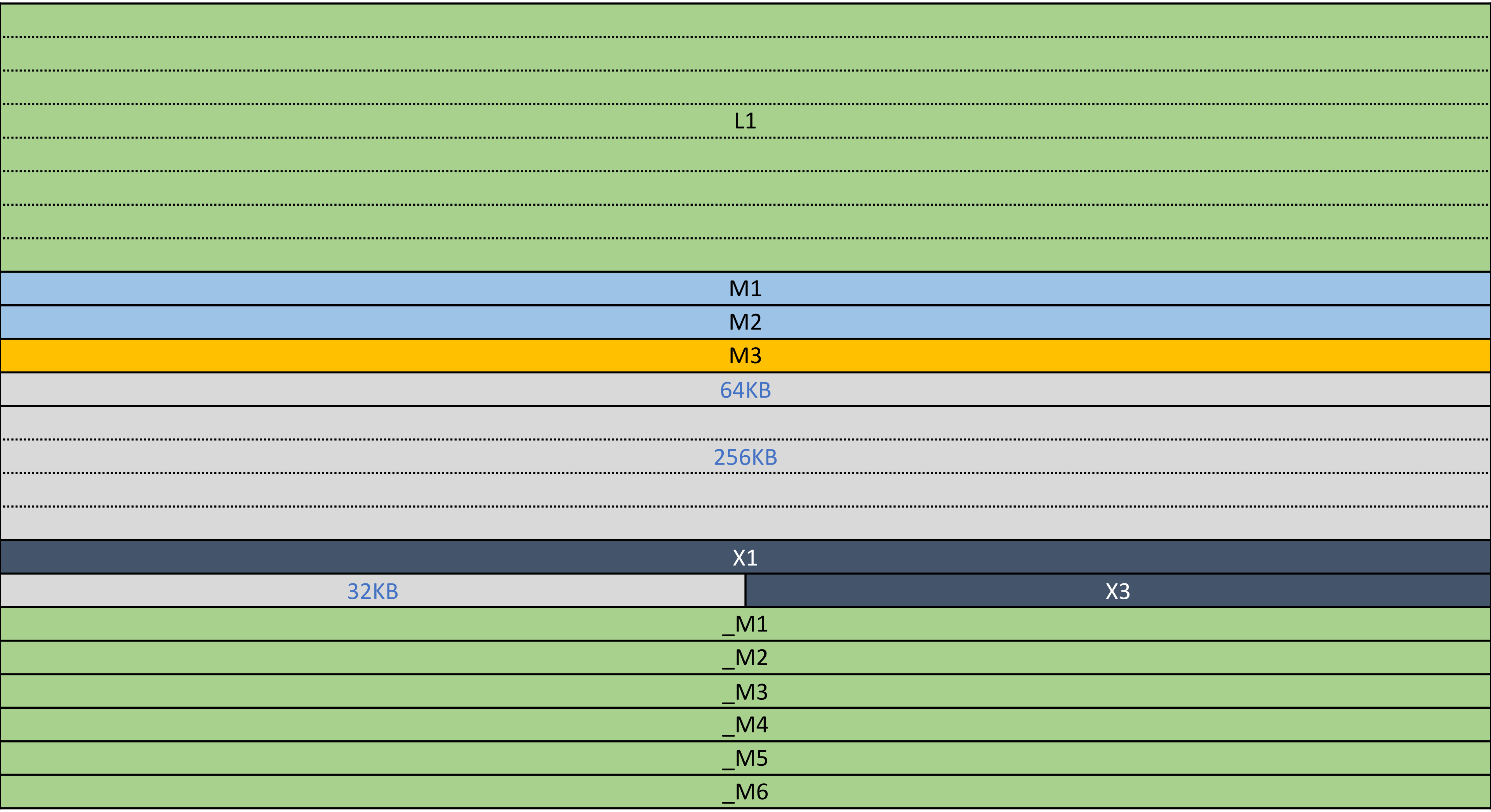
```
M1, M2, …, Mn = exhaust(6); // get all 2^6 = 64KB chunks
```



Phys Feng Shui step 4/8

Exhaust *Medium-sized* chunks (again)

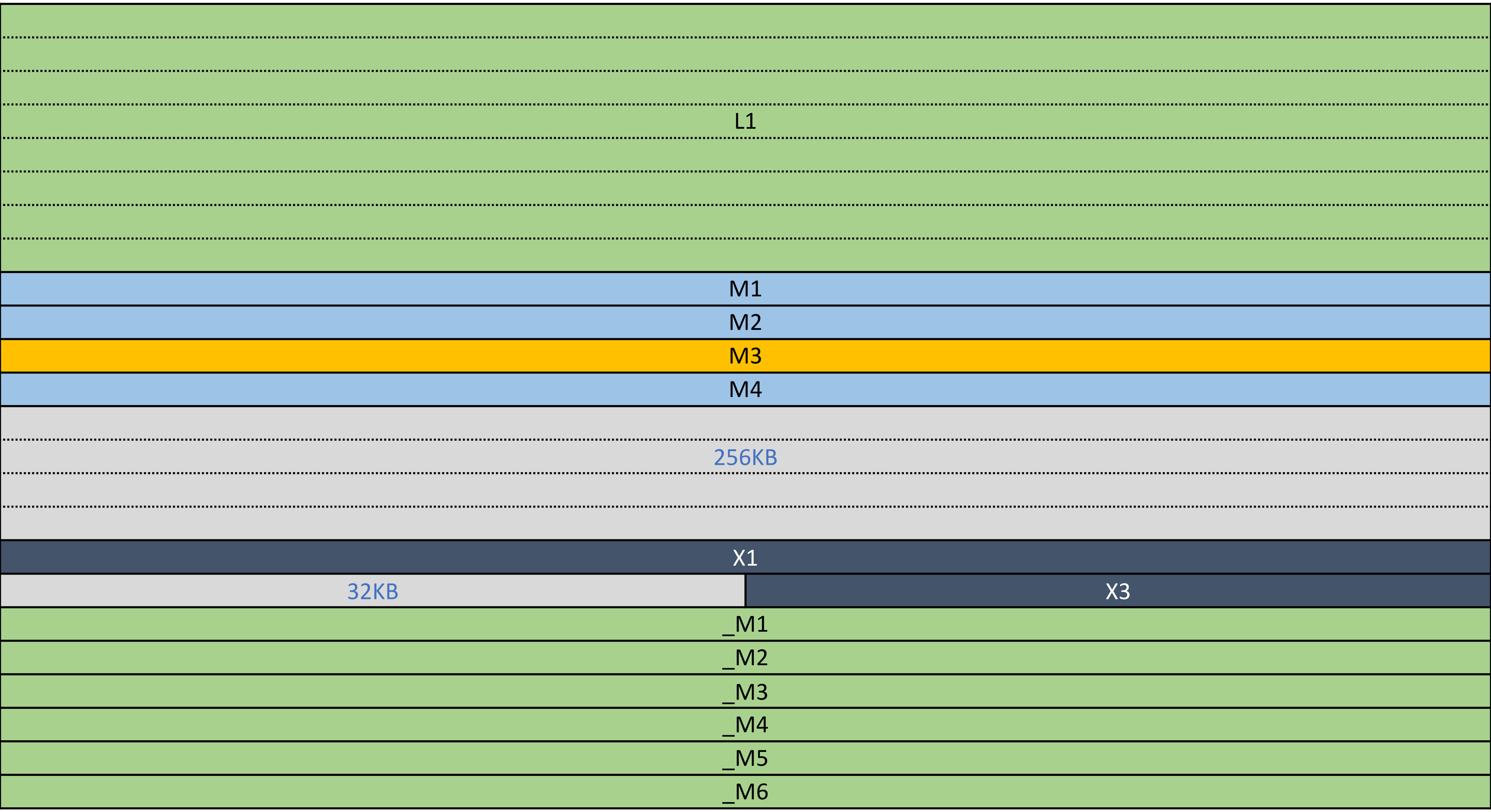
```
M1, M2, …, Mn = exhaust(6); // get all 2^6 = 64KB chunks
```



Phys Feng Shui step 4/8

Exhaust *Medium-sized* chunks (again)

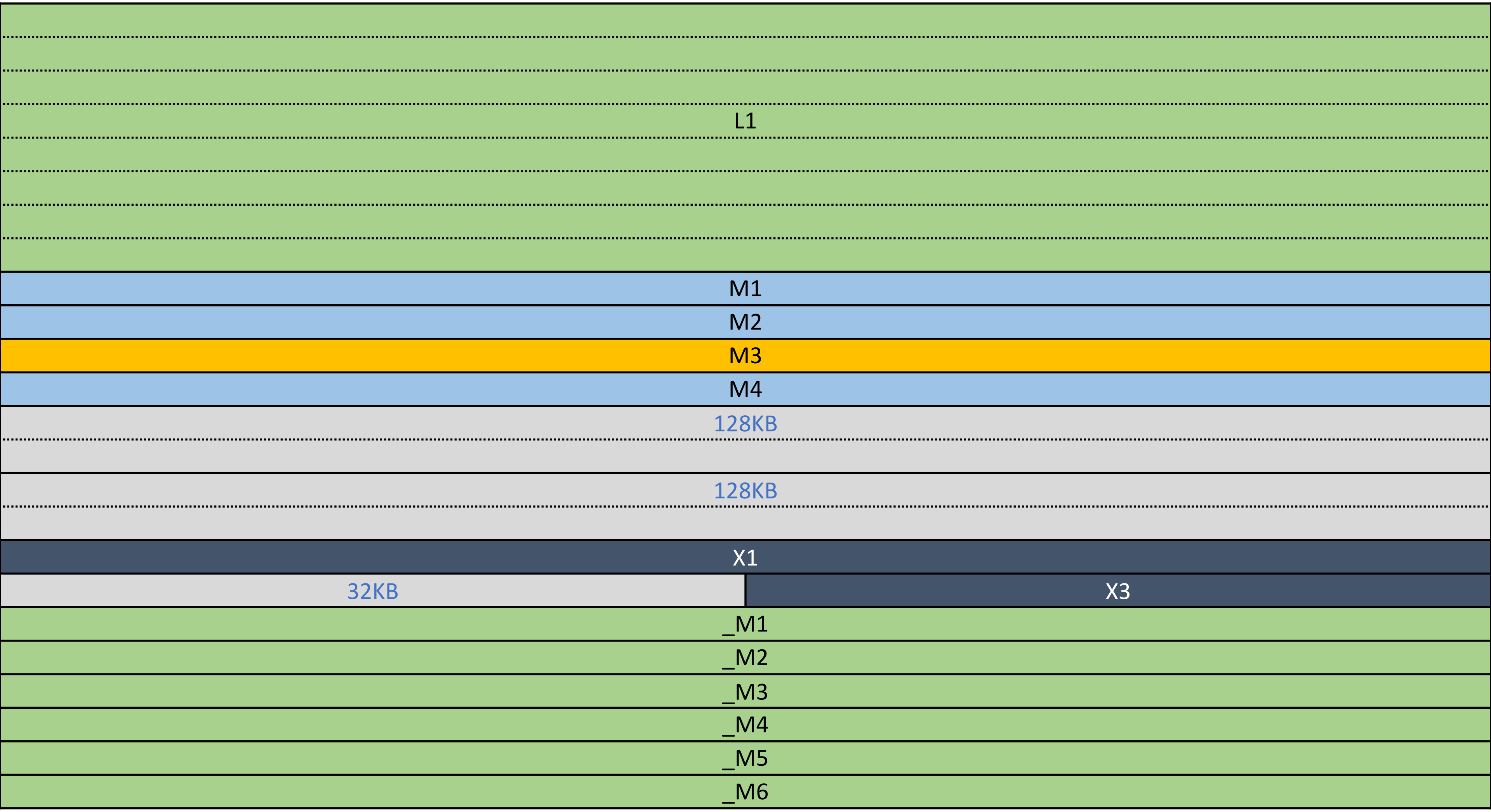
```
M1, M2, …, Mn = exhaust(6); // get all 2^6 = 64KB chunks
```



Phys Feng Shui step 4/8

Exhaust *Medium-sized* chunks (again)

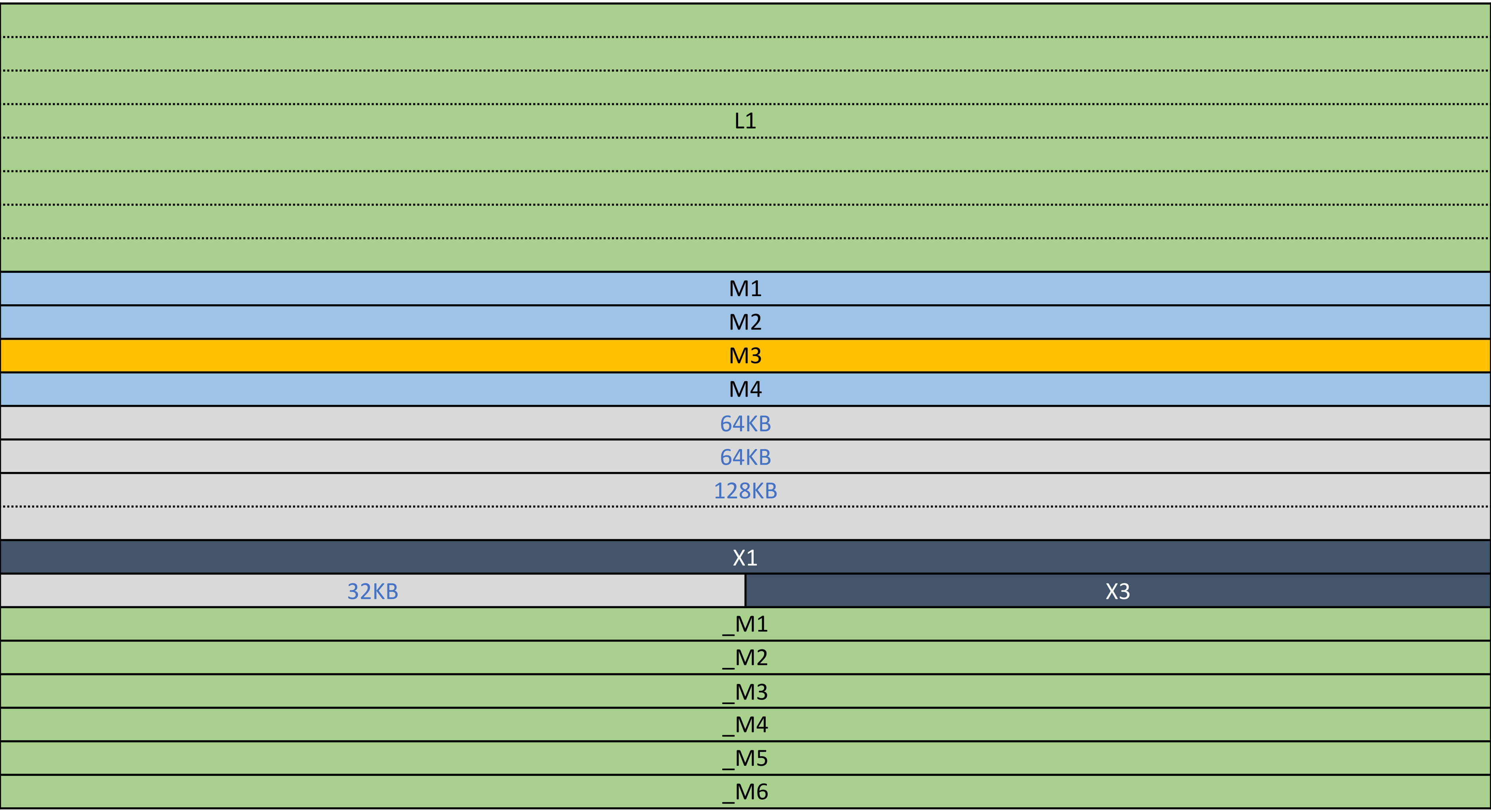
`M1, M2, …, Mn = exhaust(6); // get all 2^6 = 64KB chunks`



Phys Feng Shui step 4/8

Exhaust *Medium-sized* chunks (again)

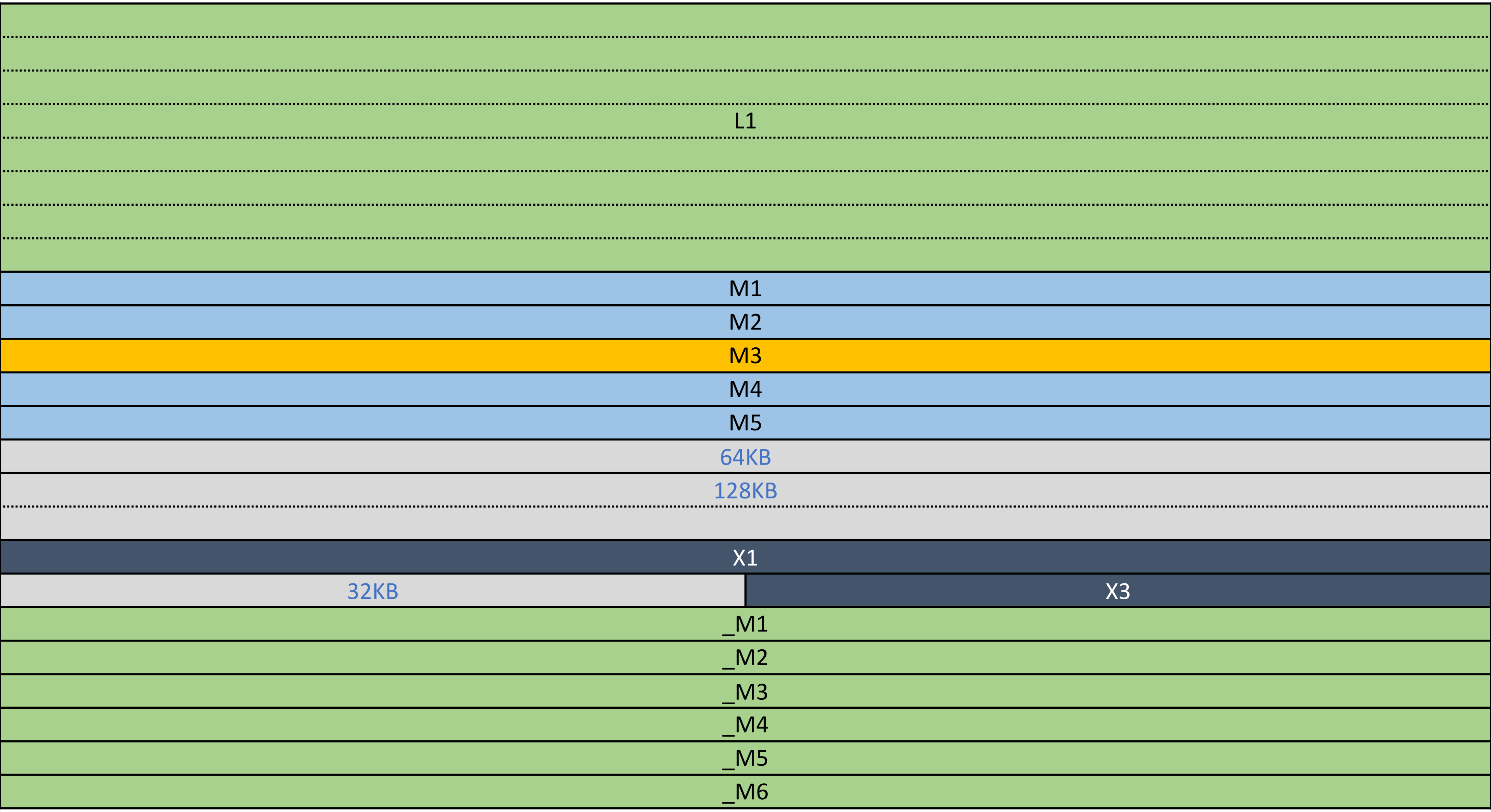
```
M1, M2, …, Mn = exhaust(6); // get all 2^6 = 64KB chunks
```



Phys Feng Shui step 4/8

Exhaust *Medium-sized* chunks (again)

```
M1, M2, …, Mn = exhaust(6); // get all 2^6 = 64KB chunks
```



Phys Feng Shui step 4/8

Exhaust *Medium-sized* chunks (again)

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M1, M2, …, Mn = exhaust(6); // get all 2^6 = 64KB chunks
```

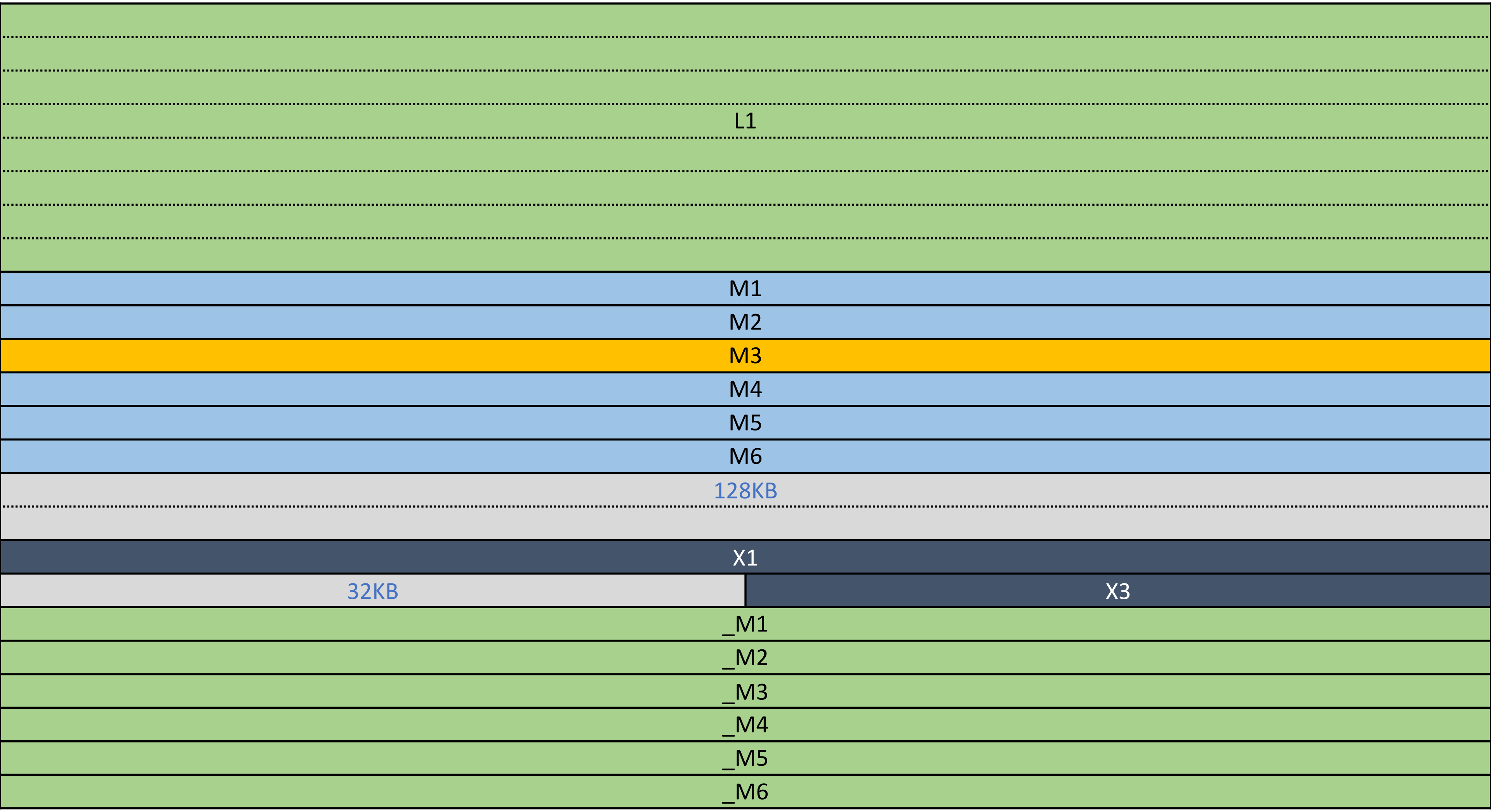

Phys Feng Shui step 4/8

Exhaust *Medium-sized* chunks (again)

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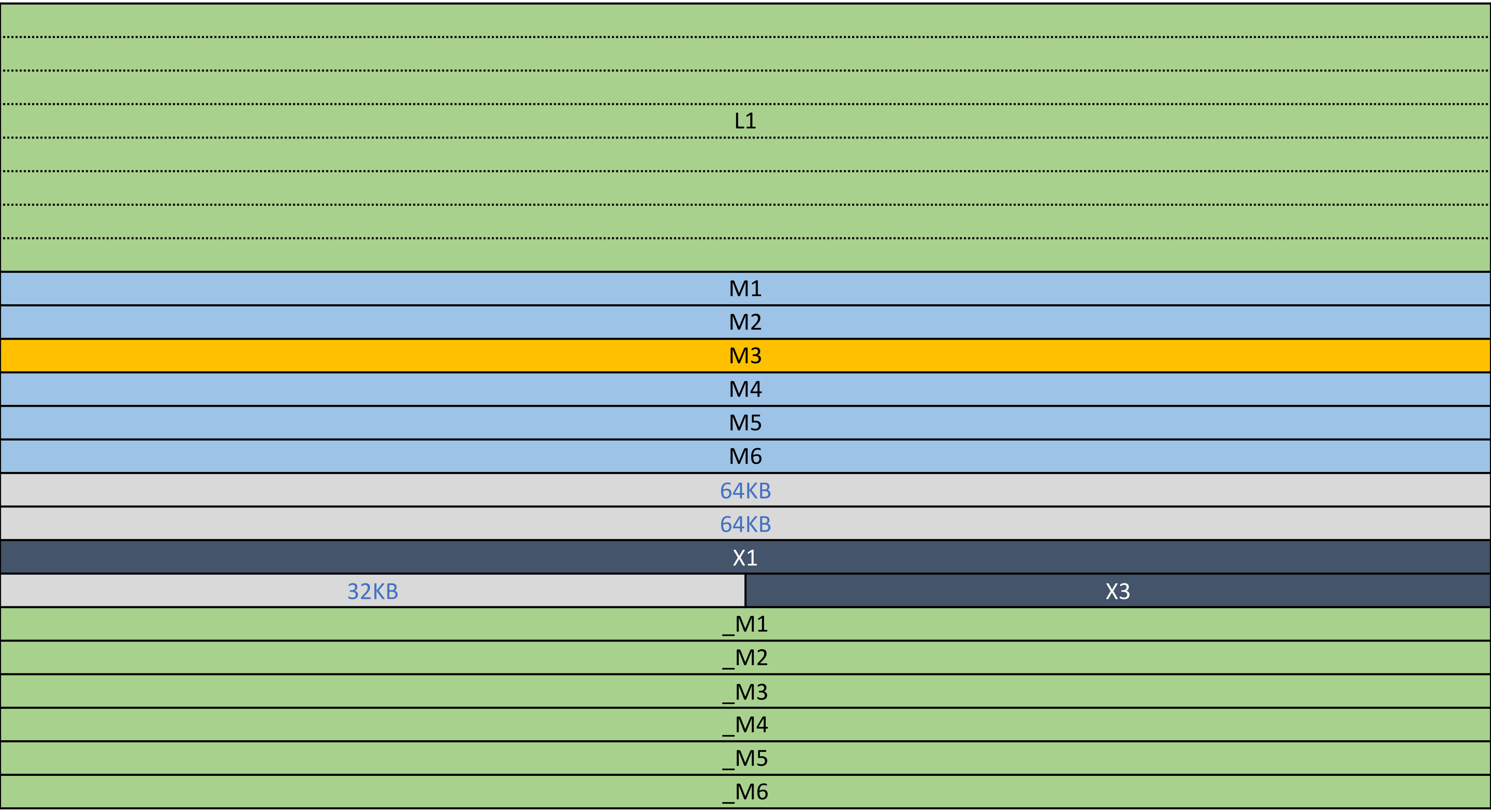
M1, M2, …, Mn = exhaust(6); // get all 2^6 = 64KB chunks
```



