# Linux Plumbers Conference

Dublin, Ireland September 12-14, 2022

# How I started chasing speculative type confusion bugs in the kernel and ended up with 'real' ones

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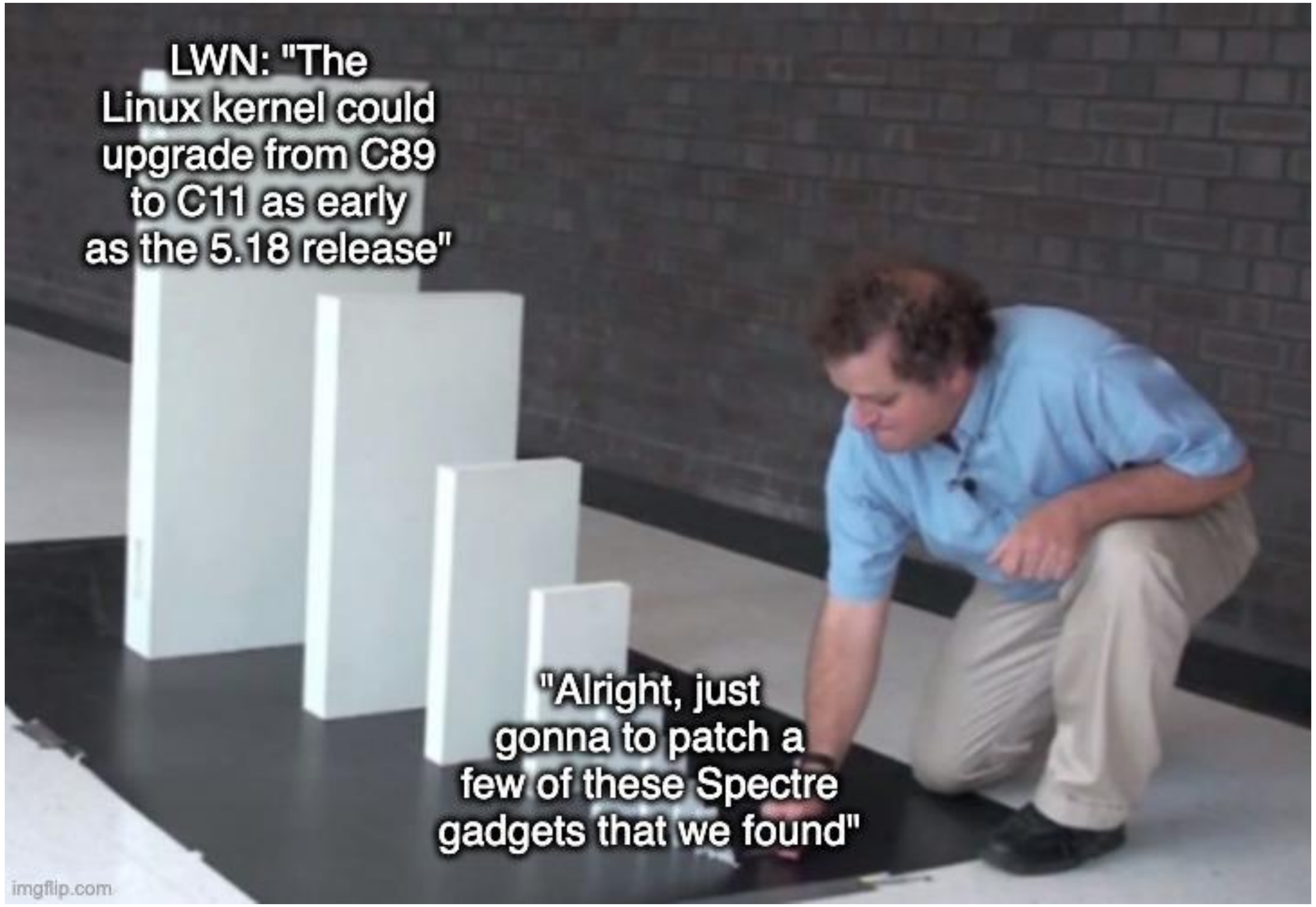
VUSec






https://twitter.com/bjohannesmeyer/status/1497199212907446274

We'll start with some **Spectre** background

followed by an **interesting case study**

revealing more 'real' bugs in the **list iterators**

# Speculative Execution & Branch Predictor

```
char msg[128] = "LPCLPCLPCLPCLPC...\0";
int count = 0;
// calculate length of string
for (int i = 0; i < 128; i ++) {
    if (msg[i] != '\0') {
        count += 1;
    } else {
        break;
    }
}
```

```
i = 0
```

# Speculative Execution & Branch Predictor

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```

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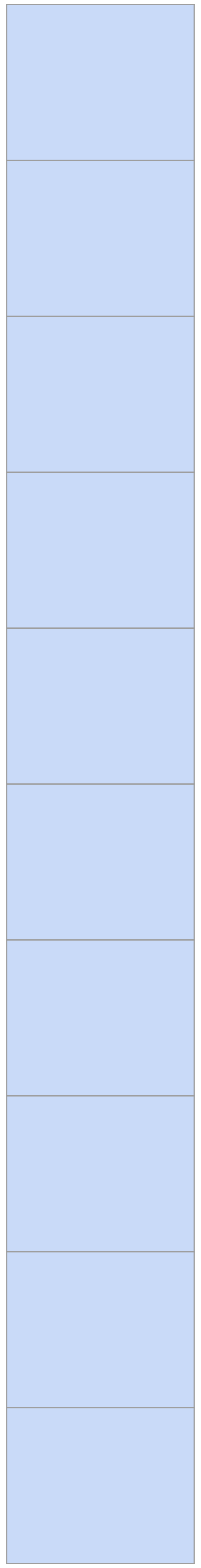
Cache



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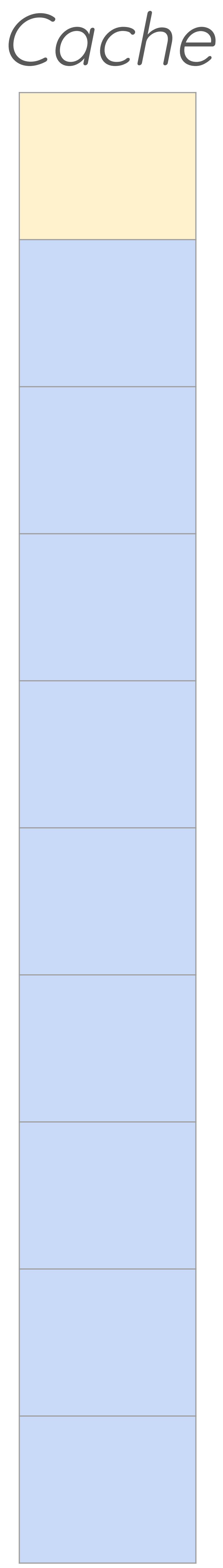
    }
}
```

i = 0



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// calculate length of string
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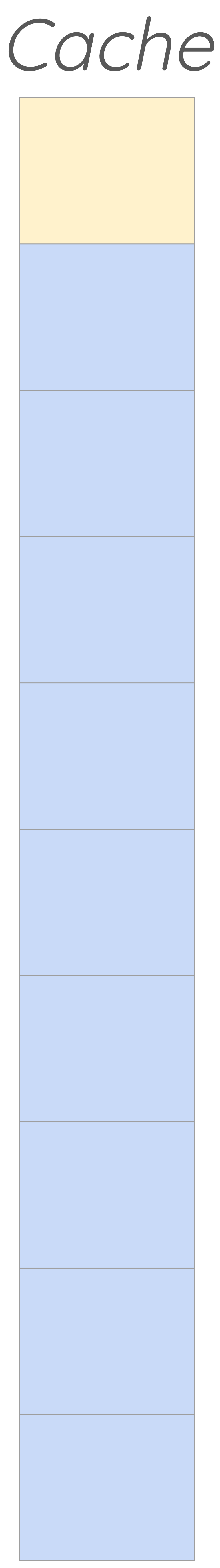
    }
}
```

i = 1



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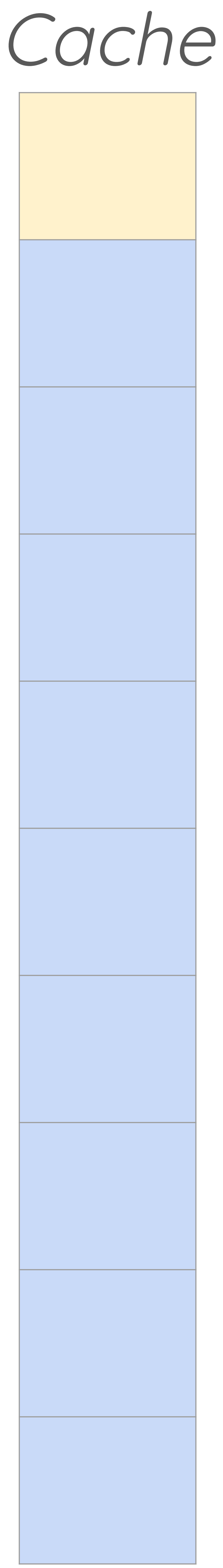
}
```

i = 2



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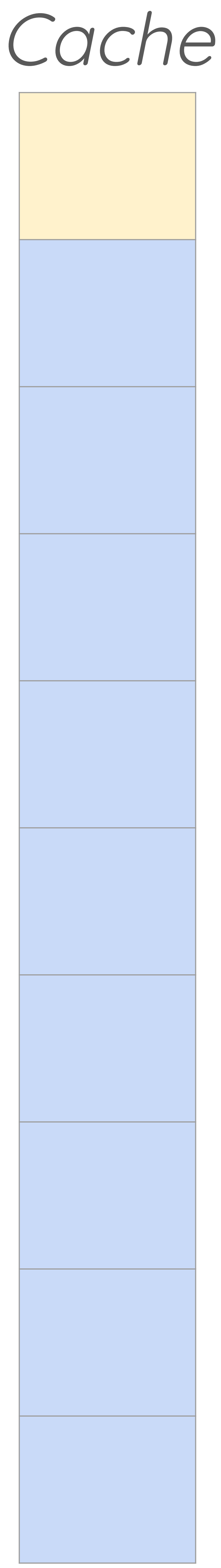
}
```

i = 3



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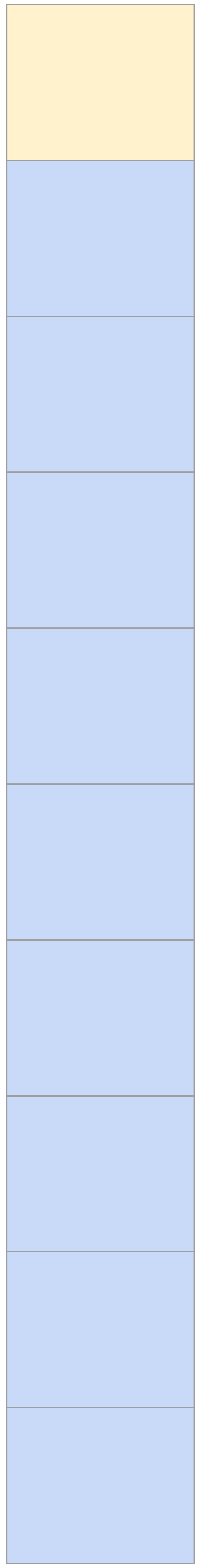
        break;
    }
}
```

i = 4

*Cache*



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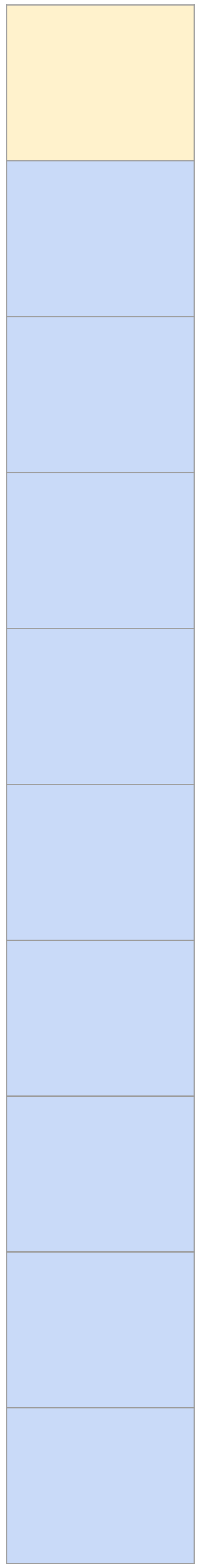
    }
}
```

i = 5

Cache



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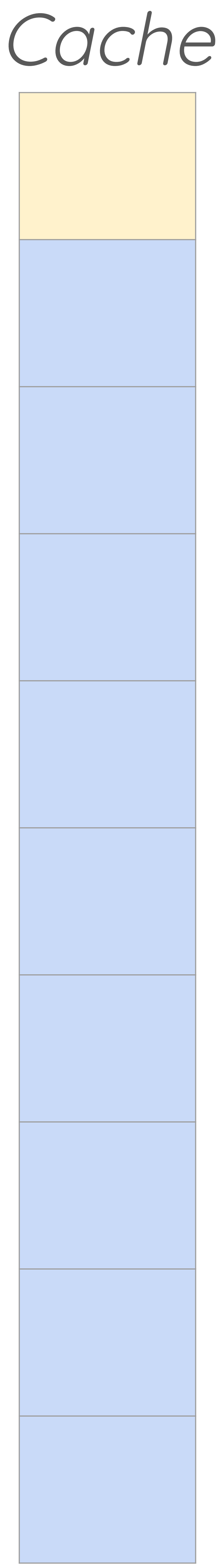
}
```

i = 6



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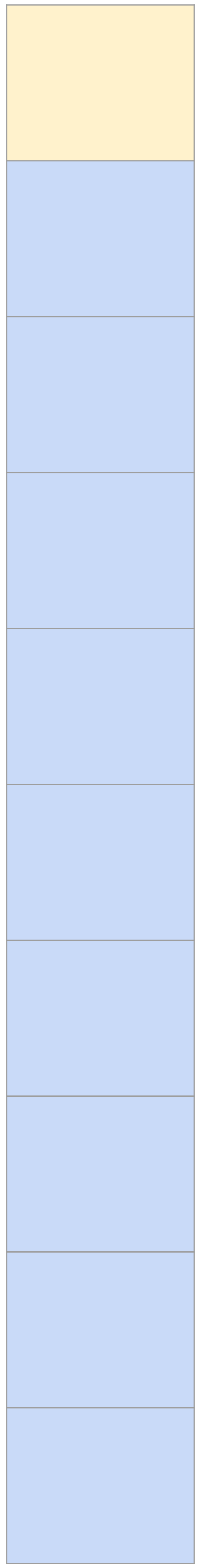
}
```

