Linux Core-api Documentation

The kernel development community

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CONTENTS

This is the beginning of a manual for core kernel APIs. The conversion (and writing!) of documents for this manual is much appreciated!

CHAPTER

ONE

CORE UTILITIES

This section has general and "core core" documentation. The first is a massive grab-bag of kerneldoc info left over from the docbook days; it should really be broken up someday when somebody finds the energy to do it.

1.1 The Linux Kernel API

1.1.1 List Management Functions

void **INIT_LIST_HEAD**(struct list_head *list)

Initialize a list_head structure

Parameters

struct list_head *list

list_head structure to be initialized.

Description

Initializes the list_head to point to itself. If it is a list header, the result is an empty list.

void **list_add**(struct list_head *new, struct list_head *head)

add a new entry

Parameters

struct list_head *new

new entry to be added

struct list_head *head

list head to add it after

Description

Insert a new entry after the specified head. This is good for implementing stacks.

void **list_add_tail**(struct list_head *new, struct list_head *head)

add a new entry

Parameters

struct list_head *new

new entry to be added

struct list_head *head
list head to add it before

Description

Insert a new entry before the specified head. This is useful for implementing queues.

void **list_del**(struct list_head *entry)
deletes entry from list.

Parameters

struct list_head *entry
the element to delete from the list.

Note

list_empty() on entry does not return true after this, the entry is in an undefined state.

void **list_replace**(struct list_head *old, struct list_head *new)
replace old entry by new one

Parameters

struct list_head *old
the element to be replaced

struct list_head *new
the new element to insert

Description

If **old** was empty, it will be overwritten.

void **list_replace_init**(struct list_head *old, struct list_head *new)
replace old entry by new one and initialize the old one

Parameters

struct list_head *old
the element to be replaced

struct list_head *new
the new element to insert

Description

If **old** was empty, it will be overwritten.

void **list_swap**(struct list_head *entry1, struct list_head *entry2)
replace entry1 with entry2 and re-add entry1 at entry2's position

Parameters

struct list_head *entry1
the location to place entry2

struct list_head *entry2
the location to place entry1

void **list_del_init**(struct list_head *entry)

deletes entry from list and reinitialize it.

Parameters

struct list_head *entry
the element to delete from the list.

void **list_move**(struct list_head *list, struct list_head *head)

delete from one list and add as another's head

Parameters

struct list_head *list
the entry to move

struct list_head *head
the head that will precede our entry

void **list_move_tail**(struct list_head *list, struct list_head *head)

delete from one list and add as another's tail

Parameters

struct list_head *list
the entry to move

struct list_head *head
the head that will follow our entry

void **list_bulk_move_tail**(struct list_head *head, struct list_head *first, struct list_head *last)

move a subsection of a list to its tail

Parameters

struct list_head *head
the head that will follow our entry

struct list_head *first
first entry to move

struct list_head *last
last entry to move, can be the same as first

Description

Move all entries between **first** and including **last** before **head**. All three entries must belong to the same linked list.

int **list_is_first**(const struct list_head *list, const struct list_head *head)

- tests whether **list** is the first entry in list **head**

Parameters

const struct list_head *list
the entry to test

const struct list_head *head
the head of the list

int **list_is_last**(const struct list_head *list, const struct list_head *head)
    tests whether **list** is the last entry in list **head**

Parameters

const struct list_head *list
    the entry to test

const struct list_head *head
    the head of the list

int **list_empty**(const struct list_head *head)
    tests whether a list is empty

Parameters

const struct list_head *head
    the list to test.

void **list_del_init_careful**(struct list_head *entry)
    deletes entry from list and reinitialize it.

Parameters

struct list_head *entry
    the element to delete from the list.

Description

This is the same as *list_del_init()*, except designed to be used together with *list_empty_careful()* in a way to guarantee ordering of other memory operations.

Any memory operations done before a *list_del_init_careful()* are guaranteed to be visible after a *list_empty_careful()* test.

int **list_empty_careful**(const struct list_head *head)
    tests whether a list is empty and not being modified

Parameters

const struct list_head *head
    the list to test

Description

tests whether a list is empty _and_ checks that no other CPU might be in the process of modifying either member (next or prev)

NOTE

using *list_empty_careful()* without synchronization can only be safe if the only activity that can happen to the list entry is *list_del_init()*. Eg. it cannot be used if another CPU could re-*list_add()* it.

void **list_rotate_left**(struct list_head *head)
    rotate the list to the left

Parameters

struct list_head *head
    the head of the list

void **list_rotate_to_front**(struct list_head *list, struct list_head *head)
    Rotate list to specific item.

Parameters

struct list_head *list
    The desired new front of the list.

struct list_head *head
    The head of the list.

Description

Rotates list so that **list** becomes the new front of the list.

int **list_is_singular**(const struct list_head *head)
    tests whether a list has just one entry.

Parameters

const struct list_head *head
    the list to test.

void **list_cut_position**(struct list_head *list, struct list_head *head, struct list_head *entry)
    cut a list into two

Parameters

struct list_head *list
    a new list to add all removed entries

struct list_head *head
    a list with entries

struct list_head *entry
    an entry within head, could be the head itself and if so we won't cut the list

Description

This helper moves the initial part of **head**, up to and including **entry**, from **head** to **list**. You should pass on **entry** an element you know is on **head**. **list** should be an empty list or a list you do not care about losing its data.

void **list_cut_before**(struct list_head *list, struct list_head *head, struct list_head *entry)
    cut a list into two, before given entry

Parameters

struct list_head *list
    a new list to add all removed entries

struct list_head *head
    a list with entries

struct list_head *entry
    an entry within head, could be the head itself

Description

This helper moves the initial part of **head**, up to but excluding **entry**, from **head** to **list**. You should pass in **entry** an element you know is on **head**. **list** should be an empty list or a list you do not care about losing its data. If **entry** == **head**, all entries on **head** are moved to **list**.

void **list_splice**(const struct list_head *list, struct list_head *head)

join two lists, this is designed for stacks

Parameters

const struct list_head *list
the new list to add.

struct list_head *head
the place to add it in the first list.

void **list_splice_tail**(struct list_head *list, struct list_head *head)

join two lists, each list being a queue

Parameters

struct list_head *list
the new list to add.

struct list_head *head
the place to add it in the first list.

void **list_splice_init**(struct list_head *list, struct list_head *head)

join two lists and reinitialise the emptied list.

Parameters

struct list_head *list
the new list to add.

struct list_head *head
the place to add it in the first list.

Description

The list at **list** is reinitialised

void **list_splice_tail_init**(struct list_head *list, struct list_head *head)

join two lists and reinitialise the emptied list

Parameters

struct list_head *list
the new list to add.

struct list_head *head
the place to add it in the first list.

Description

Each of the lists is a queue. The list at **list** is reinitialised

list_entry

`list_entry (ptr, type, member)`

get the struct for this entry

Parameters

ptr
the `struct list_head` pointer.

type
the type of the struct this is embedded in.

member
the name of the list_head within the struct.

list_first_entry

`list_first_entry (ptr, type, member)`

get the first element from a list

Parameters

ptr
the list head to take the element from.

type
the type of the struct this is embedded in.

member
the name of the list_head within the struct.

Description

Note, that list is expected to be not empty.

list_last_entry

`list_last_entry (ptr, type, member)`

get the last element from a list

Parameters

ptr
the list head to take the element from.

type
the type of the struct this is embedded in.

member
the name of the list_head within the struct.

Description

Note, that list is expected to be not empty.

list_first_entry_or_null

`list_first_entry_or_null (ptr, type, member)`

get the first element from a list

Parameters

ptr
the list head to take the element from.

type
the type of the struct this is embedded in.

member
the name of the list_head within the struct.

Description

Note that if the list is empty, it returns NULL.

list_next_entry

`list_next_entry (pos, member)`

get the next element in list

Parameters

pos
the type * to cursor

member
the name of the list_head within the struct.

list_prev_entry

`list_prev_entry (pos, member)`

get the prev element in list

Parameters

pos
the type * to cursor

member
the name of the list_head within the struct.

list_for_each

`list_for_each (pos, head)`

iterate over a list

Parameters

pos
the `struct list_head` to use as a loop cursor.

head
the head for your list.

list_for_each_continue

`list_for_each_continue (pos, head)`

continue iteration over a list

Parameters

pos
the `struct list_head` to use as a loop cursor.

head
the head for your list.

