Kernel Data Structures

Advanced Operating Systems and Virtualization

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Linux Kernel Design Patterns

- The kernel has to manage a significant amount of different data structures
- Many objects are complex
  - variable size
  - groups of other objects (collections)
  - changing frequently over time
- Performance and efficiency is fundamental
- We need abstract data types: how to do that in C?

Abstract Data Types

- Encapsulate the entire implementation of a data structure
- Provide only a well-defined interface to manipulate objects/collections
- Optimizations in the data structure implementation is directly spread across the whole source

Circular Doubly-Linked Lists

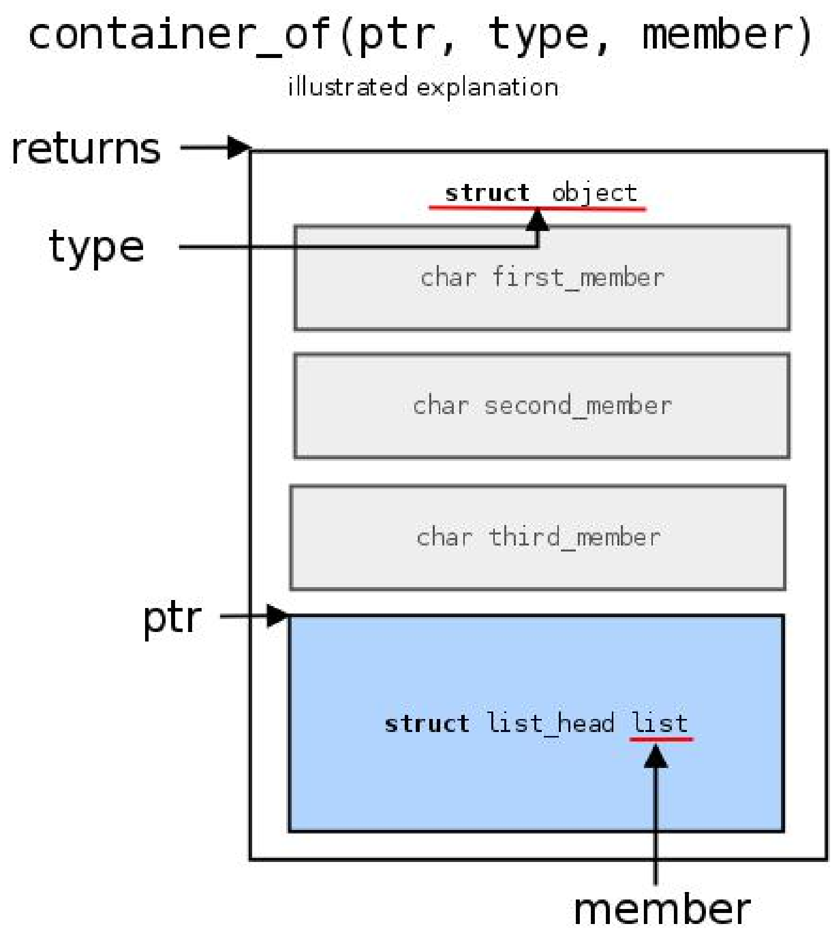
- /include/linux/list.h

```
struct list_head {
  struct list_head *next, *prev;
};
```