i = 63

Cache



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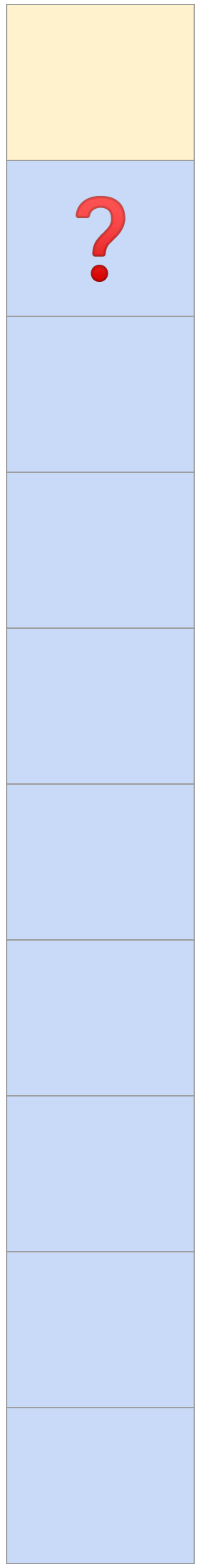
```

i = 64

Cache



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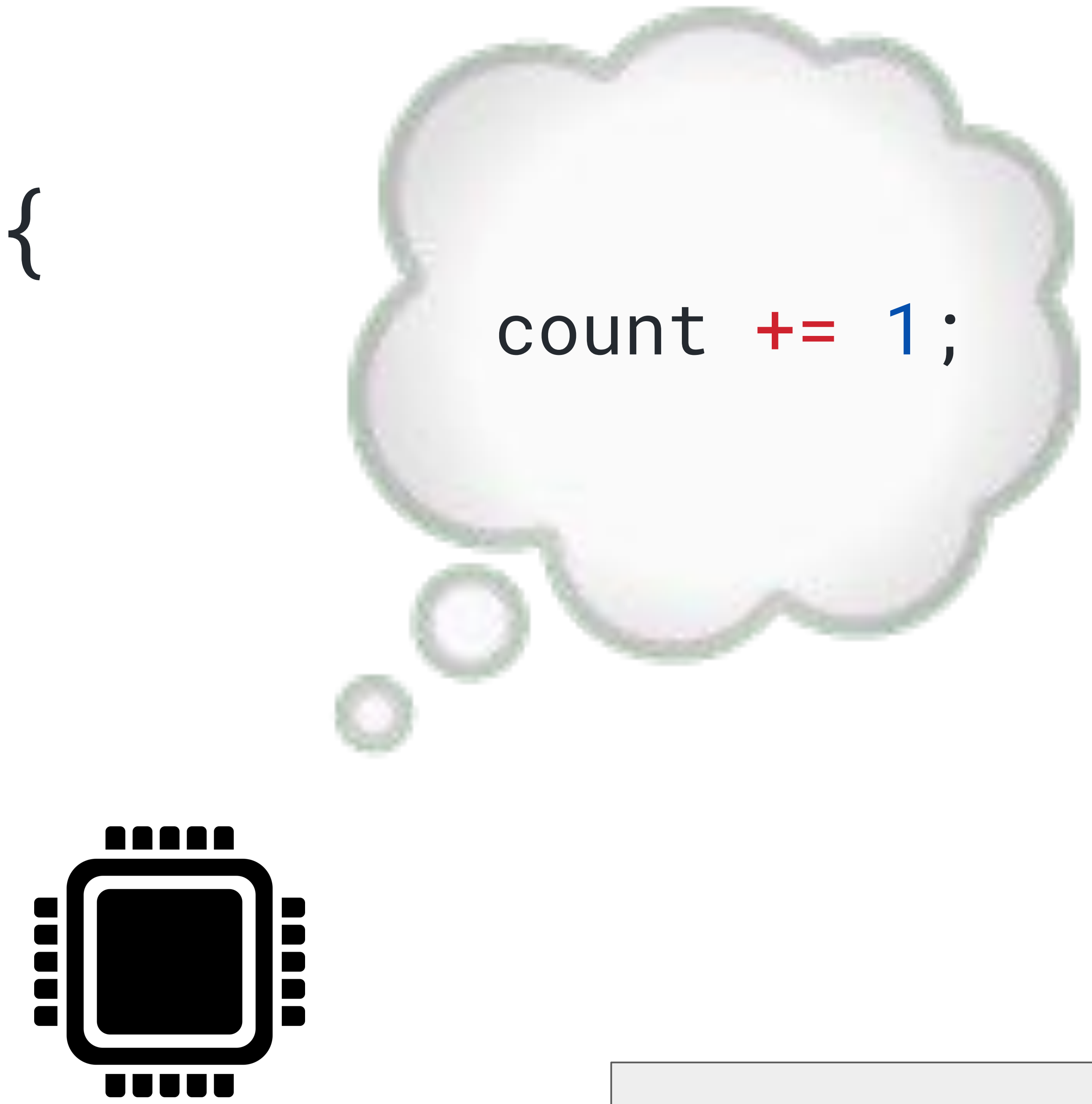


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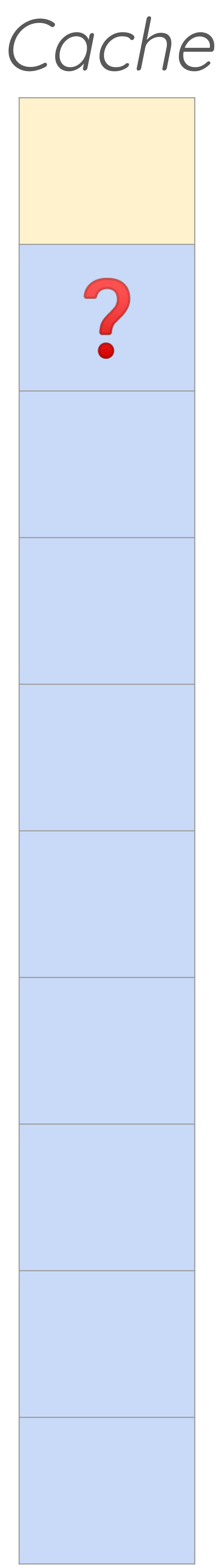

But what if the CPU is not right?

Can we fool the **Branch Predictor**?

# Misprediction

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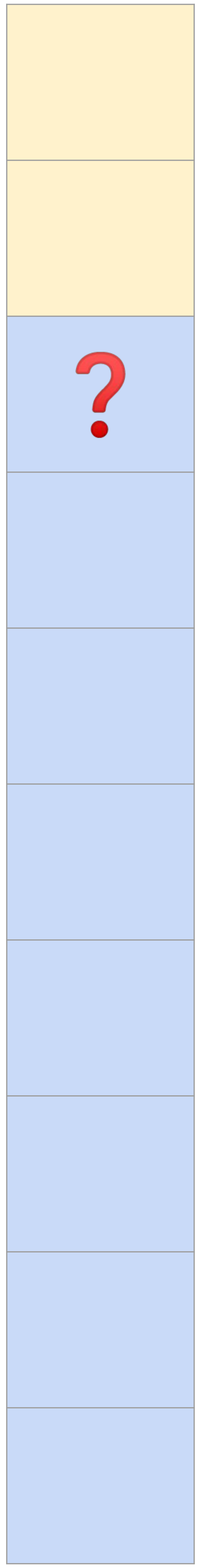

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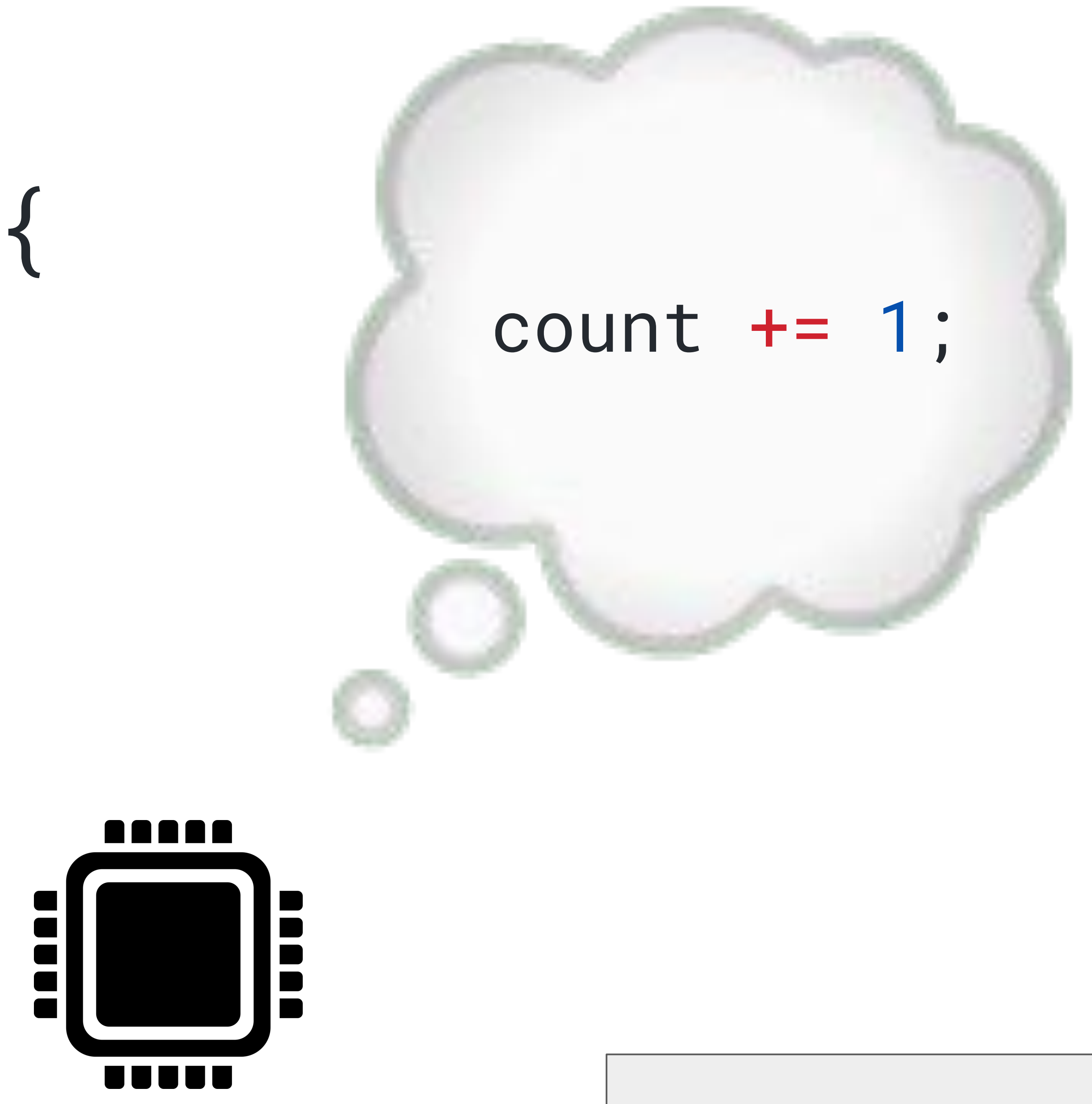


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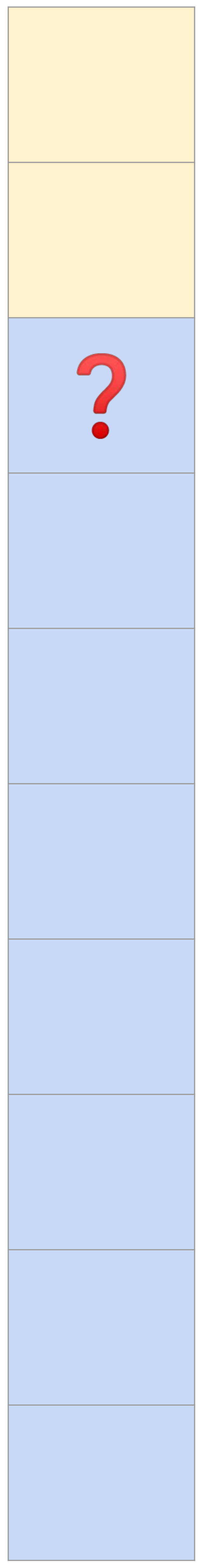
Cache



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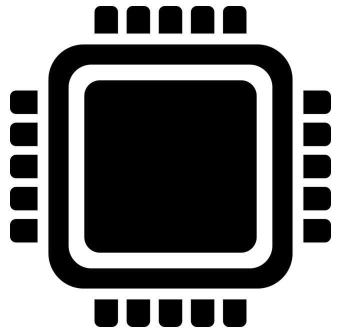

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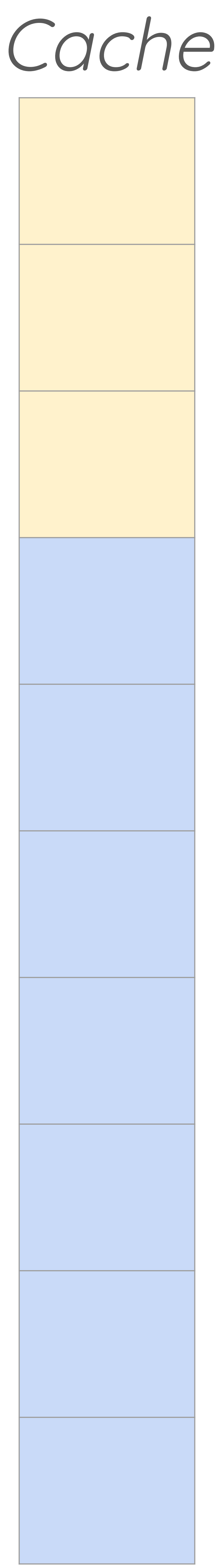

# A Spectre V1 gadget

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x = get_user(ptr);
if (x < size) {
   y = arr1[x];
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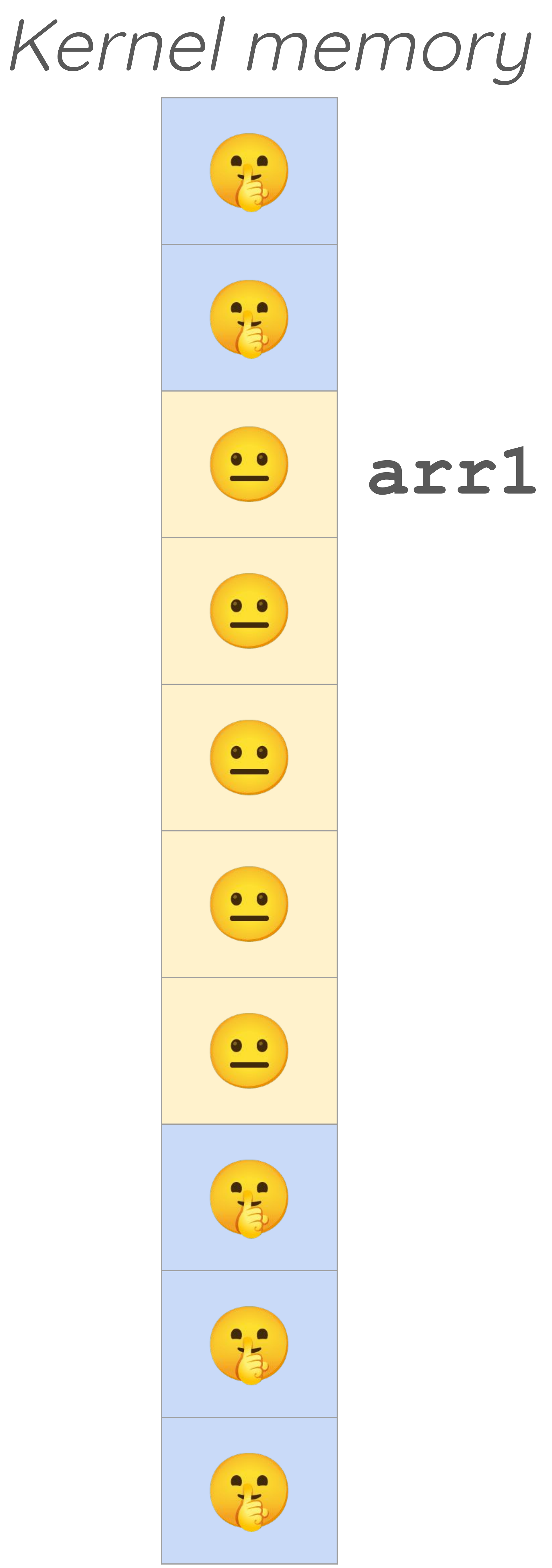

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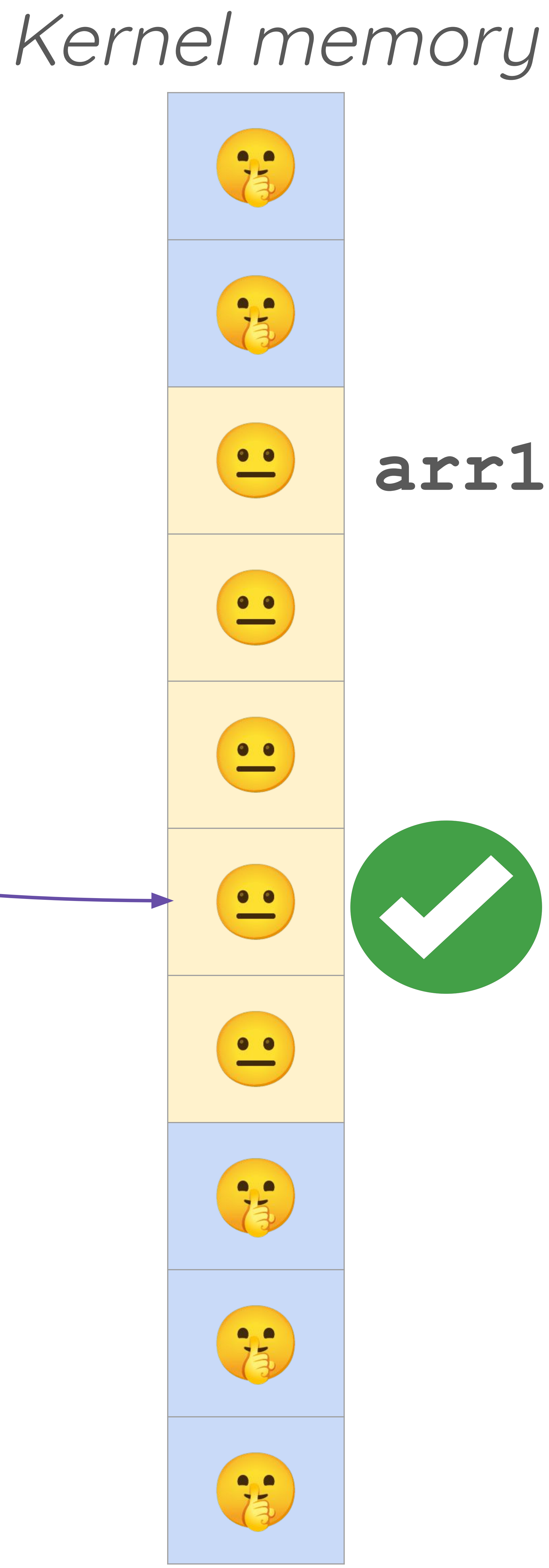

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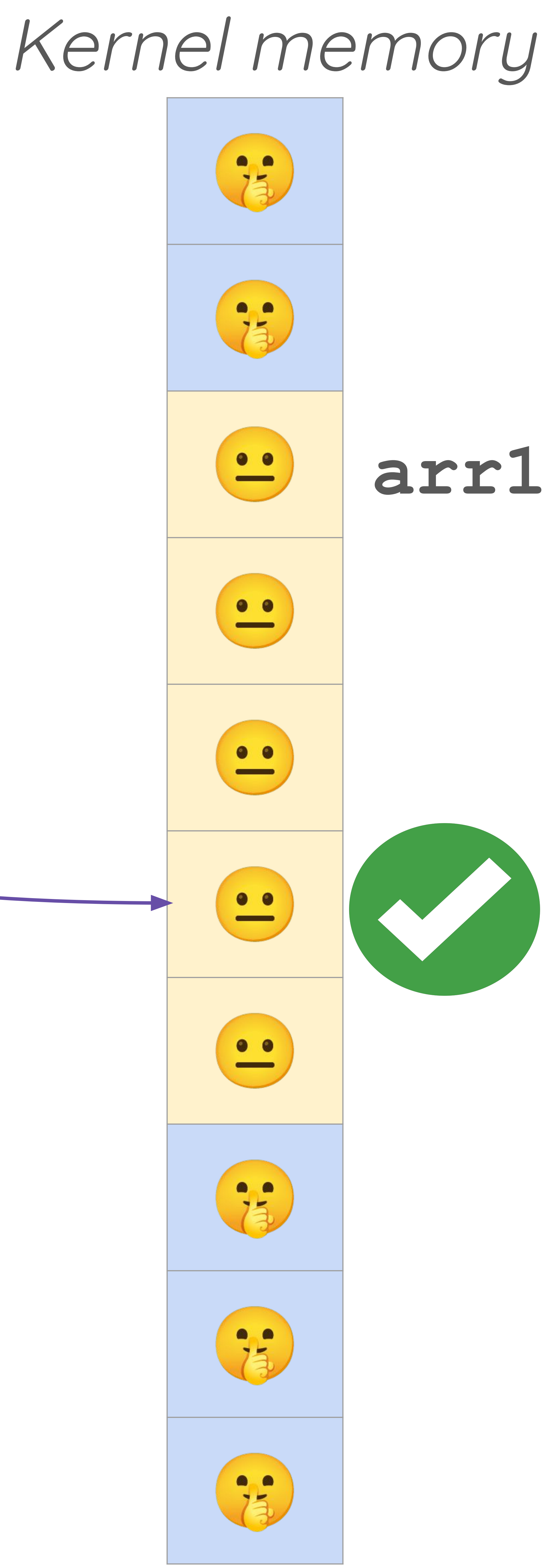

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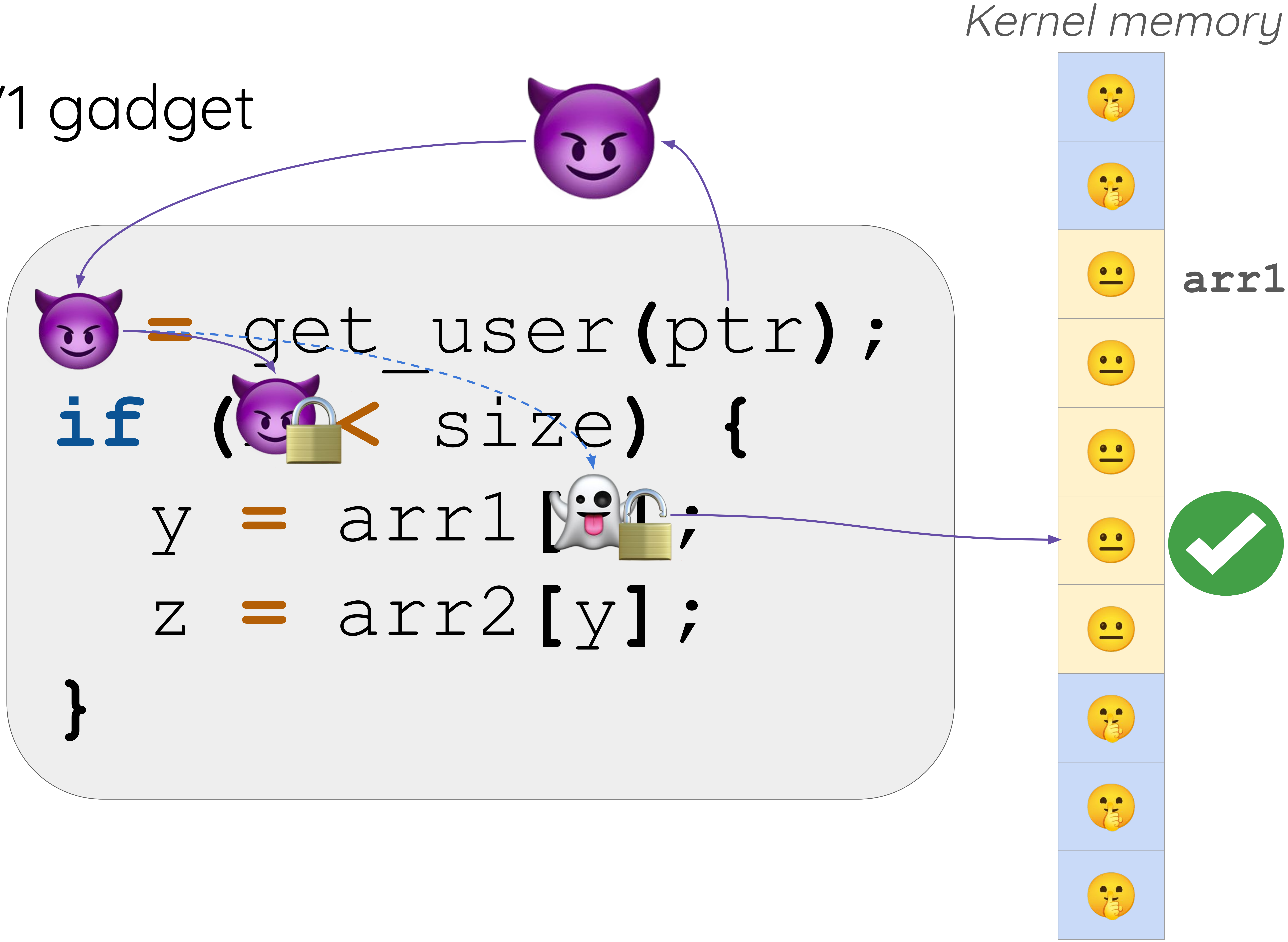

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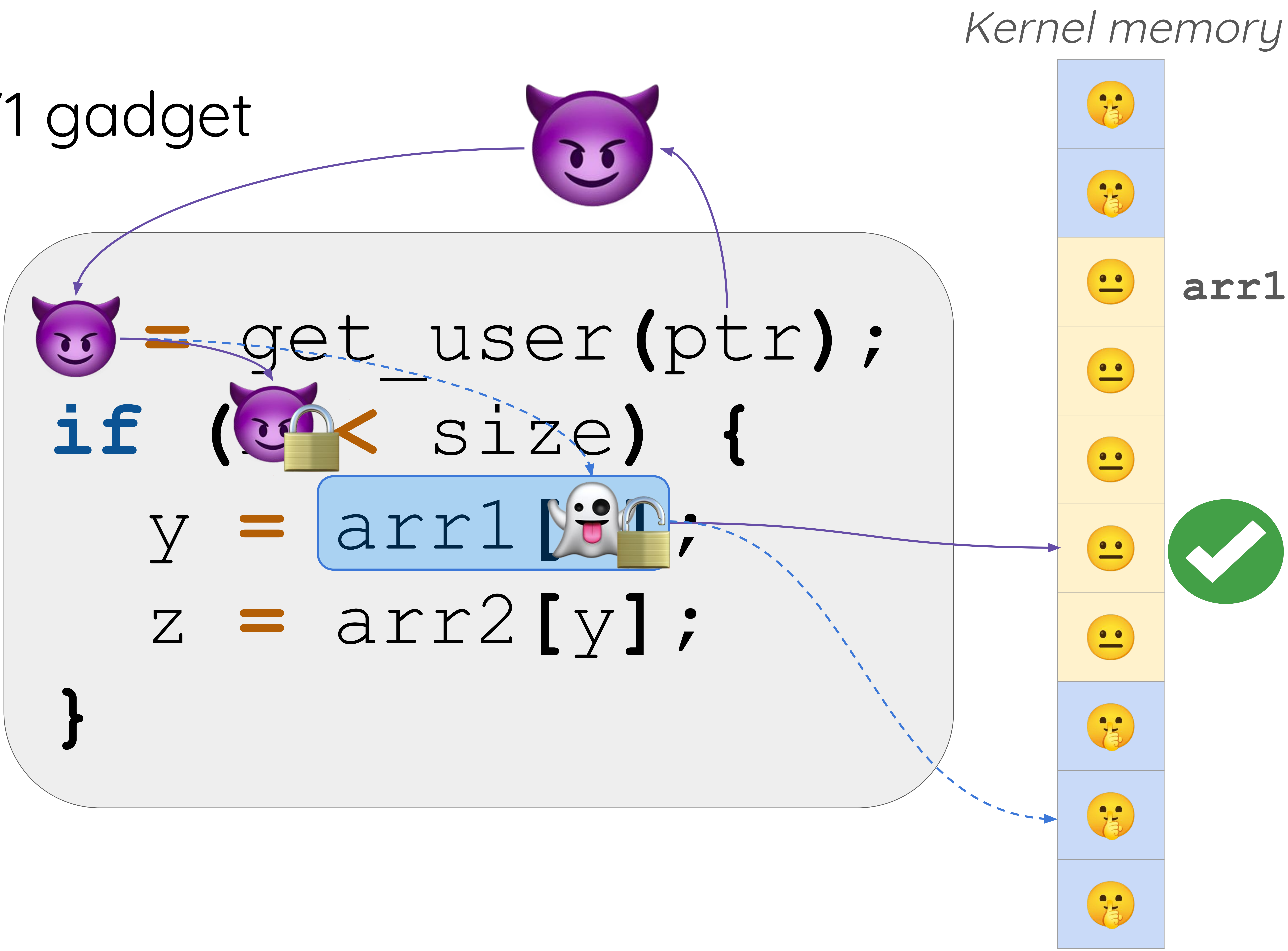

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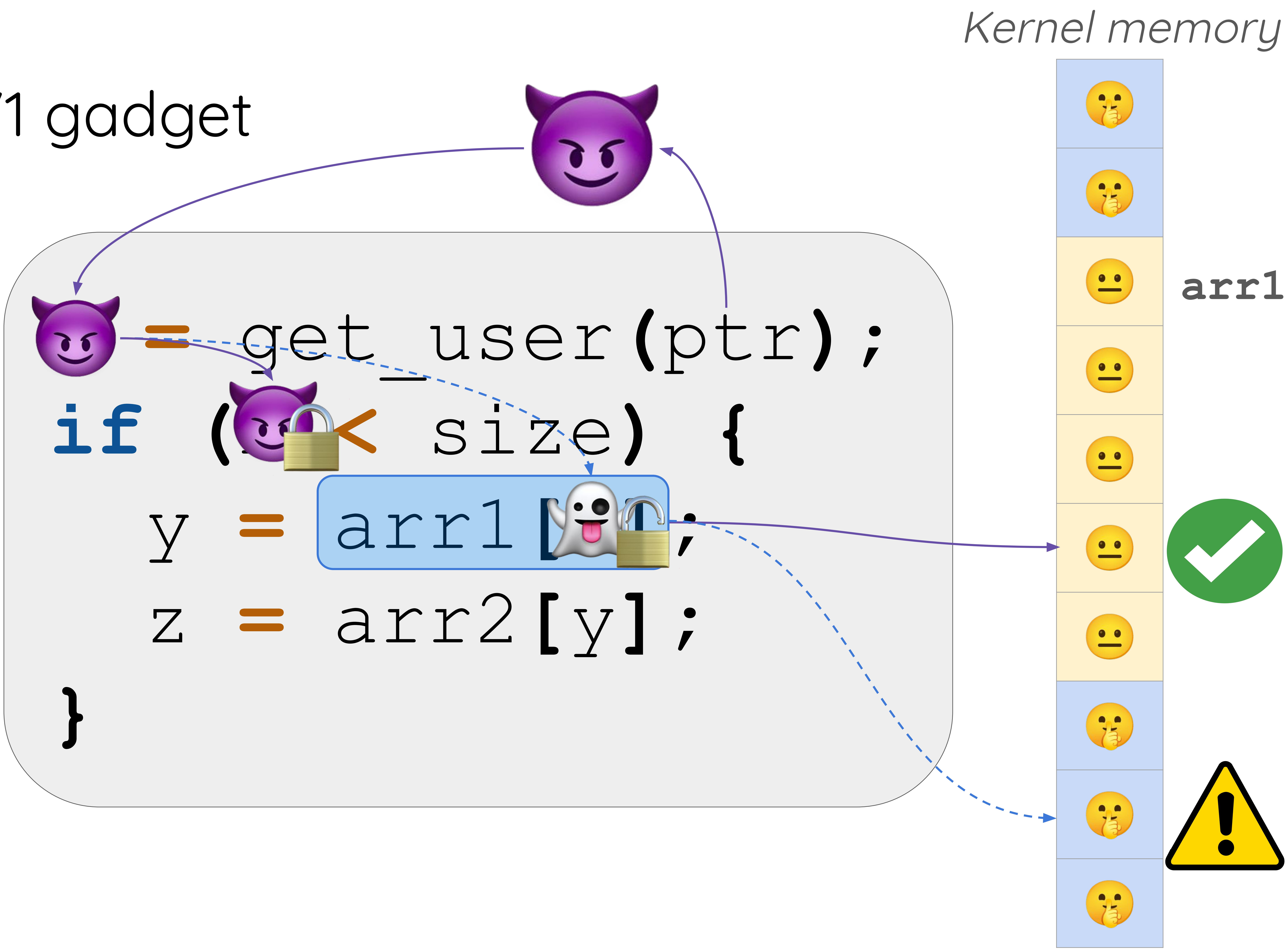

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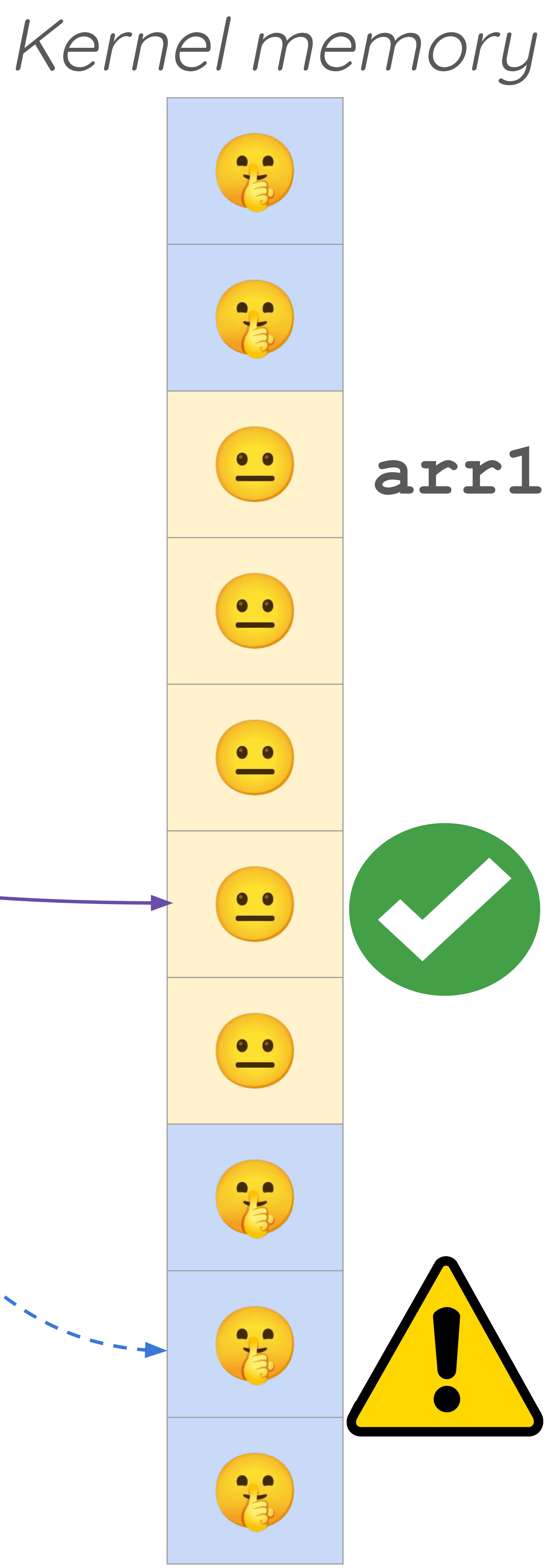

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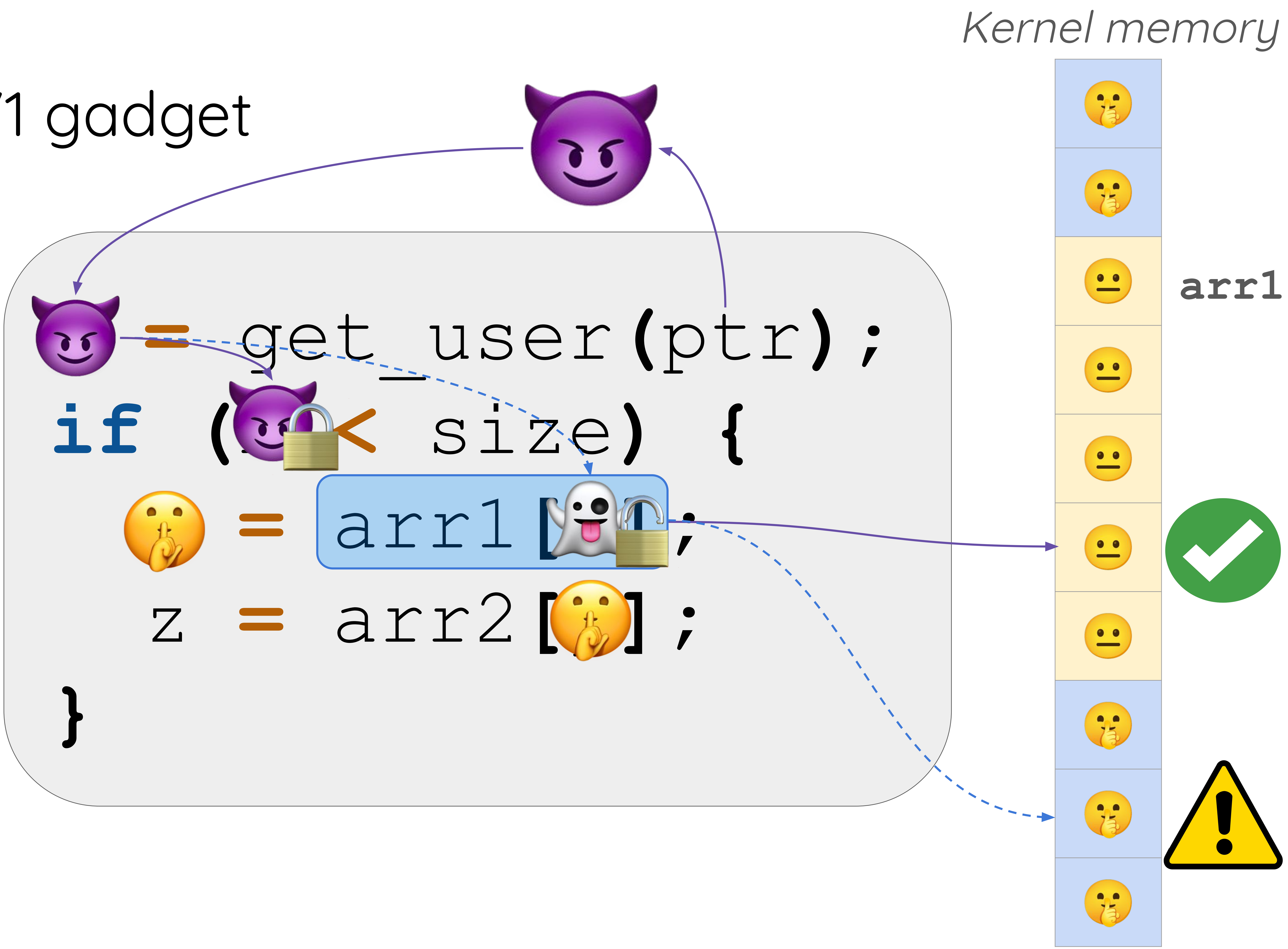

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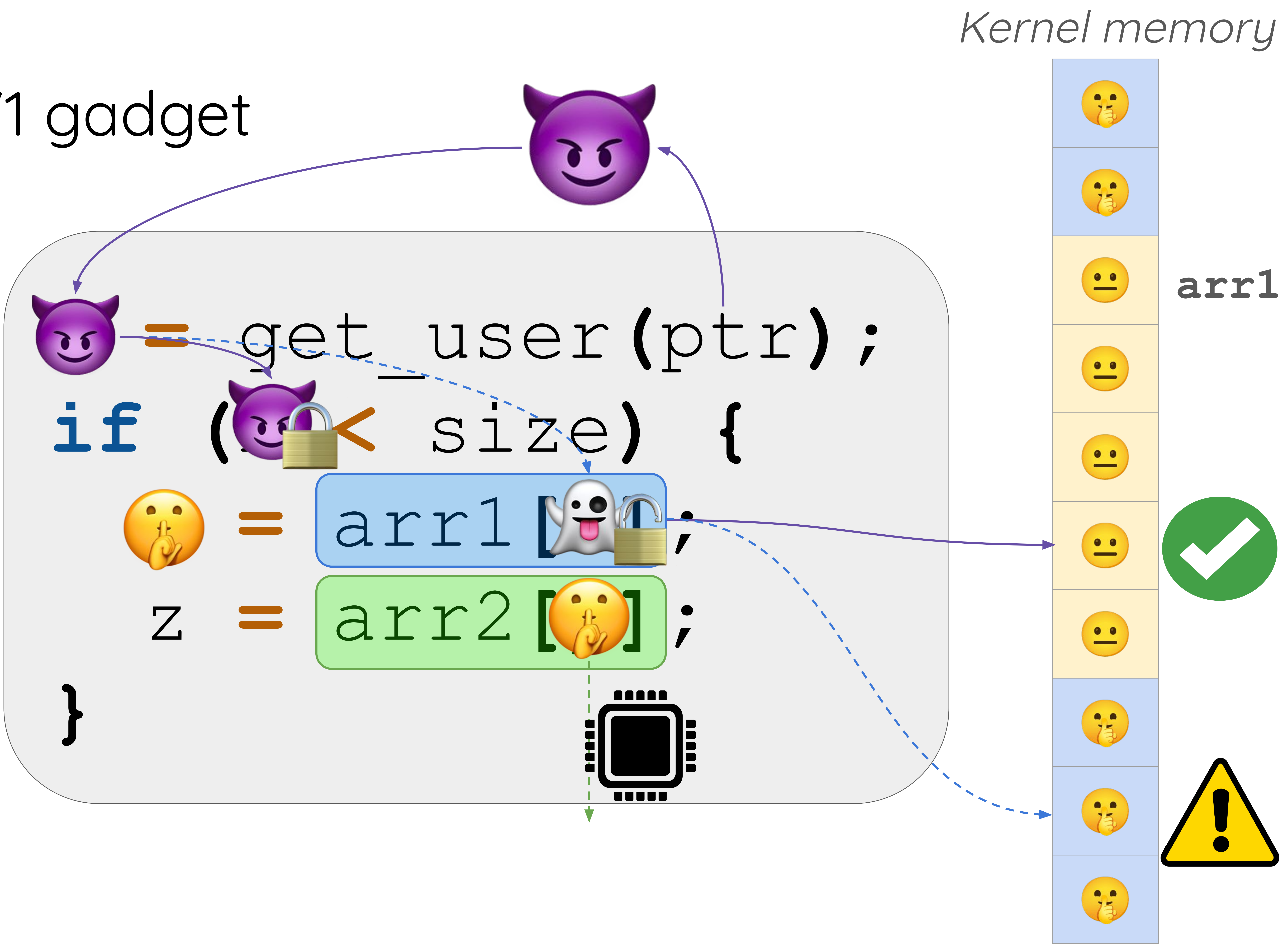

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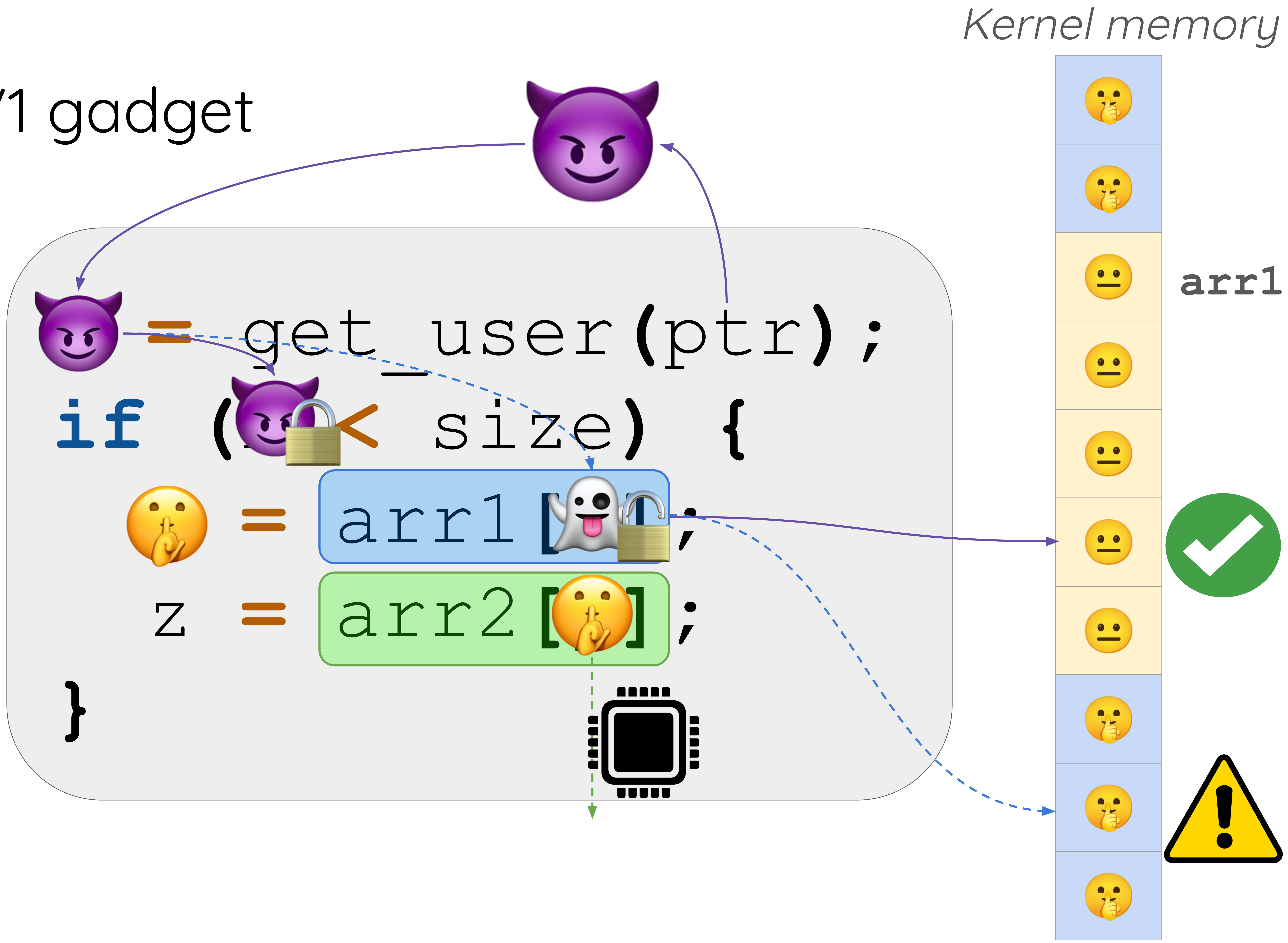

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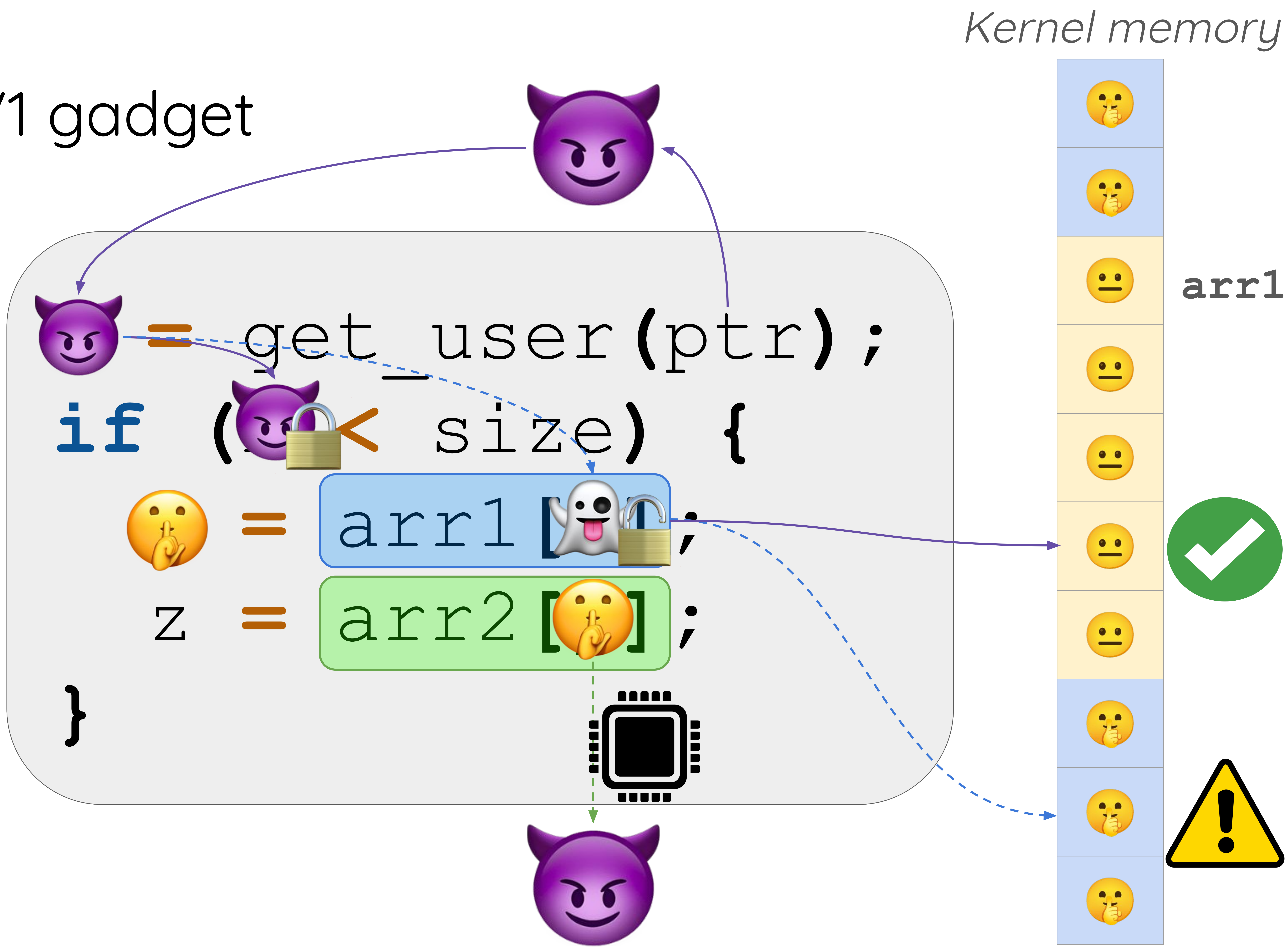

# What defenses are deployed in the kernel?

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lfence on copy-from-user:

```
static bool user_access_begin(const void __user *ptr, size_t len)
{
    if (unlikely(!access_ok(ptr,len)))
        return 0;
    __uaccess_begin_nospec();
    return 1;
}
```

# What defenses are deployed in the kernel?

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```
static __always_inline bool do_syscall_x64(struct pt_regs *regs, int nr)
{
    unsigned int unr = nr;

    if (likely(unr < NR_syscalls)) {
        unr = array_index_nospec(unr, NR_syscalls);
        regs->ax = sys_call_table[unr](regs);
        return true;
    }
    return false;
}
```

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For the Spectre variant 1, vulnerable kernel code (as determined by code audit or scanning tools) is annotated on a case by case basis to use nospec accessor macros for bounds clipping to avoid any usable disclosure gadgets.





https://www.kernel.org/doc/html/latest/admin-guide/hw-vuln/spectre.html

# What defenses are deployed in the kernel?

For the Spectre variant 1, vulnerable kernel code (as determined by code audit or scanning tools) is annotated on a case by case basis to use nospec accessor macros for bounds clipping to avoid any usable disclosure gadgets. However, it may not cover all attack vectors for Spectre variant 1.





https://www.kernel.org/doc/html/latest/admin-guide/hw-vuln/spectre.html

We can do **better**.

So Brian Johannesmeyer and I started with a **dynamic analysis approach** in 2019.

We're using something called **Dynamic Taint Analysis**, but what is it?

# Dynamic Taint Analysis

```
int main(int argc, char *argv[]) {



   char *prog = malloc(100);
   strcpy(prog, argv[1]);



   execve(prog,
          (char *[]){prog, 0},
          environ);
}
```

# Dynamic Taint Analysis

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}
```

# Dynamic Taint Analysis

Taint Source

```
int main(int argc, char *argv[]) {
    dfsan_add_label(user, argv[1],
      strlen(argv[1]));
    char *prog = malloc(100);
    strcpy(prog, argv[1]);



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Taint Propagation

# Dynamic Taint Analysis

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Taint Propagation

Taint Sink

Violation detected!

# Compiler-based dynamic taint analysis in the kernel?

Compiler-based dynamic taint analysis in the kernel?