Description

Continue to iterate over a list, continuing after the current position.

list_for_each_prev

`list_for_each_prev (pos, head)`

iterate over a list backwards

Parameters

pos
the `struct list_head` to use as a loop cursor.

head
the head for your list.

list_for_each_safe

`list_for_each_safe (pos, n, head)`

iterate over a list safe against removal of list entry

Parameters

pos
the `struct list_head` to use as a loop cursor.

n
another `struct list_head` to use as temporary storage

head
the head for your list.

list_for_each_prev_safe

`list_for_each_prev_safe (pos, n, head)`

iterate over a list backwards safe against removal of list entry

Parameters

pos
the `struct list_head` to use as a loop cursor.

n
another `struct list_head` to use as temporary storage

head
the head for your list.

list_entry_is_head

`list_entry_is_head (pos, head, member)`

test if the entry points to the head of the list

Parameters

pos
the type * to cursor

head
the head for your list.

member
the name of the list_head within the struct.

list_for_each_entry

`list_for_each_entry (pos, head, member)`

iterate over list of given type

Parameters

pos
the type * to use as a loop cursor.

head
the head for your list.

member
the name of the list_head within the struct.

list_for_each_entry_reverse

`list_for_each_entry_reverse (pos, head, member)`

iterate backwards over list of given type.

Parameters

pos
the type * to use as a loop cursor.

head
the head for your list.

member
the name of the list_head within the struct.

list_prepare_entry

`list_prepare_entry (pos, head, member)`

prepare a pos entry for use in *list_for_each_entry_continue()*

Parameters

pos
the type * to use as a start point

head
the head of the list

member
the name of the list_head within the struct.

Description

Prepares a pos entry for use as a start point in *list_for_each_entry_continue()*.

list_for_each_entry_continue

`list_for_each_entry_continue (pos, head, member)`

continue iteration over list of given type

Parameters

pos
the type * to use as a loop cursor.

head
the head for your list.

member
the name of the list_head within the struct.

Description

Continue to iterate over list of given type, continuing after the current position.

list_for_each_entry_continue_reverse

`list_for_each_entry_continue_reverse (pos, head, member)`

iterate backwards from the given point

Parameters

pos
the type * to use as a loop cursor.

head
the head for your list.

member
the name of the list_head within the struct.

Description

Start to iterate over list of given type backwards, continuing after the current position.

list_for_each_entry_from

`list_for_each_entry_from (pos, head, member)`

iterate over list of given type from the current point

Parameters

pos
the type * to use as a loop cursor.

head
the head for your list.

member
the name of the list_head within the struct.

Description

Iterate over list of given type, continuing from current position.

list_for_each_entry_from_reverse

`list_for_each_entry_from_reverse (pos, head, member)`

iterate backwards over list of given type from the current point

Parameters

pos
the type * to use as a loop cursor.

head
the head for your list.

member
the name of the list_head within the struct.

Description

Iterate backwards over list of given type, continuing from current position.

list_for_each_entry_safe

`list_for_each_entry_safe (pos, n, head, member)`

iterate over list of given type safe against removal of list entry

Parameters

pos
the type * to use as a loop cursor.

n
another type * to use as temporary storage

head
the head for your list.

member
the name of the list_head within the struct.

list_for_each_entry_safe_continue

`list_for_each_entry_safe_continue (pos, n, head, member)`

continue list iteration safe against removal

Parameters

pos
the type * to use as a loop cursor.

n
another type * to use as temporary storage

head
the head for your list.

member
the name of the list_head within the struct.

Description

Iterate over list of given type, continuing after current point, safe against removal of list entry.

`list_for_each_entry_safe_from`

`list_for_each_entry_safe_from (pos, n, head, member)`

iterate over list from current point safe against removal

Parameters

pos
: the type * to use as a loop cursor.

n
: another type * to use as temporary storage

head
: the head for your list.

member
: the name of the list_head within the struct.

Description

Iterate over list of given type from current point, safe against removal of list entry.

`list_for_each_entry_safe_reverse`

`list_for_each_entry_safe_reverse (pos, n, head, member)`

iterate backwards over list safe against removal

Parameters

pos
: the type * to use as a loop cursor.

n
: another type * to use as temporary storage

head
: the head for your list.

member
: the name of the list_head within the struct.

Description

Iterate backwards over list of given type, safe against removal of list entry.

`list_safe_reset_next`

`list_safe_reset_next (pos, n, member)`

reset a stale list_for_each_entry_safe loop

Parameters

pos
: the loop cursor used in the list_for_each_entry_safe loop

n
temporary storage used in list_for_each_entry_safe

member
the name of the list_head within the struct.

Description

list_safe_reset_next is not safe to use in general if the list may be modified concurrently (eg. the lock is dropped in the loop body). An exception to this is if the cursor element (pos) is pinned in the list, and list_safe_reset_next is called after re-taking the lock and before completing the current iteration of the loop body.

int **hlist_unhashed**(const struct hlist_node *h)
Has node been removed from list and reinitialized?

Parameters

const struct hlist_node *h
Node to be checked

Description

Not that not all removal functions will leave a node in unhashed state. For example, *hlist_nulls_del_init_rcu()* does leave the node in unhashed state, but hlist_nulls_del() does not.

int **hlist_unhashed_lockless**(const struct hlist_node *h)
Version of hlist_unhashed for lockless use

Parameters

const struct hlist_node *h
Node to be checked

Description

This variant of *hlist_unhashed()* must be used in lockless contexts to avoid potential load-tearing. The READ_ONCE() is paired with the various WRITE_ONCE() in hlist helpers that are defined below.

int **hlist_empty**(const struct hlist_head *h)
Is the specified hlist_head structure an empty hlist?

Parameters

const struct hlist_head *h
Structure to check.

void **hlist_del**(struct hlist_node *n)
Delete the specified hlist_node from its list

Parameters

struct hlist_node *n
Node to delete.

Description

Note that this function leaves the node in hashed state. Use *hlist_del_init()* or similar instead to unhash **n**.

void **hlist_del_init**(struct hlist_node *n)

Delete the specified hlist_node from its list and initialize

Parameters

struct hlist_node *n
Node to delete.

Description

Note that this function leaves the node in unhashed state.

void **hlist_add_head**(struct hlist_node *n, struct hlist_head *h)

add a new entry at the beginning of the hlist

Parameters

struct hlist_node *n
new entry to be added

struct hlist_head *h
hlist head to add it after

Description

Insert a new entry after the specified head. This is good for implementing stacks.

void **hlist_add_before**(struct hlist_node *n, struct hlist_node *next)

add a new entry before the one specified

Parameters

struct hlist_node *n
new entry to be added

struct hlist_node *next
hlist node to add it before, which must be non-NULL

void **hlist_add_behind**(struct hlist_node *n, struct hlist_node *prev)

add a new entry after the one specified

Parameters

struct hlist_node *n
new entry to be added

struct hlist_node *prev
hlist node to add it after, which must be non-NULL

void **hlist_add_fake**(struct hlist_node *n)

create a fake hlist consisting of a single headless node

Parameters

struct hlist_node *n
Node to make a fake list out of

Description

This makes **n** appear to be its own predecessor on a headless hlist. The point of this is to allow things like *hlist_del()* to work correctly in cases where there is no list.

bool **hlist_fake**(struct hlist_node *h)

Parameters

struct hlist_node *h
Node to check for being a self-referential fake hlist.

bool **hlist_is_singular_node**(struct hlist_node *n, struct hlist_head *h)
is node the only element of the specified hlist?

Parameters

struct hlist_node *n
Node to check for singularity.

struct hlist_head *h
Header for potentially singular list.

Description

Check whether the node is the only node of the head without accessing head, thus avoiding unnecessary cache misses.

void **hlist_move_list**(struct hlist_head *old, struct hlist_head *new)
Move an hlist

Parameters

struct hlist_head *old
hlist_head for old list.

struct hlist_head *new
hlist_head for new list.