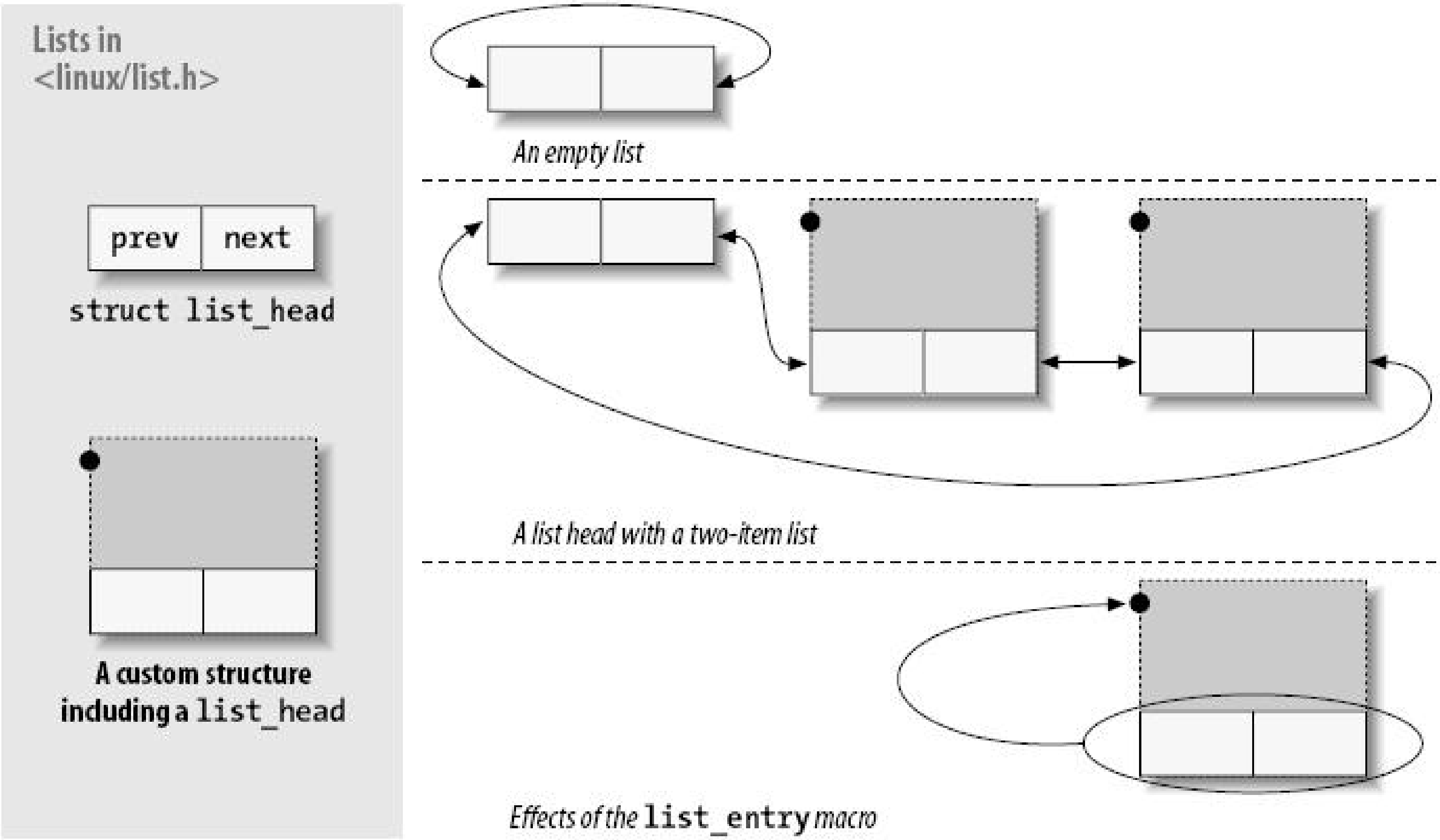
Circular Doubly-Linked Lists

```
struct my_struct {
  int priority;
  struct list_head list1;
  struct list_head list1;
  int other_member;
};
```