We've built **KDFSAN** for this project!

https://github.com/vusec/kdfsan-linux/tree/kdfsan-linux-v5.13.7

# Our approach:

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```
void syscall_handler(int x) {
  ...
  if (x < size) {
    y = arr1[x];
    z = arr2[y];
  }
}
```

# Our approach:

1. **Fuzz** the syscall interface

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void syscall_handler(int x) {
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`x = -7`    `x = 3`    `x = 100000`

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4. **Memory error detector** identifies unsafe access

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5. Add a `secret` label

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1. **Fuzz** the syscall interface

`x = -7` `x = 3` `x = 100000`

2. Add an `attacker` label

3. Start **speculative emulation**

```
void syscall_handler(int x) {
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# Our implementation: KASPER

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Linux kernel

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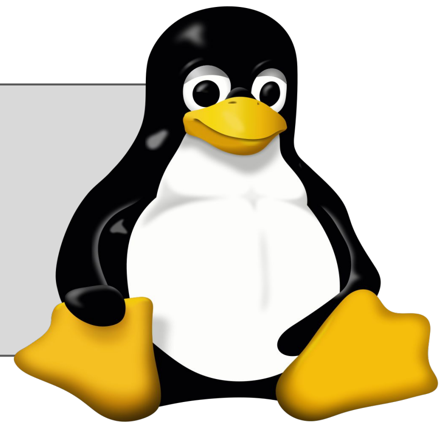
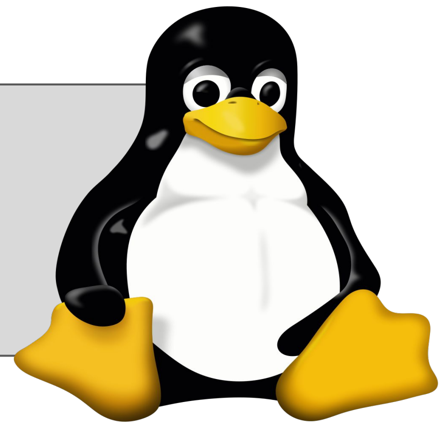
Linux kernel 

KASPER runtime libraries 

# Our implementation: KASPER

Linux kernel



KASPER runtime libraries

**Build the kernel** with KASPER's LLVM passes

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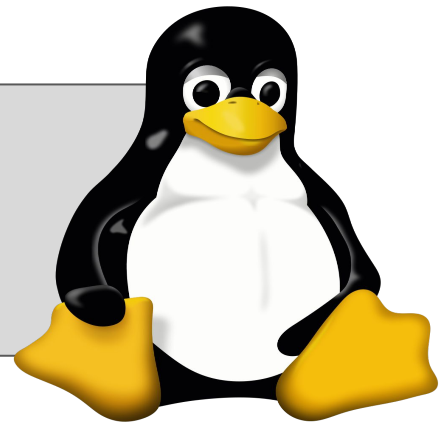
Linux kernel 

KASPER runtime libraries 

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KASPER-instrumented kernel 

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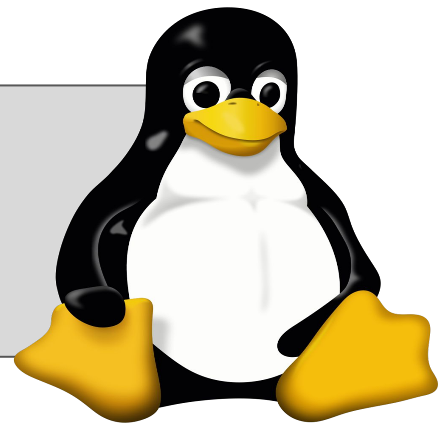
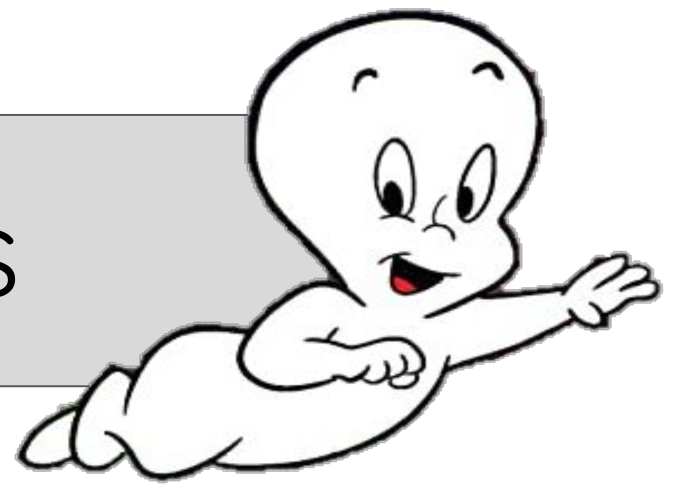
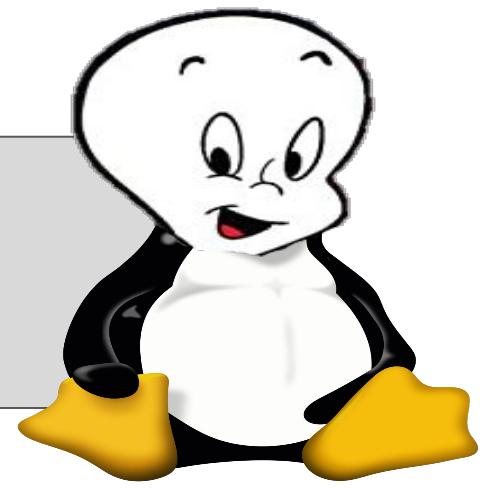
Linux kernel 

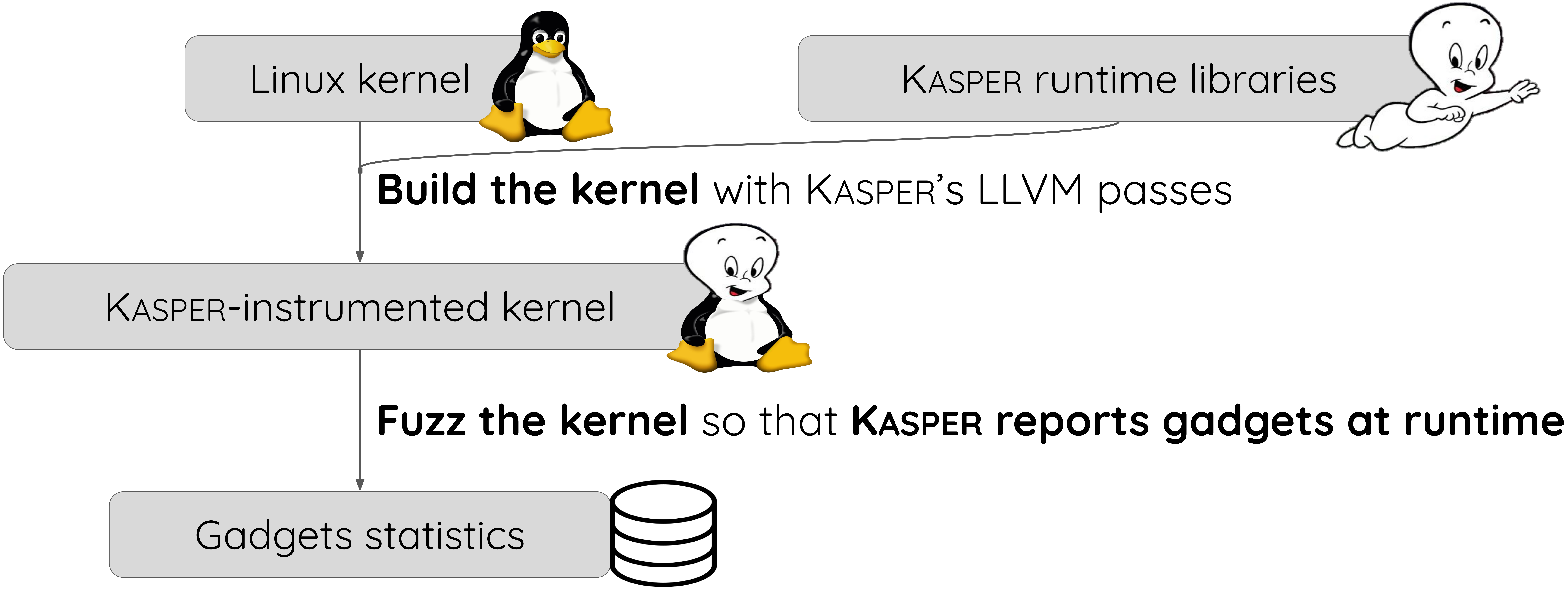
KASPER runtime libraries 

**Build the kernel** with KASPER's LLVM passes

KASPER-instrumented kernel 

**Fuzz the kernel** so that **KASPER reports gadgets at runtime**

# Our implementation: KASPER



As a result, Kasper discovered **1,379 previously unknown gadgets** in the Linux kernel.

Let's look at a case study.