Description

Move a list from one list head to another. Fixup the pprev reference of the first entry if it exists.

hlist_for_each_entry

`hlist_for_each_entry (pos, head, member)`

iterate over list of given type

Parameters

pos
the type * to use as a loop cursor.

head
the head for your list.

member
the name of the hlist_node within the struct.

hlist_for_each_entry_continue

`hlist_for_each_entry_continue (pos, member)`

iterate over a hlist continuing after current point

Parameters

pos
the type * to use as a loop cursor.

member
the name of the hlist_node within the struct.

hlist_for_each_entry_from

`hlist_for_each_entry_from (pos, member)`

iterate over a hlist continuing from current point

Parameters

pos
the type * to use as a loop cursor.

member
the name of the hlist_node within the struct.

hlist_for_each_entry_safe

`hlist_for_each_entry_safe (pos, n, head, member)`

iterate over list of given type safe against removal of list entry

Parameters

pos
the type * to use as a loop cursor.

n
a `struct hlist_node` to use as temporary storage

head
the head for your list.

member
the name of the hlist_node within the struct.

1.1.2 Basic C Library Functions

When writing drivers, you cannot in general use routines which are from the C Library. Some of the functions have been found generally useful and they are listed below. The behaviour of these functions may vary slightly from those defined by ANSI, and these deviations are noted in the text.

String Conversions

unsigned long long **simple_strtoull**(const char *cp, char **endp, unsigned int base)

convert a string to an unsigned long long

Parameters

const char *cp
The start of the string

char **endp
A pointer to the end of the parsed string will be placed here

unsigned int base
The number base to use

Description

This function has caveats. Please use kstrtoull instead.

unsigned long **simple_strtoul**(const char *cp, char **endp, unsigned int base)

convert a string to an unsigned long

Parameters

const char *cp
The start of the string

char **endp
A pointer to the end of the parsed string will be placed here

unsigned int base
The number base to use

Description

This function has caveats. Please use kstrtoul instead.

long **simple_strtol**(const char *cp, char **endp, unsigned int base)

convert a string to a signed long

Parameters

const char *cp
The start of the string

char **endp
A pointer to the end of the parsed string will be placed here

unsigned int base
The number base to use

Description

This function has caveats. Please use kstrtol instead.

long long **simple_strtoll**(const char *cp, char **endp, unsigned int base)

convert a string to a signed long long

Parameters

const char *cp
The start of the string

char **endp
A pointer to the end of the parsed string will be placed here

unsigned int base
The number base to use

Description

This function has caveats. Please use kstrtoll instead.

int **vsnprintf**(char *buf, size_t size, const char *fmt, va_list args)
Format a string and place it in a buffer

Parameters

char *buf
The buffer to place the result into

size_t size
The size of the buffer, including the trailing null space

const char *fmt
The format string to use

va_list args
Arguments for the format string

Description

This function generally follows C99 vsnprintf, but has some extensions and a few limitations:

- ``n`` is unsupported
- ``p``* is handled by pointer()

See pointer() or *How to get printk format specifiers right* for more extensive description.

Please update the documentation in both places when making changes

The return value is the number of characters which would be generated for the given input, excluding the trailing '0', as per ISO C99. If you want to have the exact number of characters written into **buf** as return value (not including the trailing '0'), use *vscnprintf()*. If the return is greater than or equal to **size**, the resulting string is truncated.

If you're not already dealing with a va_list consider using *snprintf()*.

int **vscnprintf**(char *buf, size_t size, const char *fmt, va_list args)
Format a string and place it in a buffer

Parameters

char *buf
The buffer to place the result into

size_t size
The size of the buffer, including the trailing null space

const char *fmt
The format string to use

va_list args
Arguments for the format string

Description

The return value is the number of characters which have been written into the **buf** not including the trailing '0'. If **size** is == 0 the function returns 0.

If you're not already dealing with a va_list consider using *scnprintf()*.

See the *vsnprintf()* documentation for format string extensions over C99.

int **snprintf**(char *buf, size_t size, const char *fmt, ...)
Format a string and place it in a buffer

Parameters

char *buf
The buffer to place the result into

size_t size
The size of the buffer, including the trailing null space

const char *fmt
The format string to use

...
Arguments for the format string

Description

The return value is the number of characters which would be generated for the given input, excluding the trailing null, as per ISO C99. If the return is greater than or equal to **size**, the resulting string is truncated.

See the *vsnprintf()* documentation for format string extensions over C99.

int **scnprintf**(char *buf, size_t size, const char *fmt, ...)
Format a string and place it in a buffer

Parameters

char *buf
The buffer to place the result into

size_t size
The size of the buffer, including the trailing null space

const char *fmt
The format string to use

...
Arguments for the format string

Description

The return value is the number of characters written into **buf** not including the trailing '0'. If **size** is == 0 the function returns 0.

int **vsprintf**(char *buf, const char *fmt, va_list args)
Format a string and place it in a buffer

Parameters

char *buf
The buffer to place the result into

const char *fmt
The format string to use

va_list args
Arguments for the format string

Description

The function returns the number of characters written into **buf**. Use *vsnprintf()* or *vscnprintf()* in order to avoid buffer overflows.

If you're not already dealing with a va_list consider using *sprintf()*.

See the *vsnprintf()* documentation for format string extensions over C99.

int **sprintf**(char *buf, const char *fmt, ...)
Format a string and place it in a buffer

Parameters

char *buf
The buffer to place the result into

const char *fmt
The format string to use

...
Arguments for the format string

Description

The function returns the number of characters written into **buf**. Use *snprintf()* or *scnprintf()* in order to avoid buffer overflows.

See the *vsnprintf()* documentation for format string extensions over C99.

int **vbin_printf**(u32 *bin_buf, size_t size, const char *fmt, va_list args)
Parse a format string and place args' binary value in a buffer

Parameters

u32 *bin_buf
The buffer to place args' binary value

size_t size
The size of the buffer(by words(32bits), not characters)

const char *fmt
The format string to use

va_list args
Arguments for the format string

Description

The format follows C99 vsnprintf, except `n` is ignored, and its argument is skipped.

The return value is the number of words(32bits) which would be generated for the given input.

NOTE

If the return value is greater than **size**, the resulting bin_buf is NOT valid for *bstr_printf()*.

int **bstr_printf**(char *buf, size_t size, const char *fmt, const u32 *bin_buf)

Format a string from binary arguments and place it in a buffer

Parameters

char *buf
The buffer to place the result into

size_t size
The size of the buffer, including the trailing null space

const char *fmt
The format string to use

const u32 *bin_buf
Binary arguments for the format string

Description

This function like C99 vsnprintf, but the difference is that vsnprintf gets arguments from stack, and bstr_printf gets arguments from **bin_buf** which is a binary buffer that generated by vbin_printf.

The format follows C99 vsnprintf, but has some extensions:
see vsnprintf comment for details.

The return value is the number of characters which would be generated for the given input, excluding the trailing '0', as per ISO C99. If you want to have the exact number of characters written into **buf** as return value (not including the trailing '0'), use *vscnprintf()*. If the return is greater than or equal to **size**, the resulting string is truncated.

int **bprintf**(u32 *bin_buf, size_t size, const char *fmt, ...)

Parse a format string and place args' binary value in a buffer

Parameters

u32 *bin_buf
The buffer to place args' binary value

size_t size
The size of the buffer(by words(32bits), not characters)

const char *fmt
The format string to use

...
Arguments for the format string

Description

The function returns the number of words(u32) written into **bin_buf**.

int **vsscanf**(const char *buf, const char *fmt, va_list args)

Unformat a buffer into a list of arguments

Parameters

const char *buf
input buffer

const char *fmt
format of buffer

va_list args
arguments

int **sscanf**(const char *buf, const char *fmt, ...)

Unformat a buffer into a list of arguments

Parameters

const char *buf
input buffer

const char *fmt
formatting of buffer

...
resulting arguments

int **kstrtoul**(const char *s, unsigned int base, unsigned long *res)

convert a string to an unsigned long

Parameters

const char *s
The start of the string. The string must be null-terminated, and may also include a single newline before its terminating null. The first character may also be a plus sign, but not a minus sign.

unsigned int base
The number base to use. The maximum supported base is 16. If base is given as 0, then the base of the string is automatically detected with the conventional semantics - If it begins with 0x the number will be parsed as a hexadecimal (case insensitive), if it otherwise begins with 0, it will be parsed as an octal number. Otherwise it will be parsed as a decimal.

unsigned long *res
Where to write the result of the conversion on success.