Phys Feng Shui step 4/8

Exhaust *Medium-sized* chunks (again)

```
M1, M2, …, Mn = exhaust(6); // get all 2^6 = 64KB chunks
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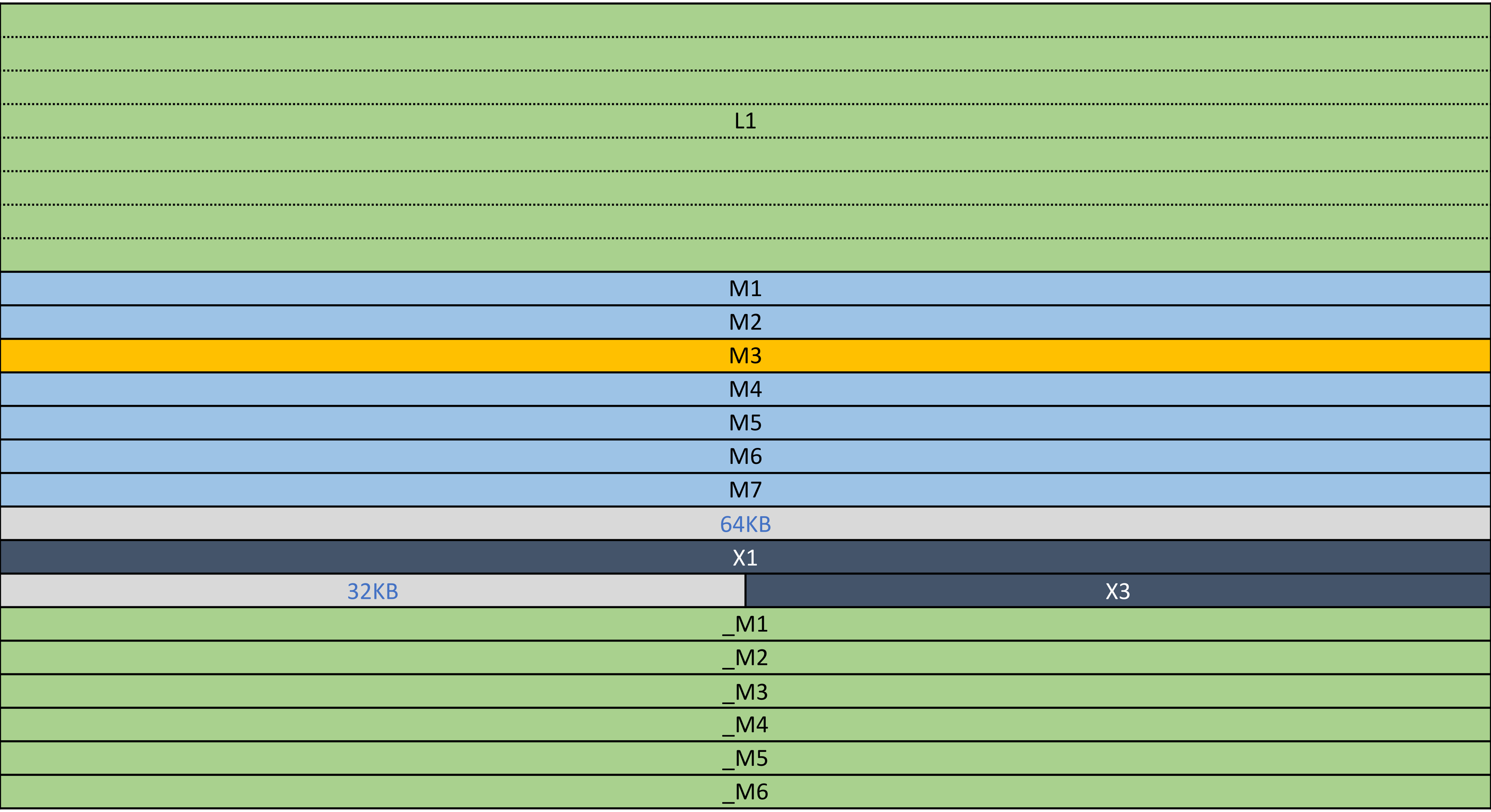

Phys Feng Shui step 4/8

Exhaust *Medium-sized* chunks (again)

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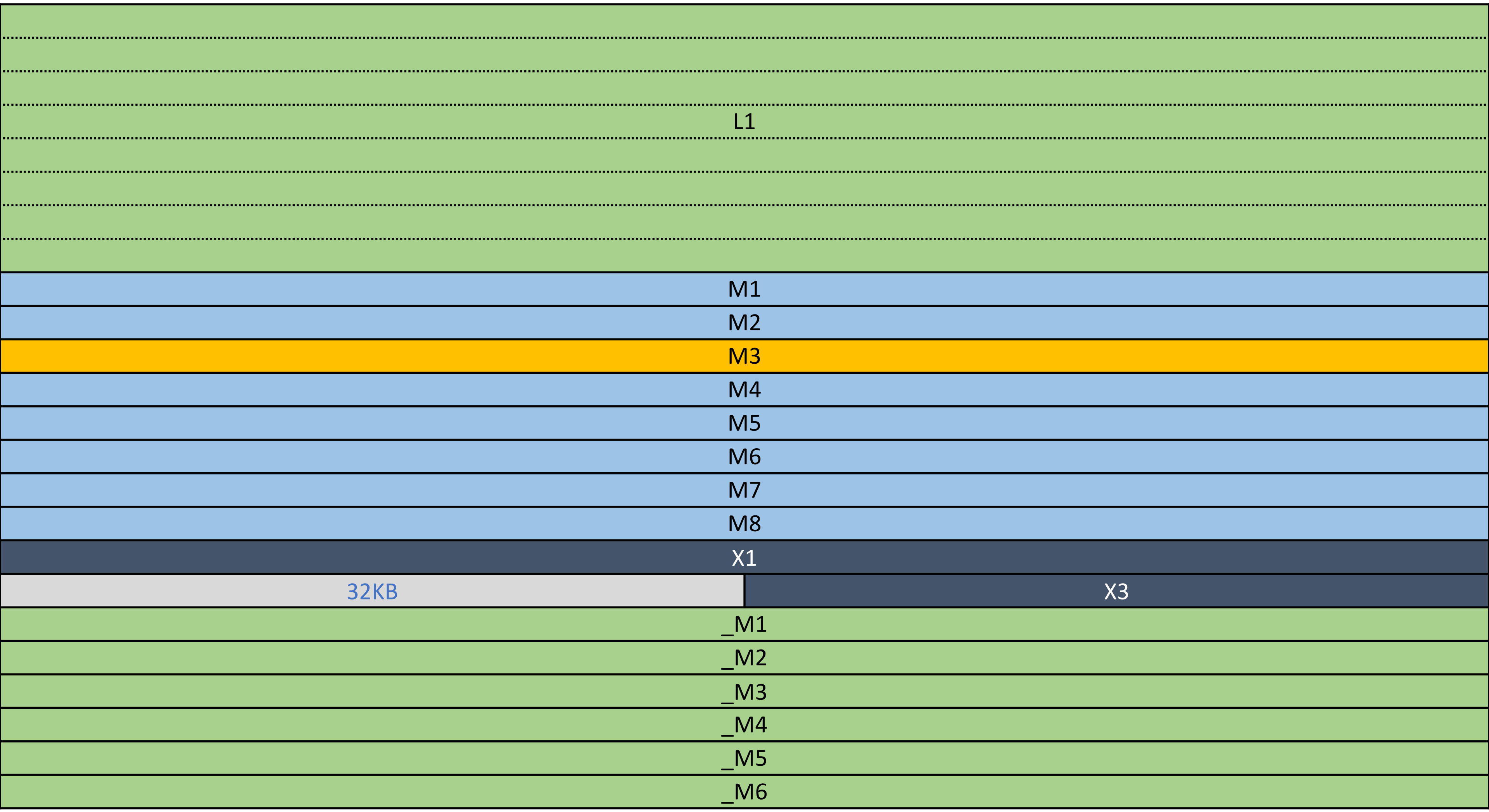
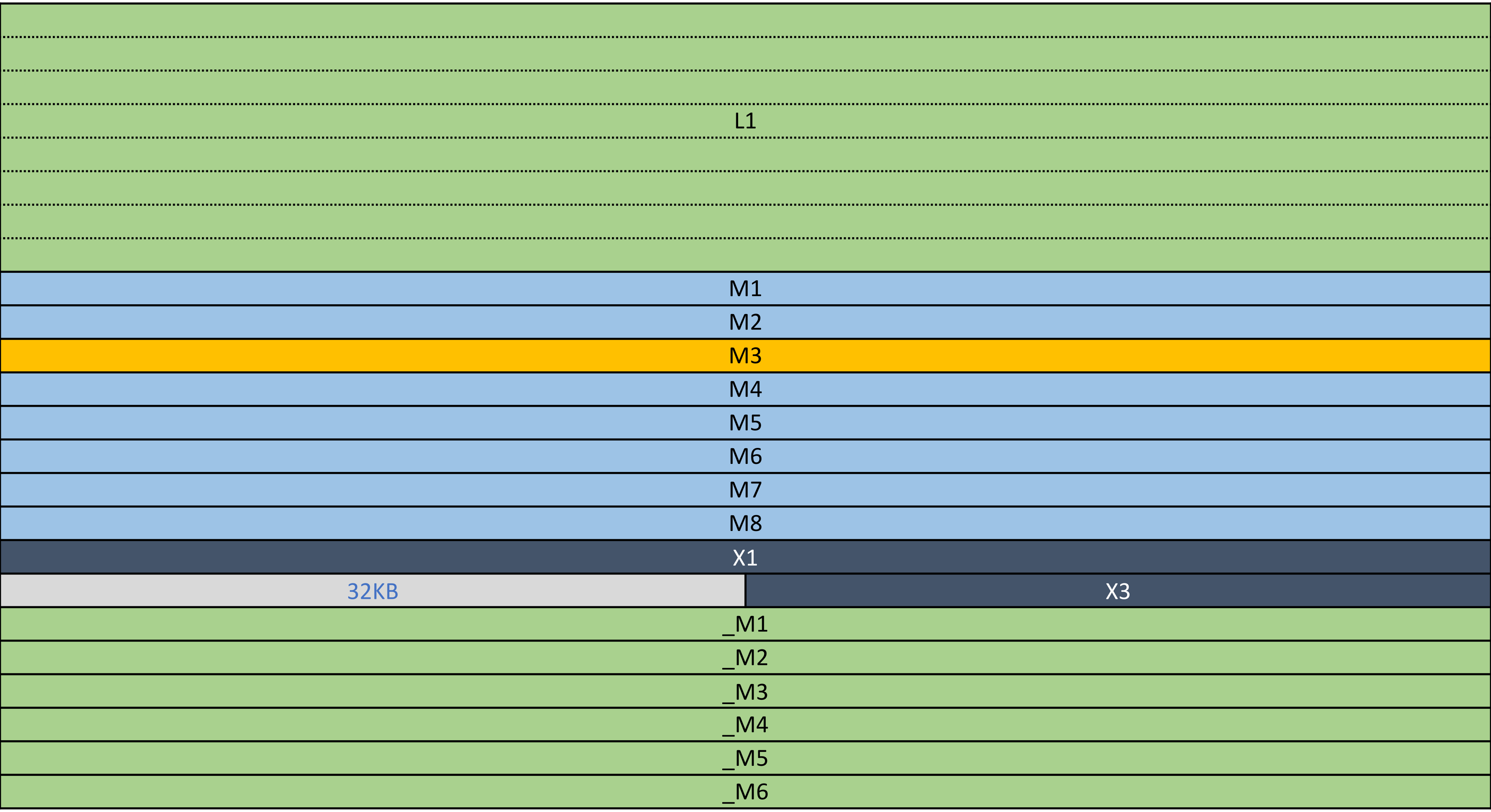


Phys Feng Shui step 5/8

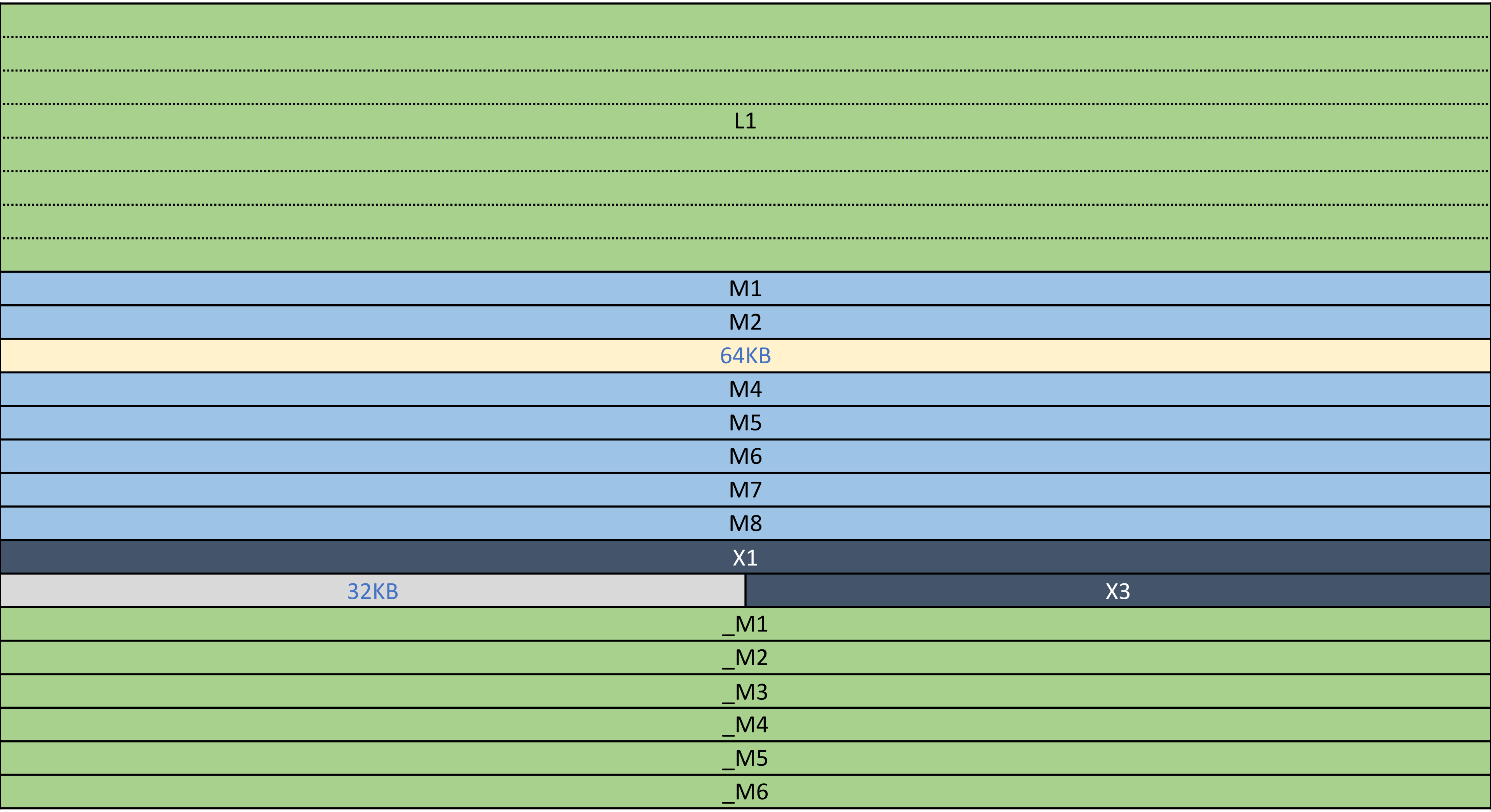
Release vulnerable *Medium-sized* chunk + Release all Large chunks



Phys Feng Shui step 5/8

Release vulnerable *Medium-sized* chunk + Release all Large chunks

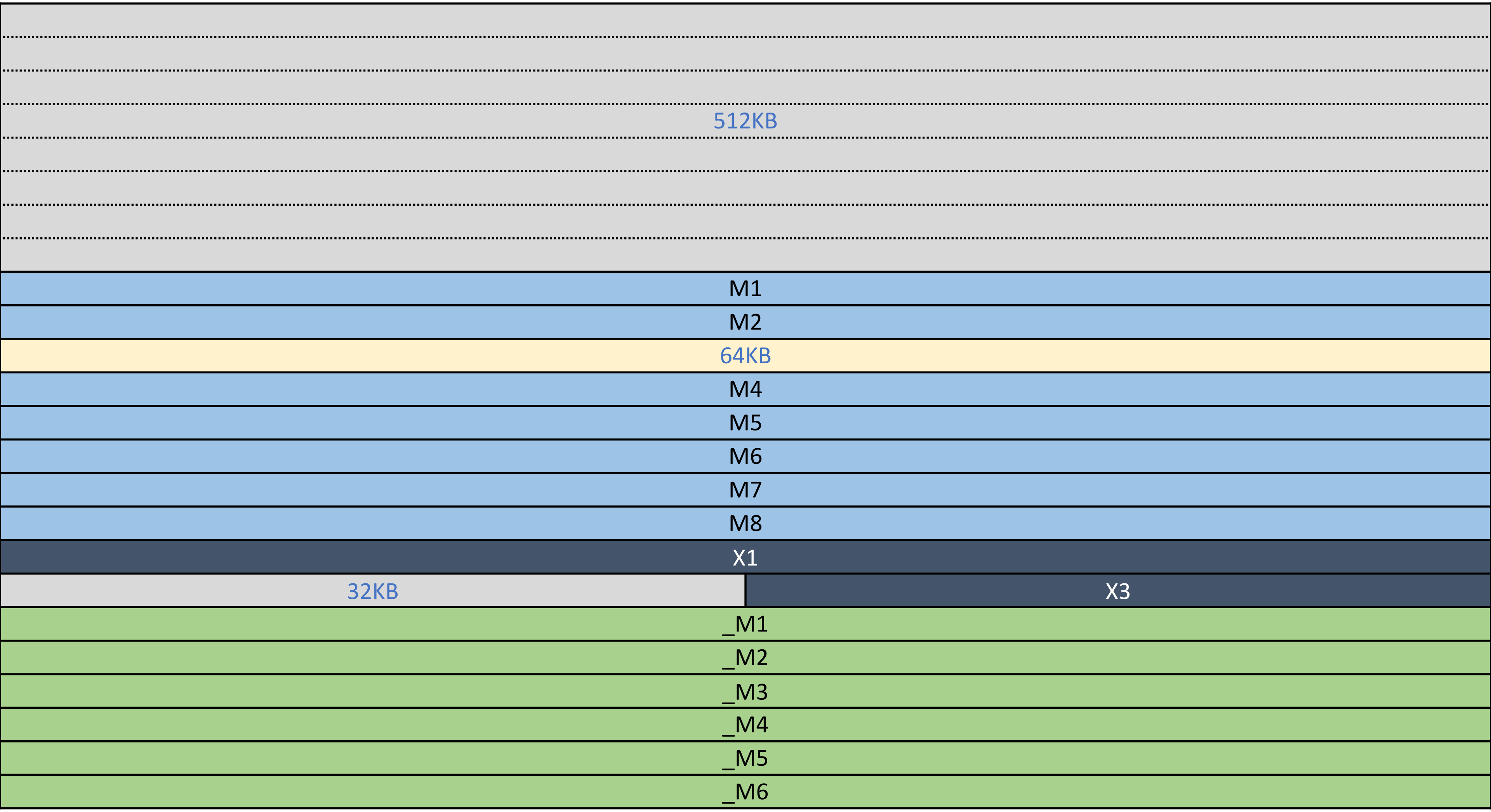
```
Release(M3); // releases the vulnerable row
```



Phys Feng Shui step 5/8

Release vulnerable *Medium-sized* chunk + Release all Large chunks

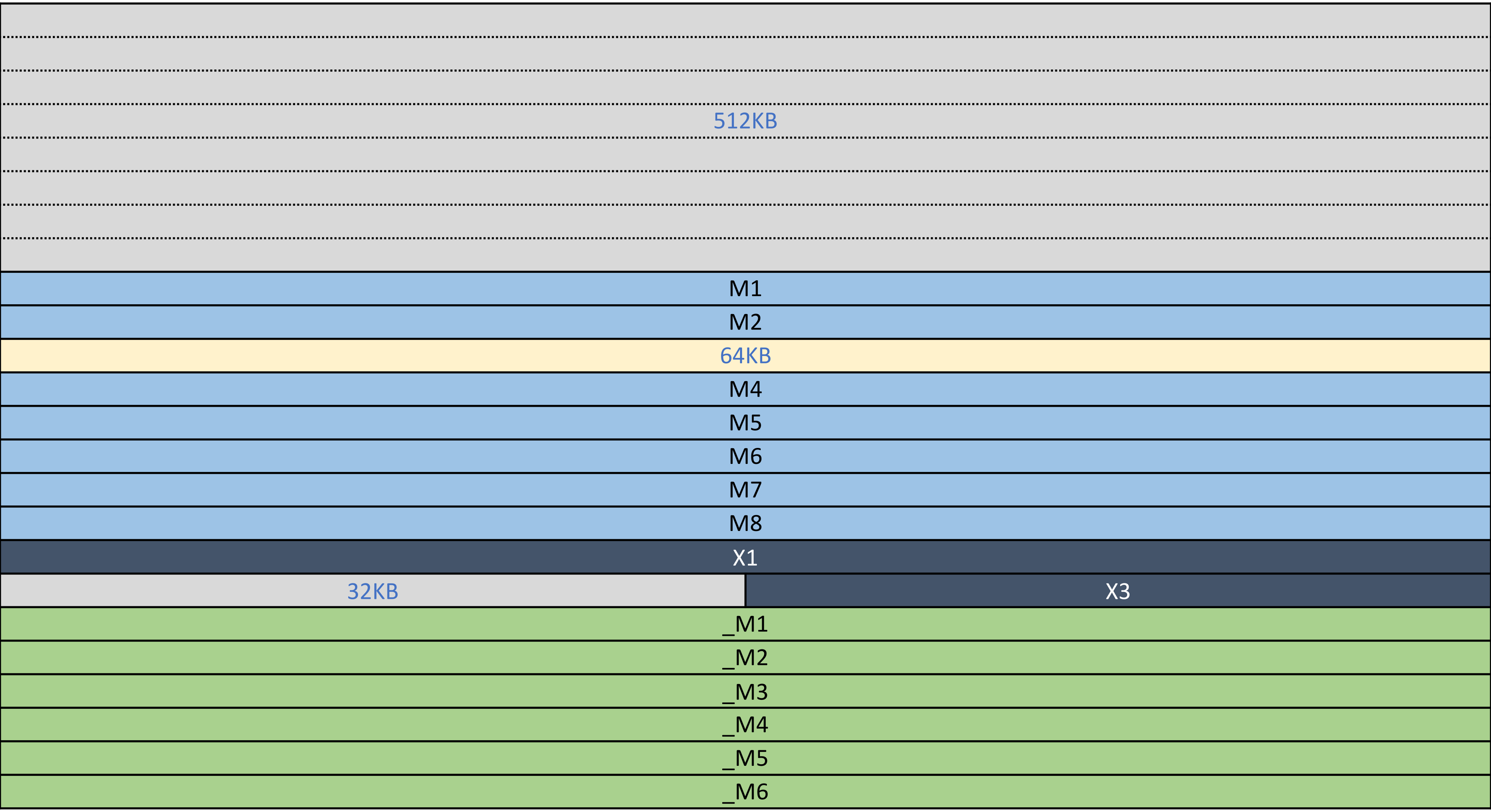
```
ReleaseAll(L); // to avoid going out-of-memory later
```



Phys Feng Shui step 6/8

Land a *small* chunk in the vulnerable 64 KB row

`Land(S); // allocate 4KB pages until the 64KB is used`