# Background: the list iterator

```
#define list_for_each_entry(pos, head, member)
   for (pos = list_first_entry(head, typeof(*pos), member);
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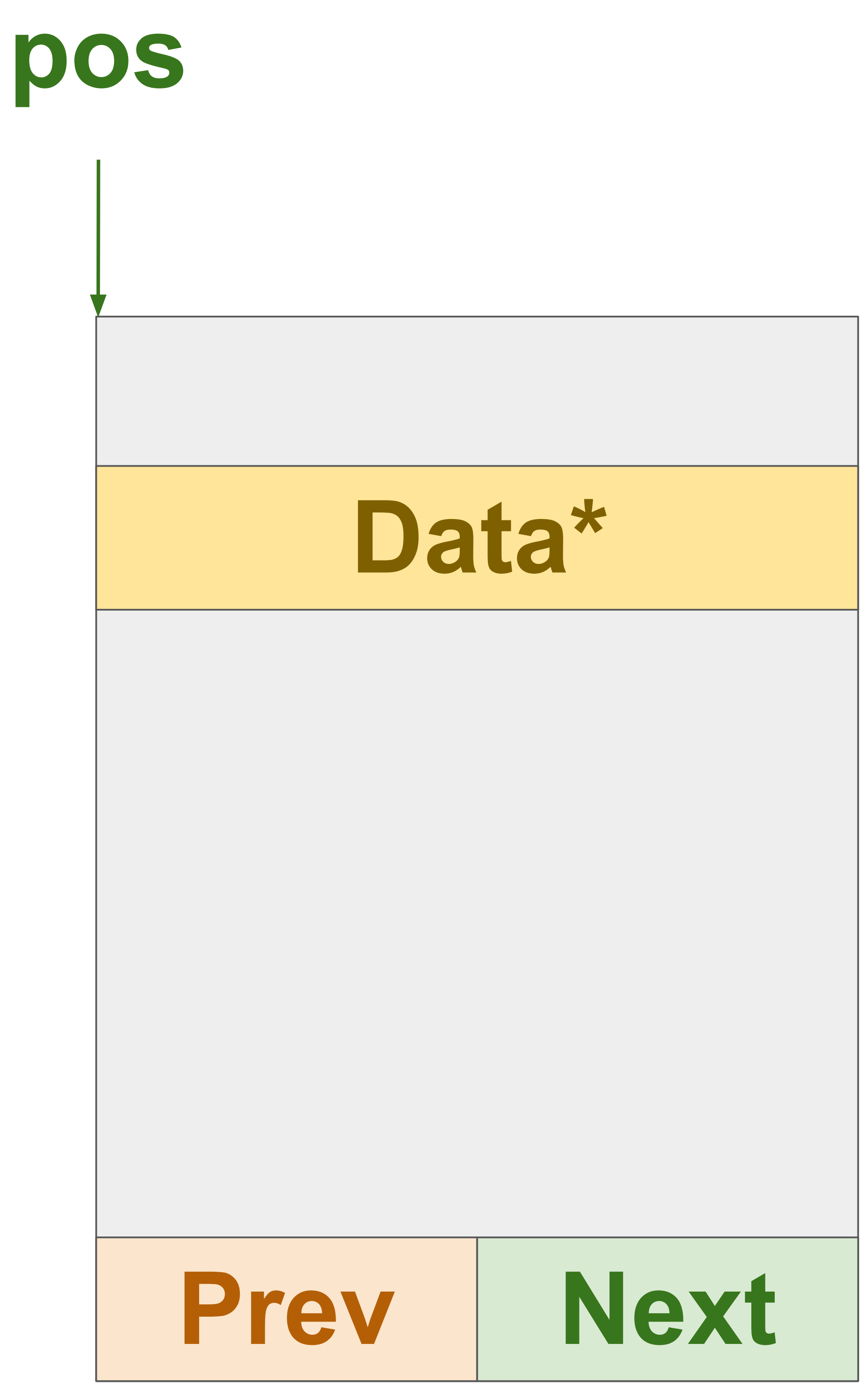

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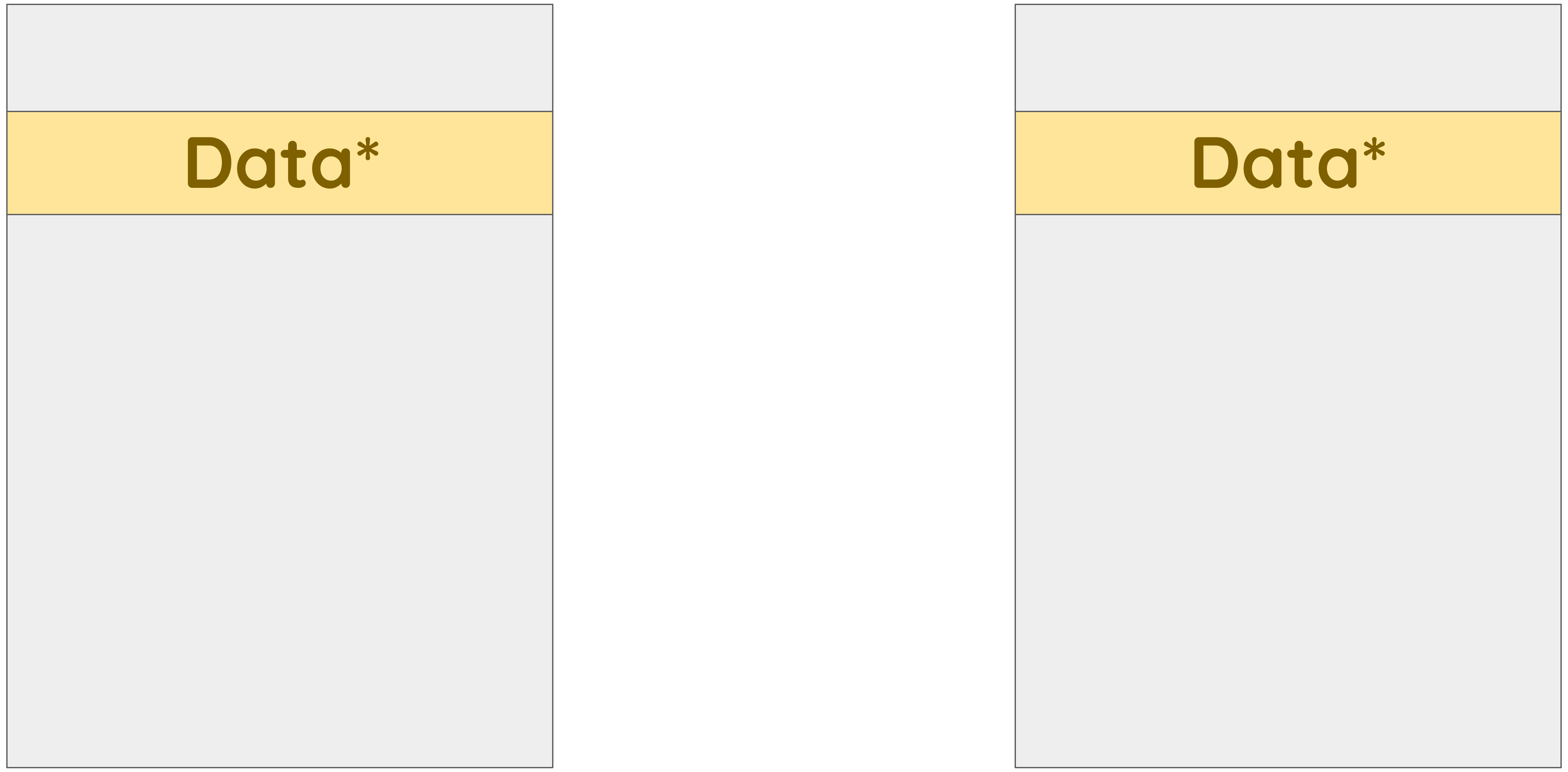

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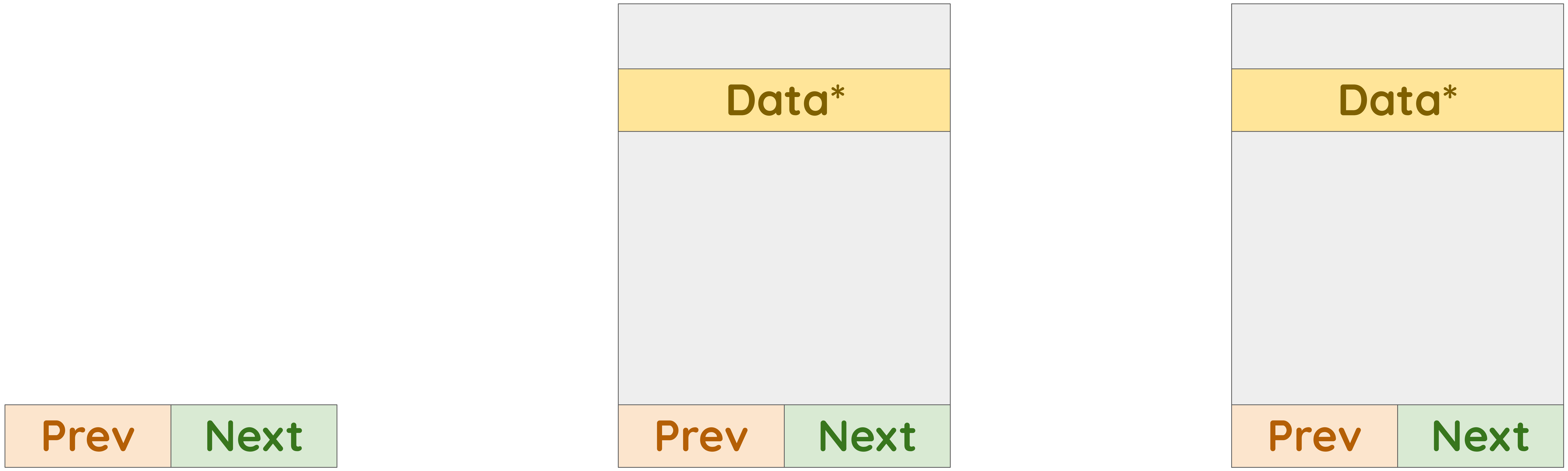

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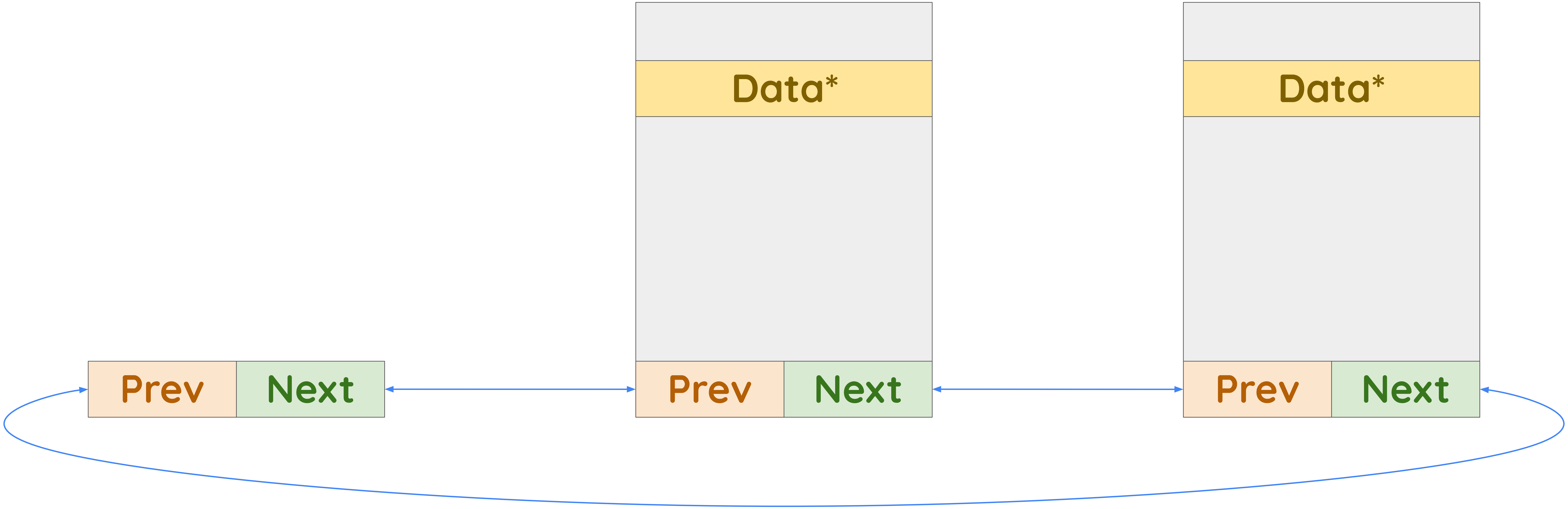

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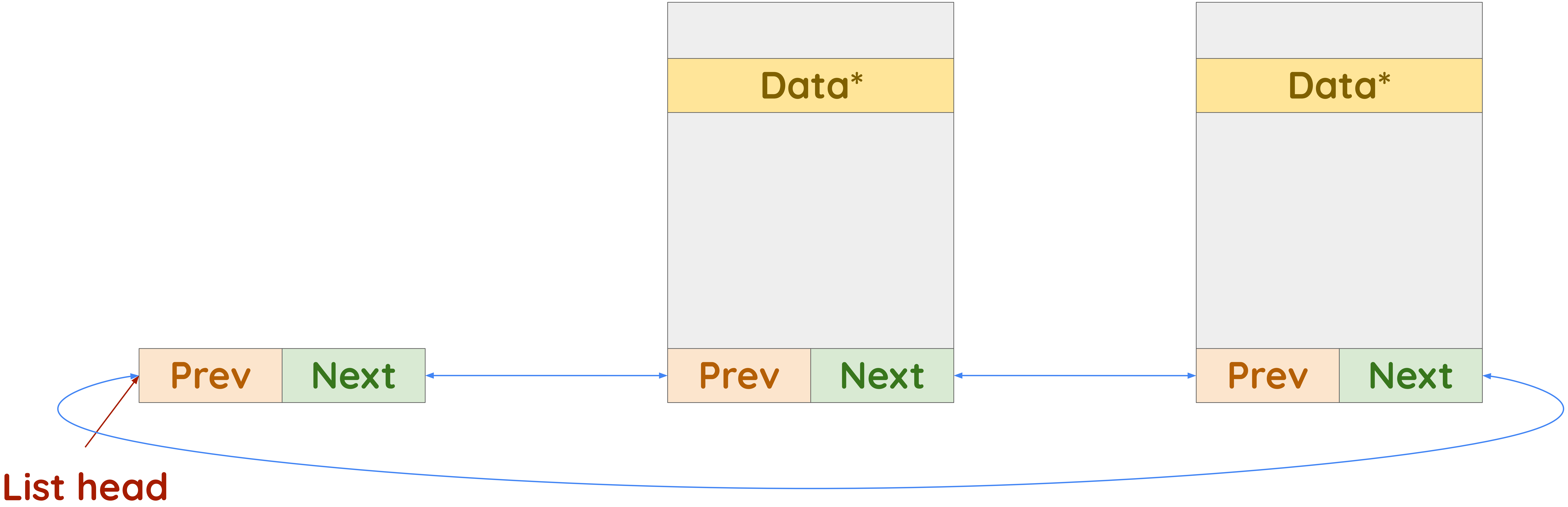

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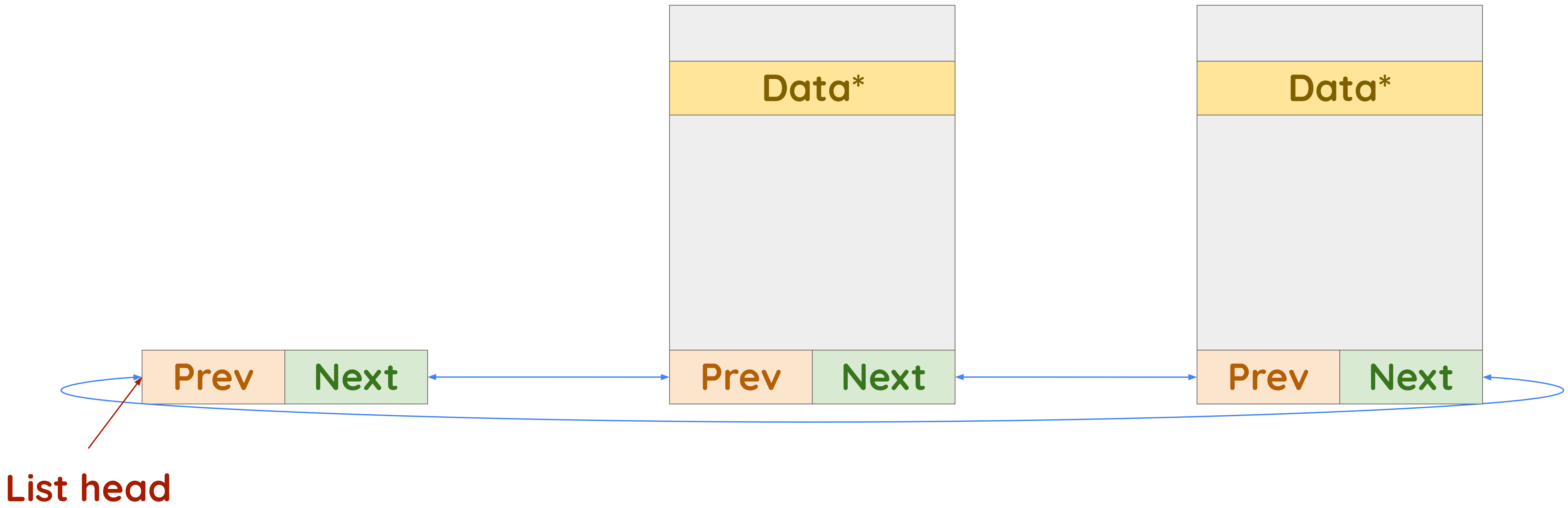

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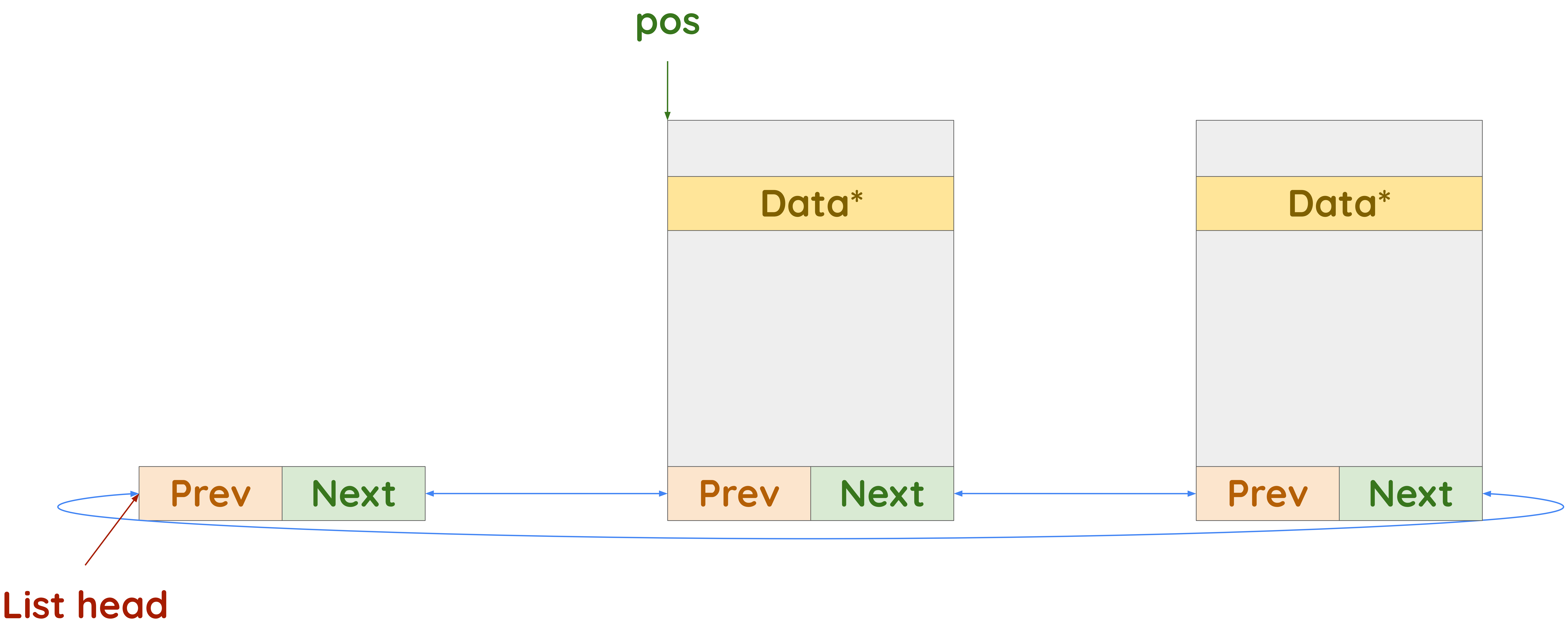

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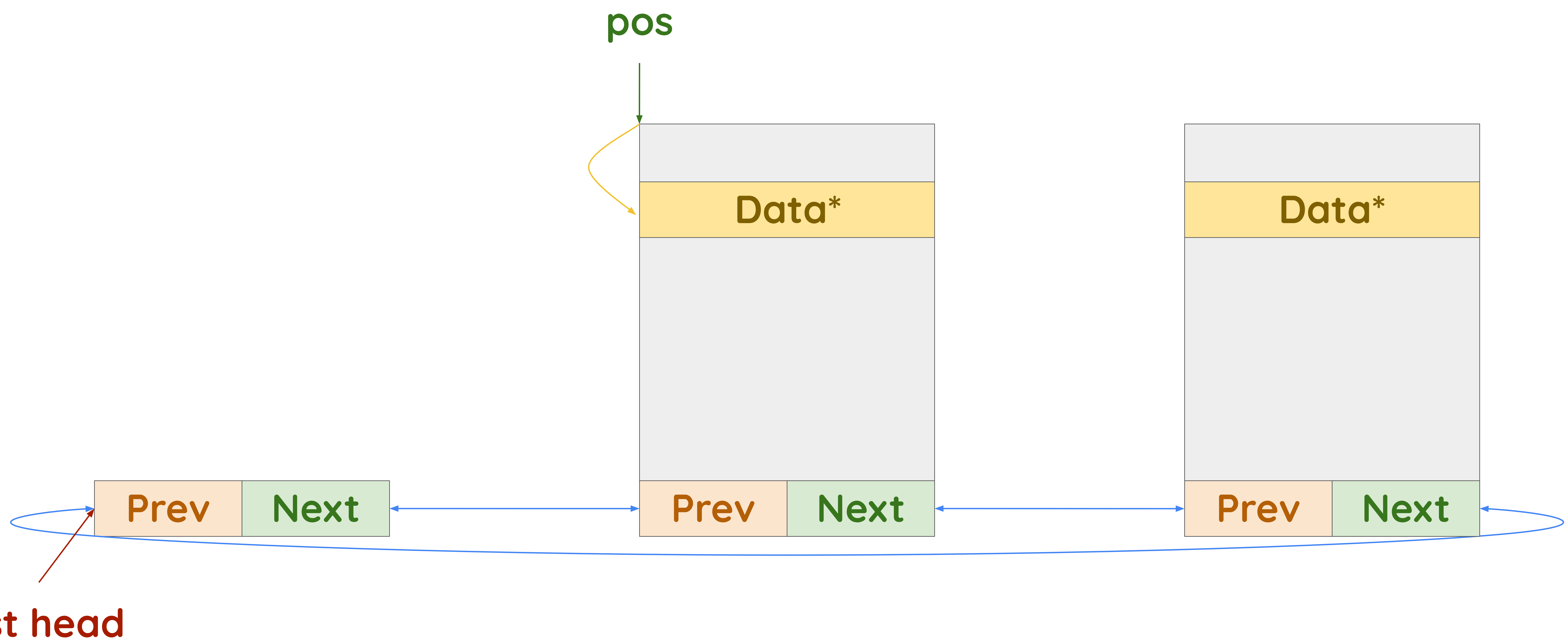

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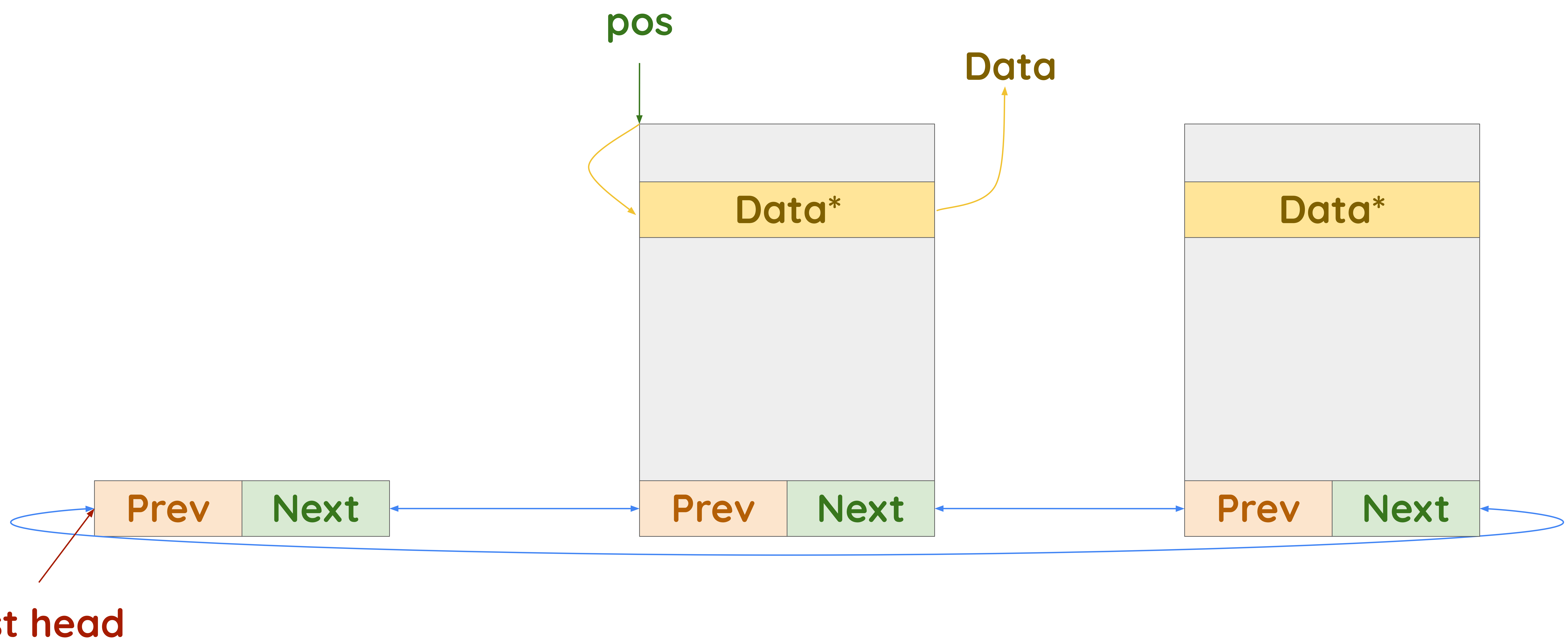

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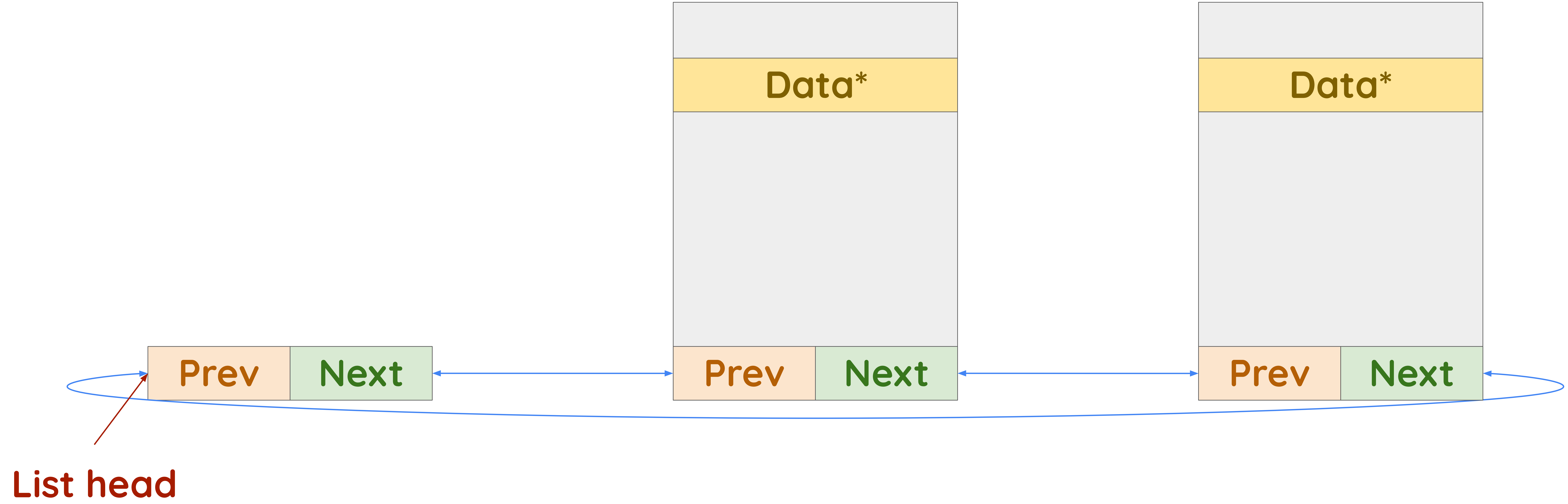

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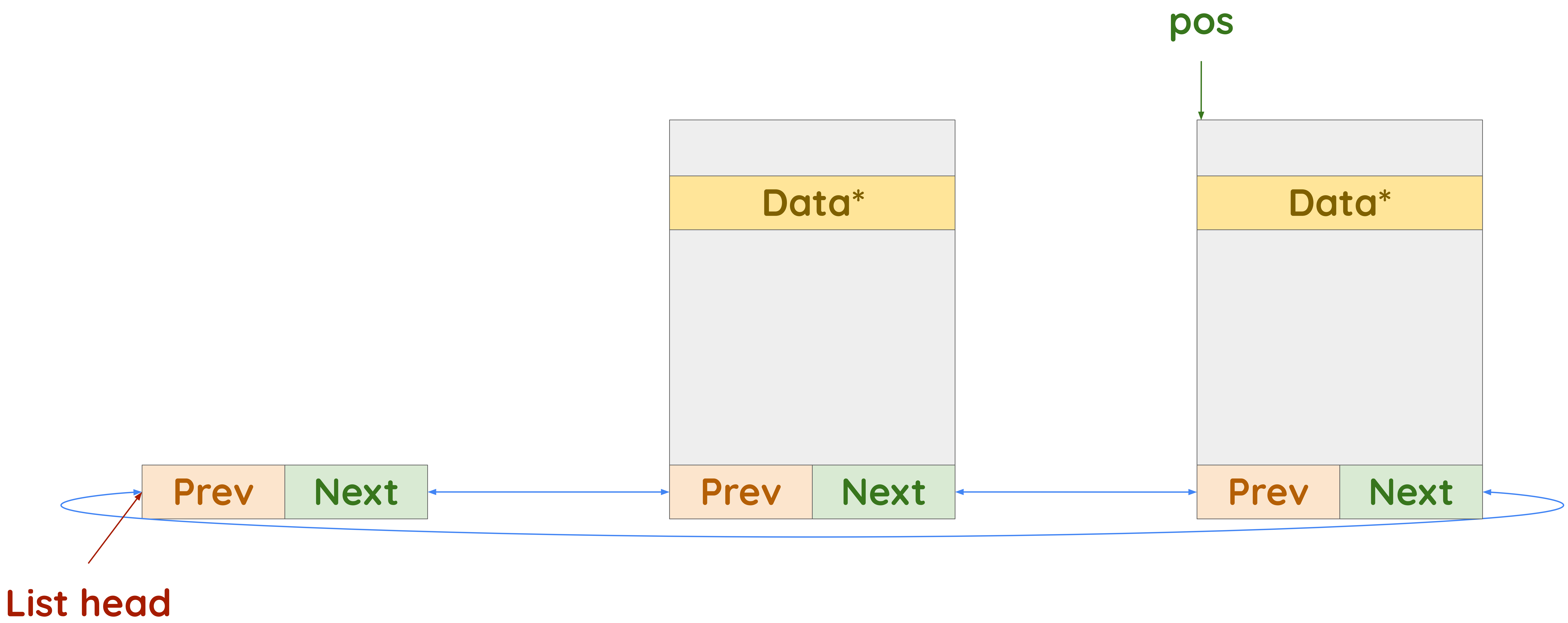

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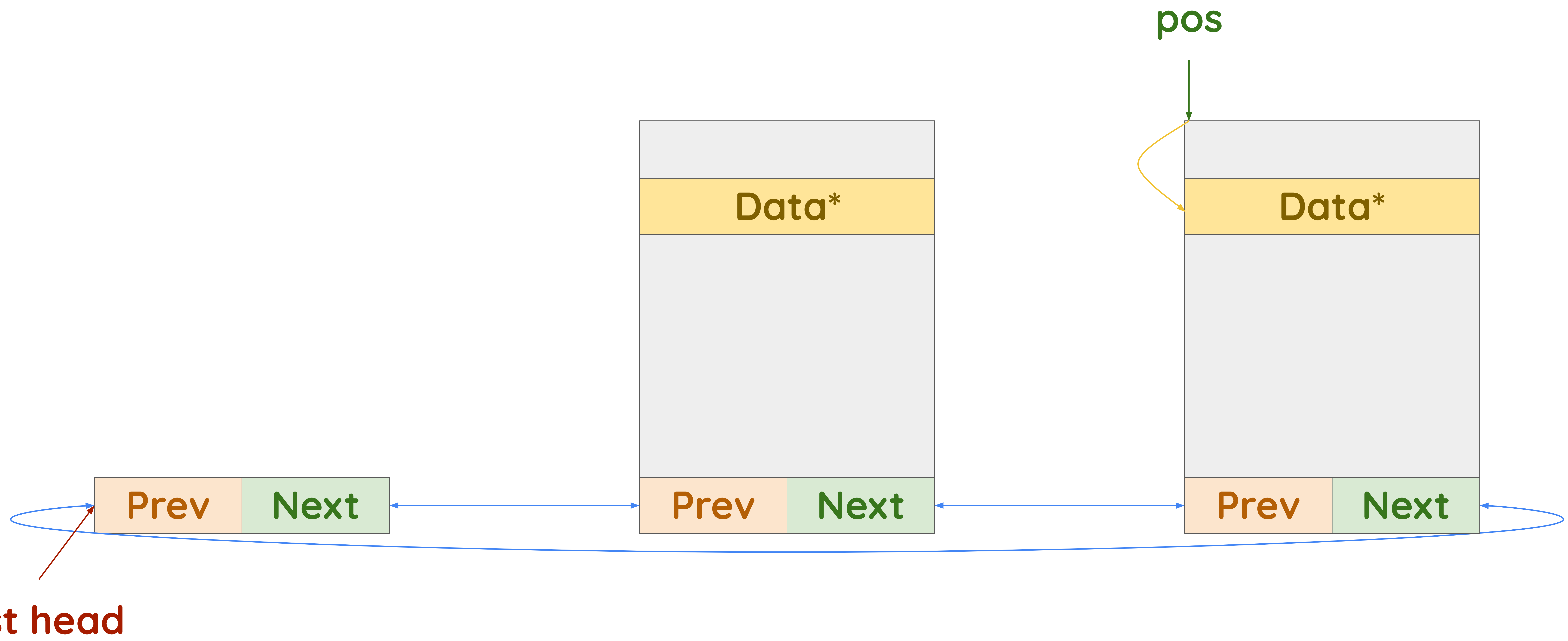

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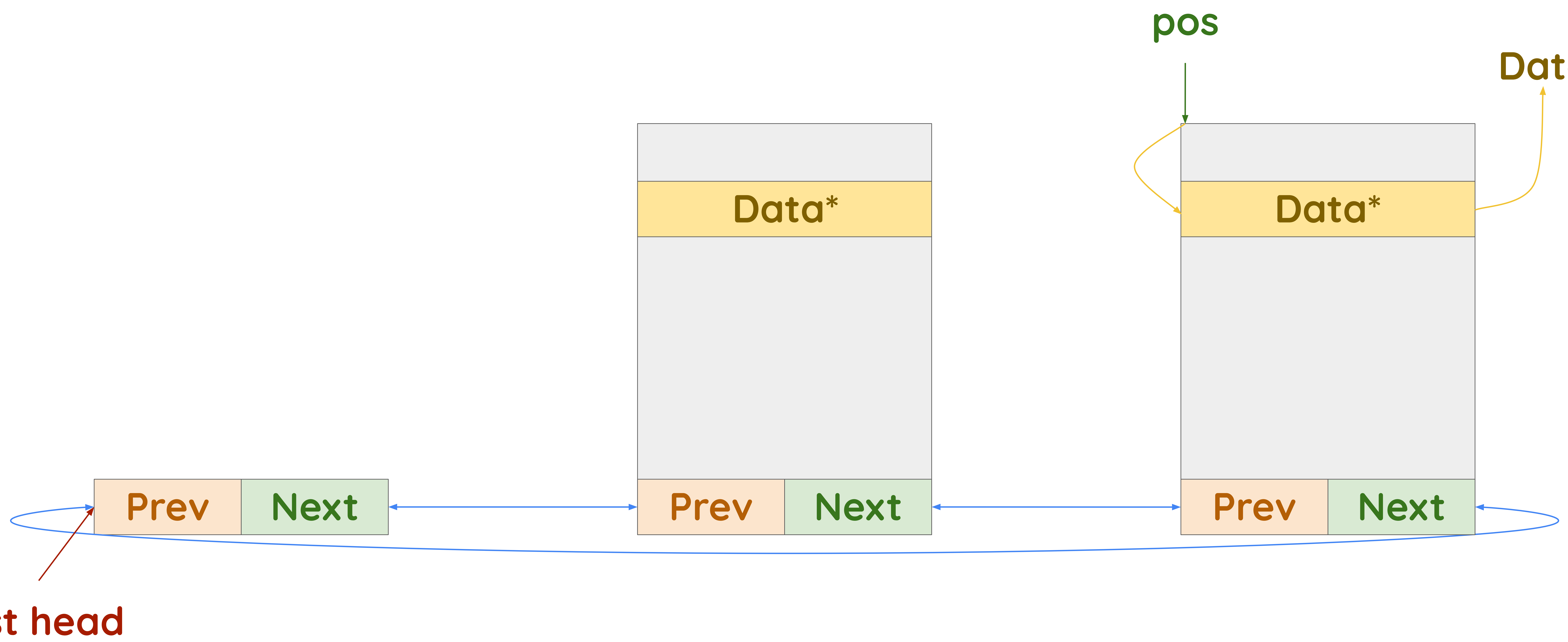

# Case study: list iterator

## Iteration 3 (termination)