Description

Returns 0 on success, -ERANGE on overflow and -EINVAL on parsing error. Preferred over *simple_strtoul()*. Return code must be checked.

int **kstrtol**(const char *s, unsigned int base, long *res)

convert a string to a long

Parameters

const char *s
The start of the string. The string must be null-terminated, and may also include a single newline before its terminating null. The first character may also be a plus sign or a minus sign.

unsigned int base
The number base to use. The maximum supported base is 16. If base is given as 0, then the base of the string is automatically detected with the conventional semantics - If it begins with 0x the number will be parsed as a hexadecimal (case insensitive), if it otherwise begins with 0, it will be parsed as an octal number. Otherwise it will be parsed as a decimal.

long *res
Where to write the result of the conversion on success.

Description

Returns 0 on success, -ERANGE on overflow and -EINVAL on parsing error. Preferred over *simple_strtol()*. Return code must be checked.

int **kstrtoull**(const char *s, unsigned int base, unsigned long long *res)
convert a string to an unsigned long long

Parameters

const char *s
The start of the string. The string must be null-terminated, and may also include a single newline before its terminating null. The first character may also be a plus sign, but not a minus sign.

unsigned int base
The number base to use. The maximum supported base is 16. If base is given as 0, then the base of the string is automatically detected with the conventional semantics - If it begins with 0x the number will be parsed as a hexadecimal (case insensitive), if it otherwise begins with 0, it will be parsed as an octal number. Otherwise it will be parsed as a decimal.

unsigned long long *res
Where to write the result of the conversion on success.

Description

Returns 0 on success, -ERANGE on overflow and -EINVAL on parsing error. Preferred over *simple_strtoull()*. Return code must be checked.

int **kstrtoll**(const char *s, unsigned int base, long long *res)
convert a string to a long long

Parameters

const char *s
The start of the string. The string must be null-terminated, and may also include a single newline before its terminating null. The first character may also be a plus sign or a minus sign.

unsigned int base
The number base to use. The maximum supported base is 16. If base is

given as 0, then the base of the string is automatically detected with the conventional semantics - If it begins with 0x the number will be parsed as a hexadecimal (case insensitive), if it otherwise begins with 0, it will be parsed as an octal number. Otherwise it will be parsed as a decimal.

long long *res
Where to write the result of the conversion on success.

Description

Returns 0 on success, -ERANGE on overflow and -EINVAL on parsing error. Preferred over *simple_strtoll()*. Return code must be checked.

int **kstrtouint**(const char *s, unsigned int base, unsigned int *res)
convert a string to an unsigned int

Parameters

const char *s
The start of the string. The string must be null-terminated, and may also include a single newline before its terminating null. The first character may also be a plus sign, but not a minus sign.

unsigned int base
The number base to use. The maximum supported base is 16. If base is given as 0, then the base of the string is automatically detected with the conventional semantics - If it begins with 0x the number will be parsed as a hexadecimal (case insensitive), if it otherwise begins with 0, it will be parsed as an octal number. Otherwise it will be parsed as a decimal.

unsigned int *res
Where to write the result of the conversion on success.

Description

Returns 0 on success, -ERANGE on overflow and -EINVAL on parsing error. Preferred over *simple_strtoul()*. Return code must be checked.

int **kstrtoint**(const char *s, unsigned int base, int *res)
convert a string to an int

Parameters

const char *s
The start of the string. The string must be null-terminated, and may also include a single newline before its terminating null. The first character may also be a plus sign or a minus sign.

unsigned int base
The number base to use. The maximum supported base is 16. If base is given as 0, then the base of the string is automatically detected with the conventional semantics - If it begins with 0x the number will be parsed as a hexadecimal (case insensitive), if it otherwise begins with 0, it will be parsed as an octal number. Otherwise it will be parsed as a decimal.

int *res
Where to write the result of the conversion on success.

Description

Returns 0 on success, -ERANGE on overflow and -EINVAL on parsing error. Preferred over *simple_strtol()*. Return code must be checked.

int **kstrtobool**(const char *s, bool *res)

convert common user inputs into boolean values

Parameters

const char *s
input string

bool *res
result

Description

This routine returns 0 iff the first character is one of 'Yy1Nn0', or [oO][NnFf] for "on" and "off". Otherwise it will return -EINVAL. Value pointed to by res is updated upon finding a match.

void **string_get_size**(u64 size, u64 blk_size, const enum string_size_units units, char *buf, int len)

get the size in the specified units

Parameters

u64 size
The size to be converted in blocks

u64 blk_size
Size of the block (use 1 for size in bytes)

const enum string_size_units units
units to use (powers of 1000 or 1024)

char *buf
buffer to format to

int len
length of buffer

Description

This function returns a string formatted to 3 significant figures giving the size in the required units. **buf** should have room for at least 9 bytes and will always be zero terminated.

int **string_unescape**(char *src, char *dst, size_t size, unsigned int flags)

unquote characters in the given string

Parameters

char *src
source buffer (escaped)

char *dst
destination buffer (unescaped)

size_t size
size of the destination buffer (0 to unlimit)

unsigned int flags
combination of the flags.

Description

The function unquotes characters in the given string.

Because the size of the output will be the same as or less than the size of the input, the transformation may be performed in place.

Caller must provide valid source and destination pointers. Be aware that destination buffer will always be NULL-terminated. Source string must be NULL-terminated as well. The supported flags are:

```
UNESCAPE_SPACE:
        '\f' - form feed
        '\n' - new line
        '\r' - carriage return
        '\t' - horizontal tab
        '\v' - vertical tab
UNESCAPE_OCTAL:
        '\NNN' - byte with octal value NNN (1 to 3 digits)
UNESCAPE_HEX:
        '\xHH' - byte with hexadecimal value HH (1 to 2 digits)
UNESCAPE_SPECIAL:
        '\"' - double quote
        '\\' - backslash
        '\a' - alert (BEL)
        '\e' - escape
UNESCAPE_ANY:
        all previous together
```

Return

The amount of the characters processed to the destination buffer excluding trailing '0' is returned.

int **string_escape_mem**(const char *src, size_t isz, char *dst, size_t osz, unsigned int flags, const char *only)

quote characters in the given memory buffer

Parameters

const char *src
source buffer (unescaped)

size_t isz
source buffer size

char *dst
destination buffer (escaped)

size_t osz
destination buffer size

unsigned int flags
combination of the flags

const char *only
NULL-terminated string containing characters used to limit the selected escape class. If characters are included in **only** that would not normally be escaped by the classes selected in **flags**, they will be copied to **dst** unescaped.

Description

The process of escaping byte buffer includes several parts. They are applied in the following sequence.

1. The character is matched to the printable class, if asked, and in case of match it passes through to the output.
2. The character is not matched to the one from **only** string and thus must go as-is to the output.
3. The character is checked if it falls into the class given by **flags**. `ESCAPE_OCTAL` and `ESCAPE_HEX` are going last since they cover any character. Note that they actually can't go together, otherwise `ESCAPE_HEX` will be ignored.

Caller must provide valid source and destination pointers. Be aware that destination buffer will not be NULL-terminated, thus caller have to append it if needs. The supported flags are:

```
%ESCAPE_SPACE: (special white space, not space itself)
        '\f' - form feed
        '\n' - new line
        '\r' - carriage return
        '\t' - horizontal tab
        '\v' - vertical tab
%ESCAPE_SPECIAL:
        '\\' - backslash
        '\a' - alert (BEL)
        '\e' - escape
%ESCAPE_NULL:
        '\0' - null
%ESCAPE_OCTAL:
        '\NNN' - byte with octal value NNN (3 digits)
%ESCAPE_ANY:
        all previous together
%ESCAPE_NP:
        escape only non-printable characters (checked by isprint)
%ESCAPE_ANY_NP:
        all previous together
%ESCAPE_HEX:
        '\xHH' - byte with hexadecimal value HH (2 digits)
```

Return

The total size of the escaped output that would be generated for the given input and flags. To check whether the output was truncated, compare the return value to osz. There is room left in dst for a '0' terminator if and only if ret < osz.

void **kfree_strarray**(char **array, size_t n)

free a number of dynamically allocated strings contained in an array and the array itself

Parameters

char **array
Dynamically allocated array of strings to free.

size_t n
Number of strings (starting from the beginning of the array) to free.