Phys Feng Shui step 6/8

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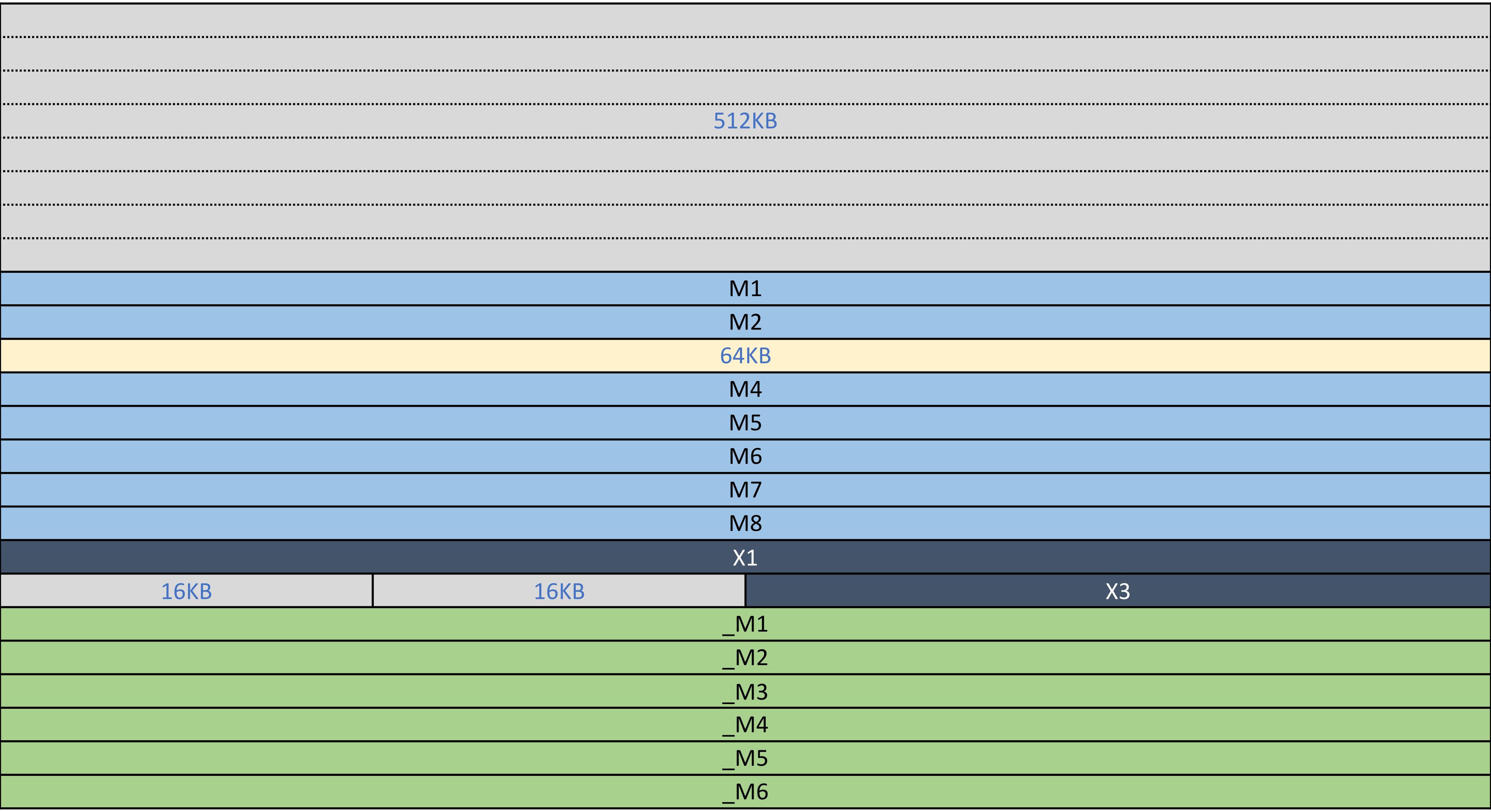

Phys Feng Shui step 6/8

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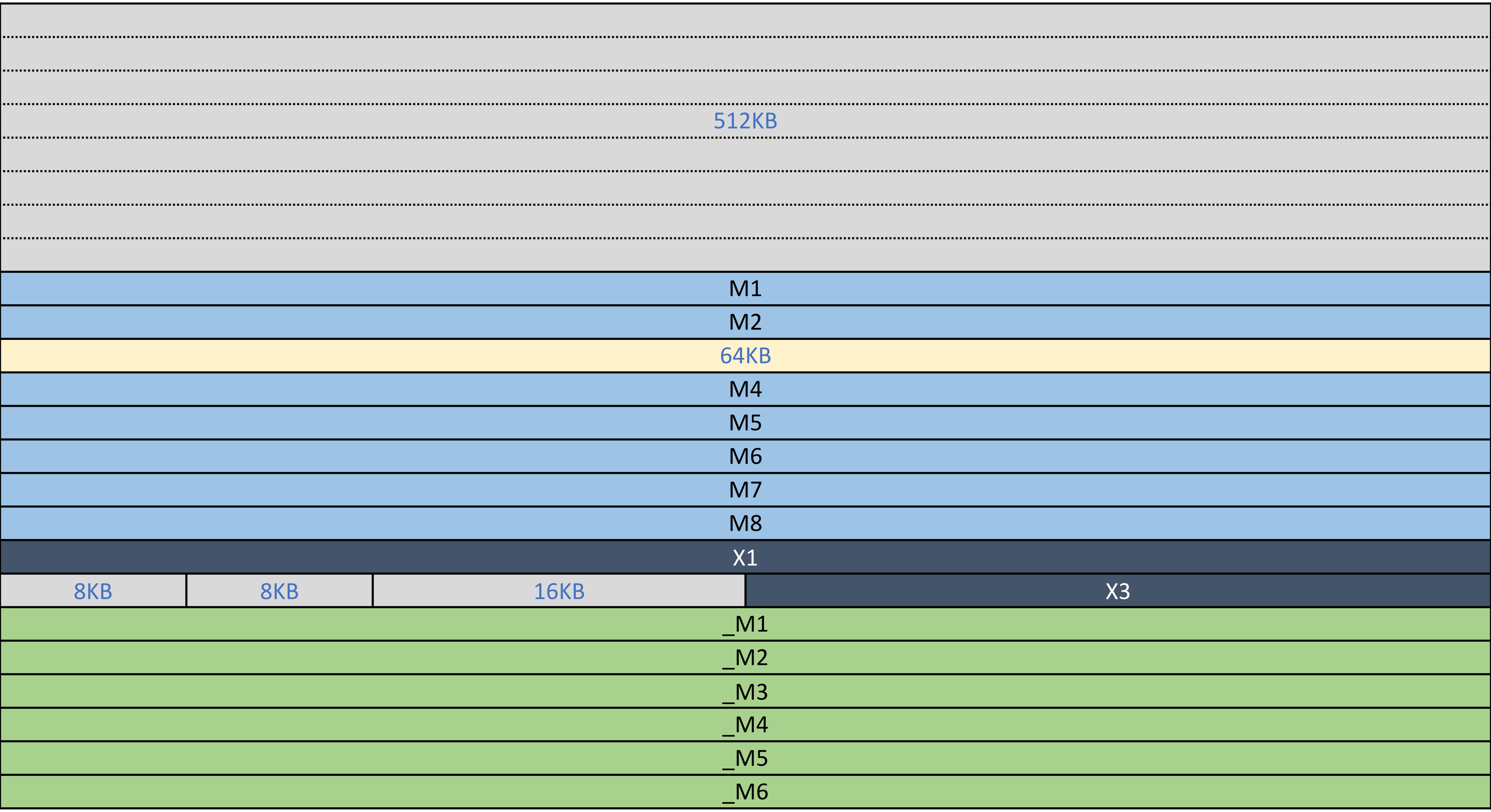

Phys Feng Shui step 6/8

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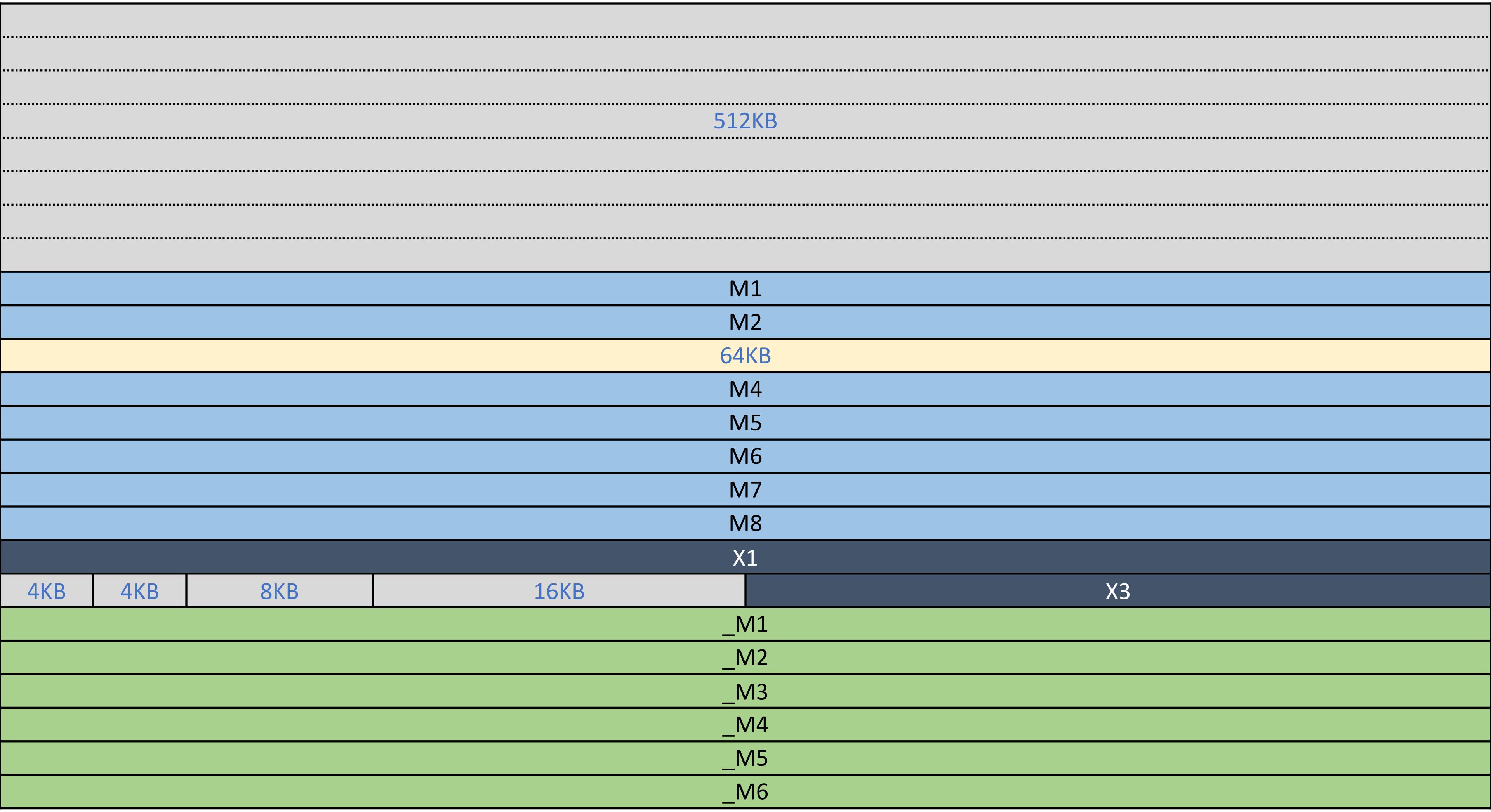

Phys Feng Shui step 6/8

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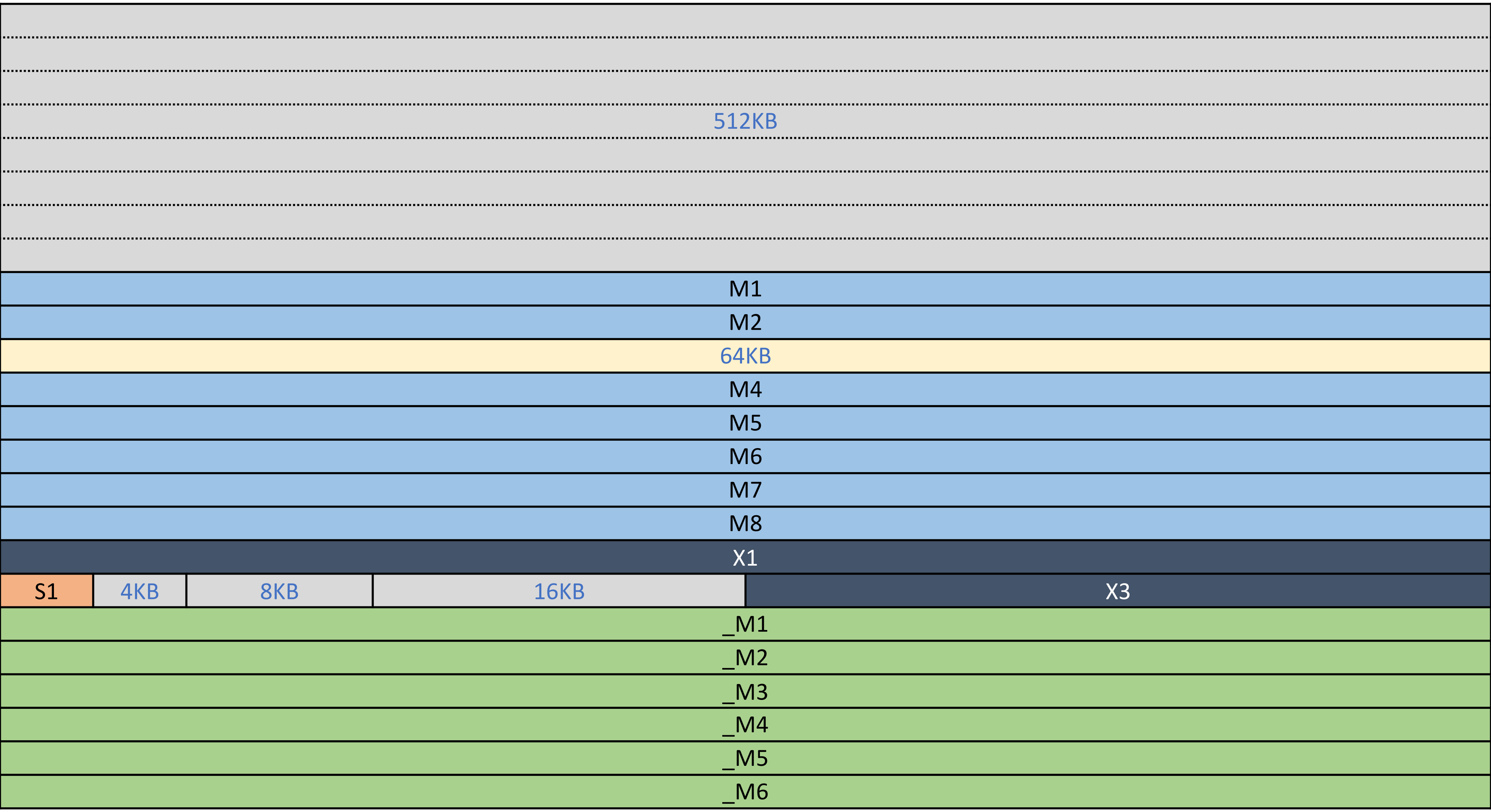

Phys Feng Shui step 6/8

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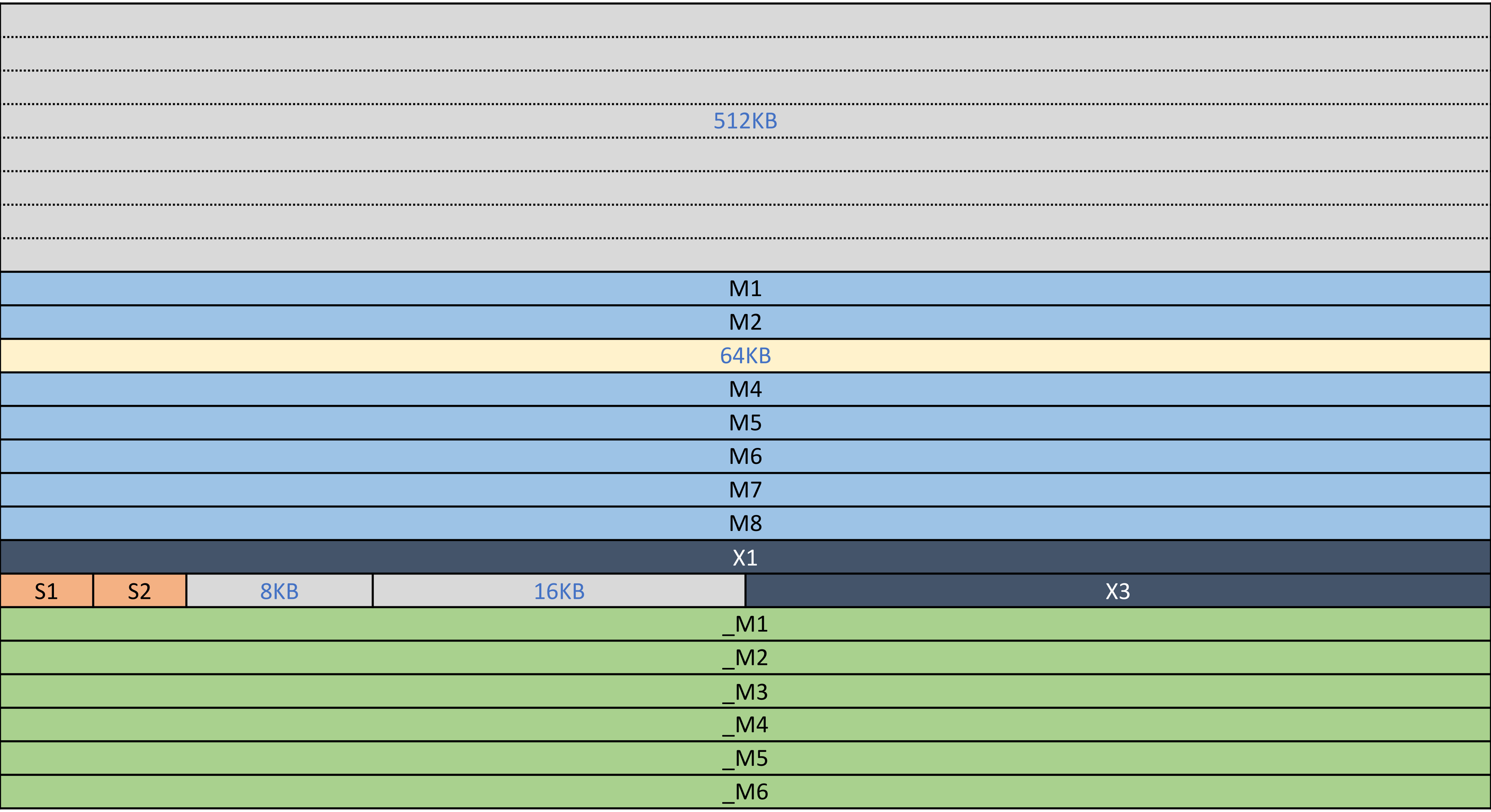

Phys Feng Shui step 6/8

Land a *small* chunk in the vulnerable 64 KB row

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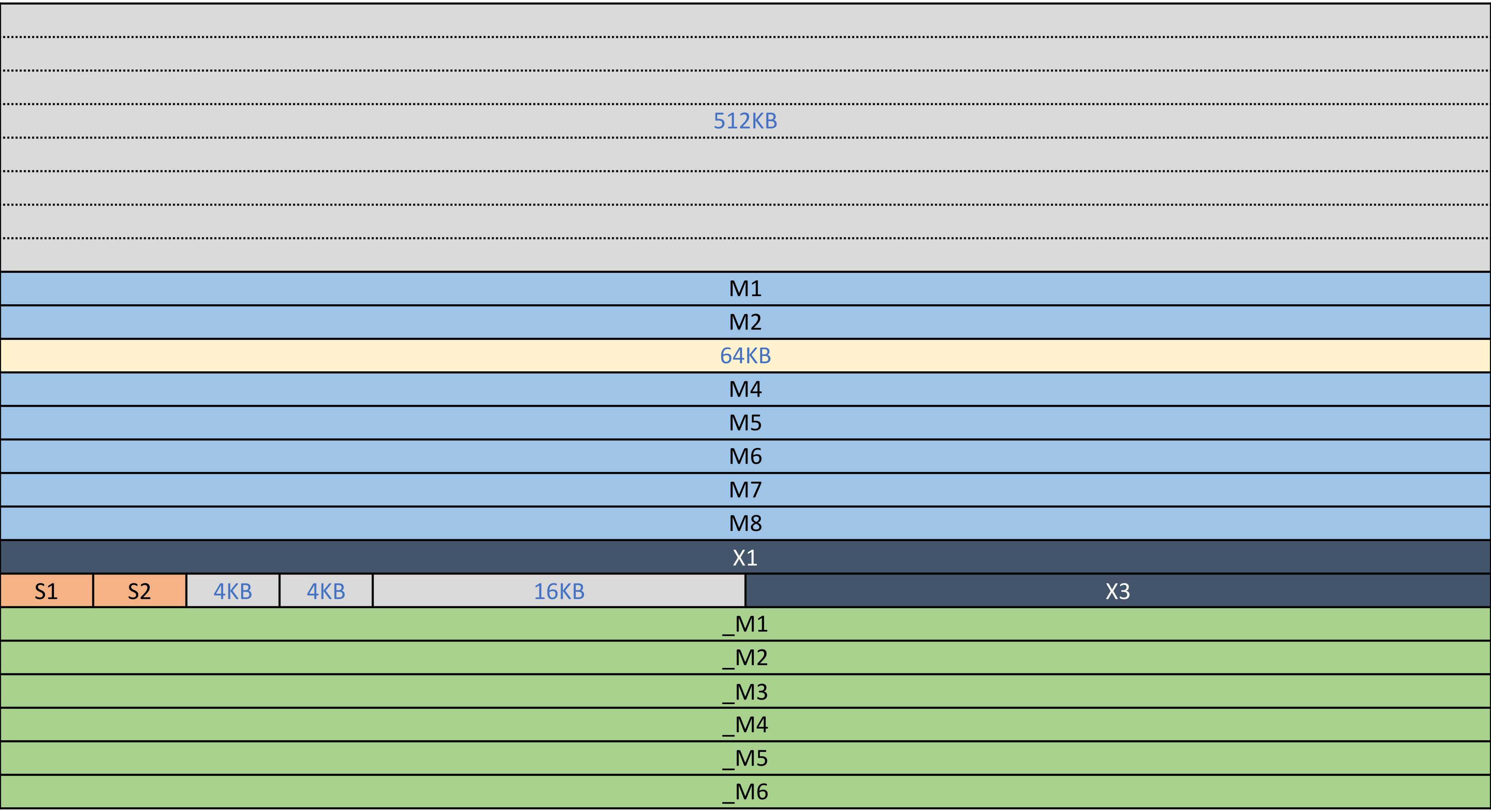

Phys Feng Shui step 6/8

Land a *small* chunk in the vulnerable 64 KB row

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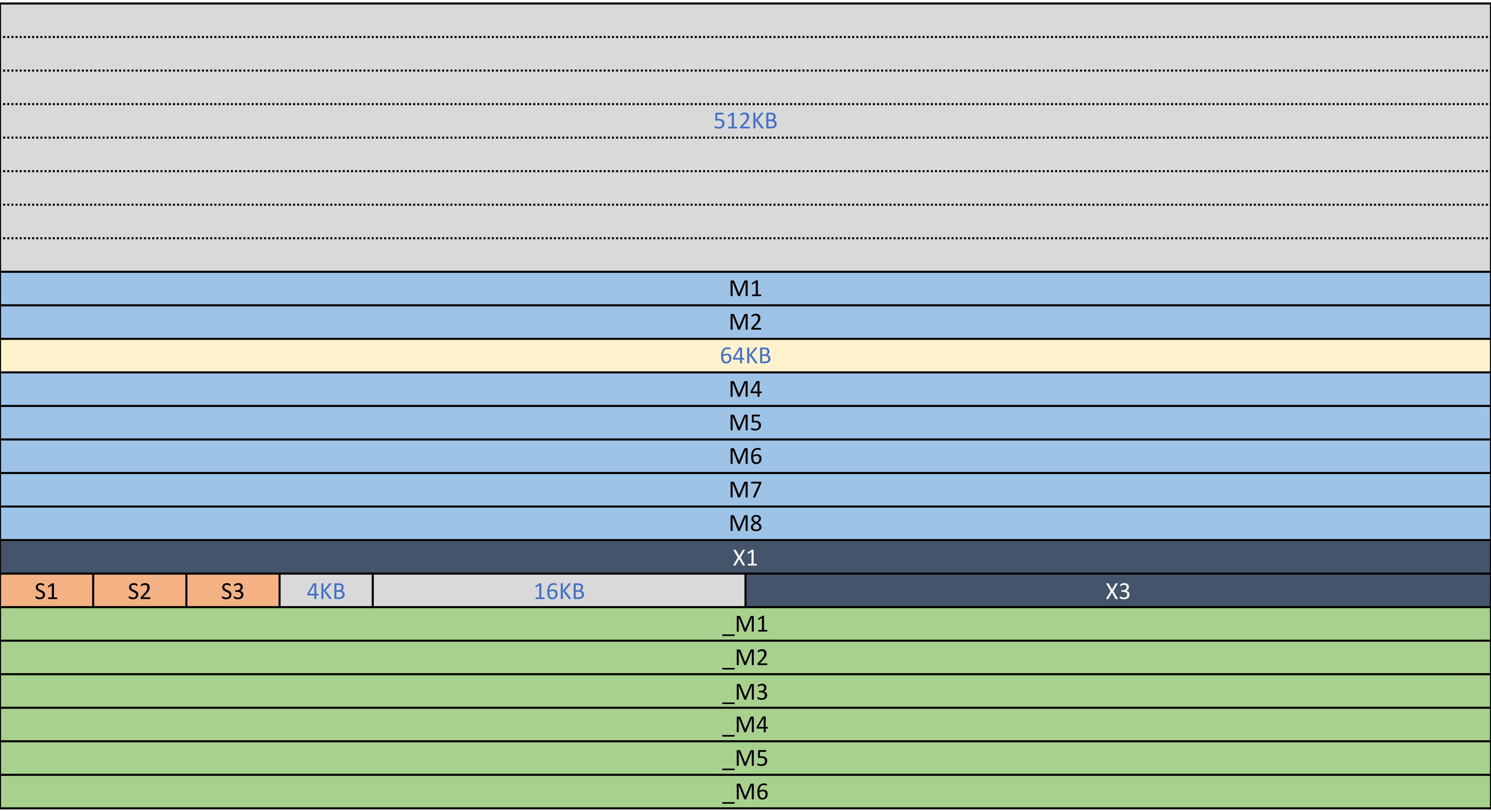
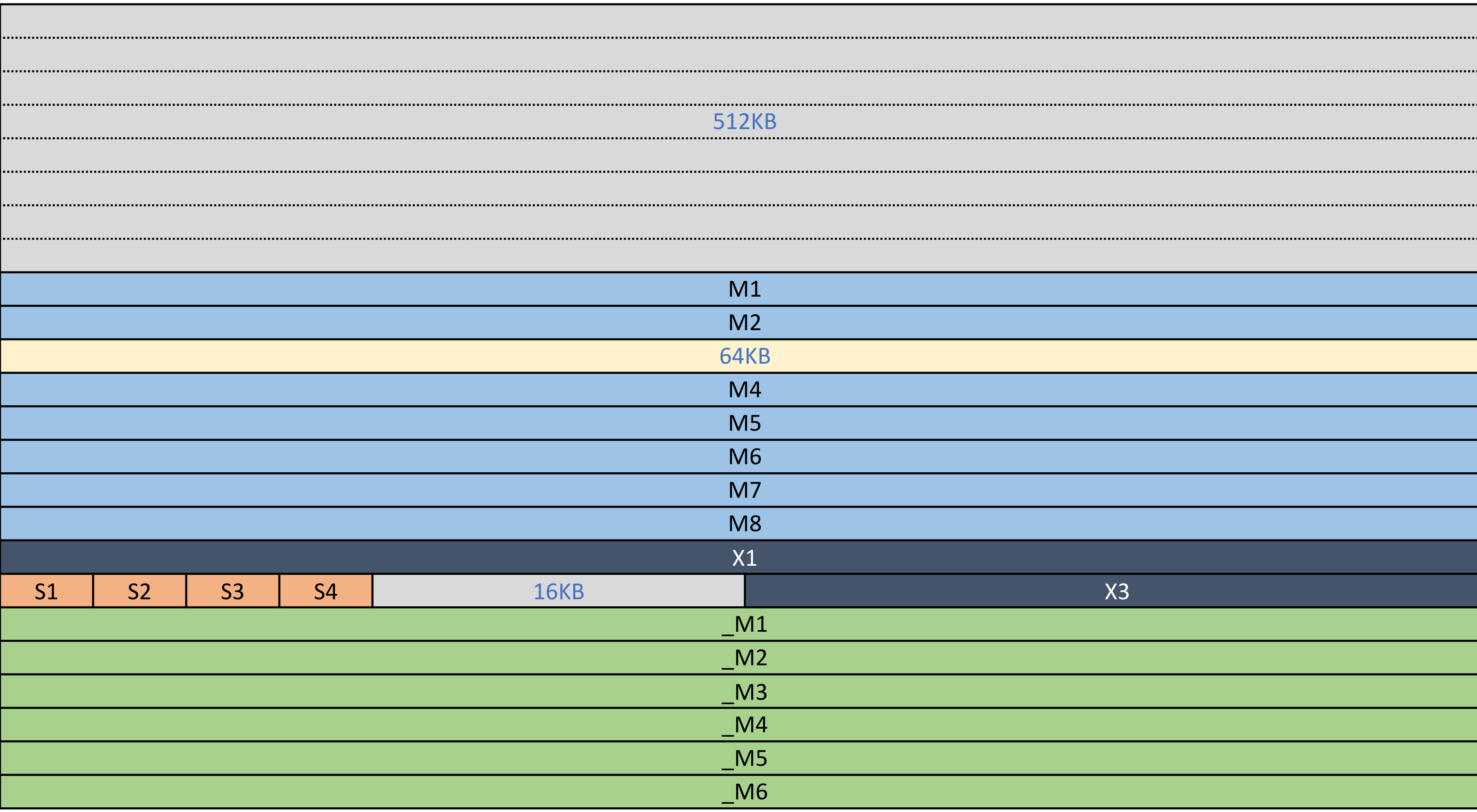


Phys Feng Shui step 6/8

Land a *small* chunk in the vulnerable 64 KB row