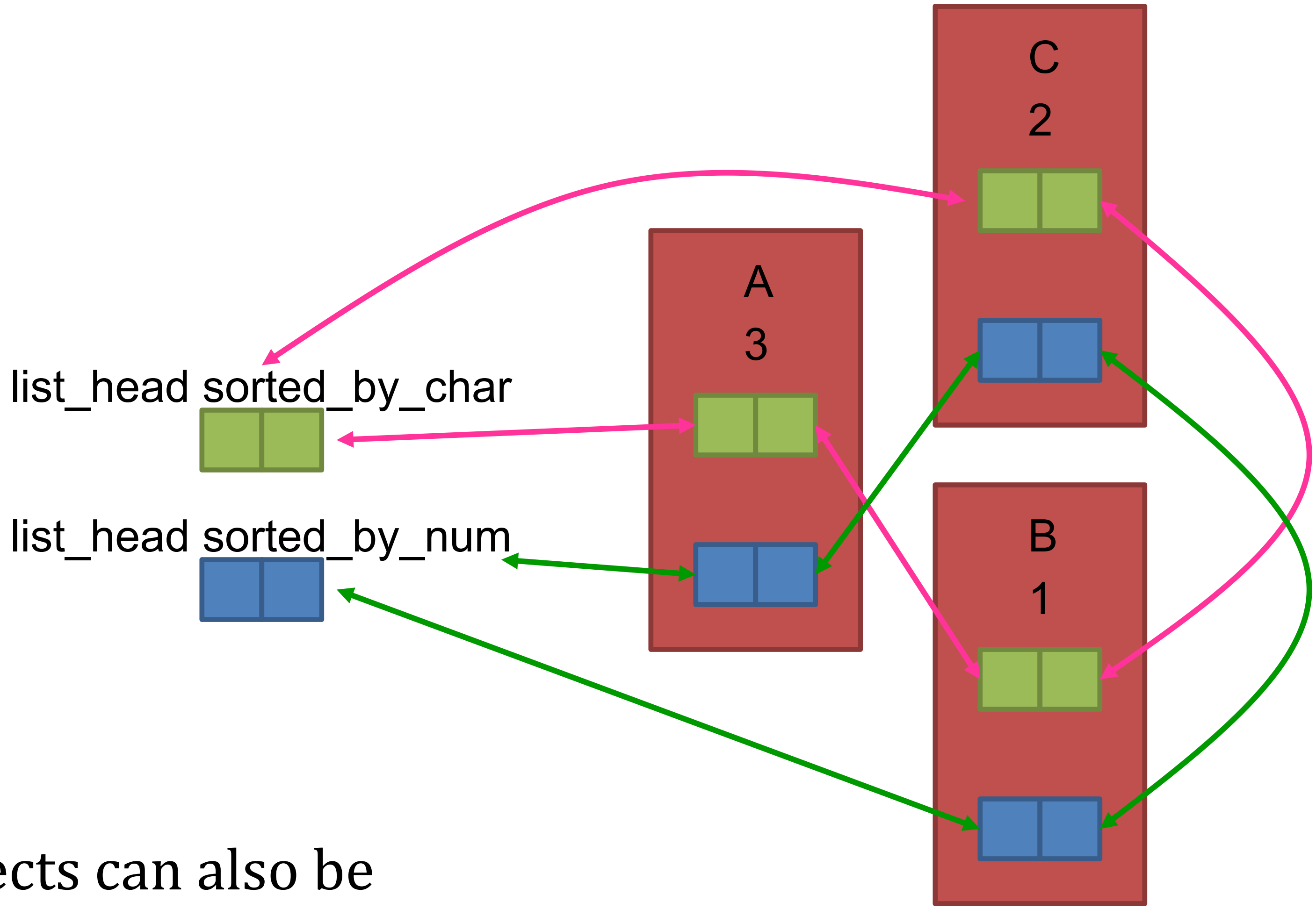
Circular Doubly-Linked Lists



Circular Doubly-Linked Lists



How to use Lists



Objects can also be allocated into an array

Head of lists

- The head of the list is usually a standalone structure:

```
struct list_head todo_list;
INIT_LIST_HEAD(&todo_list);
```

- If it is used as a global variable, it has to be initialized at compile time:

```
LIST_HEAD(todo_list);
```

Linked List API (partial)

- `list_add(struct list_head *new, struct list_head *head);`
- `list_add_tail(struct list_head *new, struct list_head *head);`
- `list_del(struct list_head *entry);`
- `list_del_init(struct list_head *entry); // To later relink`
- `list_move(struct list_head *entry, struct list_head *head);`
- `list_move_tail(struct list_head *entry, struct list_head *head);`
- `list_empty(struct list_head *head); // Non-zero if empty`