Description

Passing a non-NULL **array** and **n** == 0 as well as NULL **array** are valid use-cases. If **array** is NULL, the function does nothing.

String Manipulation

int **strncasecmp**(const char *s1, const char *s2, size_t len)

Case insensitive, length-limited string comparison

Parameters

const char *s1
One string

const char *s2
The other string

size_t len
the maximum number of characters to compare

char ***strcpy**(char *dest, const char *src)

Copy a `NUL` terminated string

Parameters

char *dest
Where to copy the string to

const char *src
Where to copy the string from

char ***strncpy**(char *dest, const char *src, size_t count)

Copy a length-limited, C-string

Parameters

char *dest
Where to copy the string to

const char *src
Where to copy the string from

size_t count
The maximum number of bytes to copy

Description

The result is not `NUL-terminated` if the source exceeds **count** bytes.

In the case where the length of **src** is less than that of count, the remainder of **dest** will be padded with `NUL`.

size_t **strlcpy**(char *dest, const char *src, size_t size)

Copy a C-string into a sized buffer

Parameters

char *dest
Where to copy the string to

const char *src
Where to copy the string from

size_t size
size of destination buffer

Description

Compatible with `*BSD`: the result is always a valid NUL-terminated string that fits in the buffer (unless, of course, the buffer size is zero). It does not pad out the result like *strncpy()* does.

ssize_t **strscpy**(char *dest, const char *src, size_t count)

Copy a C-string into a sized buffer

Parameters

char *dest
Where to copy the string to

const char *src
Where to copy the string from

size_t count
Size of destination buffer

Description

Copy the string, or as much of it as fits, into the dest buffer. The behavior is undefined if the string buffers overlap. The destination buffer is always NUL terminated, unless it's zero-sized.

Preferred to *strlcpy()* since the API doesn't require reading memory from the src string beyond the specified "count" bytes, and since the return value is easier to error-check than *strlcpy()*'s. In addition, the implementation is robust to the string changing out from underneath it, unlike the current *strlcpy()* implementation.

Preferred to *strncpy()* since it always returns a valid string, and doesn't unnecessarily force the tail of the destination buffer to be zeroed. If zeroing is desired please use *strscpy_pad()*.

Return

- The number of characters copied (not including the trailing `NUL`)

- -E2BIG if count is 0 or **src** was truncated.

ssize_t **strscpy_pad**(char *dest, const char *src, size_t count)

Copy a C-string into a sized buffer

Parameters

char *dest
Where to copy the string to

const char *src
Where to copy the string from

size_t count
Size of destination buffer

Description

Copy the string, or as much of it as fits, into the dest buffer. The behavior is undefined if the string buffers overlap. The destination buffer is always `NUL` terminated, unless it's zero-sized.

If the source string is shorter than the destination buffer, zeros the tail of the destination buffer.

For full explanation of why you may want to consider using the 'strscpy' functions please see the function docstring for *strscpy()*.

Return

- The number of characters copied (not including the trailing `NUL`)
- -E2BIG if count is 0 or **src** was truncated.

char ***stpcpy**(char *__restrict__ dest, const char *__restrict__ src)

copy a string from src to dest returning a pointer to the new end of dest, including src's `NUL-terminator`. May overrun dest.

Parameters

char *__restrict__ dest
pointer to end of string being copied into. Must be large enough to receive copy.

const char *__restrict__ src
pointer to the beginning of string being copied from. Must not overlap dest.

Description

stpcpy differs from strcpy in a key way: the return value is a pointer to the new `NUL-terminating` character in **dest**. (For strcpy, the return value is a pointer to the start of **dest**). This interface is considered unsafe as it doesn't perform bounds checking of the inputs. As such it's not recommended for usage. Instead, its definition is provided in case the compiler lowers other libcalls to stpcpy.

char ***strcat**(char *dest, const char *src)

Append one `NUL-terminated` string to another

Parameters

char *dest
The string to be appended to

const char *src
The string to append to it

char ***strncat**(char *dest, const char *src, size_t count)
Append a length-limited, C-string to another

Parameters

char *dest
The string to be appended to

const char *src
The string to append to it

size_t count
The maximum numbers of bytes to copy

Description

Note that in contrast to *strncpy()*, *strncat()* ensures the result is terminated.

size_t **strlcat**(char *dest, const char *src, size_t count)
Append a length-limited, C-string to another

Parameters

char *dest
The string to be appended to

const char *src
The string to append to it

size_t count
The size of the destination buffer.

int **strcmp**(const char *cs, const char *ct)
Compare two strings

Parameters

const char *cs
One string

const char *ct
Another string

int **strncmp**(const char *cs, const char *ct, size_t count)
Compare two length-limited strings

Parameters

const char *cs
One string

const char *ct
Another string

size_t count
The maximum number of bytes to compare

char *`strchr`(const char *s, int c)
Find the first occurrence of a character in a string

Parameters

`const char *s`
The string to be searched

`int c`
The character to search for

Description

Note that the `NUL-terminator` is considered part of the string, and can be searched for.

char *`strchrnul`(const char *s, int c)
Find and return a character in a string, or end of string

Parameters

`const char *s`
The string to be searched

`int c`
The character to search for

Description

Returns pointer to first occurrence of 'c' in s. If c is not found, then return a pointer to the null byte at the end of s.

char *`strrchr`(const char *s, int c)
Find the last occurrence of a character in a string

Parameters

`const char *s`
The string to be searched

`int c`
The character to search for

char *`strnchr`(const char *s, size_t count, int c)
Find a character in a length limited string

Parameters

`const char *s`
The string to be searched

`size_t count`
The number of characters to be searched

`int c`
The character to search for

Description

Note that the `NUL-terminator` is considered part of the string, and can be searched for.

char *`skip_spaces`(const char *str)

Removes leading whitespace from **str**.

Parameters

const char *str
The string to be stripped.

Description

Returns a pointer to the first non-whitespace character in **str**.

char *`strim`(char *s)

Removes leading and trailing whitespace from **s**.

Parameters

char *s
The string to be stripped.

Description

Note that the first trailing whitespace is replaced with a `NUL-terminator` in the given string **s**. Returns a pointer to the first non-whitespace character in **s**.

size_t `strlen`(const char *s)

Find the length of a string

Parameters

const char *s
The string to be sized

size_t `strnlen`(const char *s, size_t count)

Find the length of a length-limited string

Parameters

const char *s
The string to be sized

size_t count
The maximum number of bytes to search

size_t `strspn`(const char *s, const char *accept)

Calculate the length of the initial substring of **s** which only contain letters in **accept**

Parameters

const char *s
The string to be searched

const char *accept
The string to search for

size_t `strcspn`(const char *s, const char *reject)

Calculate the length of the initial substring of **s** which does not contain letters in **reject**

Parameters

const char *s
  The string to be searched

const char *reject
  The string to avoid

char ***strpbrk**(const char *cs, const char *ct)
  Find the first occurrence of a set of characters

Parameters

const char *cs
  The string to be searched

const char *ct
  The characters to search for

char ***strsep**(char **s, const char *ct)
  Split a string into tokens

Parameters

char **s
  The string to be searched

const char *ct
  The characters to search for

Description

strsep() updates **s** to point after the token, ready for the next call.

It returns empty tokens, too, behaving exactly like the libc function of that name. In fact, it was stolen from glibc2 and de-fancy-fied. Same semantics, slimmer shape. ;)

bool **sysfs_streq**(const char *s1, const char *s2)
  return true if strings are equal, modulo trailing newline

Parameters

const char *s1
  one string

const char *s2
  another string

Description

This routine returns true iff two strings are equal, treating both NUL and newline-then-NUL as equivalent string terminations. It's geared for use with sysfs input strings, which generally terminate with newlines but are compared against values without newlines.

int **match_string**(const char *const *array, size_t n, const char *string)
  matches given string in an array

Parameters

const char * const *array
  array of strings

size_t n
: number of strings in the array or -1 for NULL terminated arrays

const char *string
: string to match with

Description

This routine will look for a string in an array of strings up to the n-th element in the array or until the first NULL element.