```
Land(S); // allocate 4KB pages until the 64KB is used
```



Phys Feng Shui step 6/8

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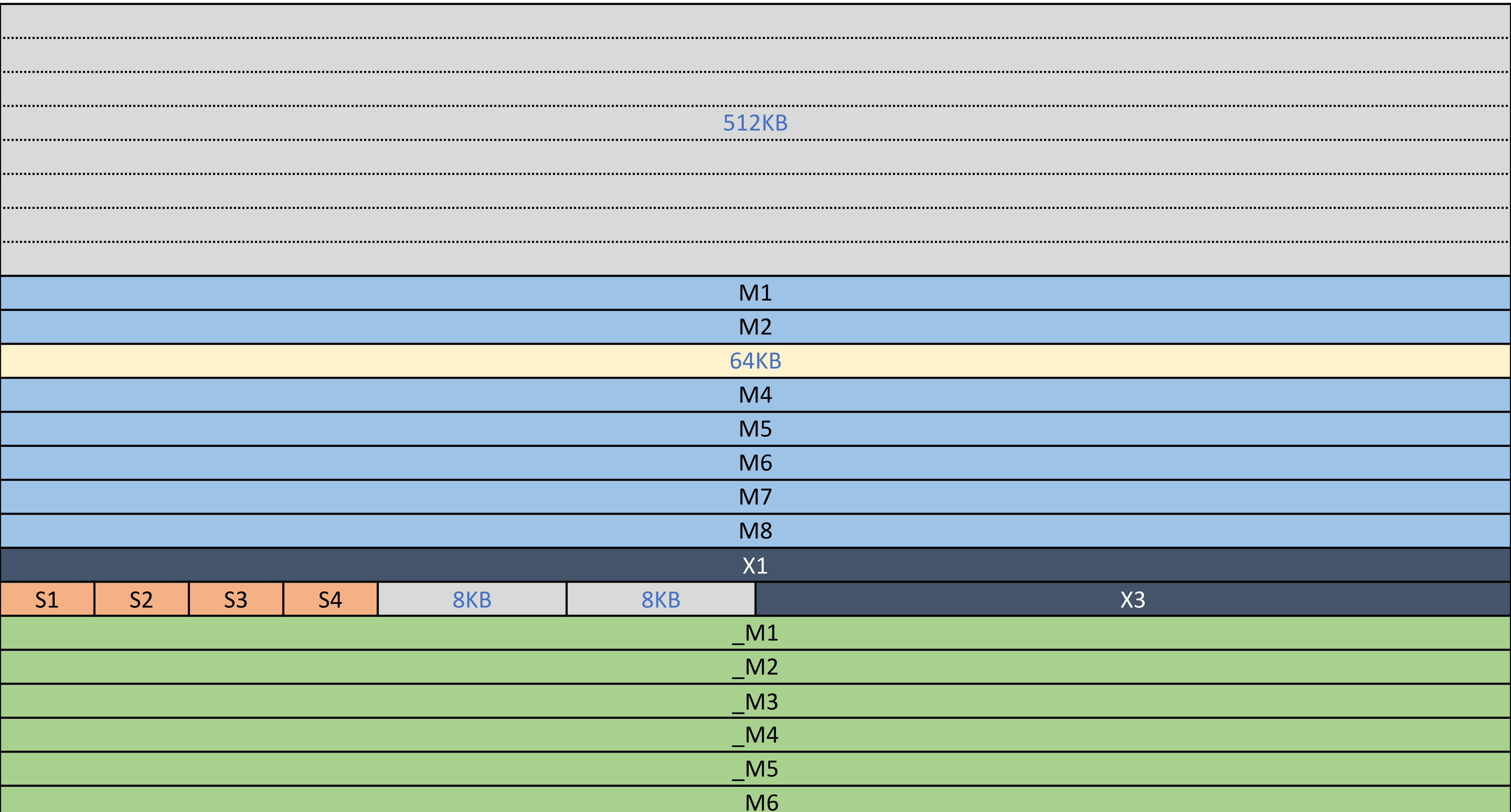
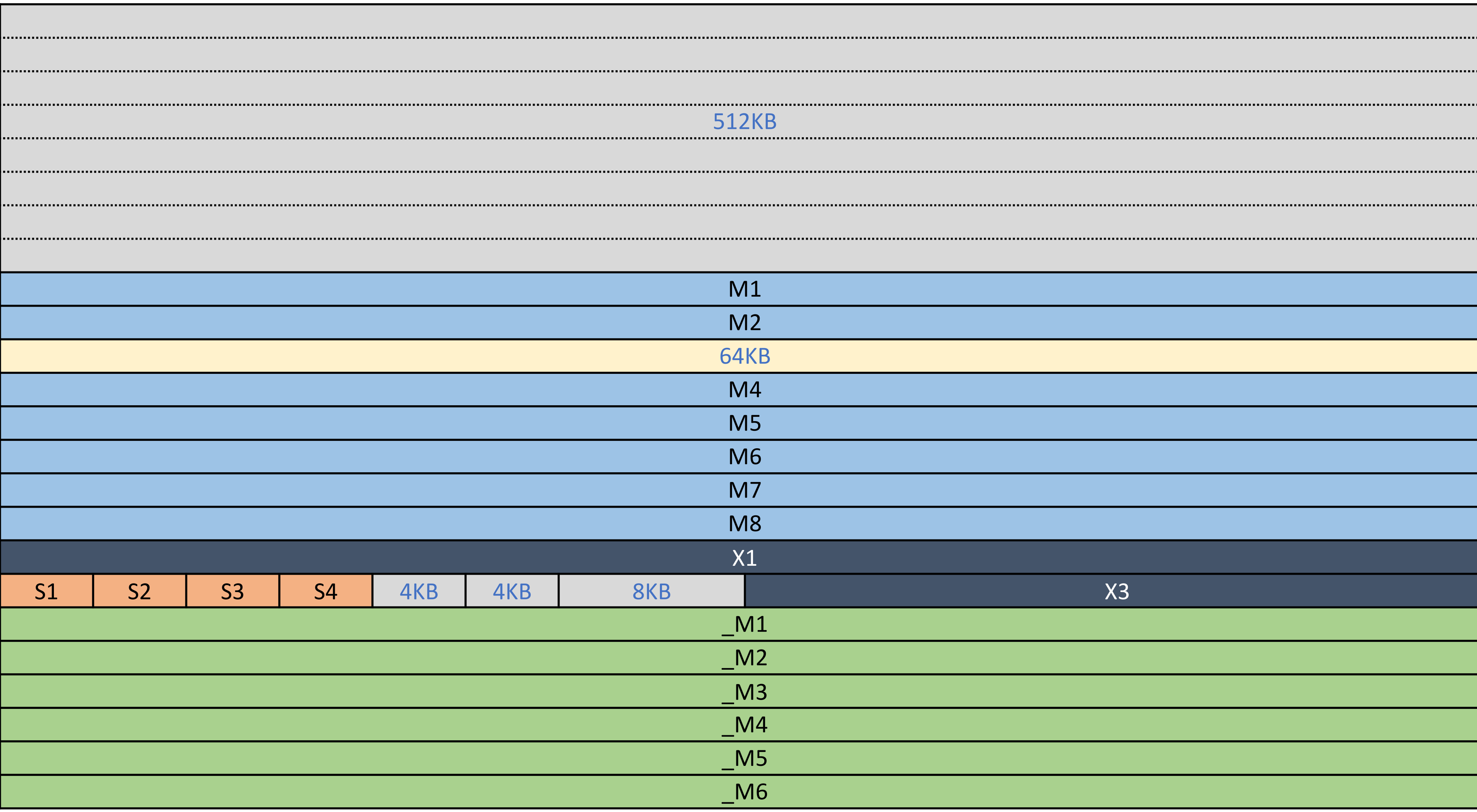


Phys Feng Shui step 6/8

Land a *small* chunk in the vulnerable 64 KB row

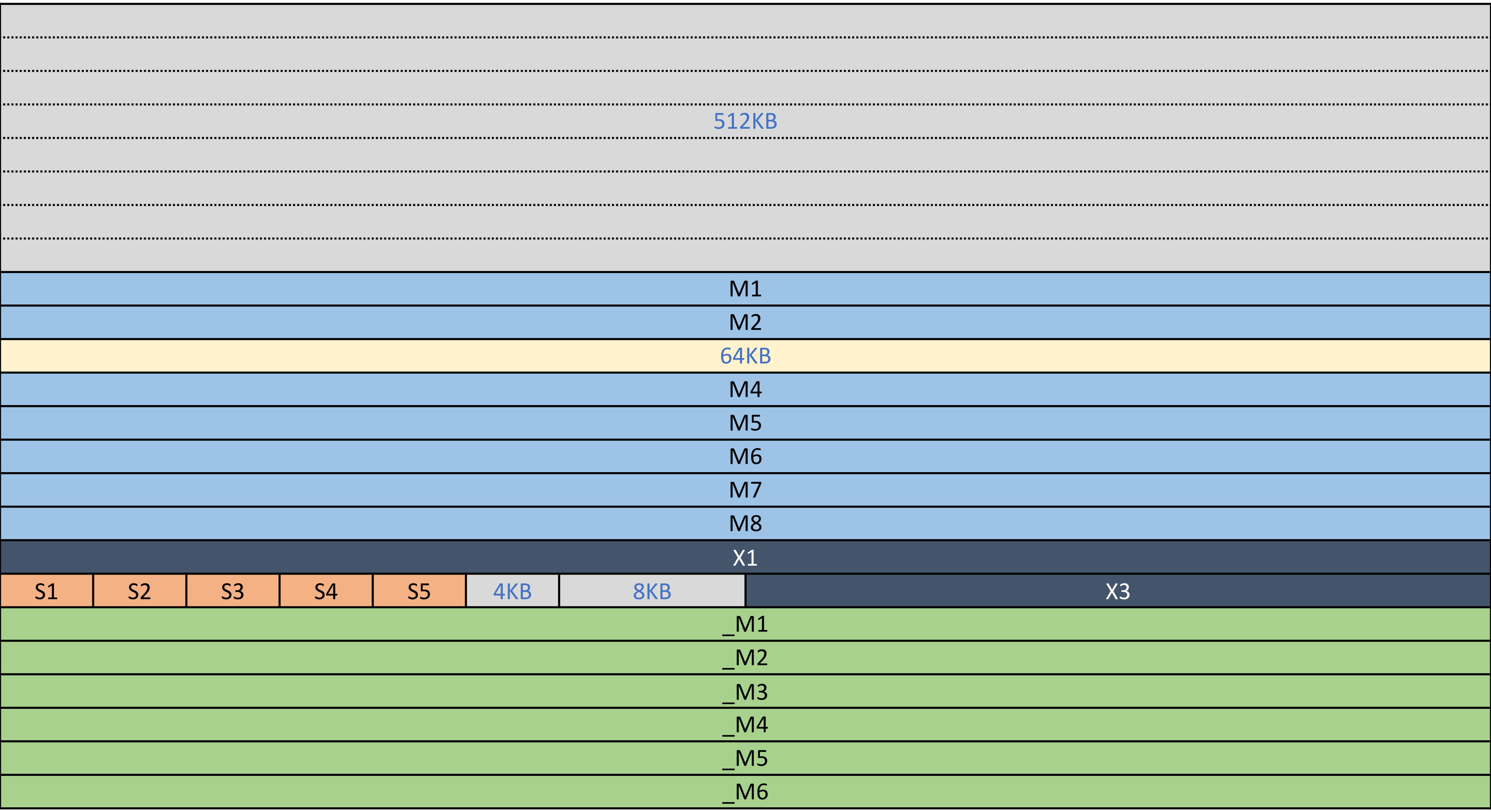
`Land(S);` `// allocate 4KB pages until the 64KB is used`



Phys Feng Shui step 6/8

Land a *small* chunk in the vulnerable 64 KB row