```
#define list_for_each_entry(pos, head, member)
    for (pos = list_first_entry(head,
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            !list_entry_is_head(pos, head, member);
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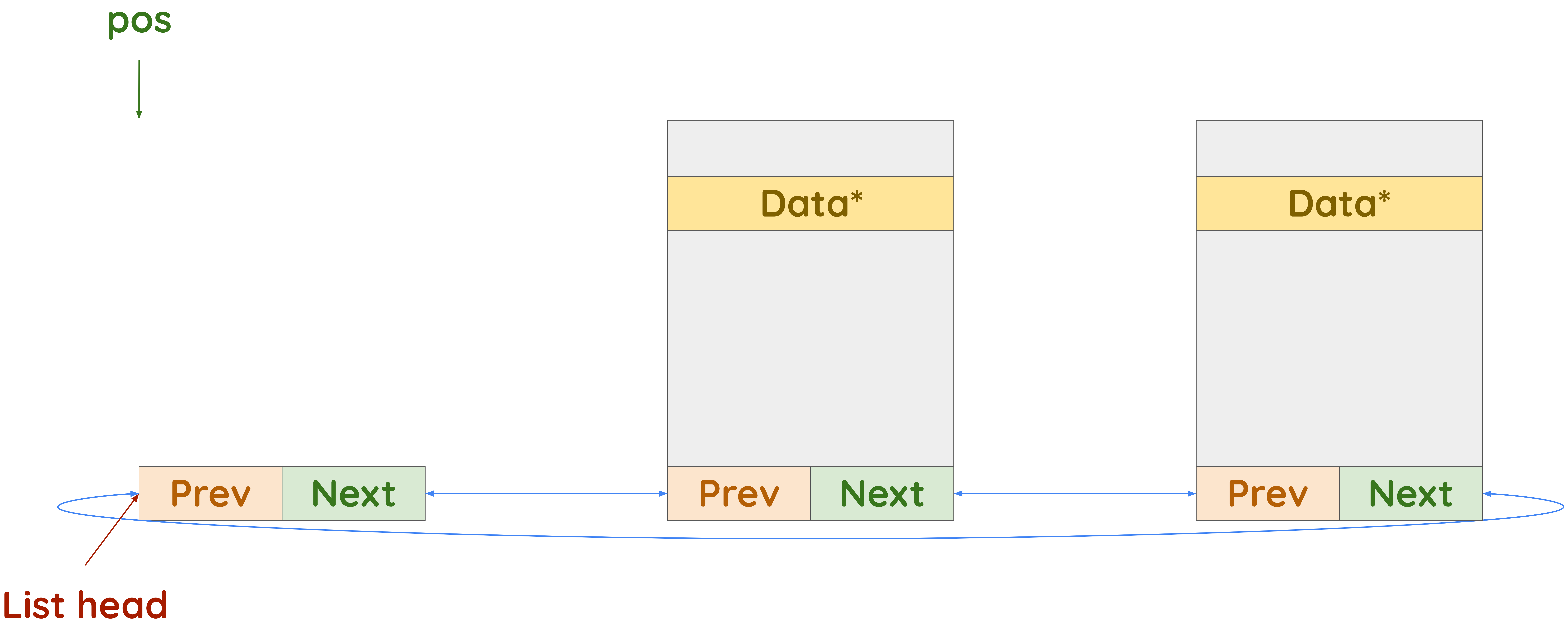

# Case study: list iterator

## Iteration 3 (misprediction)

```
#define list_for_each_entry(pos, head, member)
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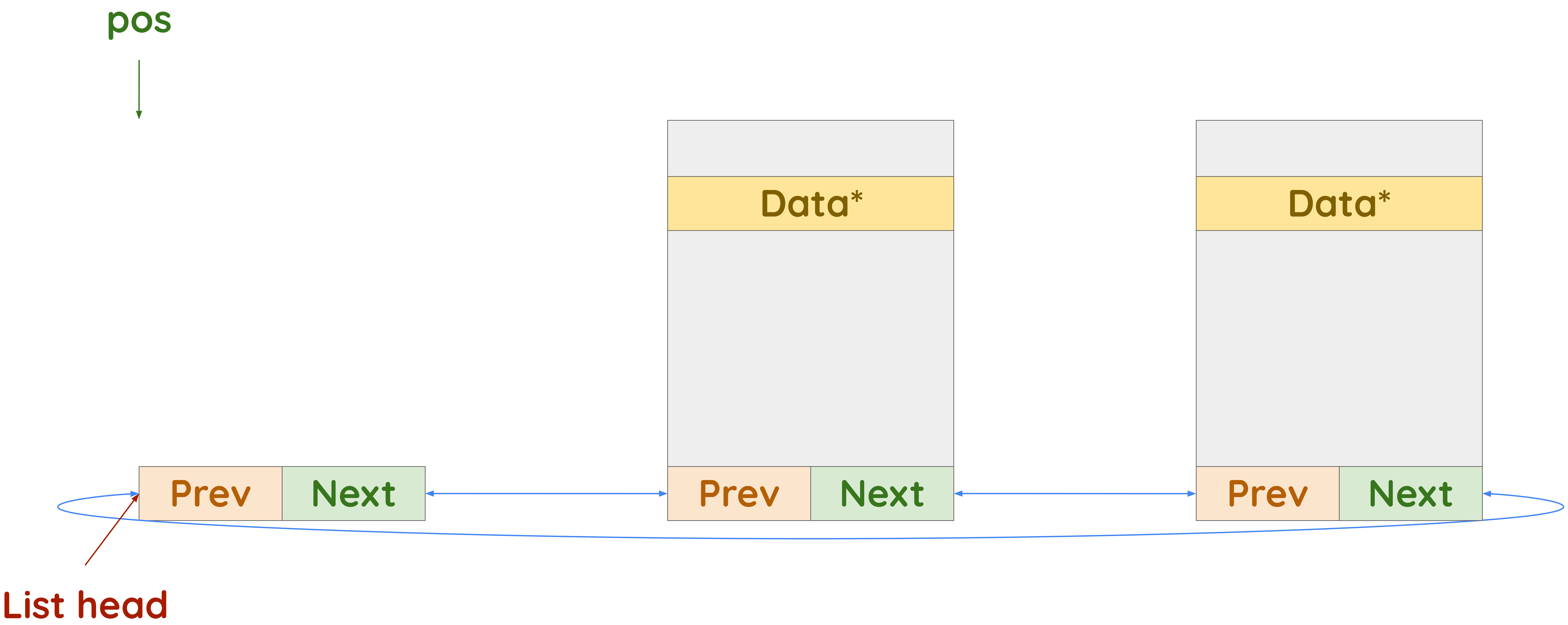

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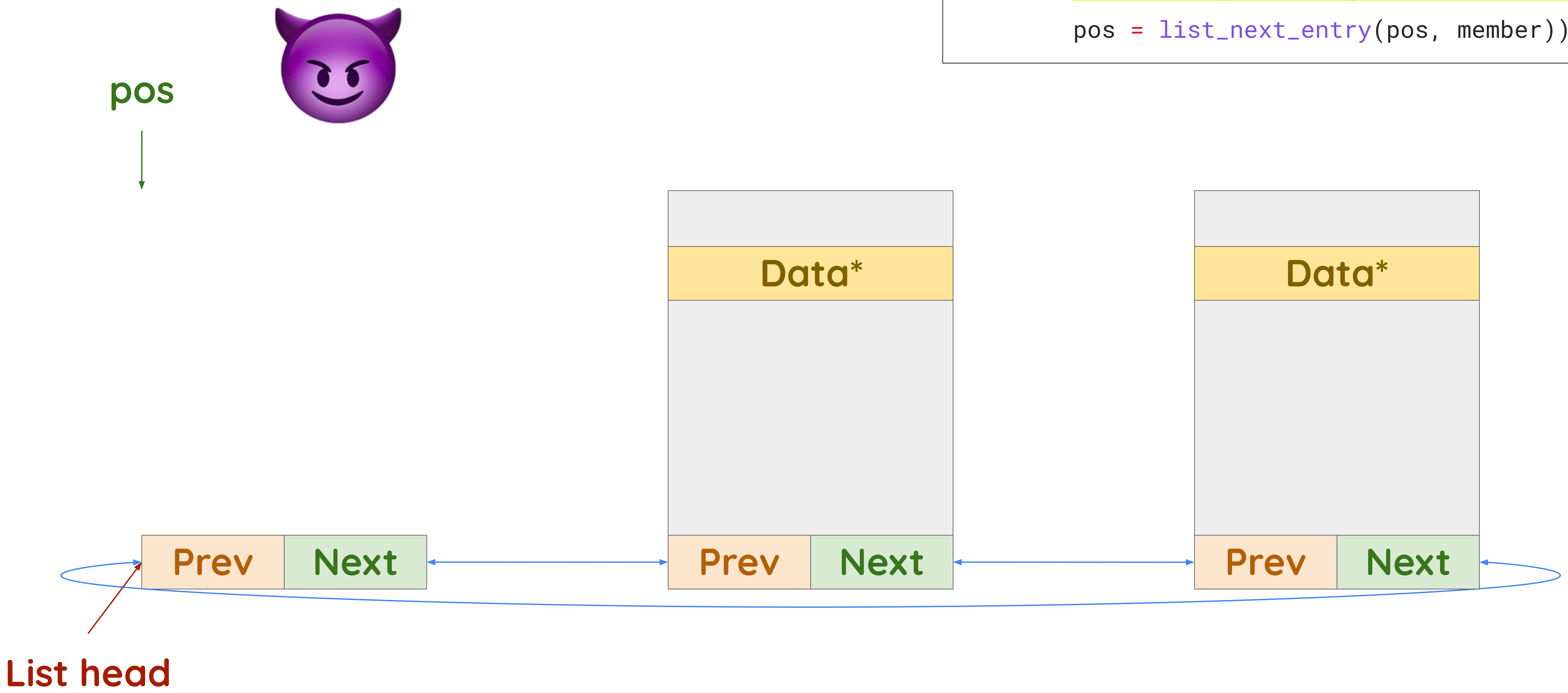

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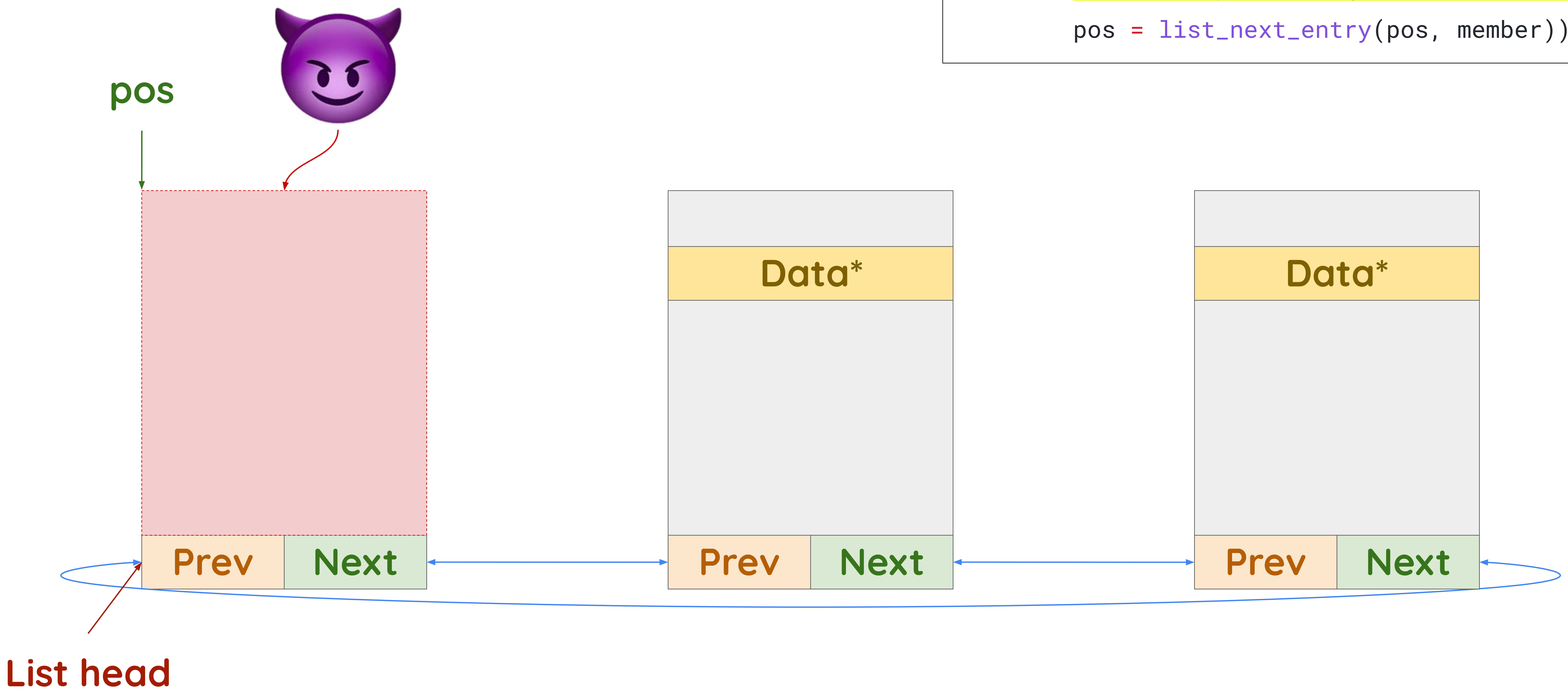

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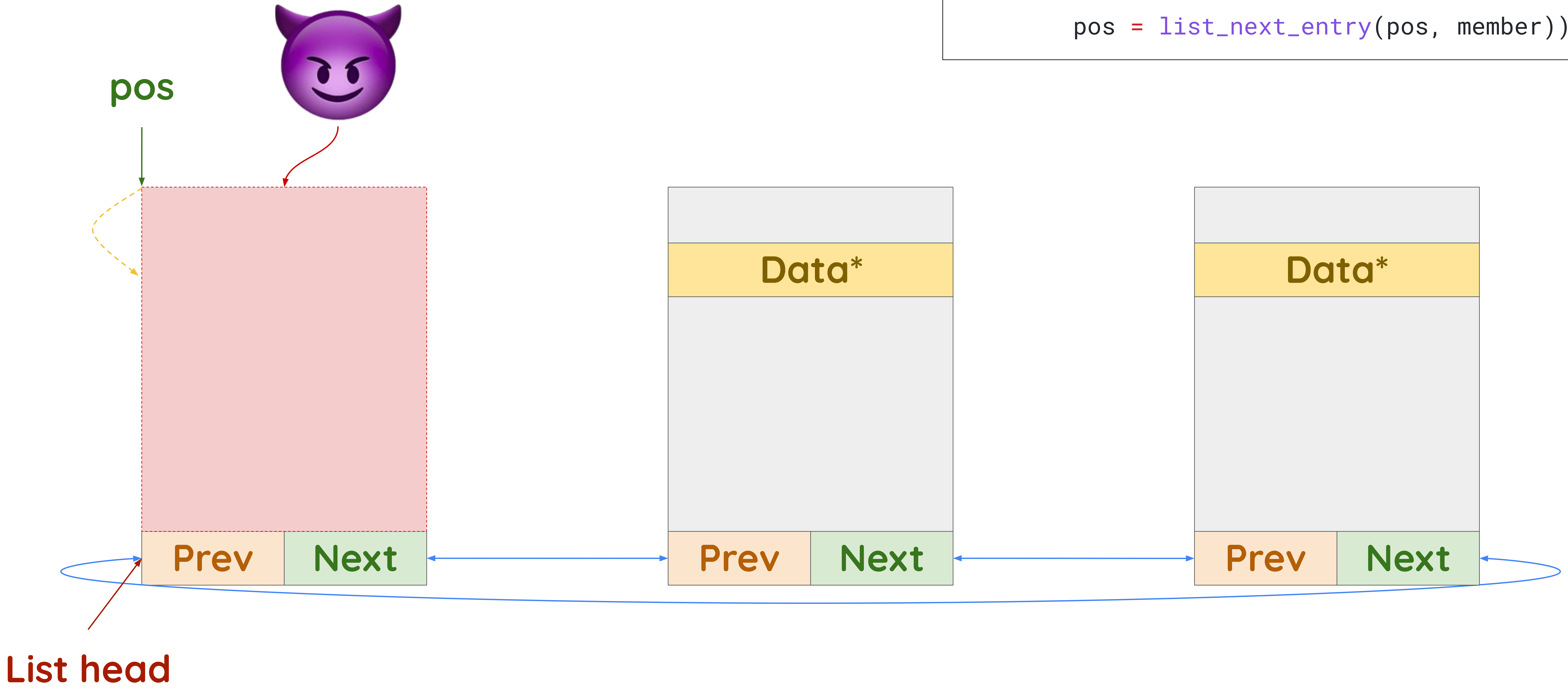

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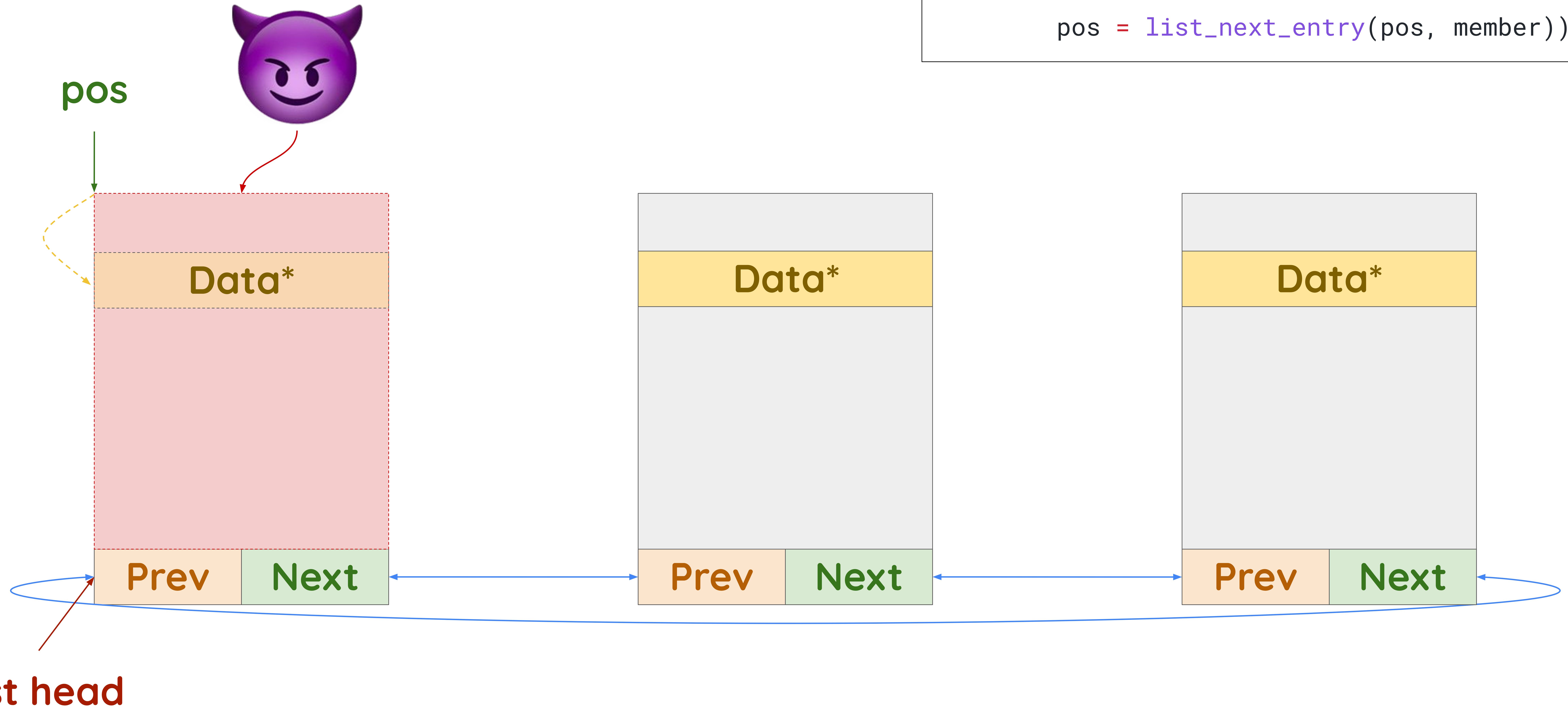

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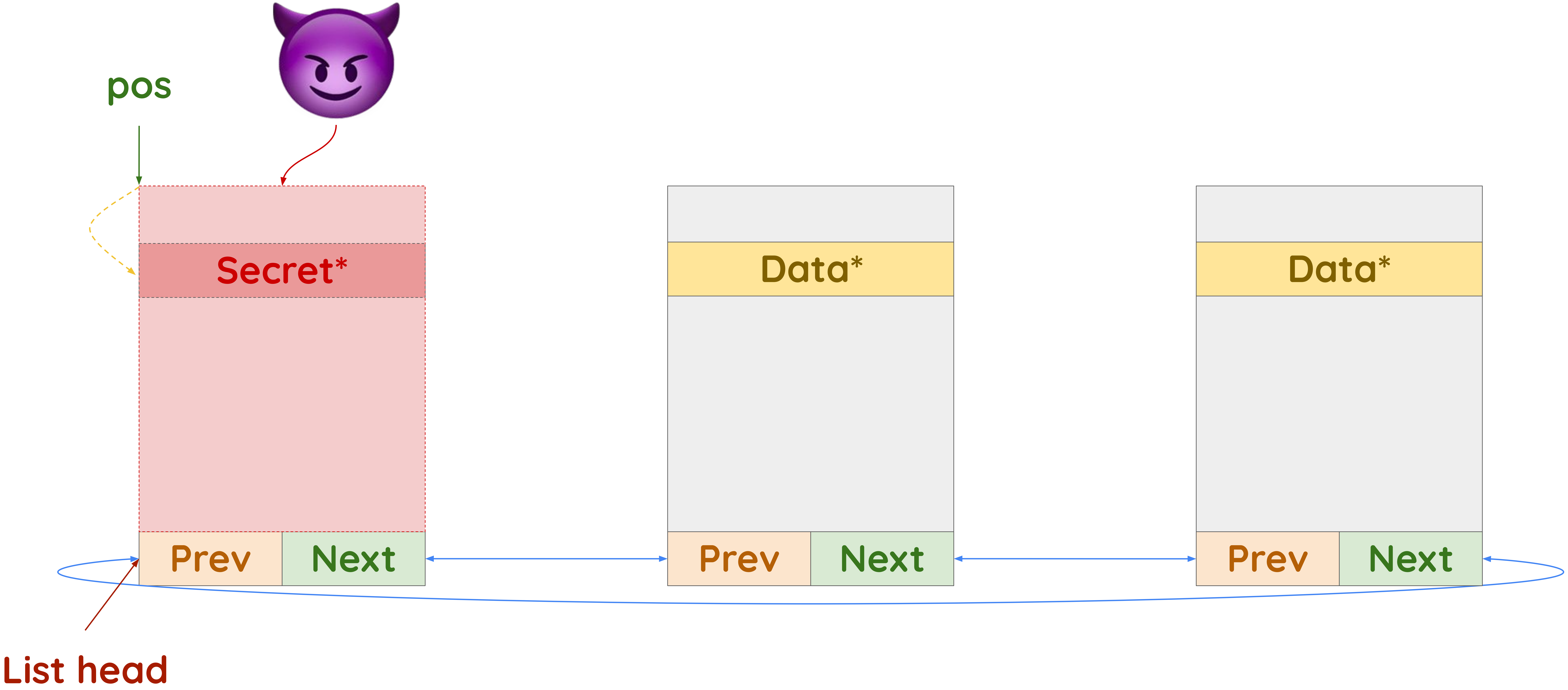

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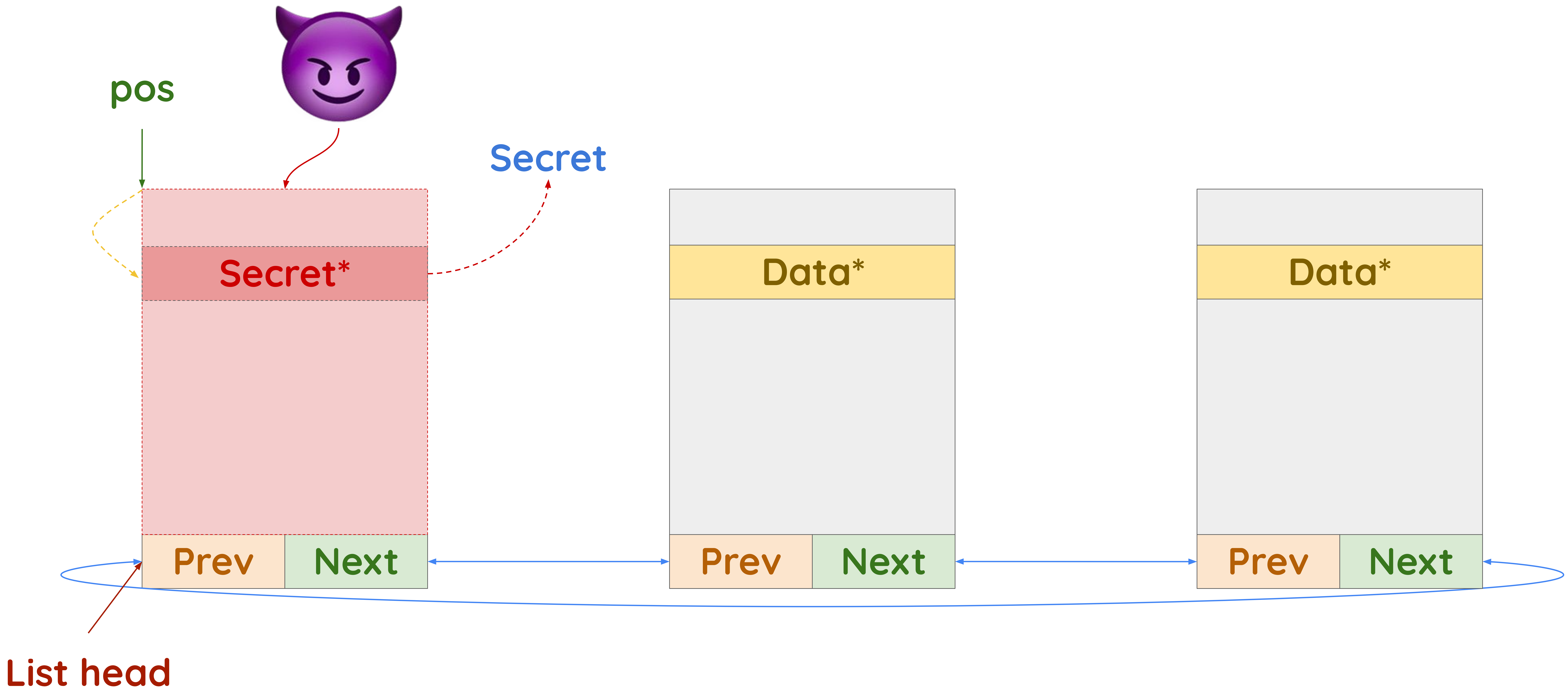

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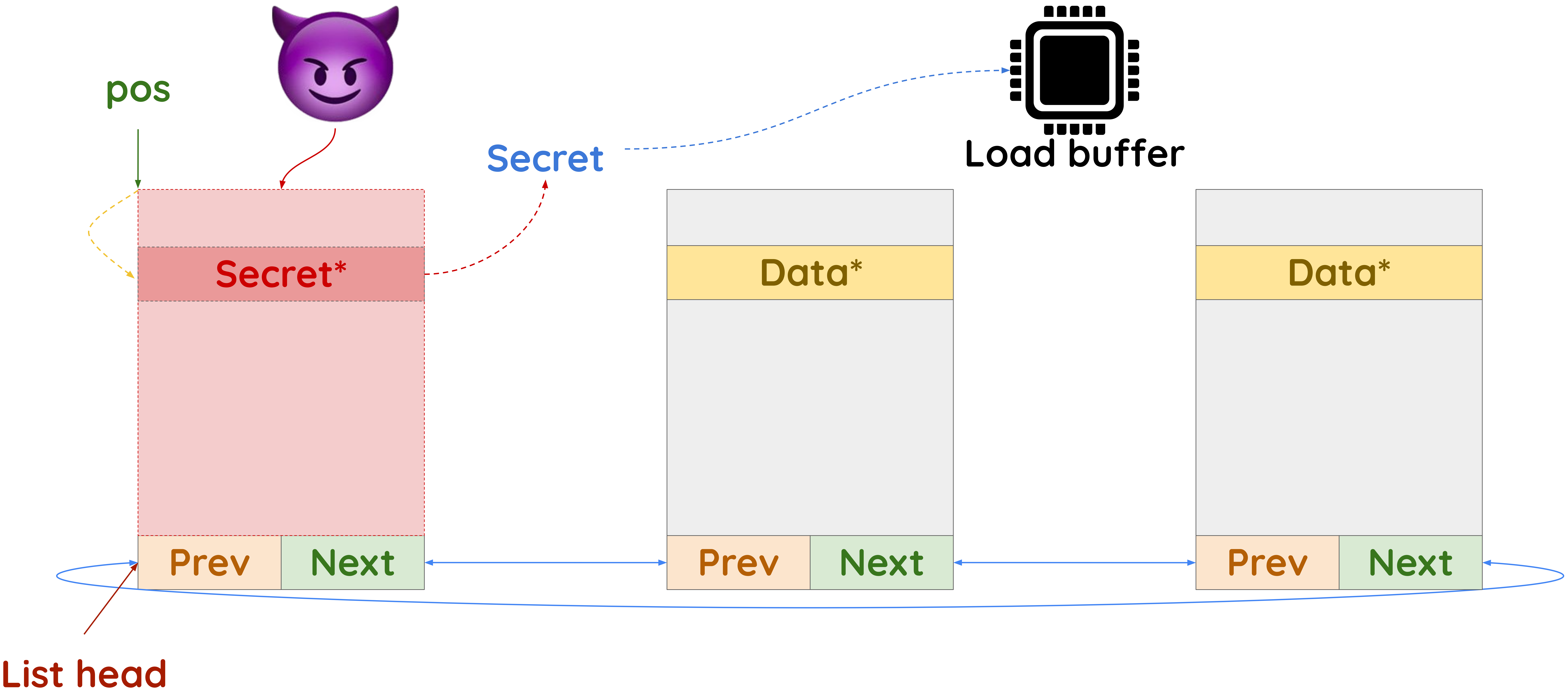
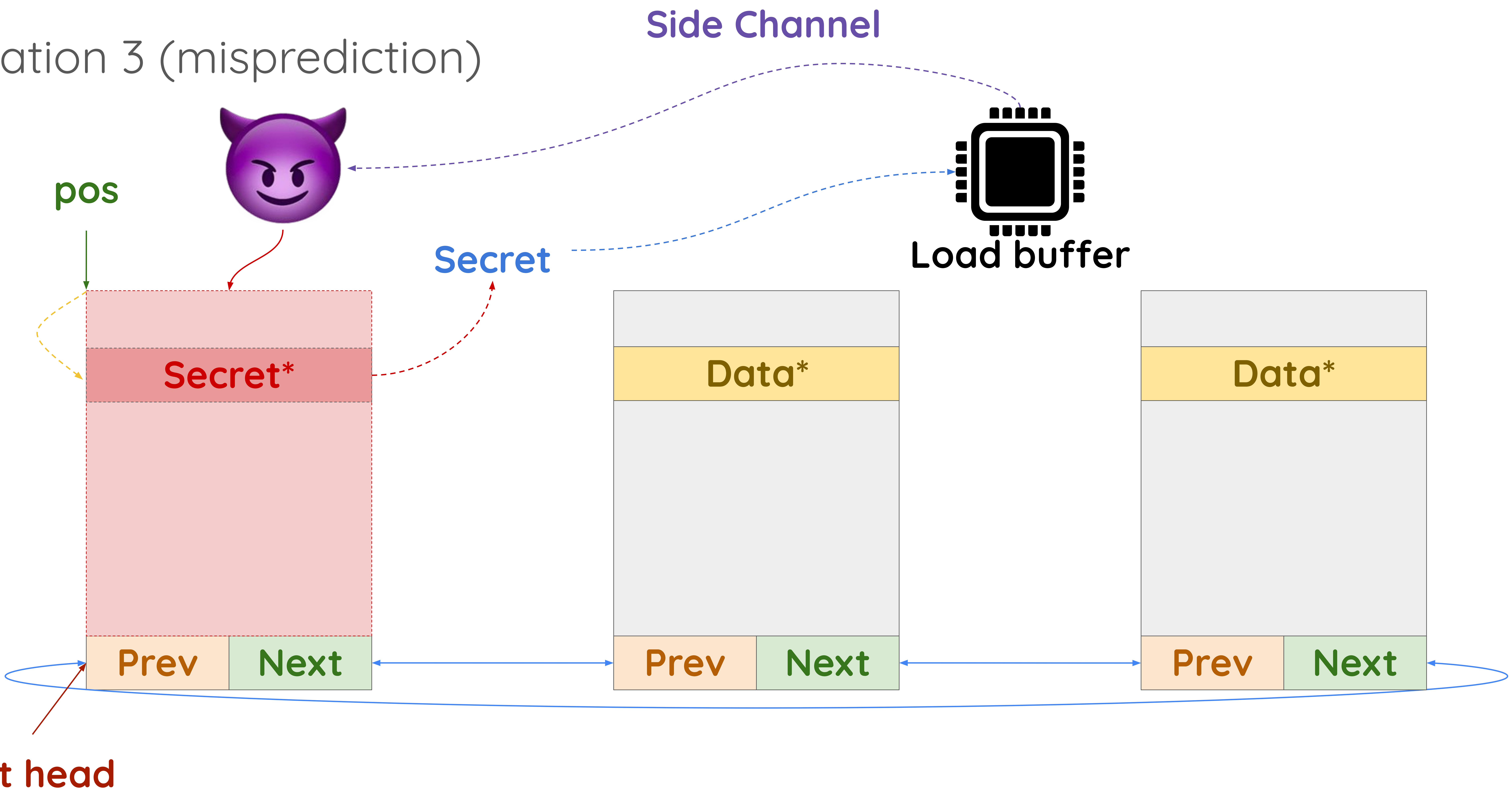


# Case study: list iterator

Iteration 3 (misprediction)



Finally, we implemented a **proof-of-concept exploit** of an instance of this gadget.

But that's just the **beginning of the story**...

The issue **cannot** be **solved** with a simple `array_index_nospec()`

# How can we fix this?