Historically the value of -1 for **n**, was used to search in arrays that are NULL terminated. However, the function does not make a distinction when finishing the search: either **n** elements have been compared OR the first NULL element was found.

Return

index of a **string** in the **array** if matches, or `-EINVAL` otherwise.

int **__sysfs_match_string**(const char *const *array, size_t n, const char *str)
: matches given string in an array

Parameters

const char * const *array
: array of strings

size_t n
: number of strings in the array or -1 for NULL terminated arrays

const char *str
: string to match with

Description

Returns index of **str** in the **array** or -EINVAL, just like *match_string()*. Uses sysfs_streq instead of strcmp for matching.

This routine will look for a string in an array of strings up to the n-th element in the array or until the first NULL element.

Historically the value of -1 for **n**, was used to search in arrays that are NULL terminated. However, the function does not make a distinction when finishing the search: either **n** elements have been compared OR the first NULL element was found.

void ***memset**(void *s, int c, size_t count)
: Fill a region of memory with the given value

Parameters

void *s
: Pointer to the start of the area.

int c
: The byte to fill the area with

size_t count
: The size of the area.

Description

Do not use *memset()* to access IO space, use memset_io() instead.

void *__memset16__(uint16_t *s, uint16_t v, size_t count)

Fill a memory area with a uint16_t

Parameters

uint16_t *s
Pointer to the start of the area.

uint16_t v
The value to fill the area with

size_t count
The number of values to store

Description

Differs from *memset()* in that it fills with a uint16_t instead of a byte. Remember that **count** is the number of uint16_ts to store, not the number of bytes.

void *__memset32__(uint32_t *s, uint32_t v, size_t count)

Fill a memory area with a uint32_t

Parameters

uint32_t *s
Pointer to the start of the area.

uint32_t v
The value to fill the area with

size_t count
The number of values to store

Description

Differs from *memset()* in that it fills with a uint32_t instead of a byte. Remember that **count** is the number of uint32_ts to store, not the number of bytes.

void *__memset64__(uint64_t *s, uint64_t v, size_t count)

Fill a memory area with a uint64_t

Parameters

uint64_t *s
Pointer to the start of the area.

uint64_t v
The value to fill the area with

size_t count
The number of values to store

Description

Differs from *memset()* in that it fills with a uint64_t instead of a byte. Remember that **count** is the number of uint64_ts to store, not the number of bytes.

void ***memcpy**(void *dest, const void *src, size_t count)

Copy one area of memory to another

Parameters

void *dest
Where to copy to

const void *src
Where to copy from

size_t count
The size of the area.

Description

You should not use this function to access IO space, use memcpy_toio() or memcpy_fromio() instead.

void ***memmove**(void *dest, const void *src, size_t count)

Copy one area of memory to another

Parameters

void *dest
Where to copy to

const void *src
Where to copy from

size_t count
The size of the area.

Description

Unlike *memcpy()*, *memmove()* copes with overlapping areas.

__visible int **memcmp**(const void *cs, const void *ct, size_t count)

Compare two areas of memory

Parameters

const void *cs
One area of memory

const void *ct
Another area of memory

size_t count
The size of the area.

int **bcmp**(const void *a, const void *b, size_t len)

returns 0 if and only if the buffers have identical contents.

Parameters

const void *a
pointer to first buffer.

const void *b
pointer to second buffer.

size_t len
    size of buffers.

Description

The sign or magnitude of a non-zero return value has no particular meaning, and architectures may implement their own more efficient *bcmp()*. So while this particular implementation is a simple (tail) call to memcmp, do not rely on anything but whether the return value is zero or non-zero.

void ***memscan**(void *addr, int c, size_t size)
    Find a character in an area of memory.

Parameters

void *addr
    The memory area

int c
    The byte to search for

size_t size
    The size of the area.

Description

returns the address of the first occurrence of **c**, or 1 byte past the area if **c** is not found

char ***strstr**(const char *s1, const char *s2)
    Find the first substring in a NUL terminated string

Parameters

const char *s1
    The string to be searched

const char *s2
    The string to search for

char ***strnstr**(const char *s1, const char *s2, size_t len)
    Find the first substring in a length-limited string

Parameters

const char *s1
    The string to be searched

const char *s2
    The string to search for

size_t len
    the maximum number of characters to search

void ***memchr**(const void *s, int c, size_t n)
    Find a character in an area of memory.

Parameters

const void *s
    The memory area

int c
The byte to search for

size_t n
The size of the area.

Description

returns the address of the first occurrence of **c**, or `NULL` if **c** is not found

void ***memchr_inv**(const void *start, int c, size_t bytes)
Find an unmatching character in an area of memory.

Parameters

const void *start
The memory area

int c
Find a character other than c

size_t bytes
The size of the area.

Description

returns the address of the first character other than **c**, or `NULL` if the whole buffer contains just **c**.

char ***strreplace**(char *s, char old, char new)
Replace all occurrences of character in string.

Parameters

char *s
The string to operate on.

char old
The character being replaced.

char new
The character **old** is replaced with.

Description

Returns pointer to the nul byte at the end of **s**.

sysfs_match_string

`sysfs_match_string (_a, _s)`

matches given string in an array

Parameters

_a
array of strings

_s
string to match with

Description

Helper for *__sysfs_match_string()*. Calculates the size of **a** automatically.

bool **strstarts**(const char *str, const char *prefix)

does **str** start with **prefix**?

Parameters

const char *str
string to examine

const char *prefix
prefix to look for.

void **memzero_explicit**(void *s, size_t count)

Fill a region of memory (e.g. sensitive keying data) with 0s.

Parameters

void *s
Pointer to the start of the area.

size_t count
The size of the area.

Note

usually using *memset()* is just fine (!), but in cases where clearing out _local_ data at the end of a scope is necessary, *memzero_explicit()* should be used instead in order to prevent the compiler from optimising away zeroing.

Description

memzero_explicit() doesn't need an arch-specific version as it just invokes the one of *memset()* implicitly.

const char ***kbasename**(const char *path)

return the last part of a pathname.

Parameters

const char *path
path to extract the filename from.

void **memcpy_and_pad**(void *dest, size_t dest_len, const void *src, size_t count, int pad)

Copy one buffer to another with padding

Parameters

void *dest
Where to copy to

size_t dest_len
The destination buffer size

const void *src
Where to copy from

size_t count
The number of bytes to copy

int pad
Character to use for padding if space is left in destination.

size_t **str_has_prefix**(const char *str, const char *prefix)
Test if a string has a given prefix

Parameters

const char *str
The string to test

const char *prefix
The string to see if **str** starts with

Description

A common way to test a prefix of a string is to do:
strncmp(str, prefix, sizeof(prefix) - 1)

But this can lead to bugs due to typos, or if prefix is a pointer and not a constant. Instead use *str_has_prefix()*.

Return

- strlen(**prefix**) if **str** starts with **prefix**
- 0 if **str** does not start with **prefix**

char ***kstrdup**(const char *s, gfp_t gfp)
allocate space for and copy an existing string

Parameters

const char *s
the string to duplicate

gfp_t gfp
the GFP mask used in the *kmalloc()* call when allocating memory

Return

newly allocated copy of **s** or `NULL` in case of error

const char ***kstrdup_const**(const char *s, gfp_t gfp)
conditionally duplicate an existing const string

Parameters

const char *s
the string to duplicate

gfp_t gfp
the GFP mask used in the *kmalloc()* call when allocating memory

Note

Strings allocated by kstrdup_const should be freed by kfree_const and must not be passed to *krealloc()*.

Return

source string if it is in .rodata section otherwise fallback to kstrdup.

char ***kstrndup**(const char *s, size_t max, gfp_t gfp)
allocate space for and copy an existing string

Parameters

const char *s
the string to duplicate

size_t max
read at most **max** chars from **s**

gfp_t gfp
the GFP mask used in the *kmalloc()* call when allocating memory

Note

Use *kmemdup_nul()* instead if the size is known exactly.