```
Land(S); // allocate 4KB pages until the 64KB is used
```



Phys Feng Shui step 6/8

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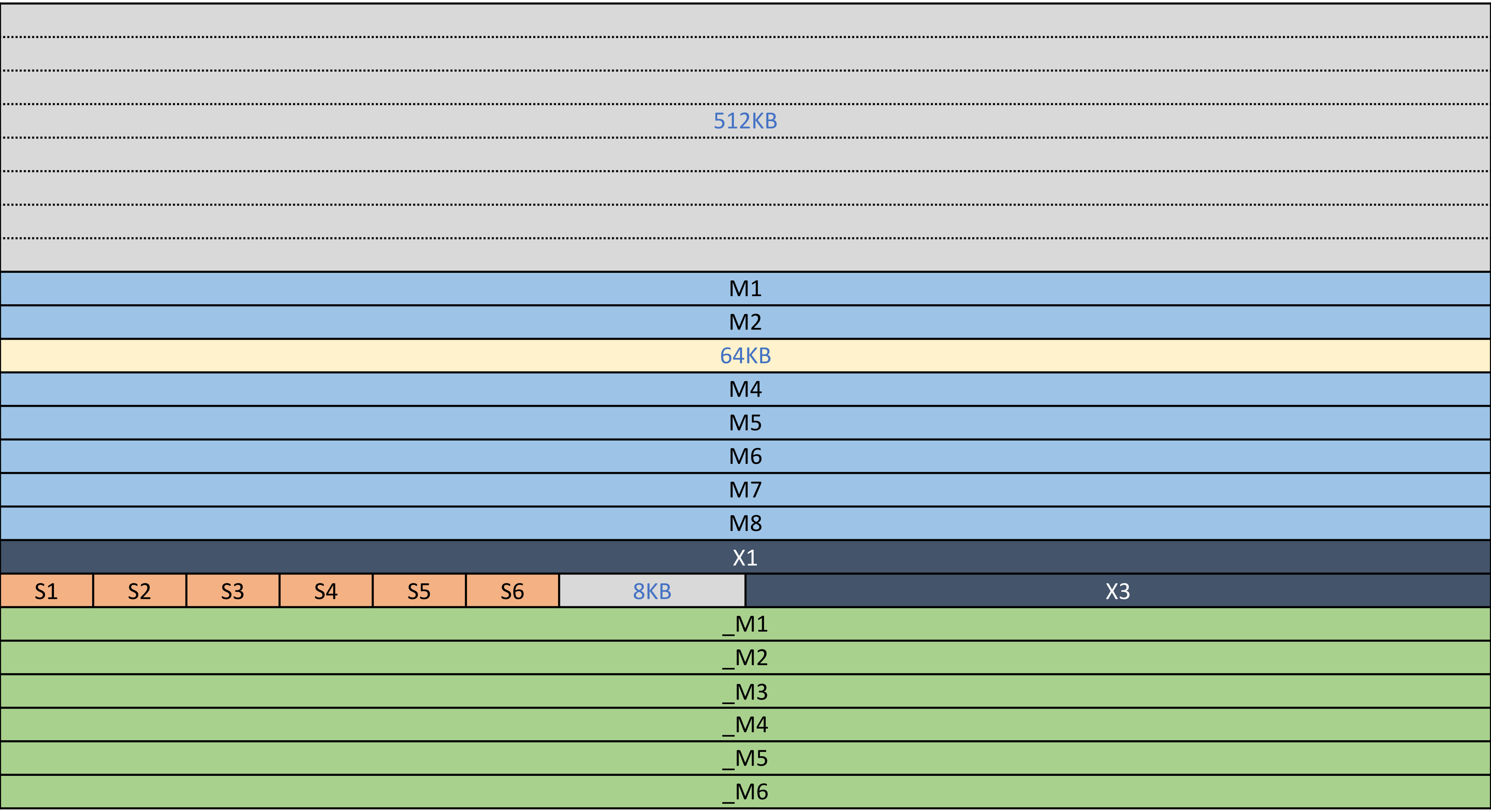

Phys Feng Shui step 6/8

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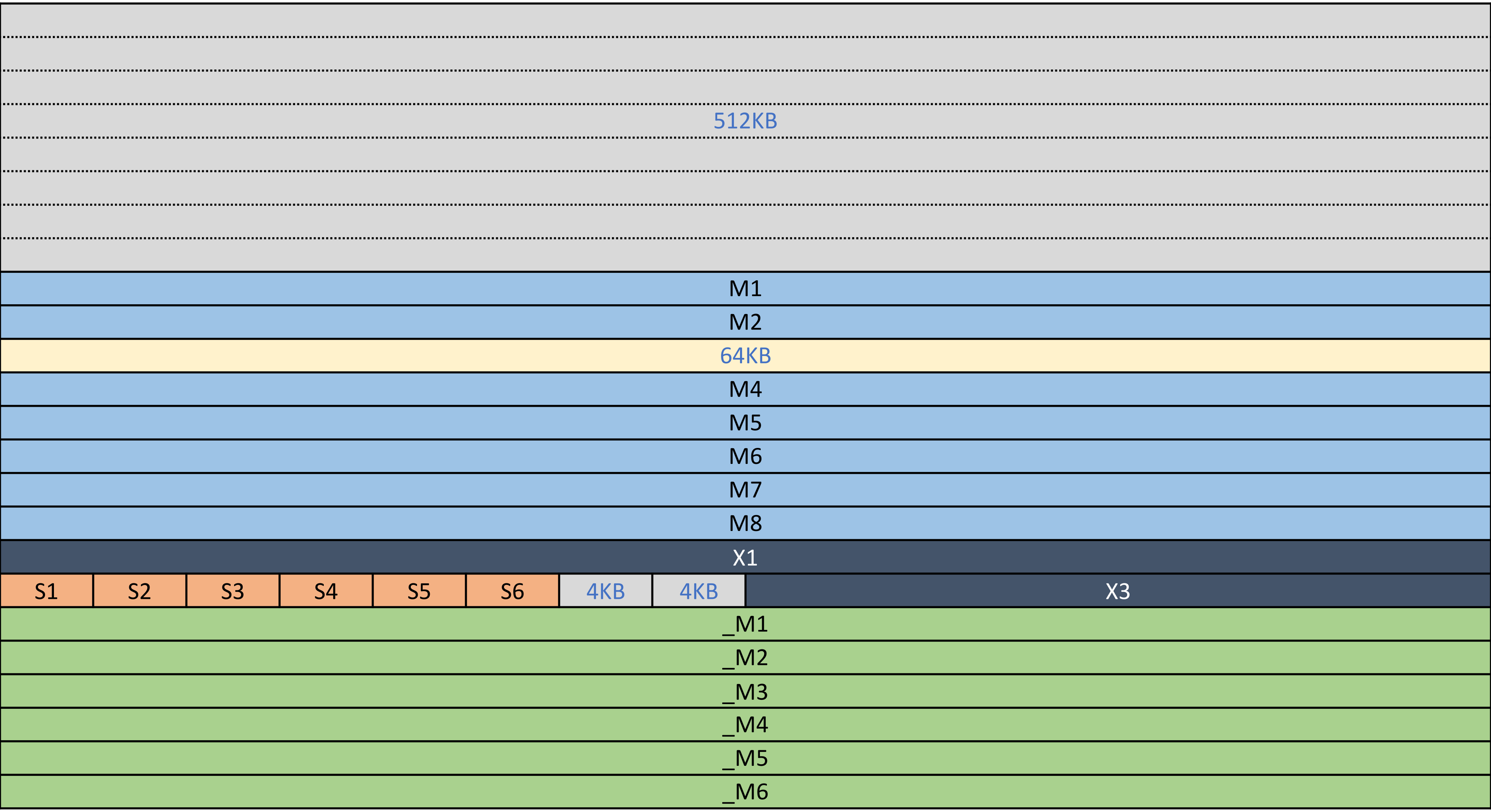

Phys Feng Shui step 6/8

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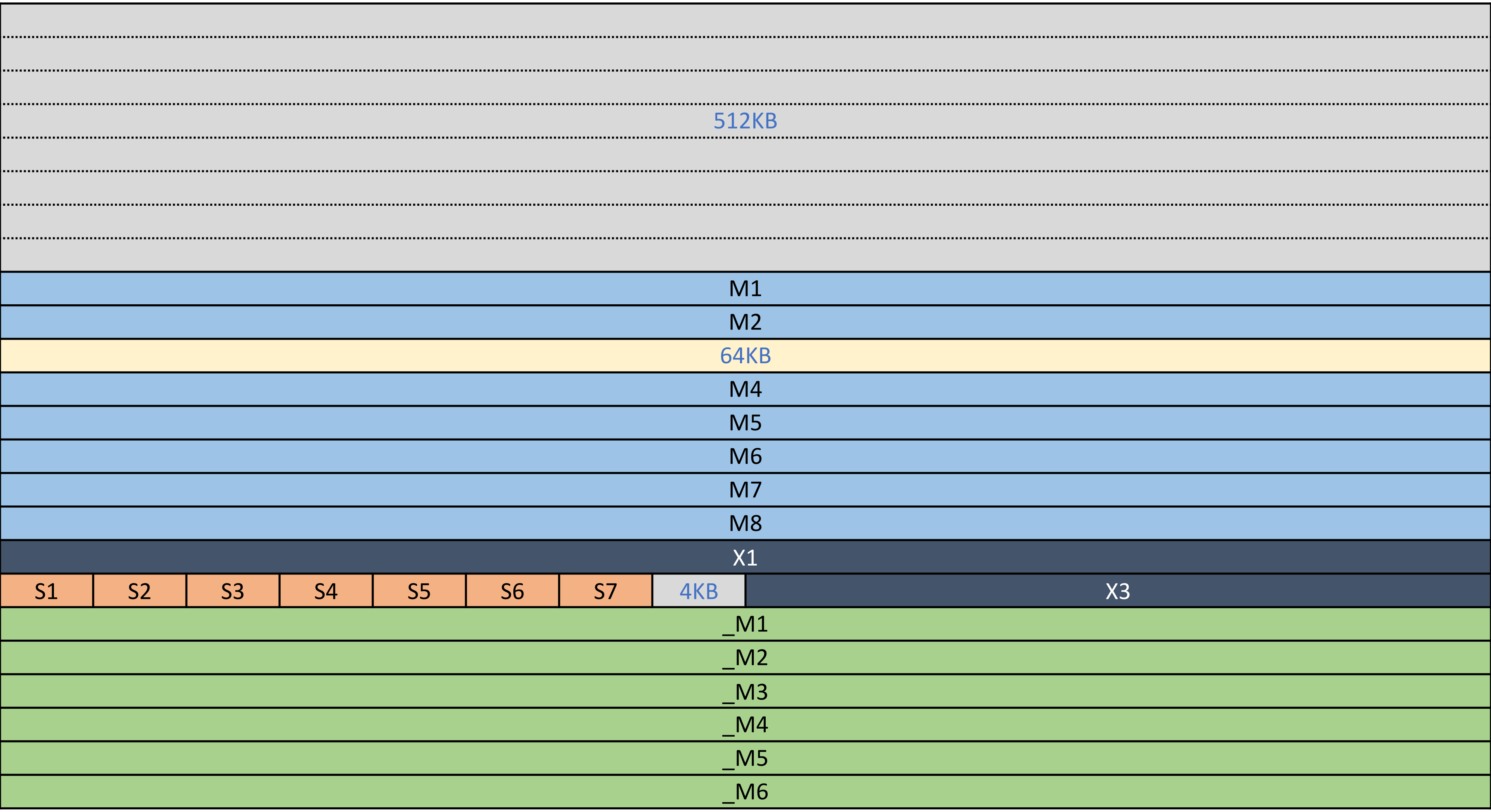

Phys Feng Shui step 6/8

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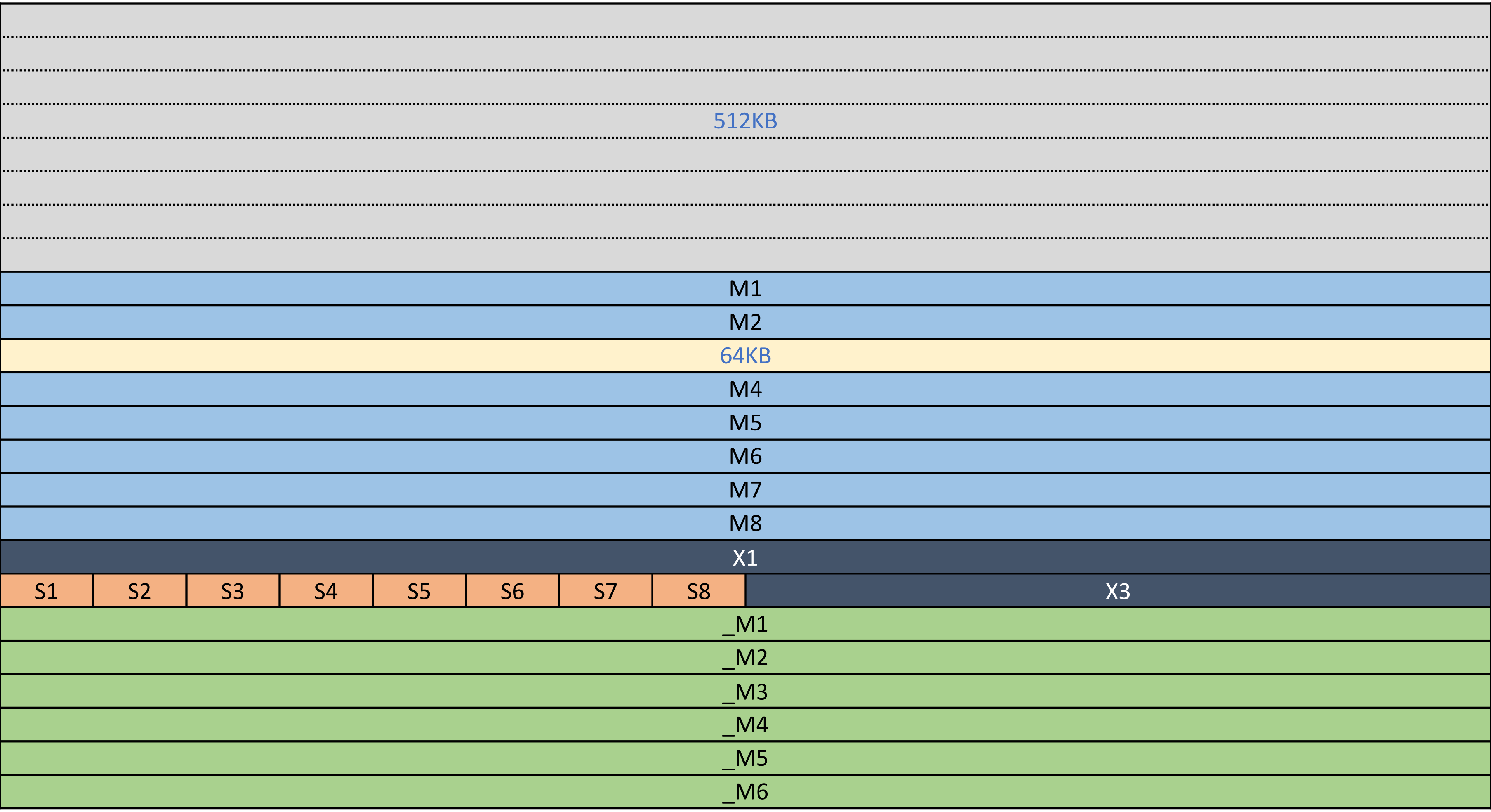

Phys Feng Shui step 6/8

Land a *small* chunk in the vulnerable 64 KB row

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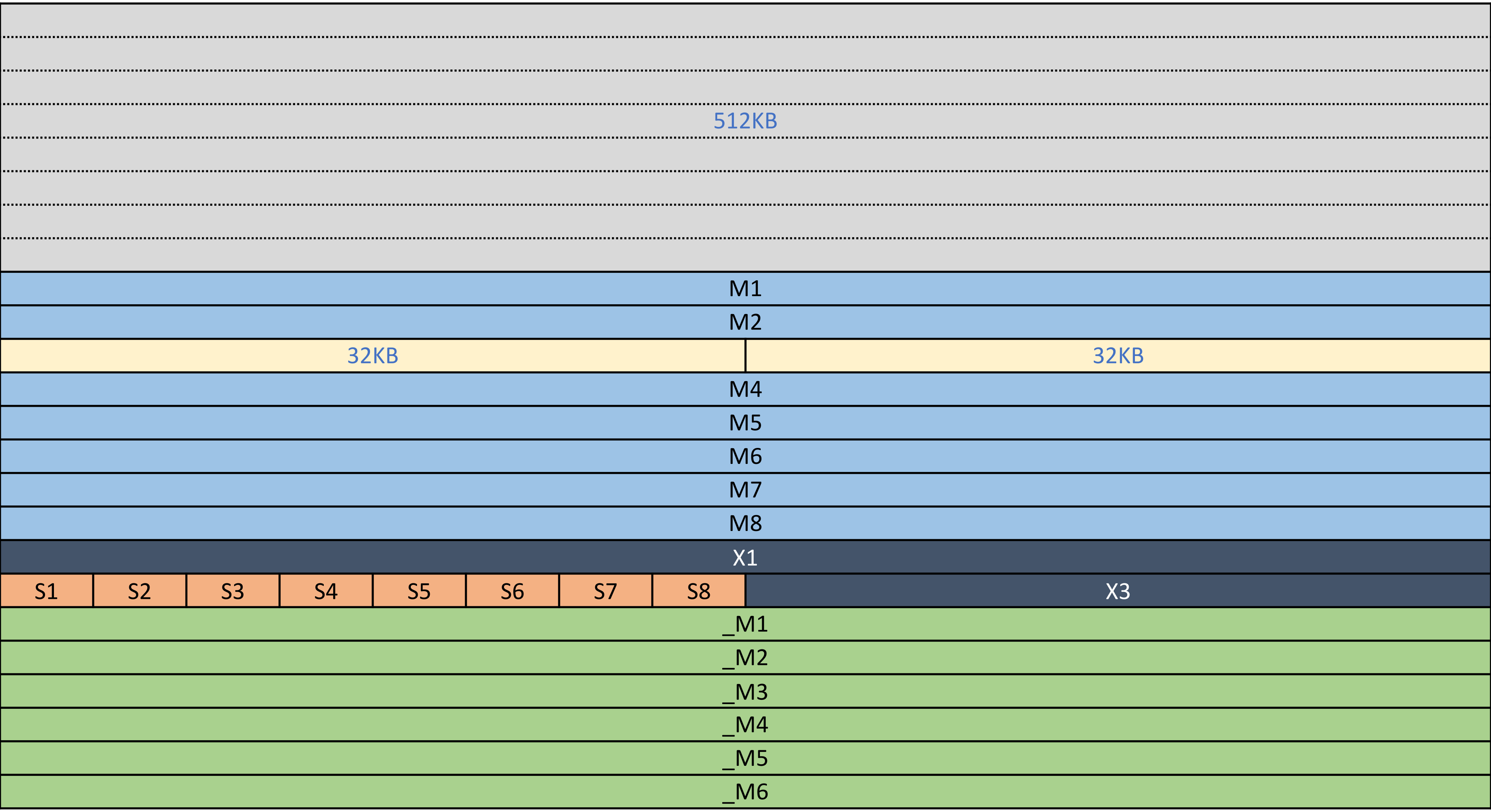
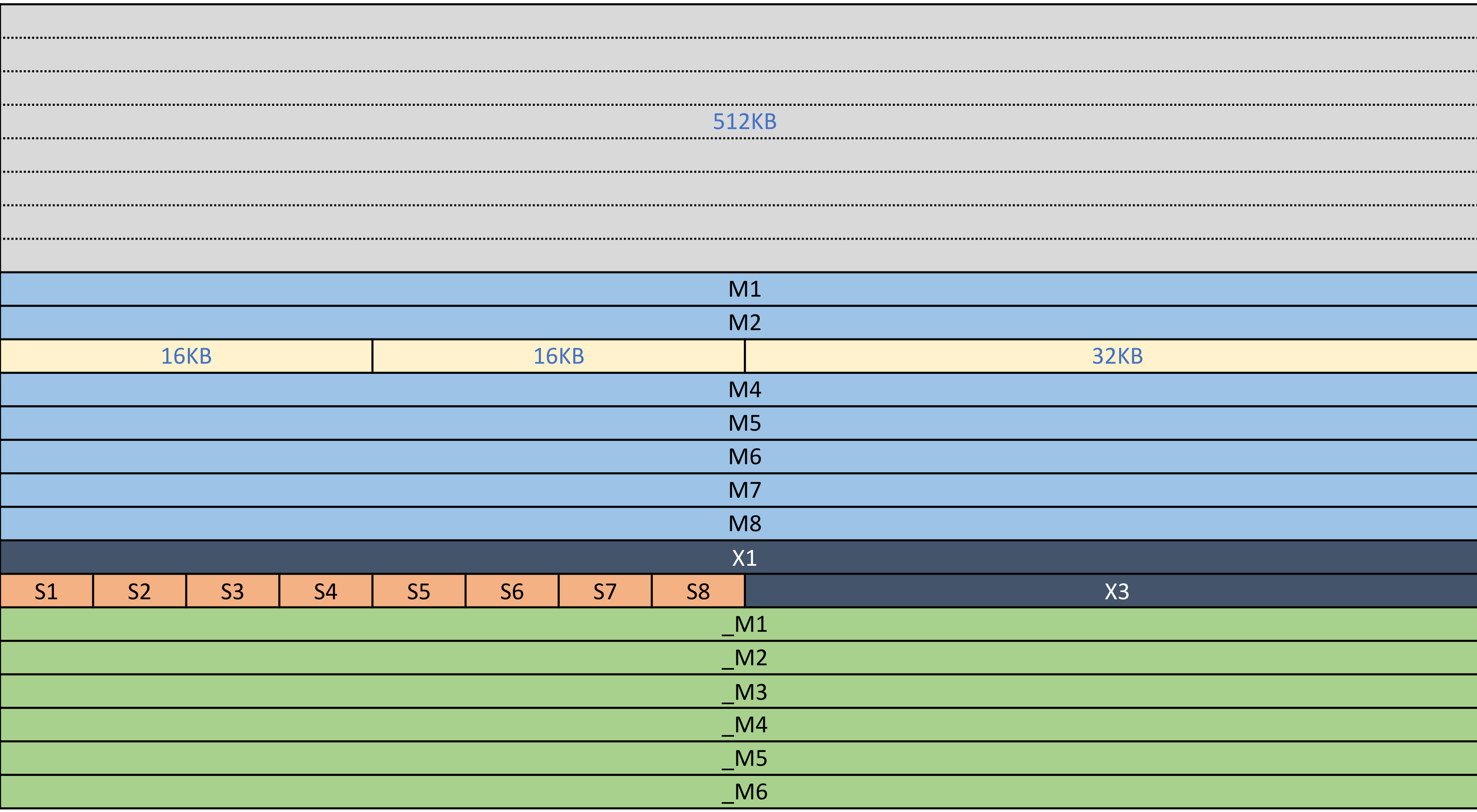
```



Phys Feng Shui step 6/8

Land a *small* chunk in the vulnerable 64 KB row

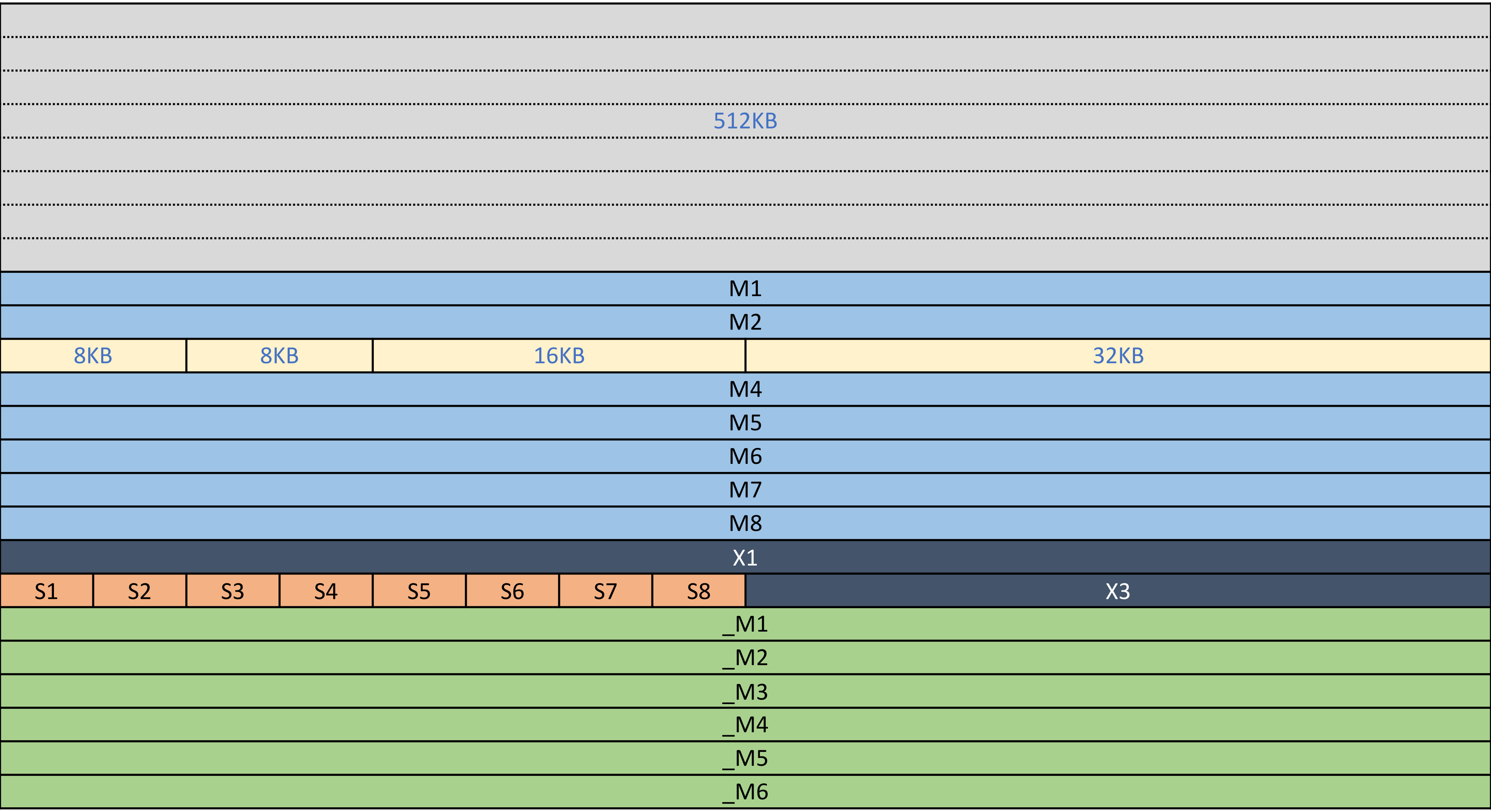
`Land(S); // allocate 4KB pages until the 64KB is used`



Phys Feng Shui step 6/8

Land a *small* chunk in the vulnerable 64 KB row

```
Land(S); // allocate 4KB pages until the 64KB is used
```