```
#define list_for_each_entry(pos, head, member)
    for (pos = list_first_entry(head, typeof(*pos), member);
         ({ bool _cond = !list_entry_is_head(pos, head, member);
          pos = select_nospec(_cond, pos, NULL); _cond; });
          pos = list_next_entry(pos, member))
```

The iterator variable is **invalidated at the end of the loop**.

But 450+ locations use it after the loop.

# But 450+ locations use it after the loop.

```
$ make coccicheck COCCI=scripts/coccinelle/iterators/use_after_iter.cocci

./arch/arm/mach-mmp/sram.c:54:6-10: ERROR: invalid reference to the index variable of the iterator on line 48
./arch/arm/plat-pxa/ssp.c:54:6-9: ERROR: invalid reference to the index variable of the iterator on line 44
./arch/arm/plat-pxa/ssp.c:78:6-9: ERROR: invalid reference to the index variable of the iterator on line 68
./block/blk-mq.c:4481:11-13: ERROR: invalid reference to the index variable of the iterator on line 4472
./drivers/block/rbd.c:776:16-27: ERROR: invalid reference to the index variable of the iterator on line 766
./drivers/dma/at_xdmac.c:1583:13-17: ERROR: invalid reference to the index variable of the iterator on line 1571
...
```

Turns out some of them are **actual bugs**!

Let's look at **architectural** bugs now.

**No speculation** beyond this point...

```
asm("lfence");
```

```
struct goku_request    *req;
list_for_each_entry(req, &ep->queue, queue) {
   if (&req->req == _req)
       break;
}
if (&req->req != _req) {
   ret = -EINVAL;
   goto out;
}
```

# It **looks** safe, right?

```
struct goku_request    *req;
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# Does it still look safe?

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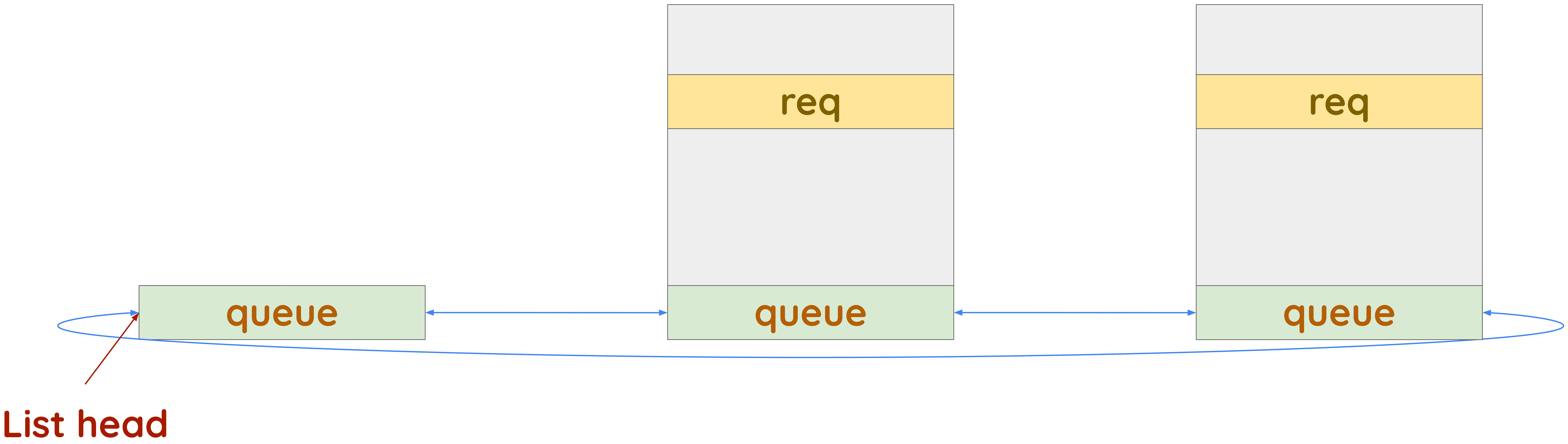
# Case study



# Case study

## Iteration 1

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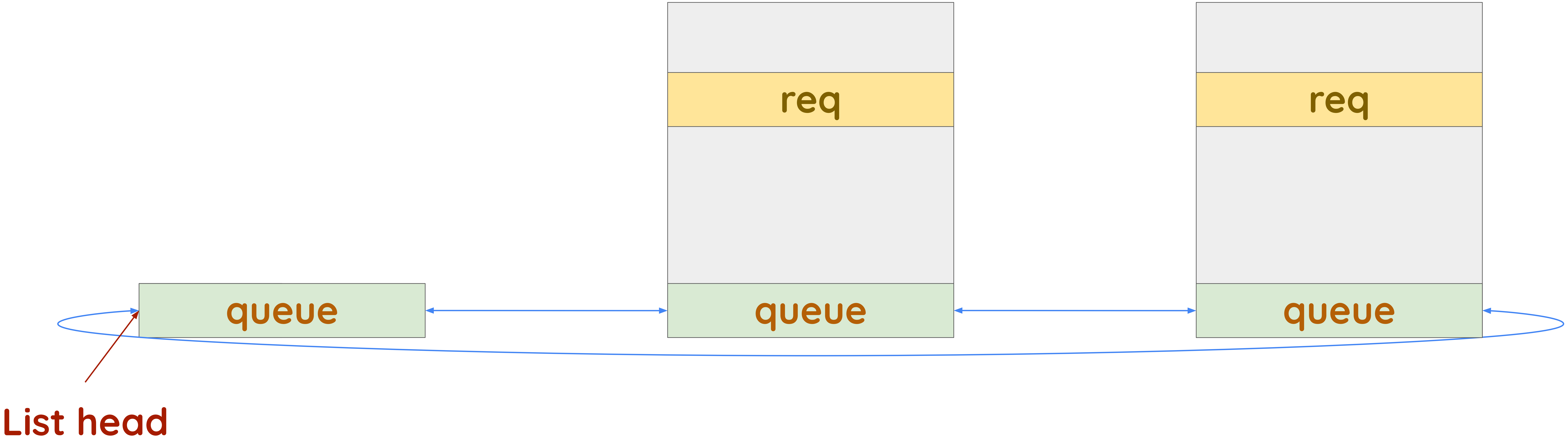

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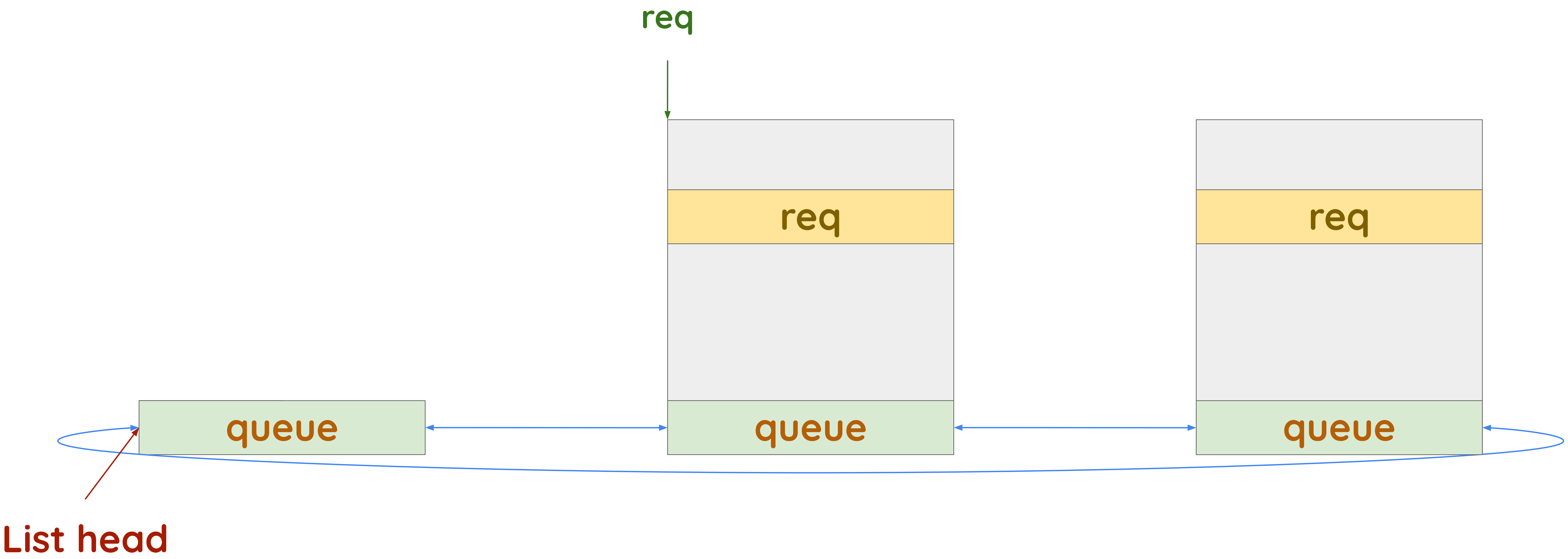

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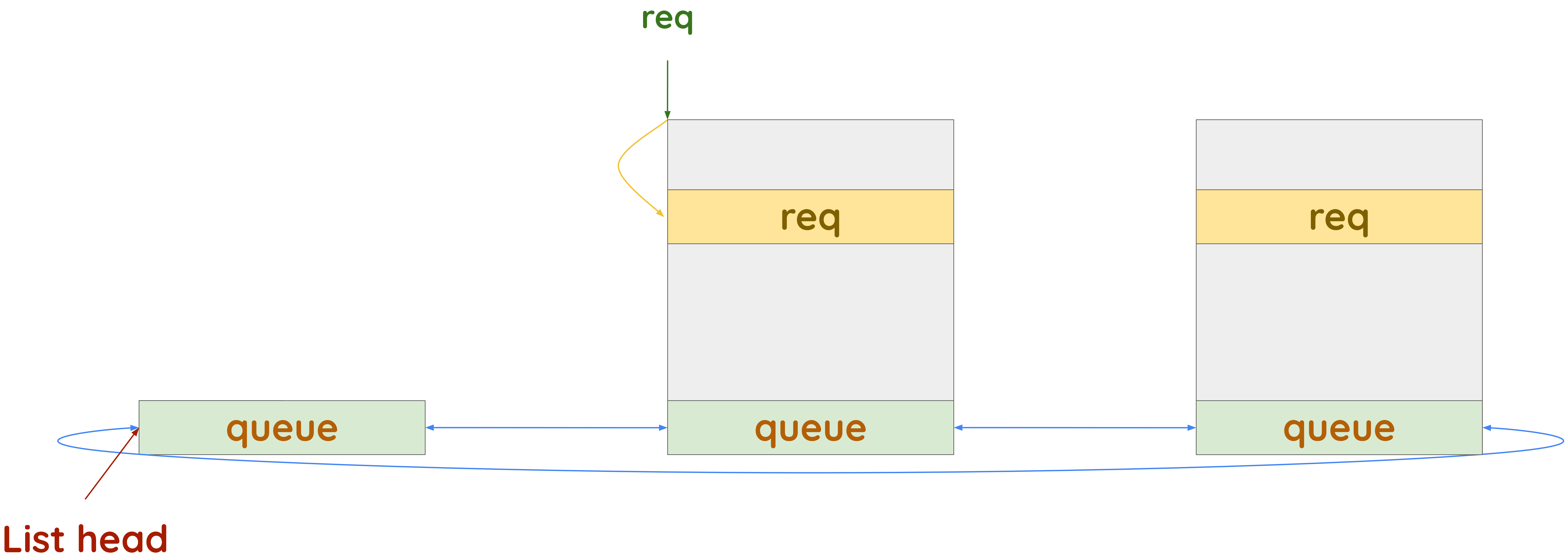