Return

newly allocated copy of **s** or NULL in case of error

void ***kmemdup**(const void *src, size_t len, gfp_t gfp)
duplicate region of memory

Parameters

const void *src
memory region to duplicate

size_t len
memory region length

gfp_t gfp
GFP mask to use

Return

newly allocated copy of **src** or NULL in case of error

char ***kmemdup_nul**(const char *s, size_t len, gfp_t gfp)
Create a NUL-terminated string from unterminated data

Parameters

const char *s
The data to stringify

size_t len
The size of the data

gfp_t gfp
the GFP mask used in the *kmalloc()* call when allocating memory

Return

newly allocated copy of **s** with NUL-termination or NULL in case of error

void *`memdup_user`(const void __user *src, size_t len)
duplicate memory region from user space

Parameters

const void __user *src
source address in user space

size_t len
number of bytes to copy

Return

an ERR_PTR() on failure. Result is physically contiguous, to be freed by *kfree()*.

void *`vmemdup_user`(const void __user *src, size_t len)
duplicate memory region from user space

Parameters

const void __user *src
source address in user space

size_t len
number of bytes to copy

Return

an ERR_PTR() on failure. Result may be not physically contiguous. Use *kvfree()* to free.

char *`strndup_user`(const char __user *s, long n)
duplicate an existing string from user space

Parameters

const char __user *s
The string to duplicate

long n
Maximum number of bytes to copy, including the trailing NUL.

Return

newly allocated copy of **s** or an ERR_PTR() in case of error

void *`memdup_user_nul`(const void __user *src, size_t len)
duplicate memory region from user space and NUL-terminate

Parameters

const void __user *src
source address in user space

size_t len
number of bytes to copy

Return

an ERR_PTR() on failure.

1.1.3 Basic Kernel Library Functions

The Linux kernel provides more basic utility functions.

Bit Operations

void **set_bit**(long nr, volatile unsigned long *addr)

Atomically set a bit in memory

Parameters

long nr
the bit to set

volatile unsigned long *addr
the address to start counting from

Description

This is a relaxed atomic operation (no implied memory barriers).

Note that **nr** may be almost arbitrarily large; this function is not restricted to acting on a single-word quantity.

void **clear_bit**(long nr, volatile unsigned long *addr)

Clears a bit in memory

Parameters

long nr
Bit to clear

volatile unsigned long *addr
Address to start counting from

Description

This is a relaxed atomic operation (no implied memory barriers).

void **change_bit**(long nr, volatile unsigned long *addr)

Toggle a bit in memory

Parameters

long nr
Bit to change

volatile unsigned long *addr
Address to start counting from

Description

This is a relaxed atomic operation (no implied memory barriers).

Note that **nr** may be almost arbitrarily large; this function is not restricted to acting on a single-word quantity.

bool **test_and_set_bit**(long nr, volatile unsigned long *addr)
Set a bit and return its old value

Parameters

long nr
Bit to set

volatile unsigned long *addr
Address to count from

Description

This is an atomic fully-ordered operation (implied full memory barrier).

bool **test_and_clear_bit**(long nr, volatile unsigned long *addr)
Clear a bit and return its old value

Parameters

long nr
Bit to clear

volatile unsigned long *addr
Address to count from

Description

This is an atomic fully-ordered operation (implied full memory barrier).

bool **test_and_change_bit**(long nr, volatile unsigned long *addr)
Change a bit and return its old value

Parameters

long nr
Bit to change

volatile unsigned long *addr
Address to count from

Description

This is an atomic fully-ordered operation (implied full memory barrier).

void **__set_bit**(long nr, volatile unsigned long *addr)
Set a bit in memory

Parameters

long nr
the bit to set

volatile unsigned long *addr
the address to start counting from

Description

Unlike *set_bit()*, this function is non-atomic. If it is called on the same region of memory concurrently, the effect may be that only one operation succeeds.

void **__clear_bit**(long nr, volatile unsigned long *addr)

Clears a bit in memory

Parameters

long nr
the bit to clear

volatile unsigned long *addr
the address to start counting from

Description

Unlike *clear_bit()*, this function is non-atomic. If it is called on the same region of memory concurrently, the effect may be that only one operation succeeds.

void **__change_bit**(long nr, volatile unsigned long *addr)

Toggle a bit in memory

Parameters

long nr
the bit to change

volatile unsigned long *addr
the address to start counting from

Description

Unlike *change_bit()*, this function is non-atomic. If it is called on the same region of memory concurrently, the effect may be that only one operation succeeds.

bool **__test_and_set_bit**(long nr, volatile unsigned long *addr)

Set a bit and return its old value

Parameters

long nr
Bit to set

volatile unsigned long *addr
Address to count from

Description

This operation is non-atomic. If two instances of this operation race, one can appear to succeed but actually fail.

bool **__test_and_clear_bit**(long nr, volatile unsigned long *addr)

Clear a bit and return its old value

Parameters

long nr
Bit to clear

volatile unsigned long *addr
Address to count from

Description

This operation is non-atomic. If two instances of this operation race, one can appear to succeed but actually fail.

bool **__test_and_change_bit**(long nr, volatile unsigned long *addr)

Change a bit and return its old value

Parameters

long nr
Bit to change

volatile unsigned long *addr
Address to count from

Description

This operation is non-atomic. If two instances of this operation race, one can appear to succeed but actually fail.

bool **test_bit**(long nr, volatile const unsigned long *addr)

Determine whether a bit is set

Parameters

long nr
bit number to test

const volatile unsigned long *addr
Address to start counting from

void **clear_bit_unlock**(long nr, volatile unsigned long *addr)

Clear a bit in memory, for unlock

Parameters

long nr
the bit to set

volatile unsigned long *addr
the address to start counting from

Description

This operation is atomic and provides release barrier semantics.

void **__clear_bit_unlock**(long nr, volatile unsigned long *addr)

Clears a bit in memory

Parameters

long nr
Bit to clear

volatile unsigned long *addr
Address to start counting from

Description

This is a non-atomic operation but implies a release barrier before the memory operation. It can be used for an unlock if no other CPUs can concurrently modify other bits in the word.

bool **test_and_set_bit_lock**(long nr, volatile unsigned long *addr)
Set a bit and return its old value, for lock

Parameters

long nr
Bit to set

volatile unsigned long *addr
Address to count from

Description

This operation is atomic and provides acquire barrier semantics if the returned value is 0. It can be used to implement bit locks.

bool **clear_bit_unlock_is_negative_byte**(long nr, volatile unsigned long *addr)
Clear a bit in memory and test if bottom byte is negative, for unlock.

Parameters

long nr
the bit to clear

volatile unsigned long *addr
the address to start counting from

Description

This operation is atomic and provides release barrier semantics.

This is a bit of a one-trick-pony for the filemap code, which clears PG_locked and tests PG_waiters,

Bitmap Operations

bitmaps provide an array of bits, implemented using an array of unsigned longs. The number of valid bits in a given bitmap does _not_ need to be an exact multiple of BITS_PER_LONG.

The possible unused bits in the last, partially used word of a bitmap are 'don't care'. The implementation makes no particular effort to keep them zero. It ensures that their value will not affect the results of any operation. The bitmap operations that return Boolean (bitmap_empty, for example) or scalar (bitmap_weight, for example) results carefully filter out these unused bits from impacting their results.

The byte ordering of bitmaps is more natural on little endian architectures. See the big-endian headers include/asm-ppc64/bitops.h and include/asm-s390/bitops.h for the best explanations of this ordering.

The DECLARE_BITMAP(name,bits) macro, in linux/types.h, can be used to declare an array named 'name' of just enough unsigned longs to contain all bit positions from 0 to 'bits' - 1.