Phys Feng Shui step 6/8

Land a *small* chunk in the vulnerable 64 KB row

```
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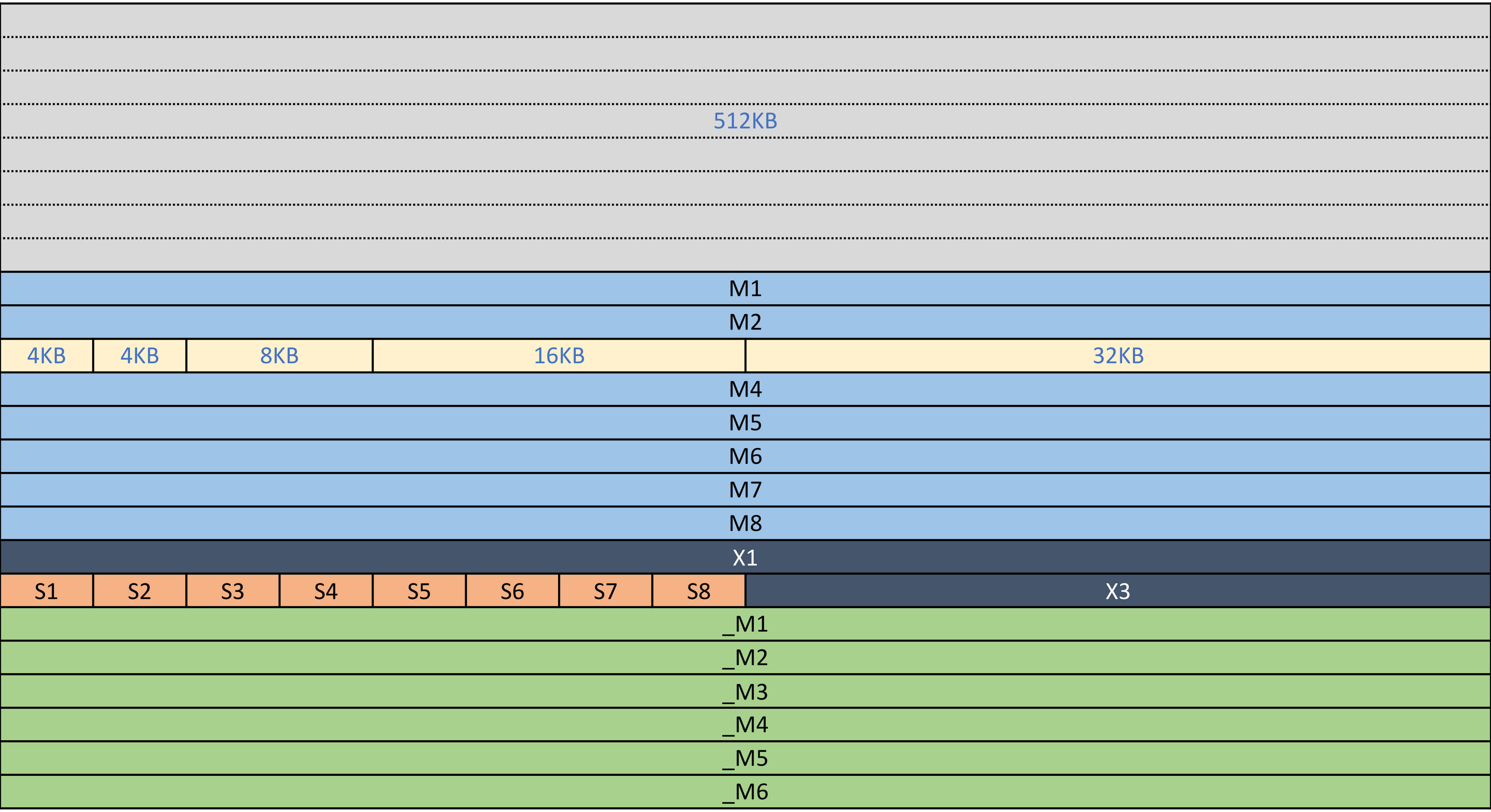
```



Phys Feng Shui step 6/8

Land a *small* chunk in the vulnerable 64 KB row

```
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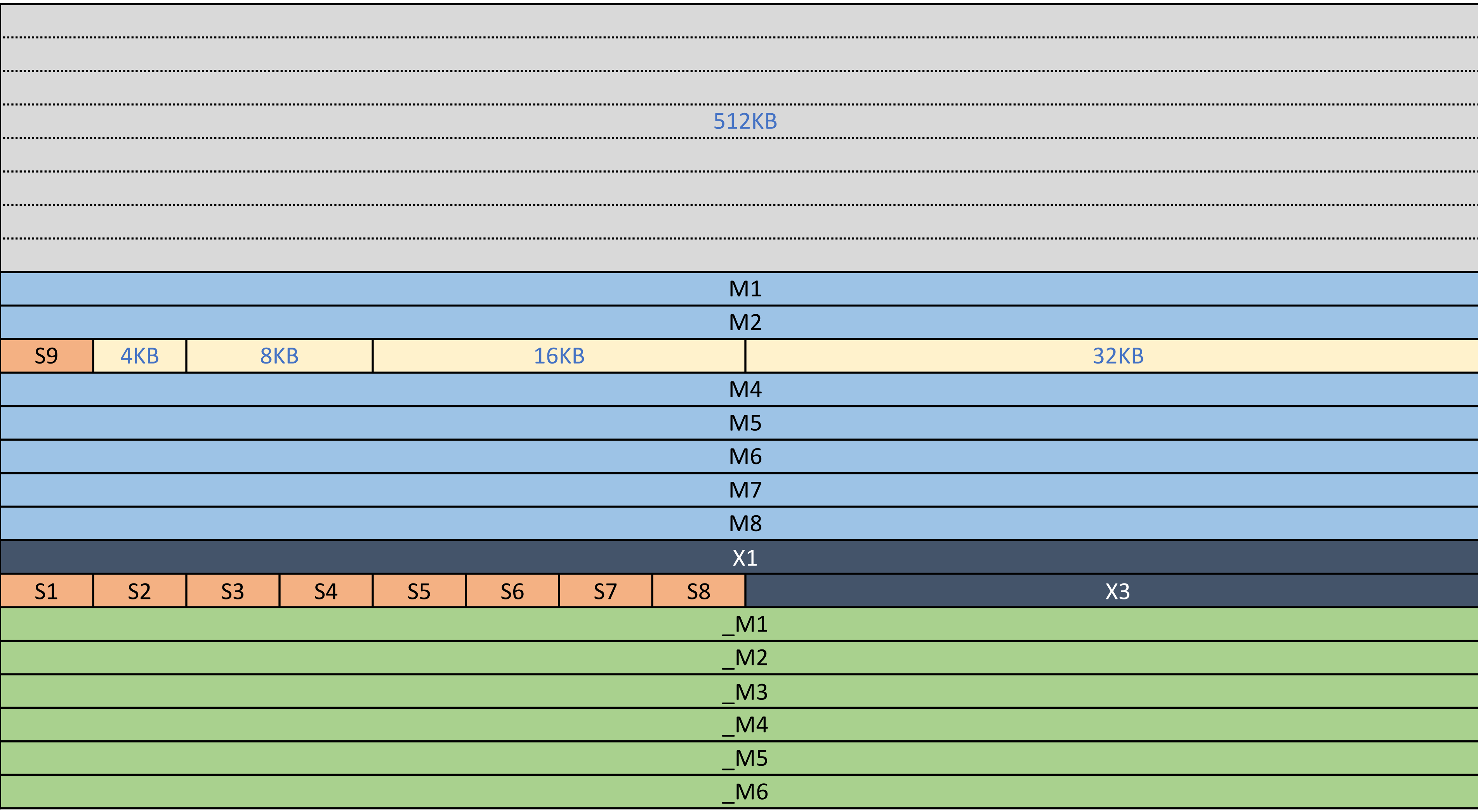
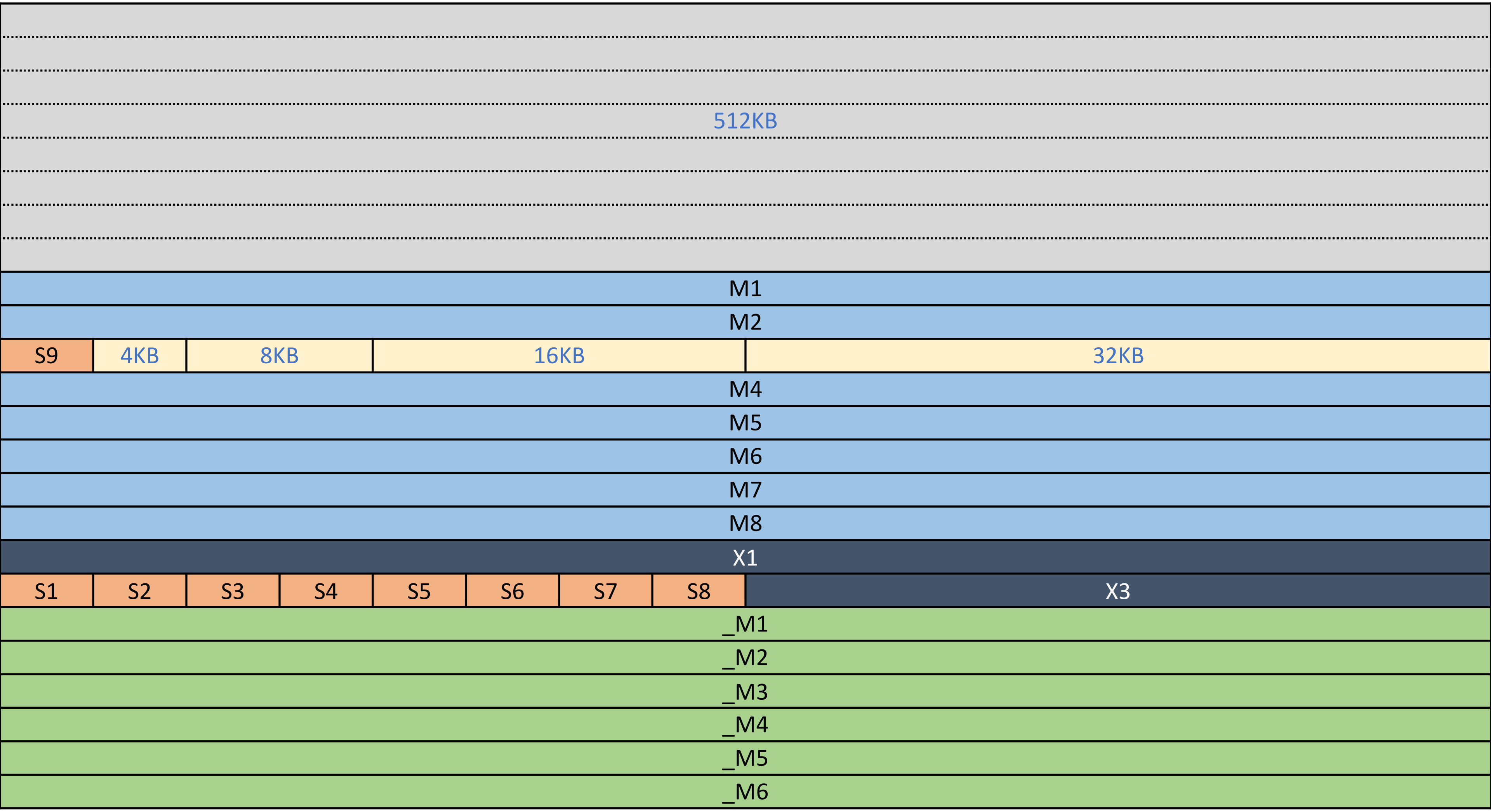


Phys Feng Shui step 7/8

Pad *small* chunks until the vulnerable page

Pad(P); // insert padding until vulnerable page



Phys Feng Shui step 7/8

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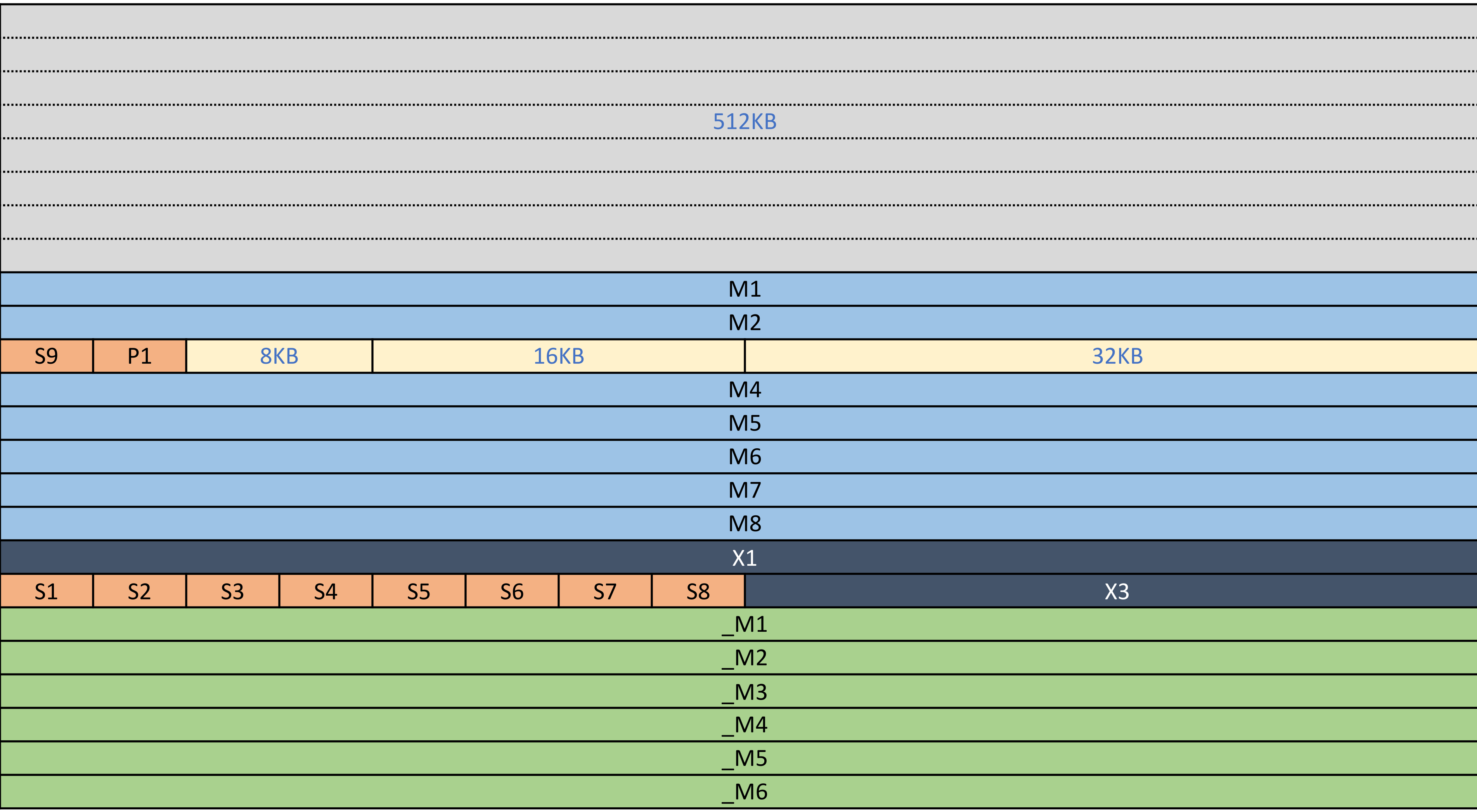

Phys Feng Shui step 7/8

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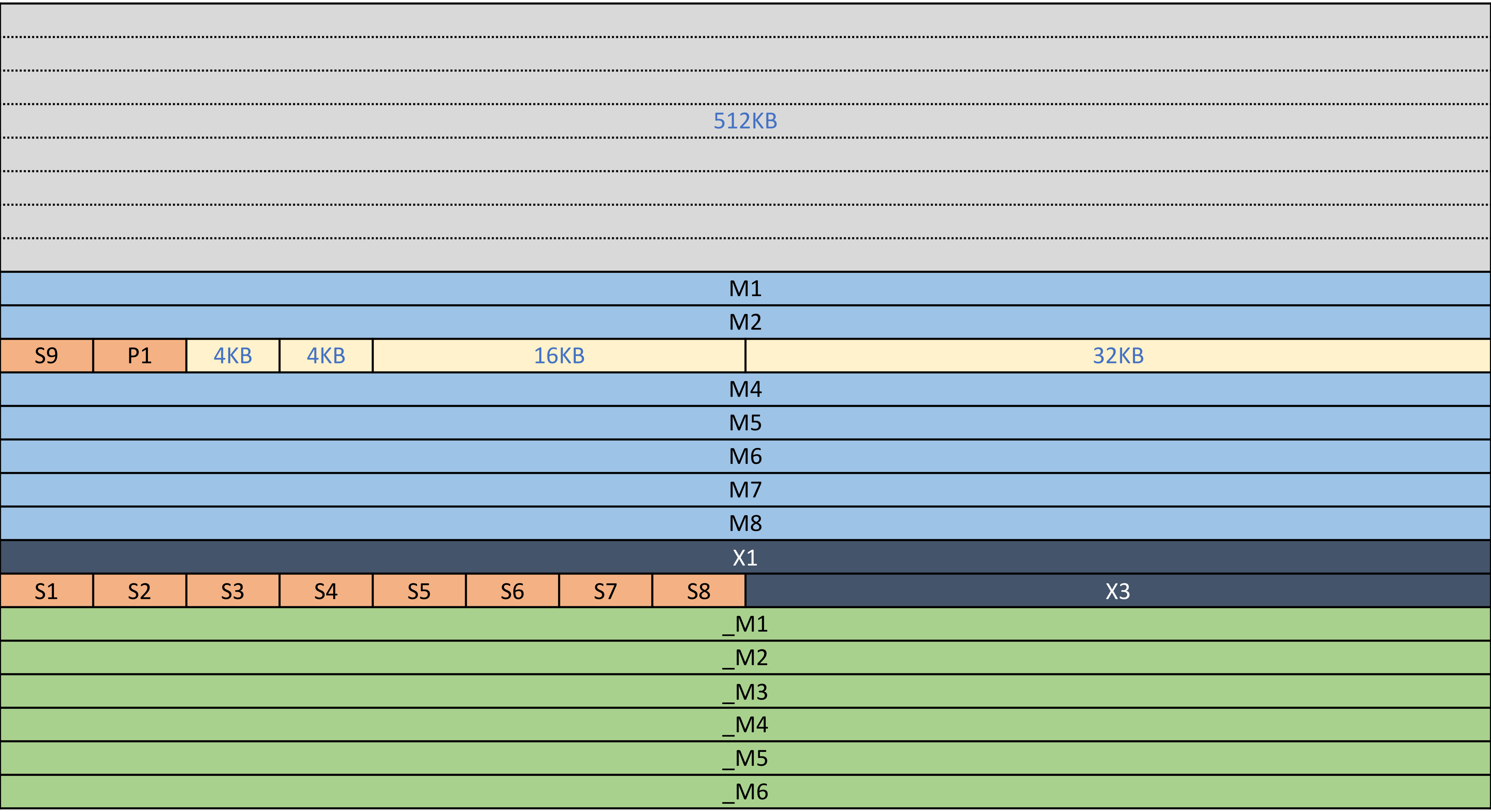

Phys Feng Shui step 7/8

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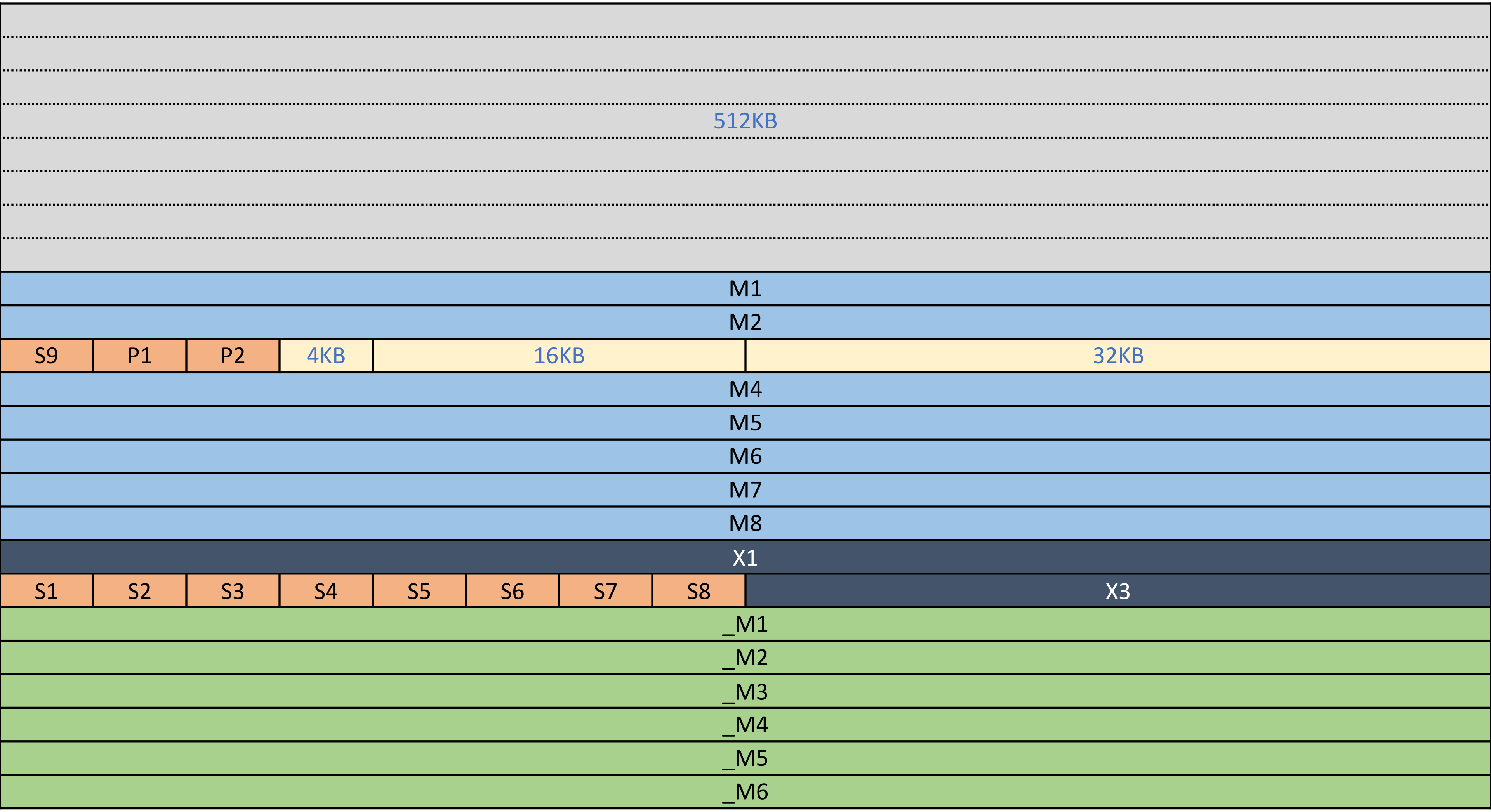

Phys Feng Shui step 7/8

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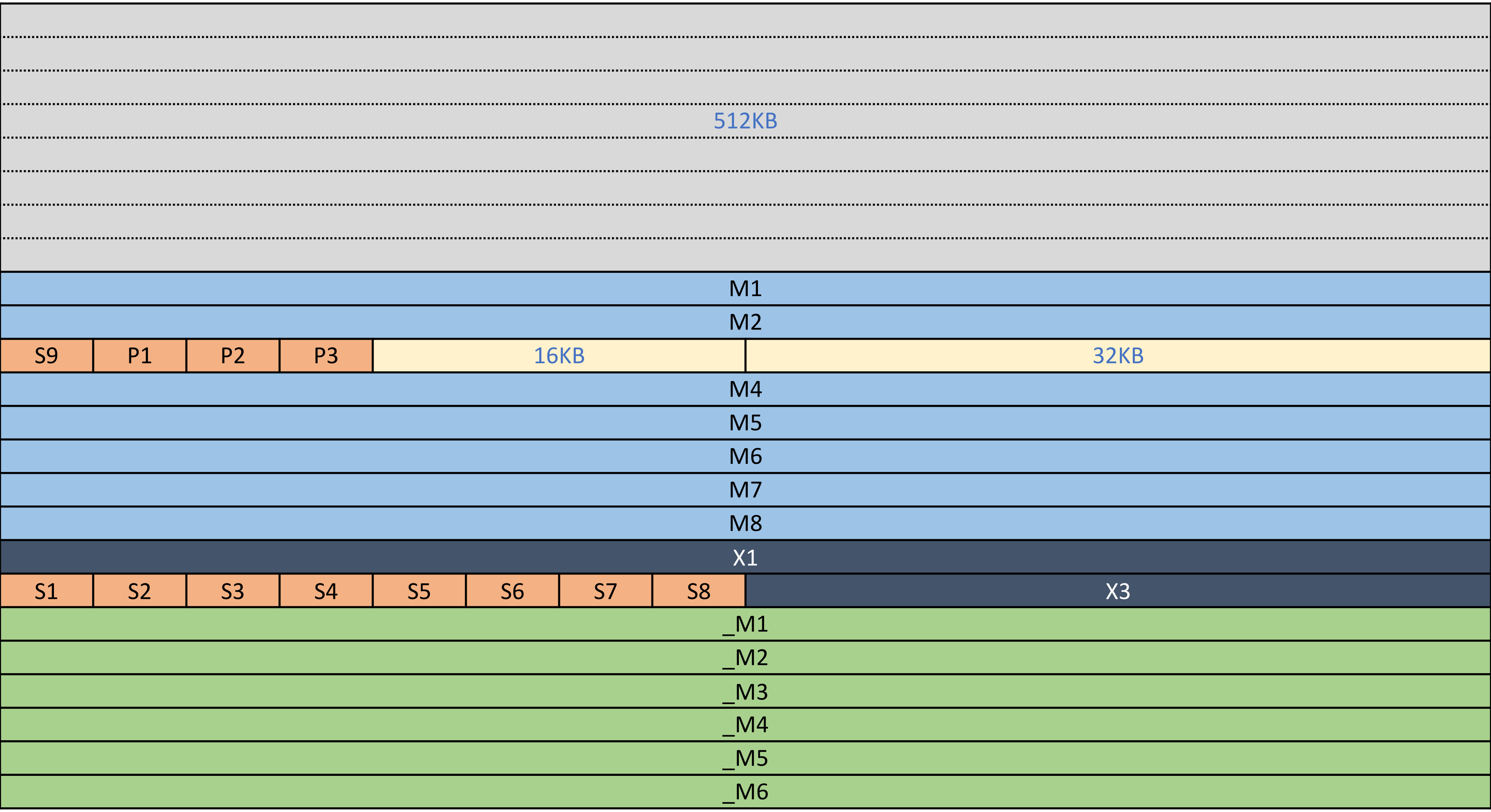
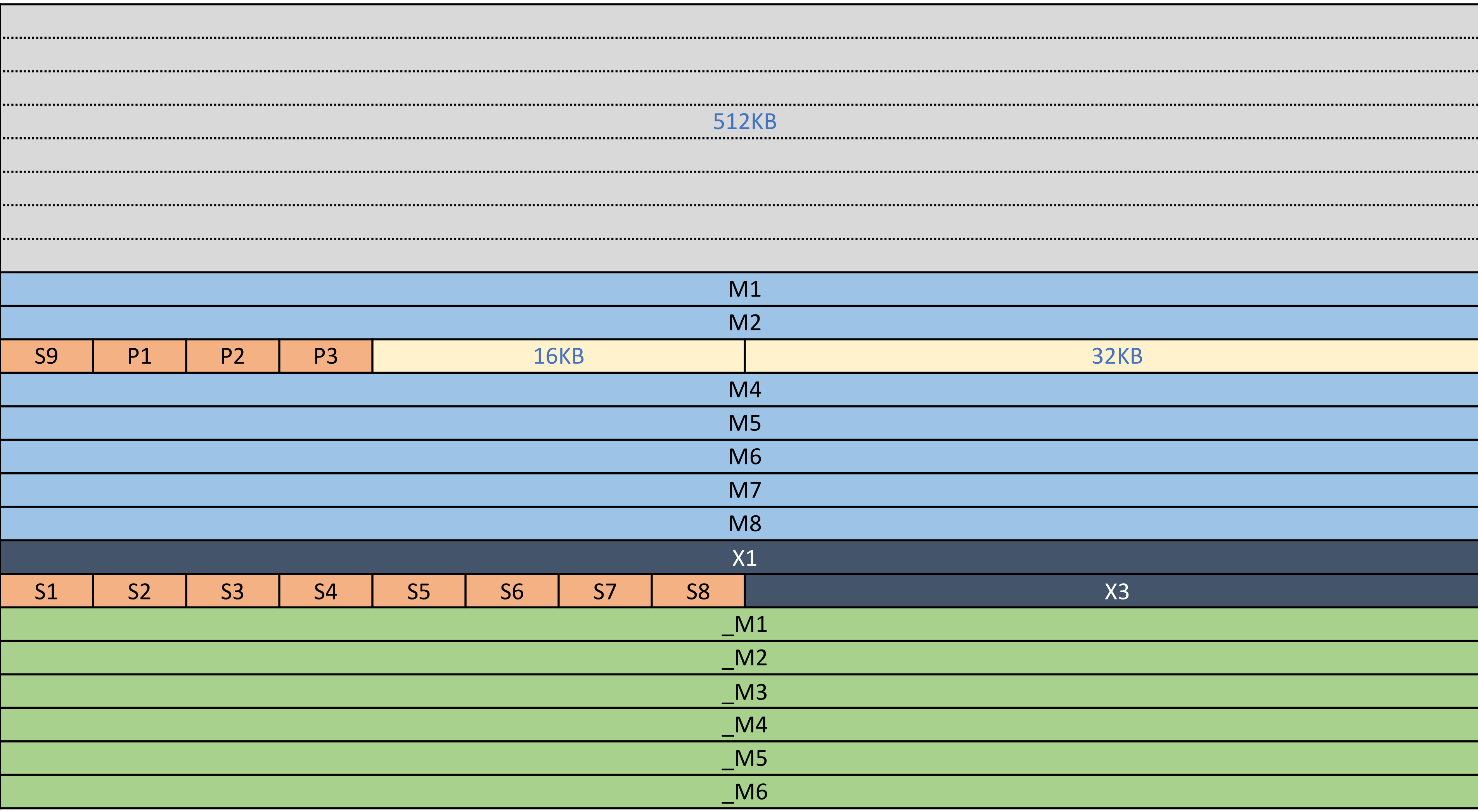


Phys Feng Shui step 8/8

Force a Page Table allocation + map the vulnerable PTE