List Traversal

```
void my_add_entry(struct my_struct *new) {
    struct list_head *ptr;
    struct my_struct *entry;
    for (ptr = my_list.next; ptr != &my_list; ptr = ptr->next) {
    entry = list_entry(ptr, struct my_struct, list);
    if (entry->priority < new->priority) {
      list_add_tail(&new->list, ptr);
      return;
    }
  }
  list_add_tail(&new->list, &my_list);
}
```

List Traversal

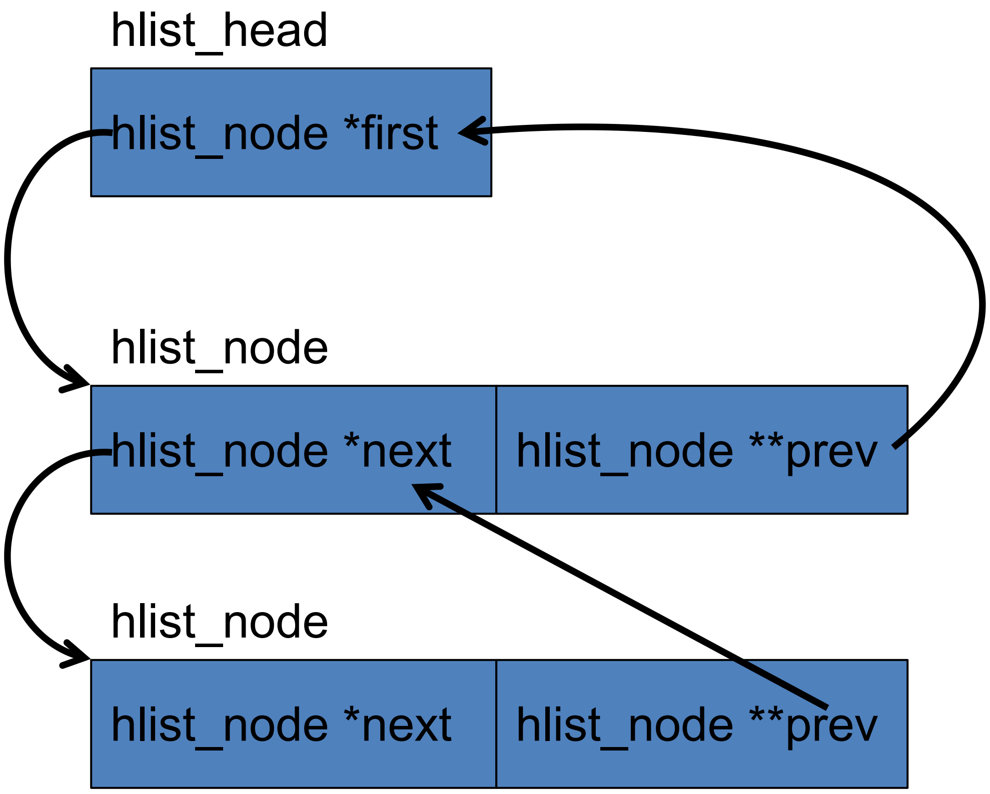
```
void my_add_entry(struct my_struct *new) {
    struct list_head *ptr;
    struct my_struct *entry;
    list_for_each(ptr, &todo_list) {
    entry = list_entry(ptr, struct my_struct, list);
    if (entry->priority < new->priority) {
      list_add_tail(&new->list, ptr);
      return;
    }
  }
  list_add_tail(&new->list, &my_list);
}
```

Hash Lists

- In some cases, storing two pointers in the head is a waste of memory (e.g., hash tables)