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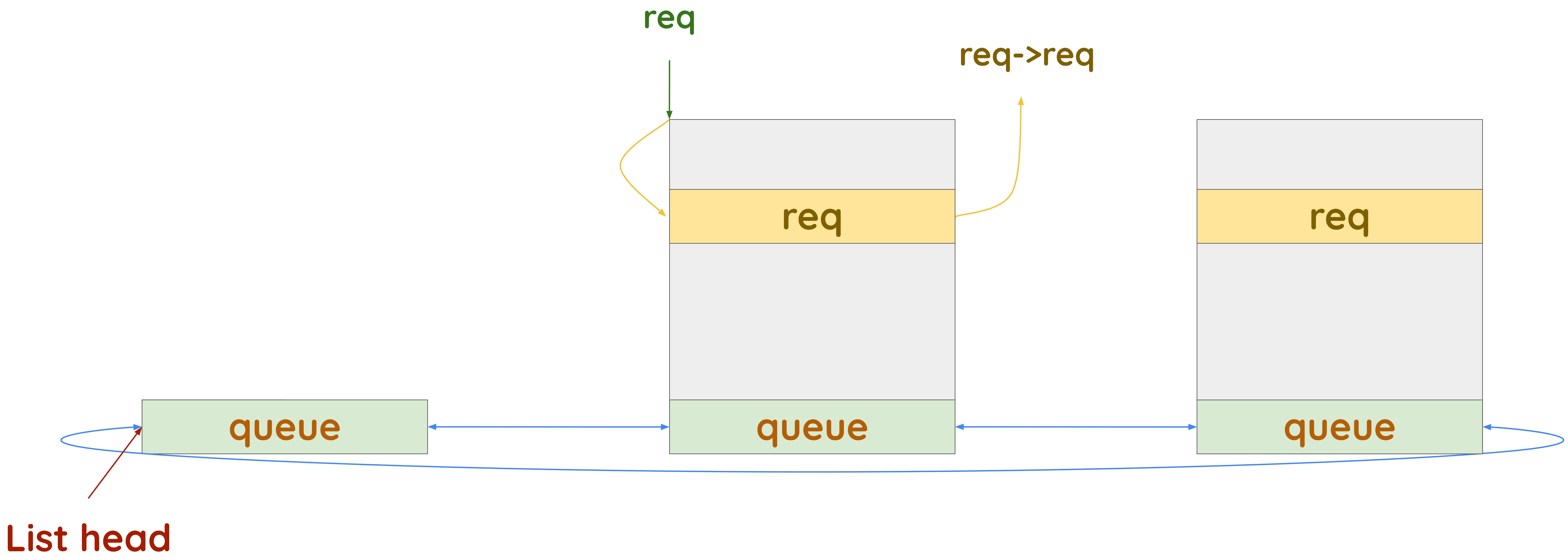
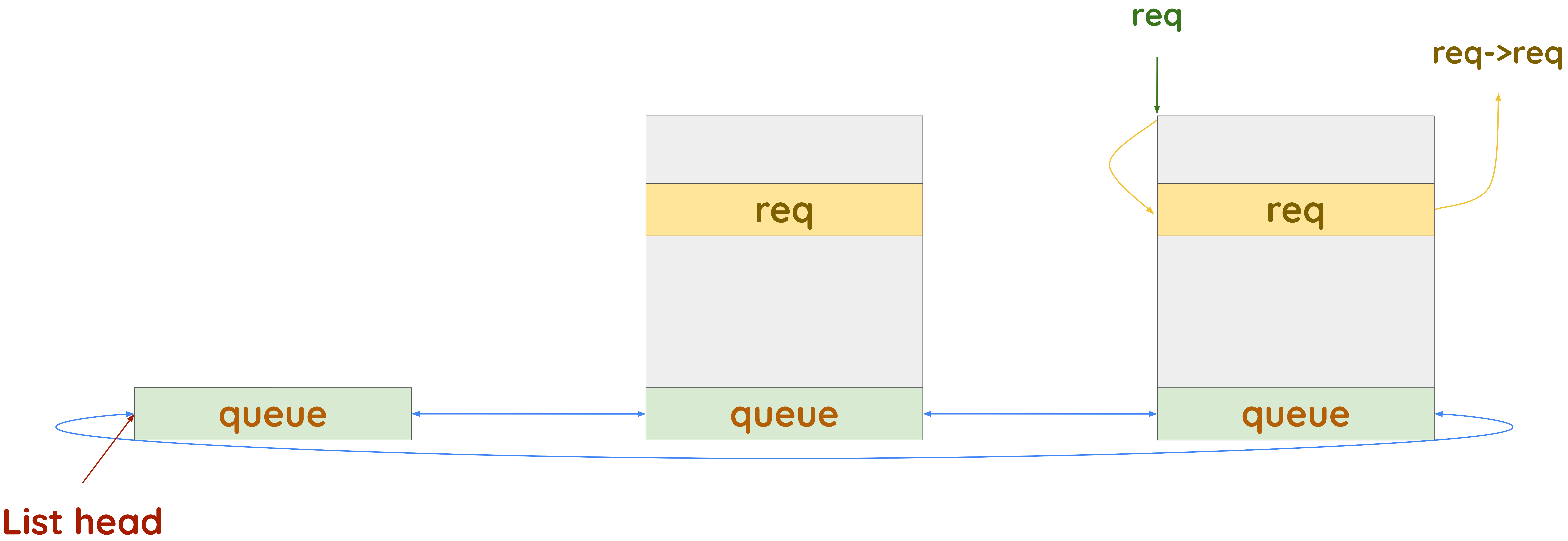


# Case study

## Iteration 2

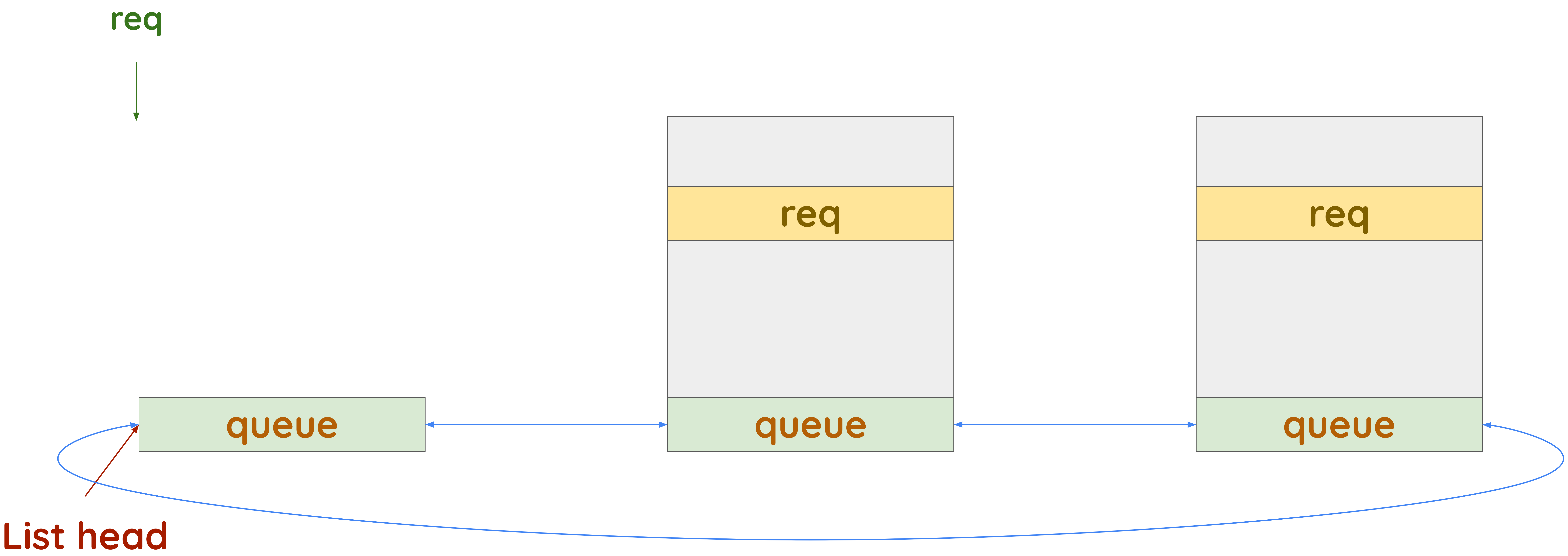
```
list_for_each_entry(req, &ep->queue, queue) {
    if (&req->req == _req)
        break;
}
if (&req->req != _req) {
    ...
}
```



# Case study

## After loop

```
list_for_each_entry(req, &ep->queue, queue) {
    if (&req->req == _req)
        break;
}
if (&req->req != _req) {
    ...
}
```



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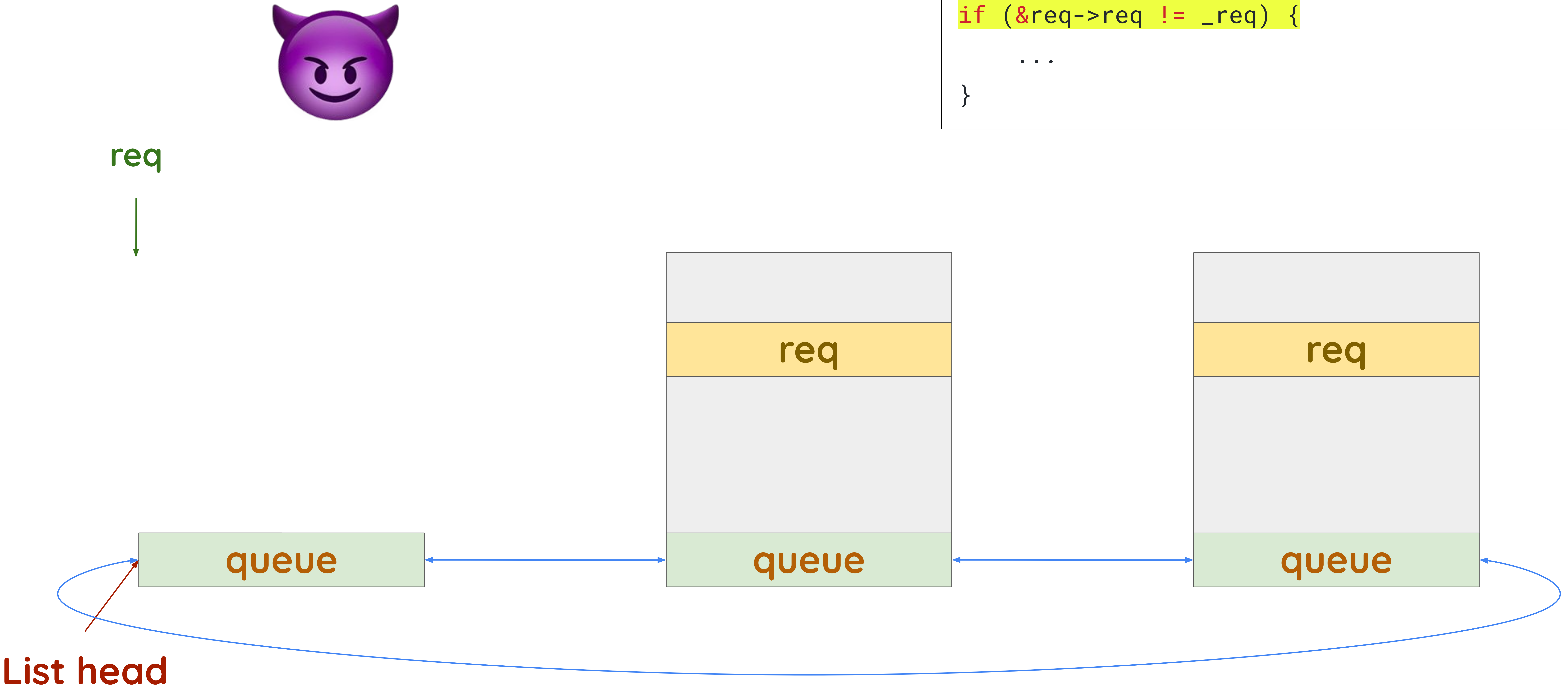

# Case study

## After loop

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list_for_each_entry(req, &ep->queue, queue) {
    if (&req->req == _req)
        break;
}
if (&req->req != _req) {
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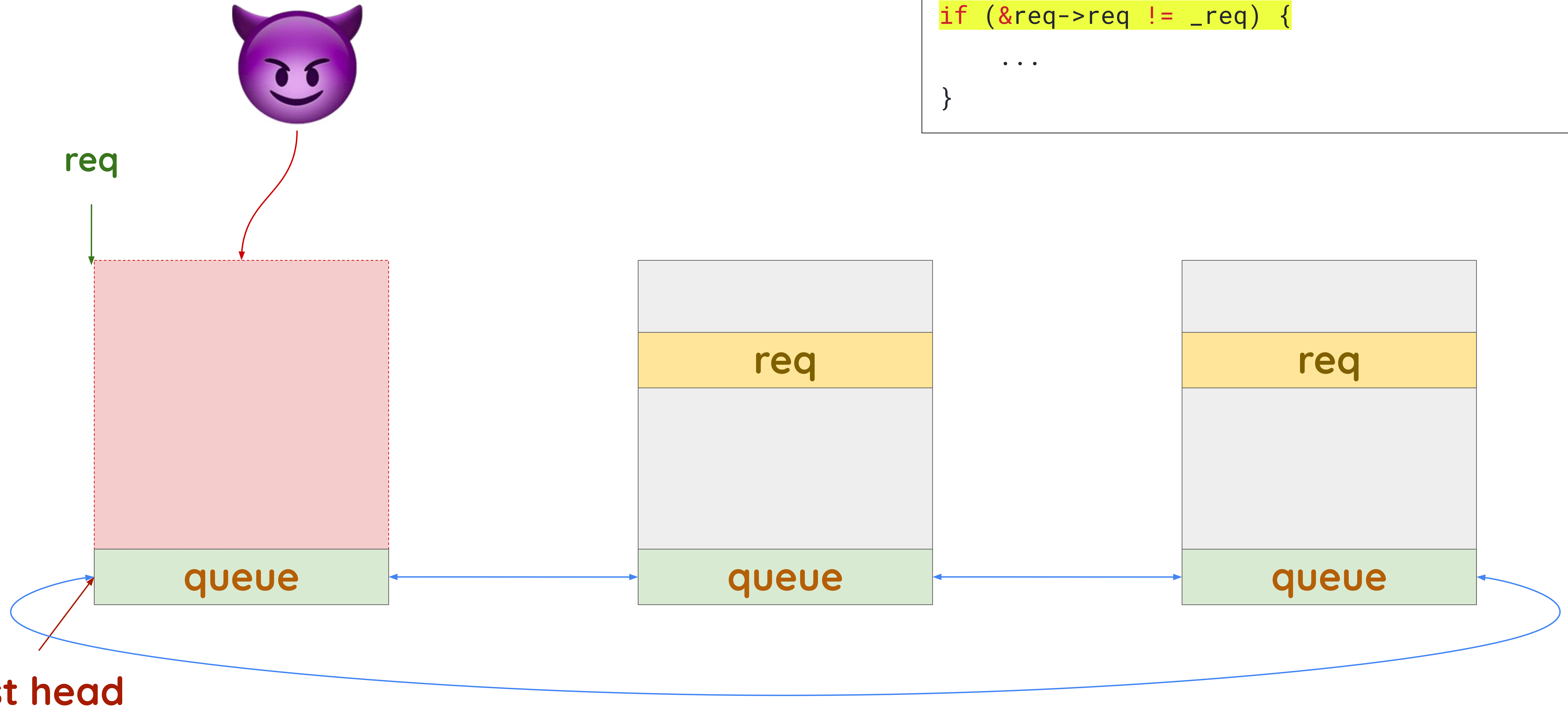

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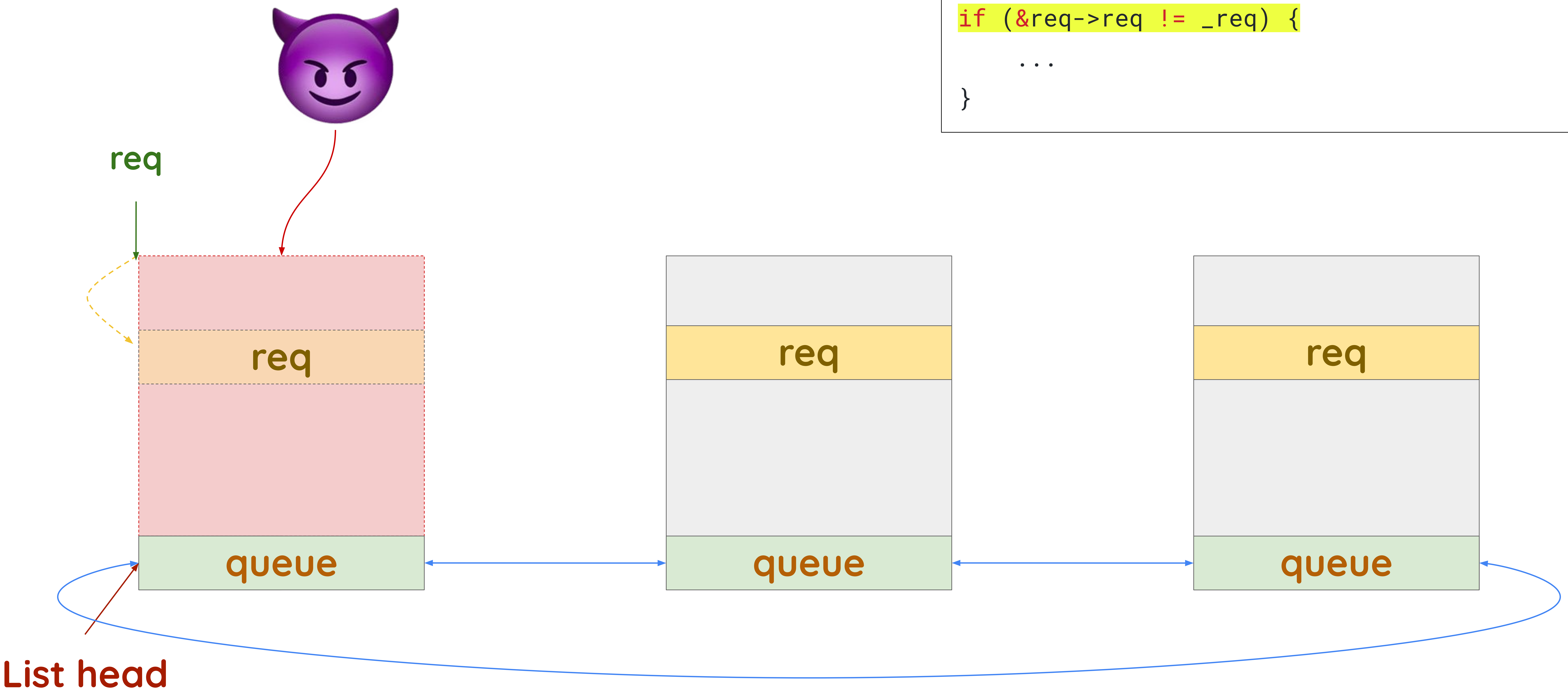

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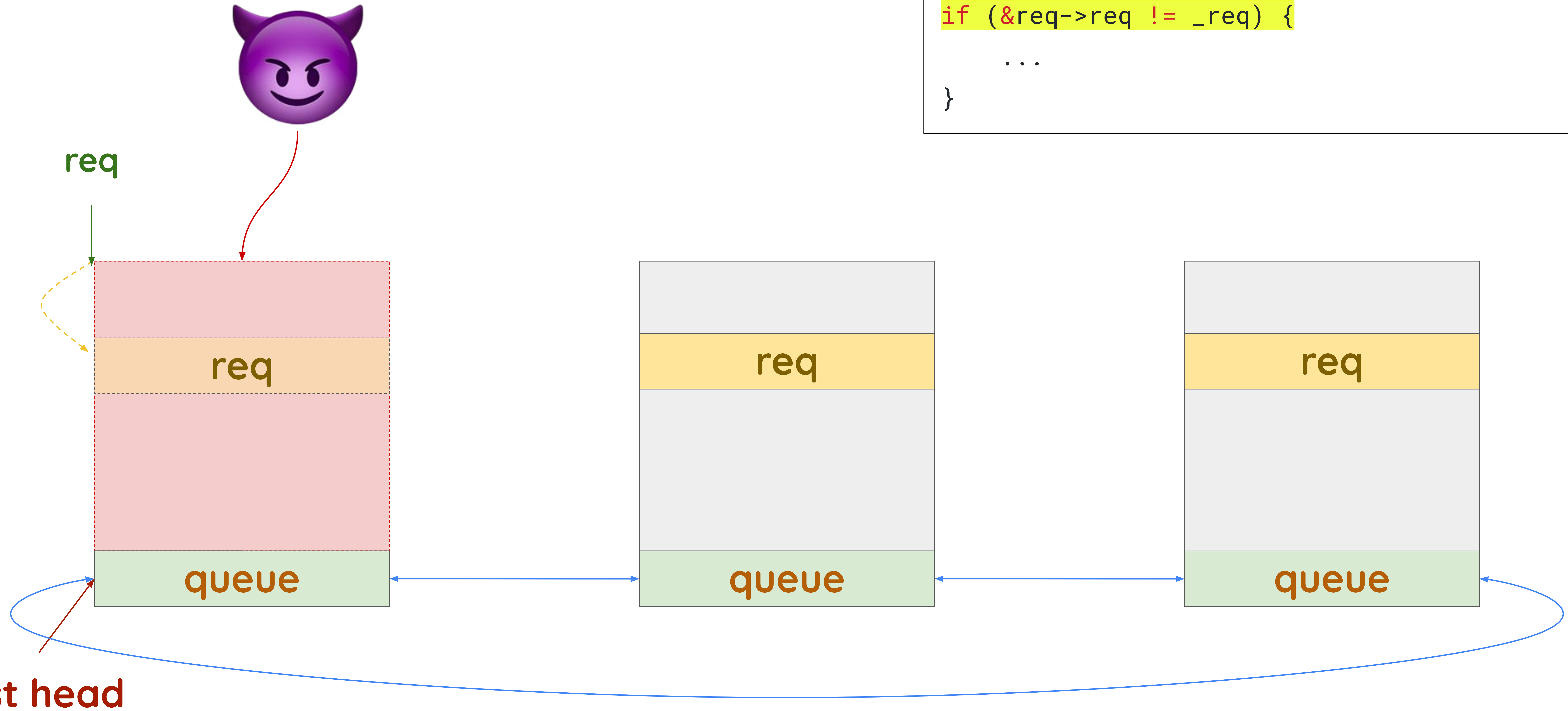

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- **container_of()** is performed on the **list_head** which is **not contained** in a struct
- it resembles an **invalid downcast** in object oriented programming
- that's why we call it a **type confusion**

# Quotes from Linus

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"we could finally start using variable declarations in for-statements"

# The correct way

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```
struct goku_request    *req = NULL, *iter;
list_for_each_entry(iter, &ep->queue, queue) {
    if (&iter->req == _req) {
        req = iter;
        break;
    }
}
if (!req) {
    ret = -EINVAL;
    goto out;
}
```

# Moving the kernel to modern C

By **Jonathan Corbet**
February 24, 2022

Despite its generally fast-moving nature, the kernel project relies on a number of old tools. While critics like to focus on the community's extensive use of email, a possibly more significant anachronism is the use of the 1989 version of the C language standard for kernel code — a standard that was codified before the kernel project even began over 30 years ago. It is looking like that longstanding practice could be coming to an end as the 5.18 kernel, which can be expected in May of this year.

**Linked-list concerns**

The discussion started with this patch series from Jakob Koschel, who is trying to prevent speculative-execution



https://lwn.net/Articles/885941/

Submitting patches is **fun but very time intensive**.

Around 80 patches have been merged so far.

~300 locations still use the list iterator **after the loop**!

Patching has to be done **one by one**.

Without fixing them there is **no real benefit** of moving to C11.

Treewide changesets is **a tricky entry** to submitting patches.

Same bugs will need **different fixes** depending on the maintainer.

Knowing how to split them into pieces is **difficult**.

Different subsystems have **different rules**.

Big shoutout to Mike Rapoport for his massive help!

There might be **more type confusions** in the kernel.

Maybe it's time for a **new scanner**...

Any use of `container_of()` can potentially result in a **type confusion**…

Detecting those is ongoing work.

We've started with building a **speculative gadget scanner**...

... ended up with **real type confusion bugs**

and caused the kernel to move to a **more modern version of C**.

Thank you!


Jakob-Koschel

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Linux
Plumbers
Conference

Dublin, Ireland September 12-14, 2022