```
PT = mmap(MAP_FIXED); // Force a Page Table allocation
```



Phys Feng Shui step 8/8

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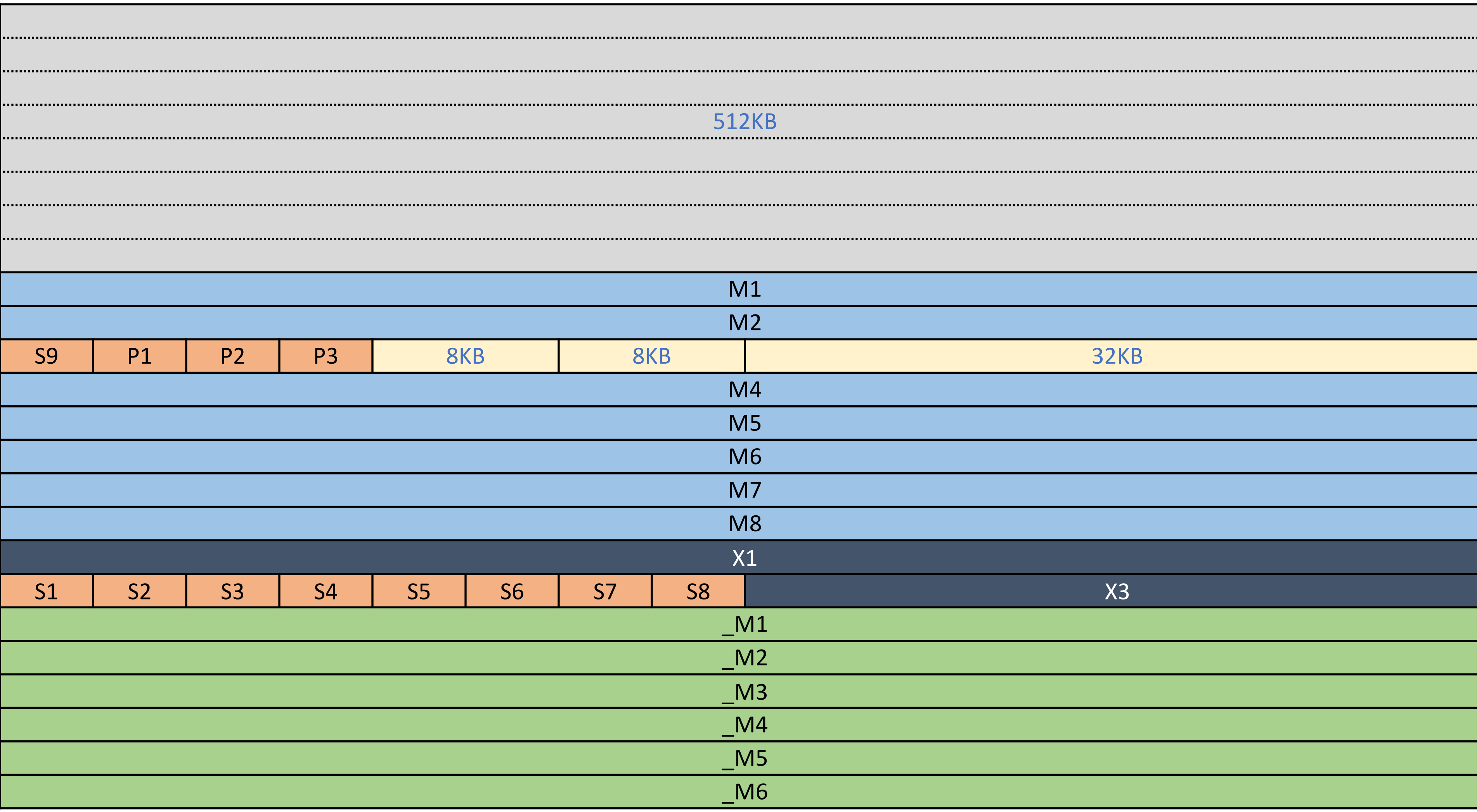

Phys Feng Shui step 8/8

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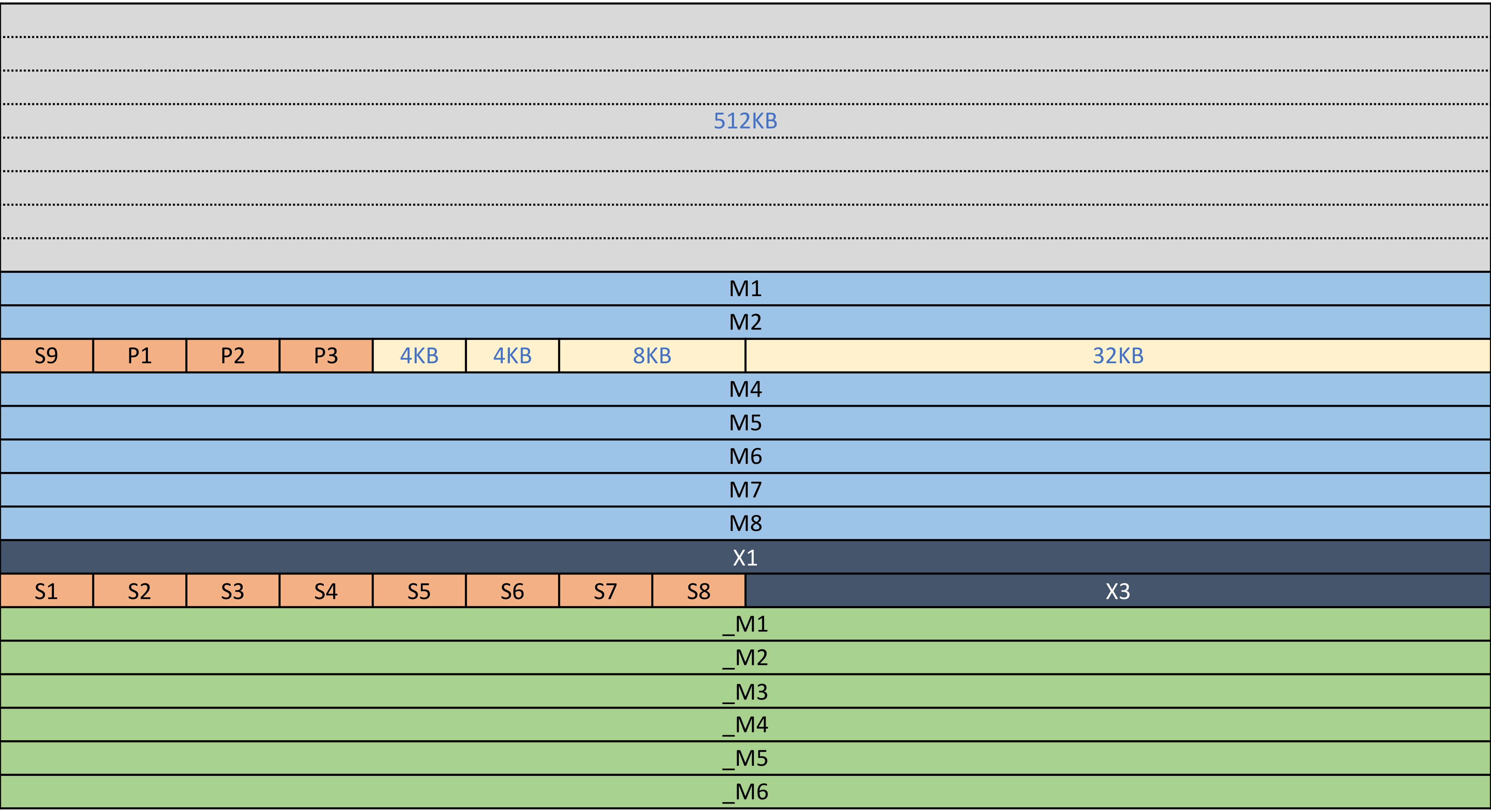

Phys Feng Shui step 8/8

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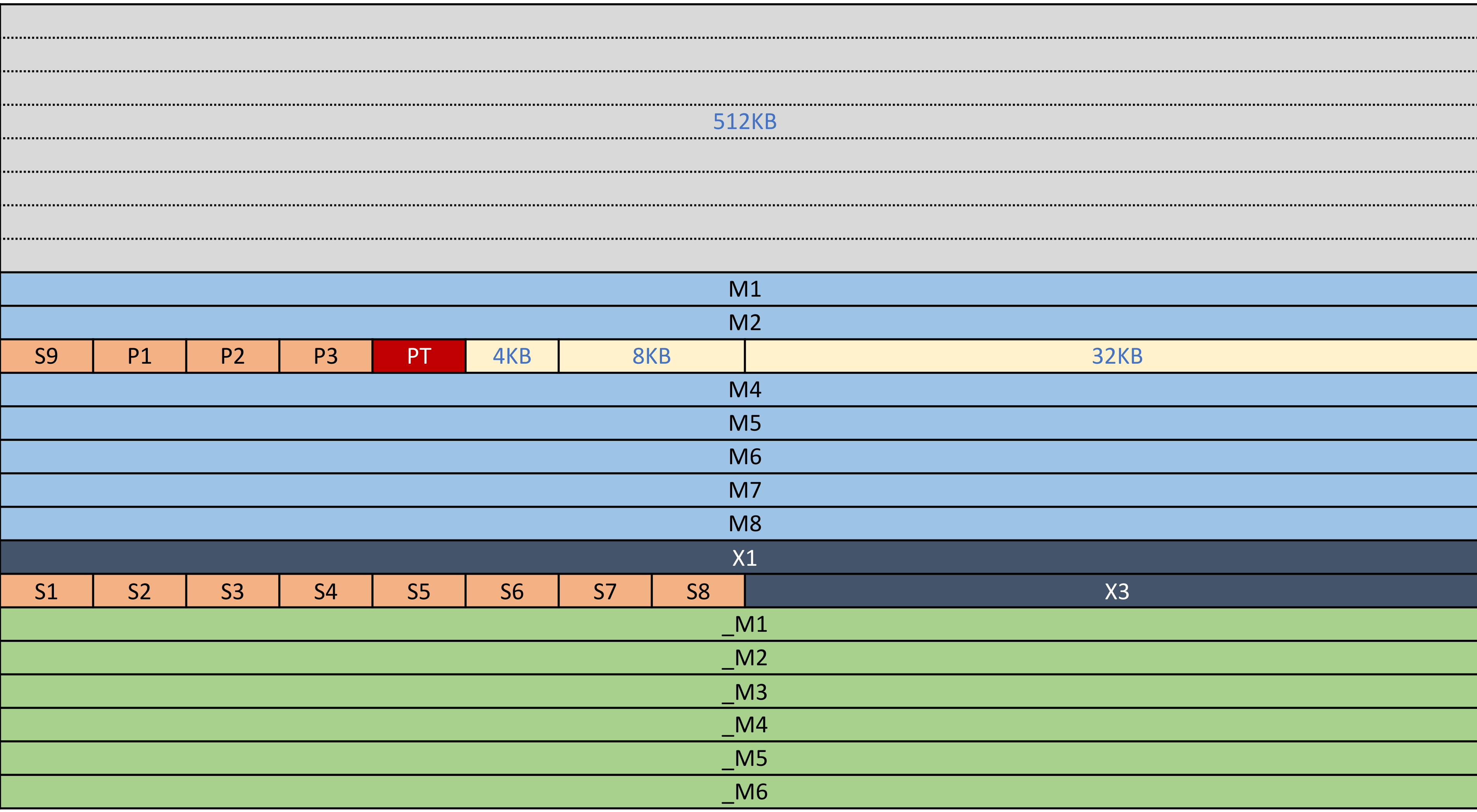

Phys Feng Shui step 8/8

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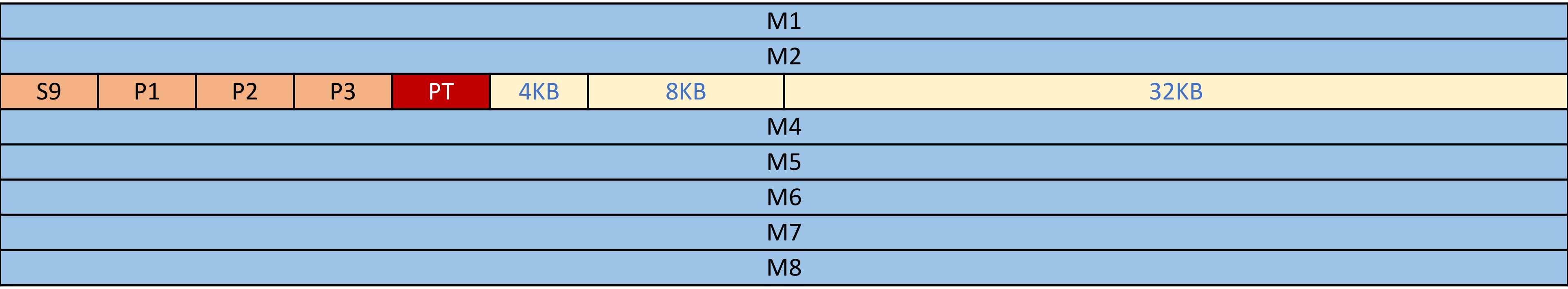

Phys Feng Shui step 8/8

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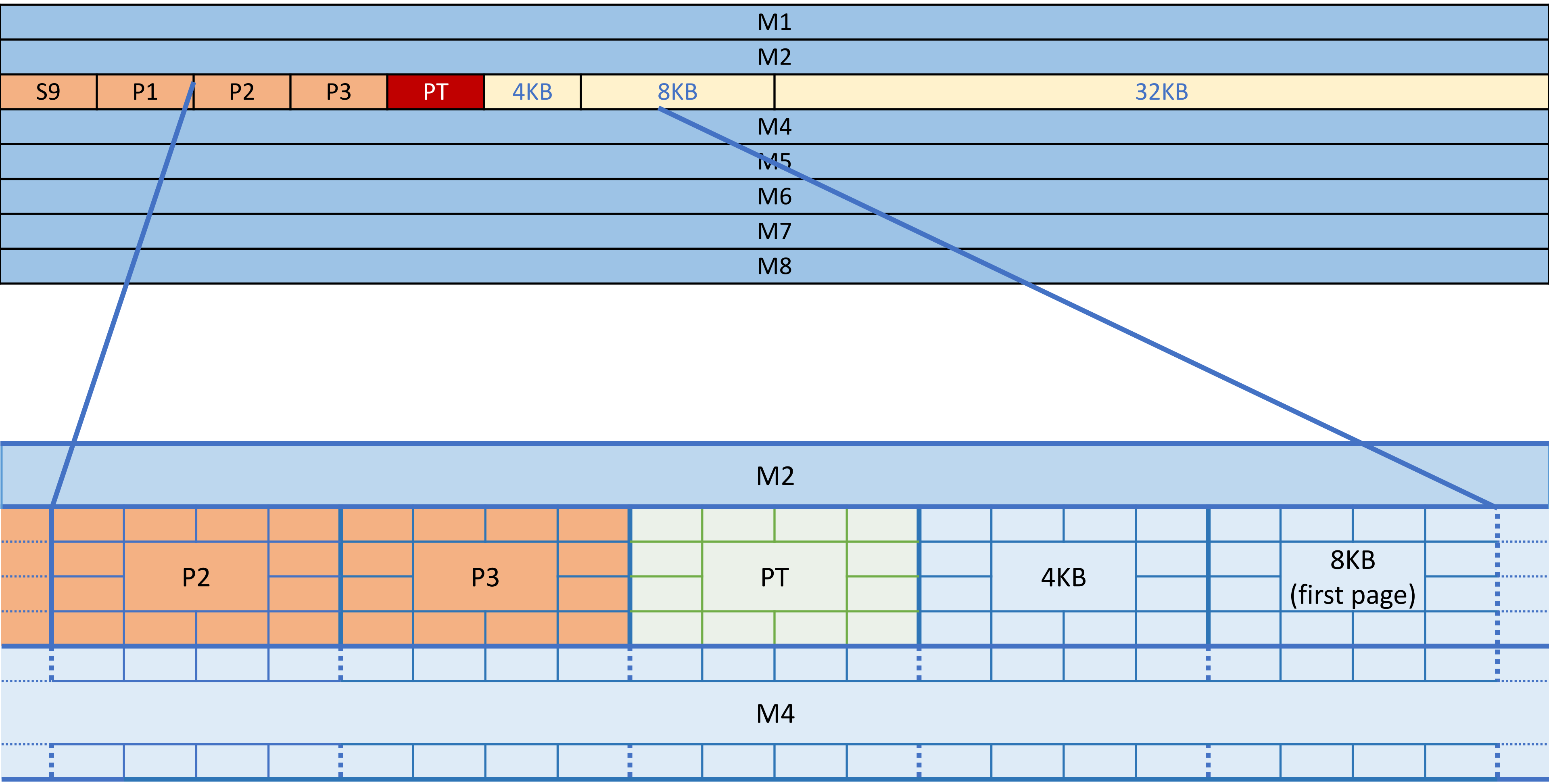
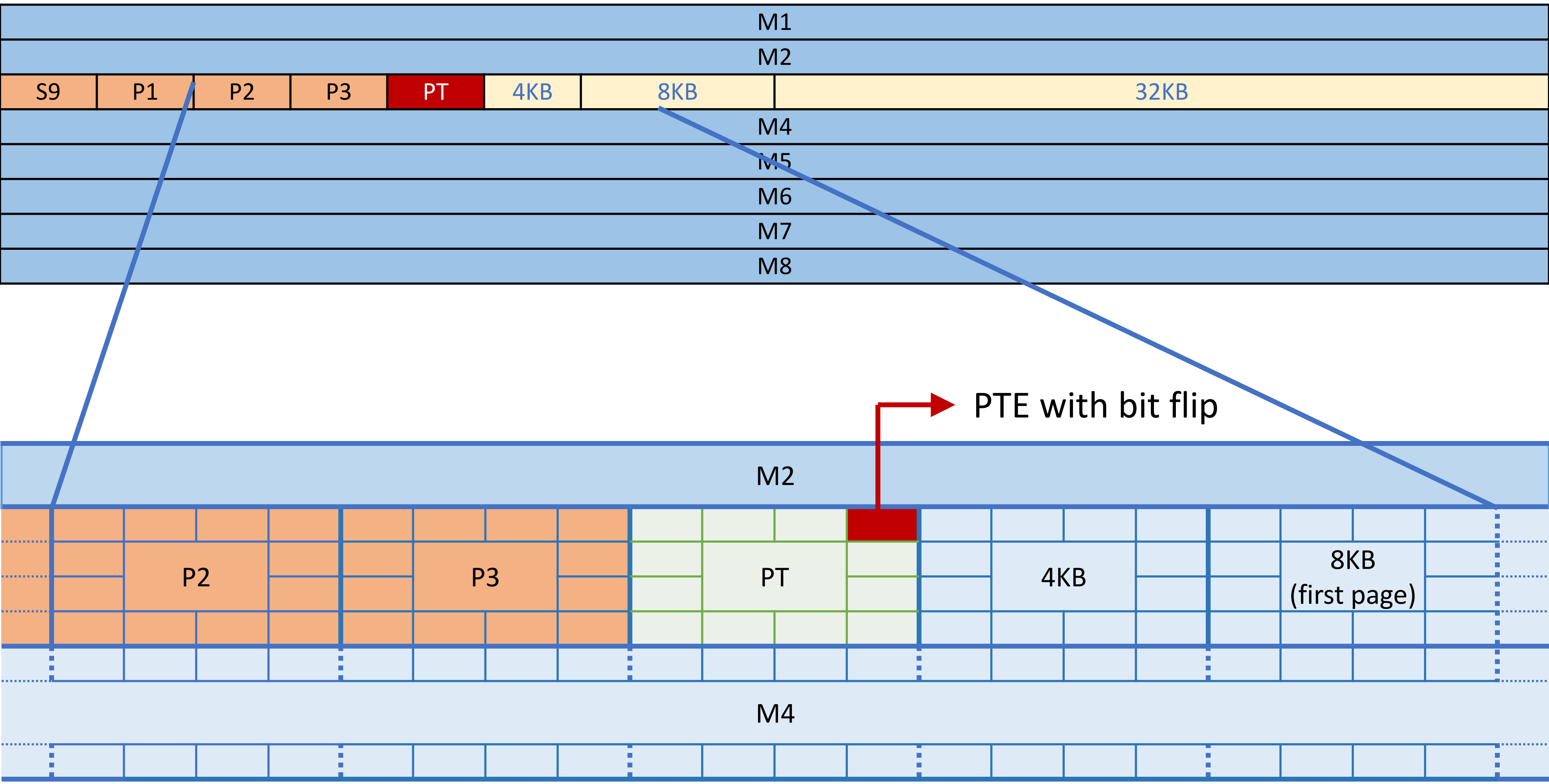


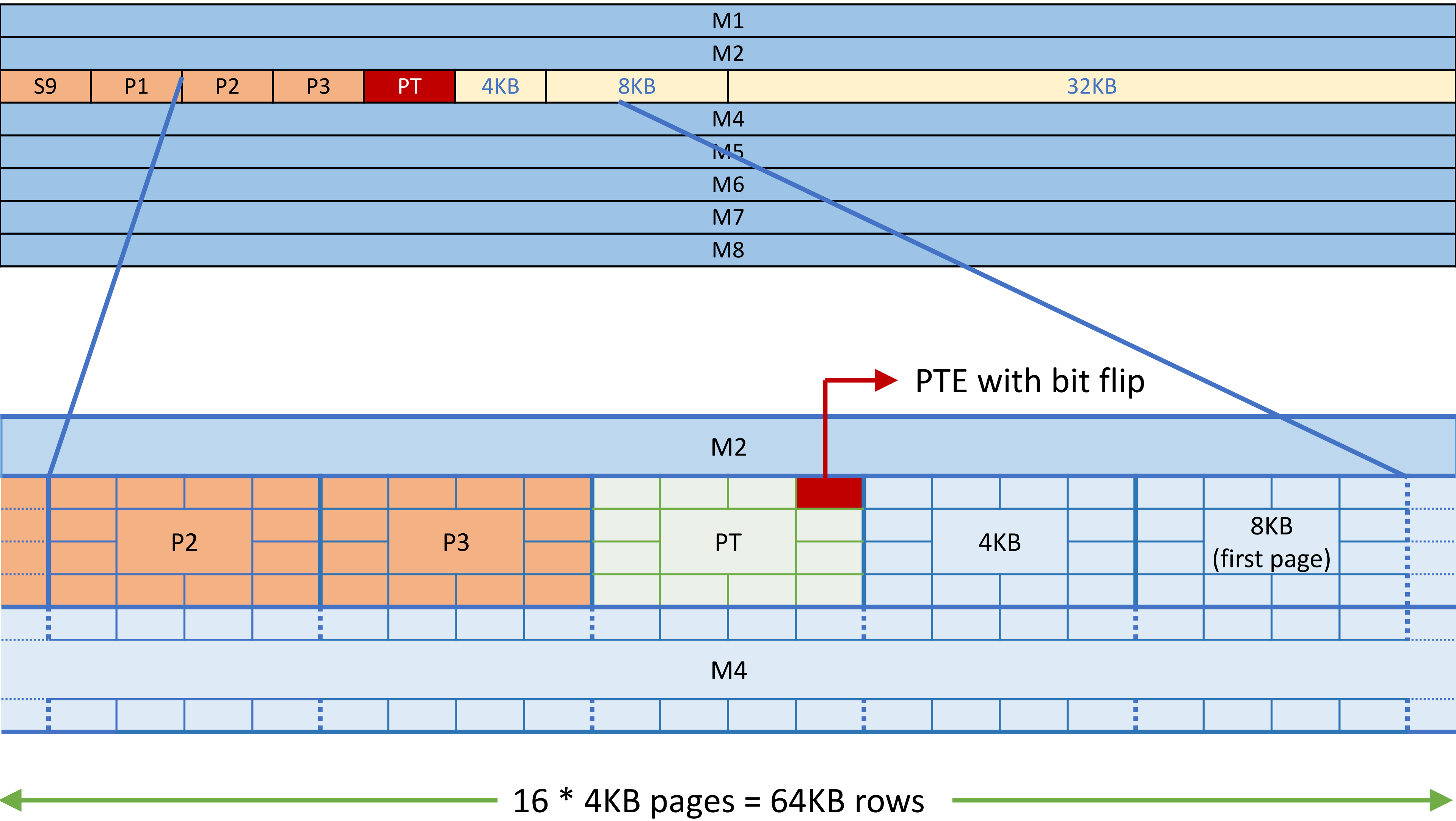
Phys Feng Shui step 8/8

Force a Page Table allocation + map the vulnerable PTE



Phys Feng Shui step 8/8

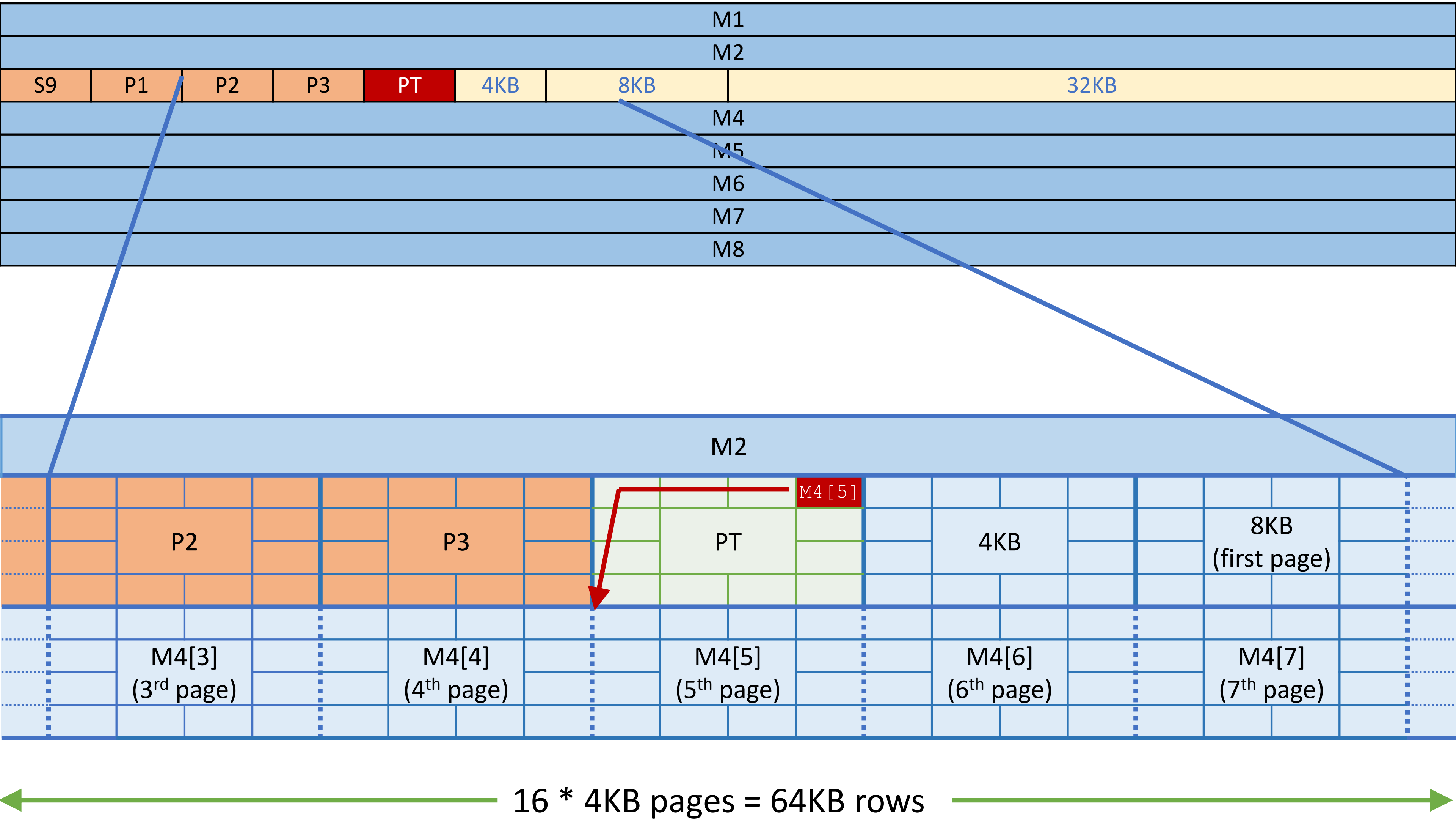
Force a Page Table allocation + map the vulnerable PTE



Phys Feng Shui step 8/8

Force a Page Table allocation + map the vulnerable PTE