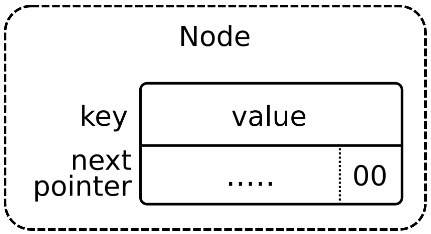
```
struct list_head {
    struct list_head *next, *prev;
};

struct hlist_head {
    struct hlist_node *first;
};

struct hlist_node {
    struct hlist_node *next, **pprev;
```

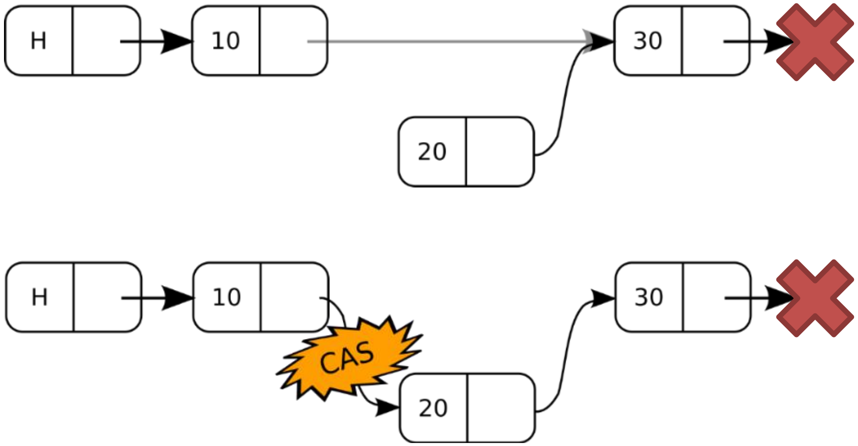
Hash Lists


hlist_head
hlist_node *first
hlist_node
hlist_node *next
hlist_node **prev
hlist_node
hlist_node *next
hlist_node **prev

Lock-less Lists

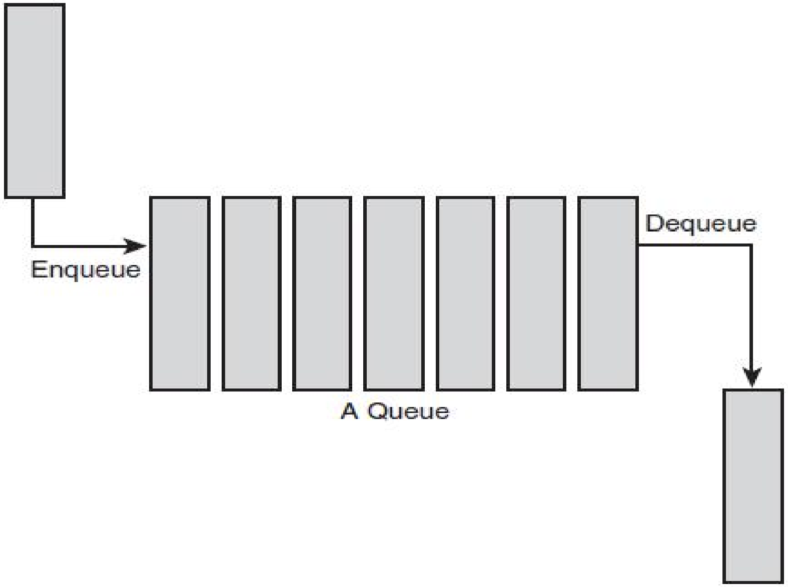
- Singly-linked NULL-terminated non-blocking lists
- Based on compare and swap to update pointers
- If operations are carried out accessing only the single next pointer, RMW instructions allow concurrent access with no locking