```
mmap(M4[5], MAP_FIXED); // map vulnerable PTE 64KB 'away'
```

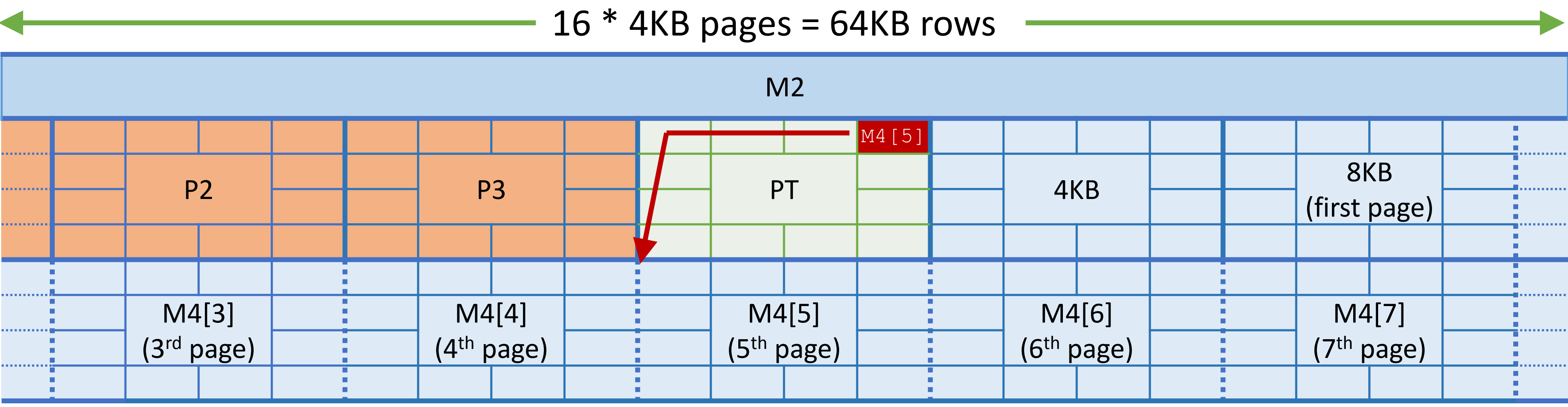


Overview

1. Memory Templating
   Scan memory for useful bit flips
2. Land a Page Table
   Store a page table on a vulnerable page
3. Reproduce the bit flip
   Modify the data structure and get root acces

Drammer

Perform double-sided rowhammer to flip a bit in the PTE



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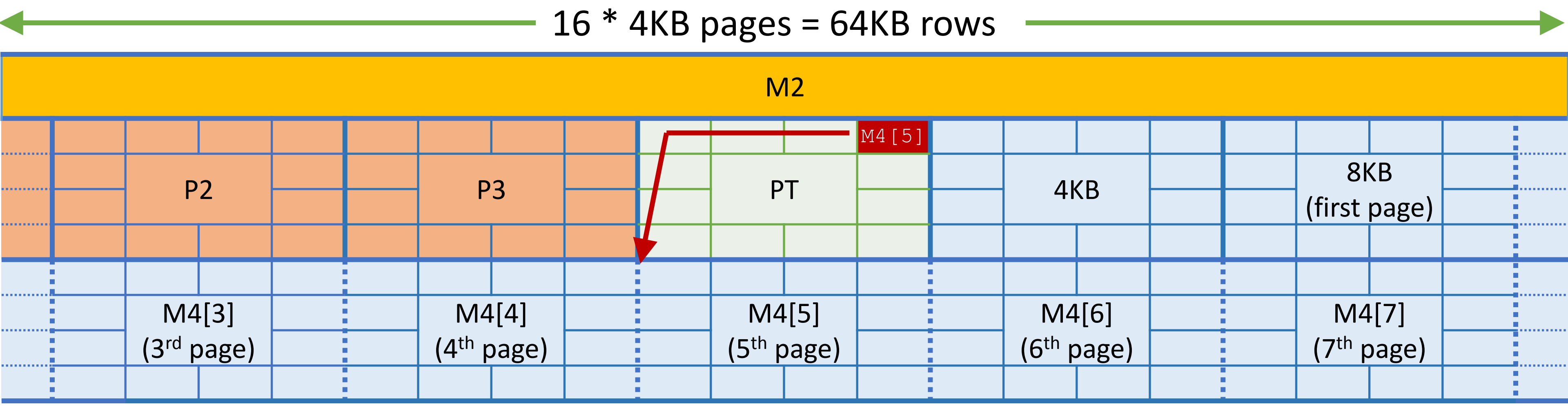

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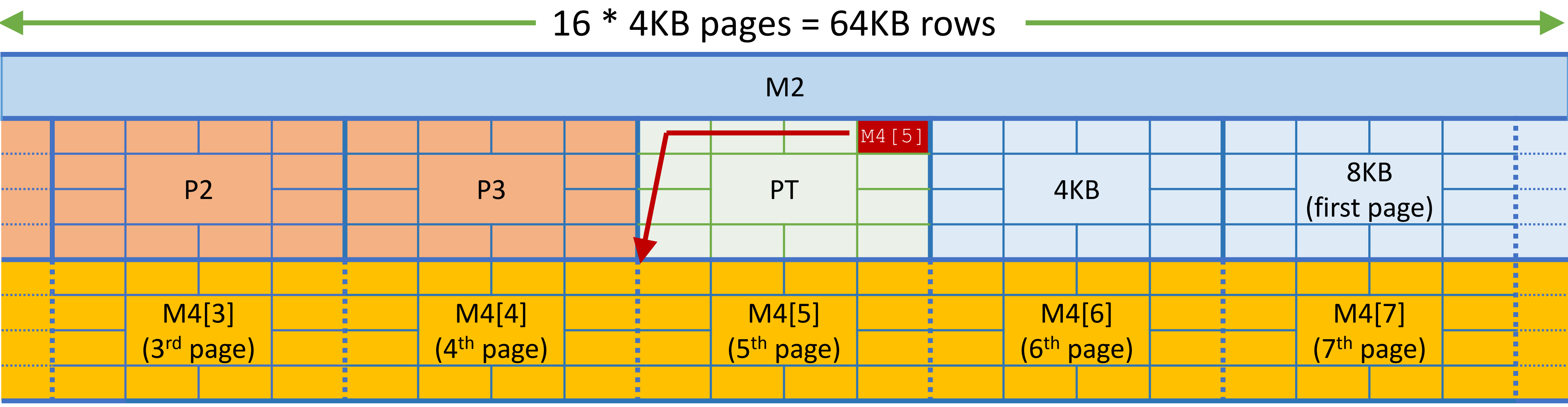
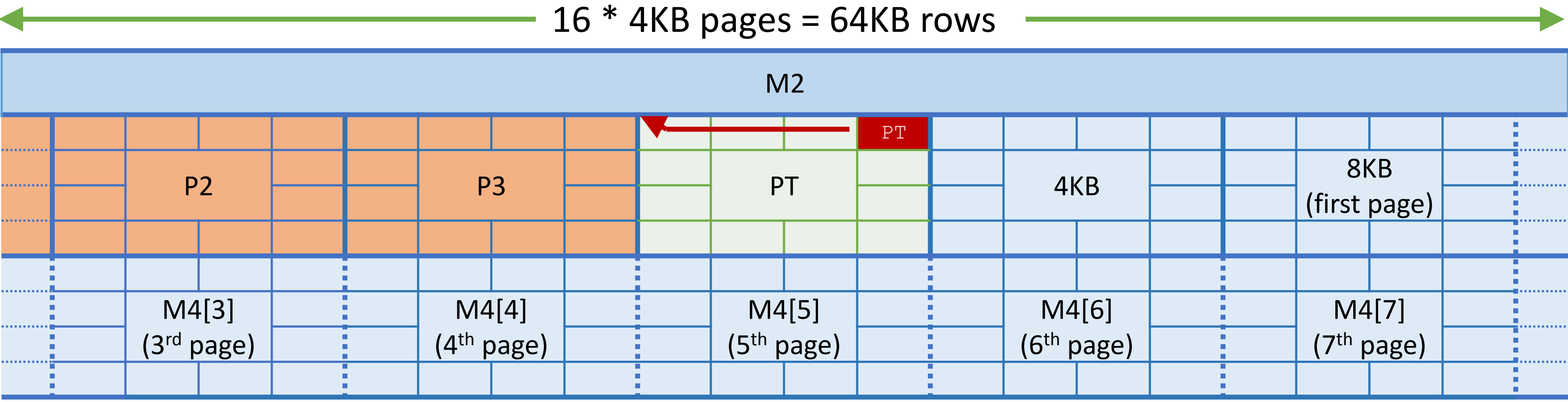


Drammer

Write access to a Page Table



Drammer

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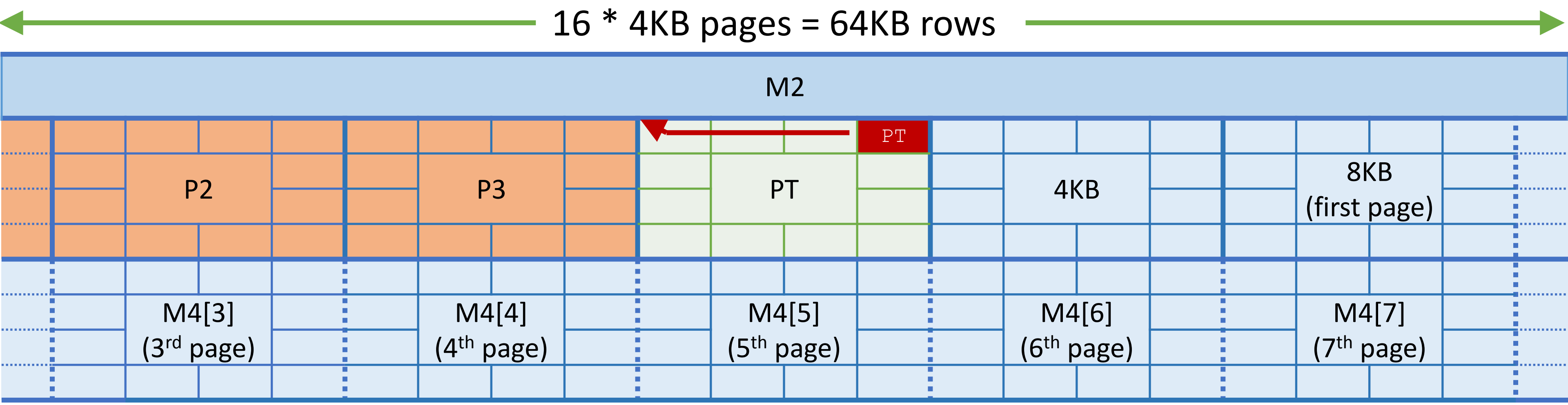
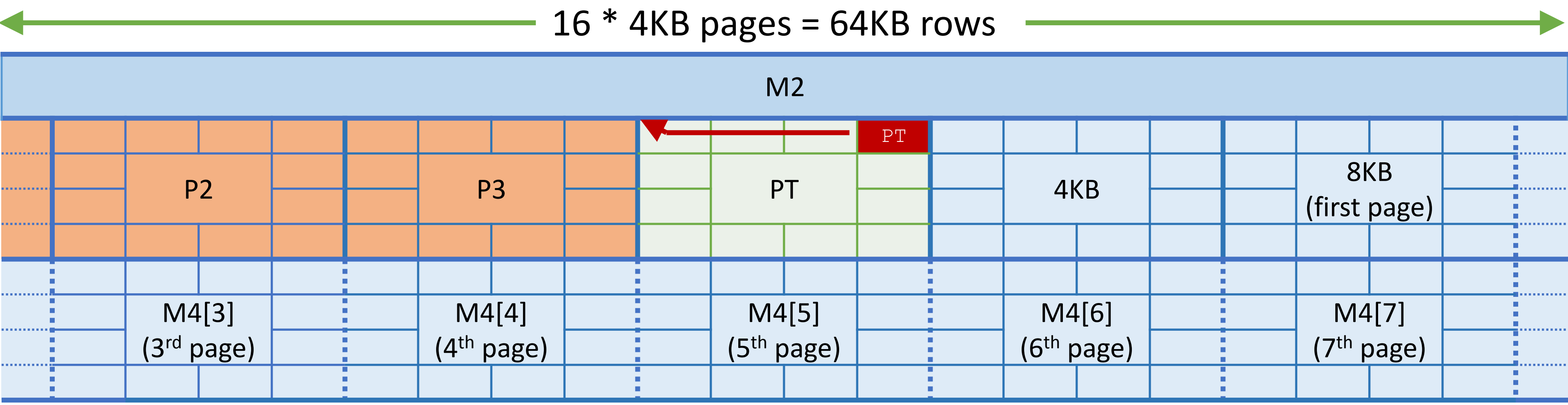


1. Fill PT with Page Table Entries to kernel memory

Drammer

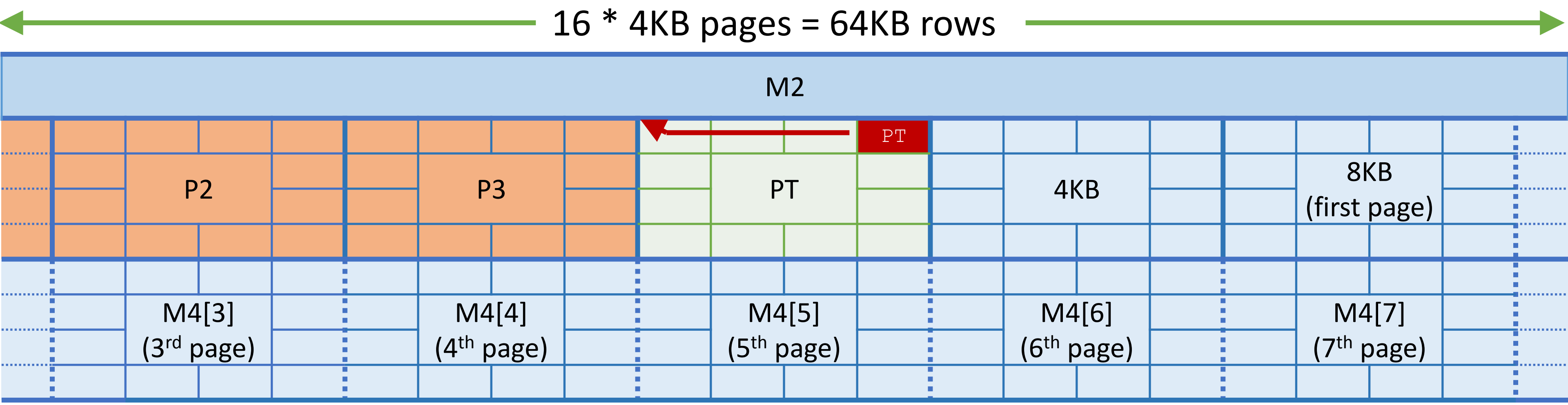
Write access to a Page Table



1. Fill PT with Page Table Entries to kernel memory
2. Search kernel memory for our **`struct cred`**

Drammer

Write access to a Page Table



1. Fill PT with Page Table Entries to kernel memory
2. Search kernel memory for our **`struct cred`**
3. Overwrite our **`uid`** and **`gid`** to get root privileges

Evaluation

Device	#flips	1st exploitable flip after
LG Nexus 5[1]	1058	116s
LG Nexus 5[4]	0	-
LG Nexus 5[5]	747,013	1s
LG Nexus 4	1,328	7s
OnePlus One	3,981	942s
Motorola Moto G (2013)	429	441s
LG G4 (ARMv8 – 64-bit)	117,496	5s

Bit flips on 18 out of 27 tested devices

Evaluation

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After the 1st exploitable flip, exploitation takes at most 22 seconds

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LG Nexus 5[5]	747,013	1s
LG Nexus 4	1,328	7s
OnePlus One	3,981	942s
Motorola Moto G (2013)	429	441s
LG G4 (ARMv8 – 64-bit)	117,496	5s

After the 1^{st} exploitable flip, exploitation takes at most 22 seconds

Drammer test app reported bit flips on:

Google Pixel, OnePlus 3, Galaxy Note 7, HTC One M8, …

Disclosure

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"What if we support you financially?"

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But now it does

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Partial hardening in November's updates

"We will continue to work on a longer term solution"

Conclusion

- Deterministic Rowhammer exploitation
- **No special memory management features required (e.g., deduplication)**
- ARM memory controllers are fast enough to do Rowhammer
- LPDDR* found vulnerable
- No easy software fix

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- More details
  - Demos, statistics and test app:
    https://vusec.net/projects/drammer
  - Open source:
    https://github.com/vusec/drammer