Queues

- Producer/consumer model

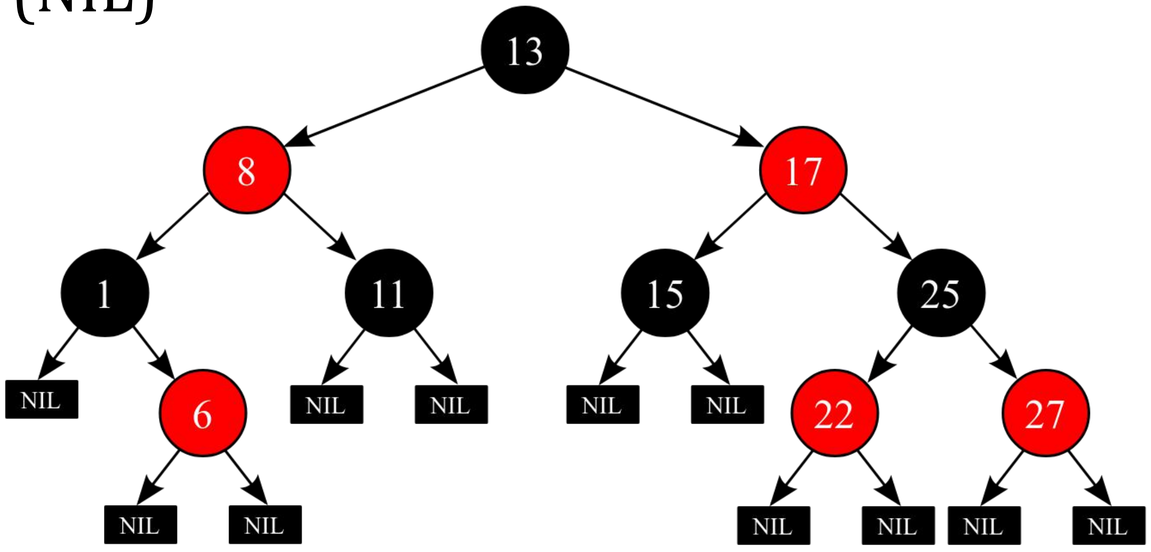


Queues

- Called `kfifo` in `/include/linux/kfifo.h`
- Two main operations:
  - Enqueue: `kfifo_in()`
  - Dequeue: `kfifo_out()`
- Creation:
  - `kfifo_alloc(struct kfifo *fifo, unsigned int size, gfp_t gfp_mask)`
- Removal:
  - `kfifo_free(struct kfifo *fifo)`

Red-Black Trees

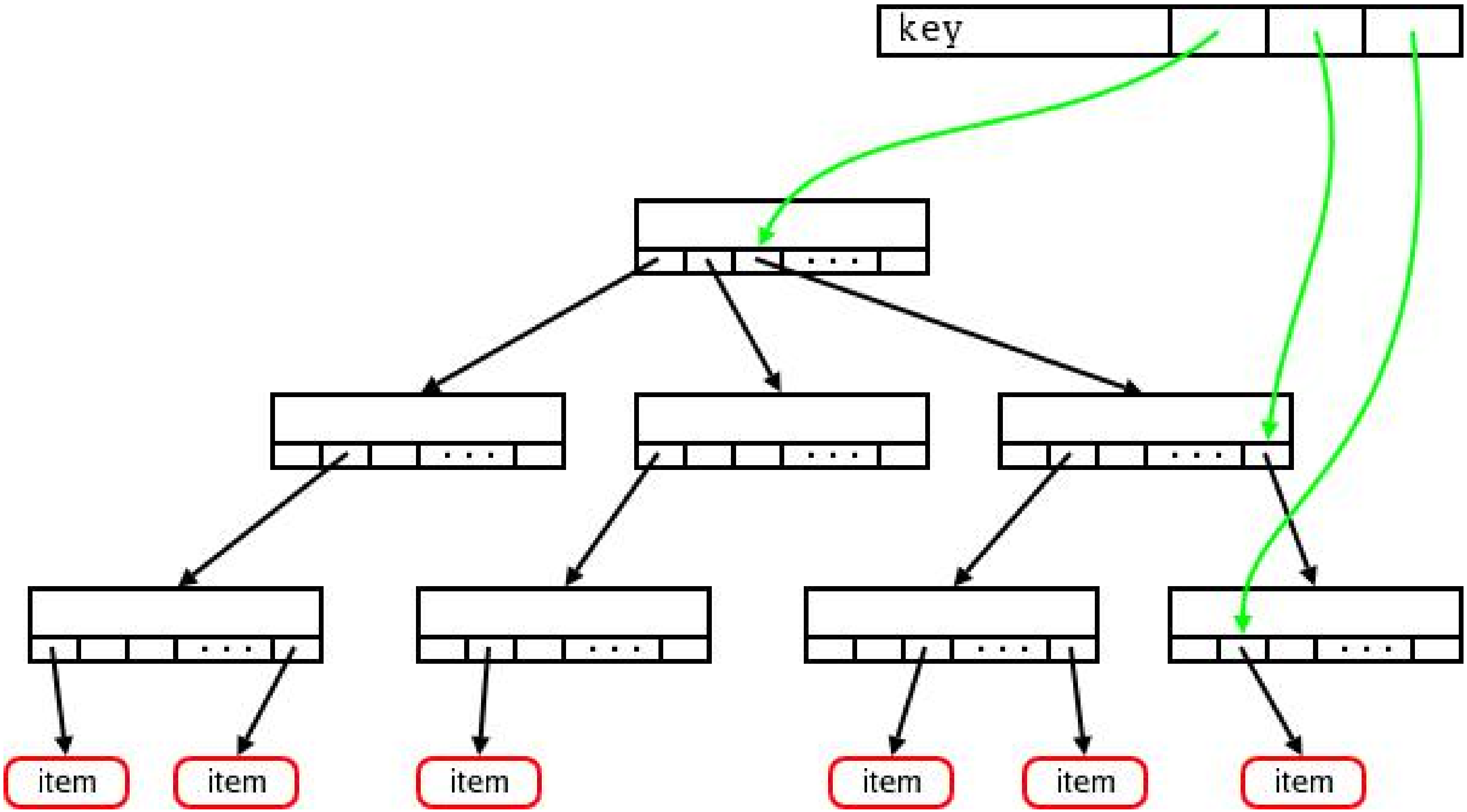
- Self-balancing binary search tree
- Properties:
  - Each node is either black or red
  - Each path to leaf traverses the same number of black nodes
  - Each red node has two black children
  - All leaves are black (NIL)



Red-Black Trees

- Defined in `/include/linux/rbtree.h`
- `Initialization:`
  - **`struct rb_root root = RB_ROOT;`**
- The API provides functions to:
  - get the payload of a node: `rb_entry()`
  - insert a node: `rb_link_node()`
  - set the color (trigger rebalancing): `rb_insert_color()`
  - remove a node: `rb_erase()`
- Traversal must be implemented by hand (what should the default implementation compare?)

Radix Tree



Radix Tree

- There are two different implementations:
  - `/include/linux/radix-tree.h`
  - `/include/linux/idr.h` (simpler, based on the former)
- Both provide a mapping from a number (`unsigned long`) to a pointer (`void *`)
- They can be used to implement (sparse) maps
  - Empty nodes are not kept in the representation

idr Example

- This code allows any to cores to compete at allocating an ID.

can sleep, no lock

```
again:
	if (idr_pre_get(&my_idr, GFP_KERNEL) == 0) {
		/* No memory, give up entirely */
	}
	spin_lock(&my_lock);
	result = idr_get_new(&my_idr, &target, &id);
	if (result == -EAGAIN) {
		sigh();
		spin_unlock(&my_lock);
		goto again;
	}
```

Per-CPU Variables

- They are variables referenced with the same name
- Depending on the core on which the code runs, this name is automatically mapped to different storage
- They are based on a reserved zone in the linear addressing space
- Macros allows to retrieve the actual address for the running core

Per-CPU Variables

- Definition and usage:

```
DEFINE_PER_CPU(int, x);
int z;
z = this_cpu_read(x);
```

- This is compiled to:

```
movl %gs:x, %eax
```

Per-CPU Variables

- The %gs segment points to a per-CPU area
  - This works only because we have a different GDT for each CPU!