The available bitmap operations and their rough meaning in the case that the bitmap is a single unsigned long are thus:

The generated code is more efficient when nbits is known at compile-time and at most BITS_PER_LONG.

```
bitmap_zero(dst, nbits)                     *dst = 0UL
bitmap_fill(dst, nbits)                     *dst = ~0UL
bitmap_copy(dst, src, nbits)                *dst = *src
bitmap_and(dst, src1, src2, nbits)          *dst = *src1 & *src2
bitmap_or(dst, src1, src2, nbits)           *dst = *src1 | *src2
bitmap_xor(dst, src1, src2, nbits)          *dst = *src1 ^ *src2
bitmap_andnot(dst, src1, src2, nbits)       *dst = *src1 & ~(*src2)
bitmap_complement(dst, src, nbits)          *dst = ~(*src)
bitmap_equal(src1, src2, nbits)             Are *src1 and *src2␣
↪equal?
bitmap_intersects(src1, src2, nbits)        Do *src1 and *src2␣
↪overlap?
bitmap_subset(src1, src2, nbits)            Is *src1 a subset of␣
↪*src2?
bitmap_empty(src, nbits)                    Are all bits zero in␣
↪*src?
bitmap_full(src, nbits)                     Are all bits set in␣
↪*src?
bitmap_weight(src, nbits)                   Hamming Weight: number␣
↪set bits
bitmap_set(dst, pos, nbits)                 Set specified bit area
bitmap_clear(dst, pos, nbits)               Clear specified bit area
bitmap_find_next_zero_area(buf, len, pos, n, mask)  Find bit free␣
↪area
bitmap_find_next_zero_area_off(buf, len, pos, n, mask, mask_off) ␣
↪as above
bitmap_next_clear_region(map, :c:type:`start`, :c:type:`end`,␣
↪nbits)  Find next clear region
bitmap_next_set_region(map, :c:type:`start`, :c:type:`end`, nbits) ␣
↪Find next set region
bitmap_for_each_clear_region(map, rs, re, start, end)
                                            Iterate over all clear␣
↪regions
bitmap_for_each_set_region(map, rs, re, start, end)
                                            Iterate over all set␣
↪regions
bitmap_shift_right(dst, src, n, nbits)      *dst = *src >> n
bitmap_shift_left(dst, src, n, nbits)       *dst = *src << n
bitmap_cut(dst, src, first, n, nbits)       Cut n bits from first,␣
↪copy rest
bitmap_replace(dst, old, new, mask, nbits)  *dst = (*old & ~
↪(*mask)) | (*new & *mask)
bitmap_remap(dst, src, old, new, nbits)     *dst = map(old,␣
↪new)(src)
bitmap_bitremap(oldbit, old, new, nbits)    newbit = map(old,␣
↪new)(oldbit)
bitmap_onto(dst, orig, relmap, nbits)       *dst = orig relative to␣
↪relmap
```

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```
bitmap_fold(dst, orig, sz, nbits)           dst bits = orig bits␣
↪mod sz
bitmap_parse(buf, buflen, dst, nbits)       Parse bitmap dst from␣
↪kernel buf
bitmap_parse_user(ubuf, ulen, dst, nbits)   Parse bitmap dst from␣
↪user buf
bitmap_parselist(buf, dst, nbits)           Parse bitmap dst from␣
↪kernel buf
bitmap_parselist_user(buf, dst, nbits)      Parse bitmap dst from␣
↪user buf
bitmap_find_free_region(bitmap, bits, order)  Find and allocate bit␣
↪region
bitmap_release_region(bitmap, pos, order)   Free specified bit␣
↪region
bitmap_allocate_region(bitmap, pos, order)  Allocate specified bit␣
↪region
bitmap_from_arr32(dst, buf, nbits)          Copy nbits from u32[]␣
↪buf to dst
bitmap_to_arr32(buf, src, nbits)            Copy nbits from buf to␣
↪u32[] dst
bitmap_get_value8(map, start)               Get 8bit value from map␣
↪at start
bitmap_set_value8(map, value, start)        Set 8bit value to map␣
↪at start
```

Note, bitmap_zero() and bitmap_fill() operate over the region of unsigned longs, that is, bits behind bitmap till the unsigned long boundary will be zeroed or filled as well. Consider to use bitmap_clear() or bitmap_set() to make explicit zeroing or filling respectively.

Also the following operations in asm/bitops.h apply to bitmaps.:

```
set_bit(bit, addr)                  *addr |= bit
clear_bit(bit, addr)                *addr &= ~bit
change_bit(bit, addr)               *addr ^= bit
test_bit(bit, addr)                 Is bit set in *addr?
test_and_set_bit(bit, addr)         Set bit and return old value
test_and_clear_bit(bit, addr)       Clear bit and return old value
test_and_change_bit(bit, addr)      Change bit and return old value
find_first_zero_bit(addr, nbits)    Position first zero bit in *addr
find_first_bit(addr, nbits)         Position first set bit in *addr
find_next_zero_bit(addr, nbits, bit)
                                    Position next zero bit in *addr␣
↪>= bit
find_next_bit(addr, nbits, bit)     Position next set bit in *addr >
↪= bit
find_next_and_bit(addr1, addr2, nbits, bit)
                                    Same as find_next_bit, but in
                                    (*addr1 & *addr2)
```

void **__bitmap_shift_right**(unsigned long *dst, const unsigned long *src, unsigned shift, unsigned nbits)

logical right shift of the bits in a bitmap

Parameters

unsigned long *dst
destination bitmap

const unsigned long *src
source bitmap

unsigned shift
shift by this many bits

unsigned nbits
bitmap size, in bits

Description

Shifting right (dividing) means moving bits in the MS -> LS bit direction. Zeros are fed into the vacated MS positions and the LS bits shifted off the bottom are lost.

void **__bitmap_shift_left**(unsigned long *dst, const unsigned long *src, unsigned int shift, unsigned int nbits)

logical left shift of the bits in a bitmap

Parameters

unsigned long *dst
destination bitmap

const unsigned long *src
source bitmap

unsigned int shift
shift by this many bits

unsigned int nbits
bitmap size, in bits

Description

Shifting left (multiplying) means moving bits in the LS -> MS direction. Zeros are fed into the vacated LS bit positions and those MS bits shifted off the top are lost.

void **bitmap_cut**(unsigned long *dst, const unsigned long *src, unsigned int first, unsigned int cut, unsigned int nbits)

remove bit region from bitmap and right shift remaining bits

Parameters

unsigned long *dst
destination bitmap, might overlap with src

const unsigned long *src
source bitmap

unsigned int first
start bit of region to be removed

unsigned int cut
number of bits to remove

unsigned int nbits
bitmap size, in bits

Description

Set the n-th bit of **dst** iff the n-th bit of **src** is set and n is less than **first**, or the m-th bit of **src** is set for any m such that **first** <= n < nbits, and m = n + **cut**.

In pictures, example for a big-endian 32-bit architecture:

The **src** bitmap is:

```
31                                 63
|                                  |
10000000 11000001 11110010 00010101  10000000 11000001 01110010␣
↪00010101
                |  |              |                                   ␣
↪    |
               16  14             0                                   ␣
↪   32
```

if **cut** is 3, and **first** is 14, bits 14-16 in **src** are cut and **dst** is:

```
31                                 63
|                                  |
10110000 00011000 00110010 00010101  00010000 00011000 00101110␣
↪01000010
                   |              |                                   ␣
↪    |
                   14 (bit 17     0                                   ␣
↪   32
                       from @src)
```

Note that **dst** and **src** might overlap partially or entirely.

This is implemented in the obvious way, with a shift and carry step for each moved bit. Optimisation is left as an exercise for the compiler.

unsigned long **bitmap_find_next_zero_area_off**(unsigned long *map, unsigned long size, unsigned long start, unsigned int nr, unsigned long align_mask, unsigned long align_offset)

find a contiguous aligned zero area

Parameters

unsigned long *map
The address to base the search on

unsigned long size
The bitmap size in bits

unsigned long start
The bitnumber to start searching at

unsigned int nr
The number of zeroed bits we' re looking for

unsigned long align_mask
Alignment mask for zero area

unsigned long align_offset
Alignment offset for zero area.

Description

The **align_mask** should be one less than a power of 2; the effect is that the bit offset of all zero areas this function finds plus **align_offset** is multiple of that power of 2.

int **bitmap_parse_user**(const char __user *ubuf, unsigned int ulen, unsigned long *maskp, int nmaskbits)

convert an ASCII hex string in a user buffer into a bitmap

Parameters

const char __user *ubuf
pointer to user buffer containing string.

unsigned int ulen
buffer size in bytes. If string is smaller than this then it must be terminated with a 0.

unsigned long *maskp
pointer to bitmap array that will contain result.

int nmaskbits
size of bitmap, in bits.

int **bitmap_print_to_pagebuf**(bool list, char *buf, const unsigned long *maskp, int nmaskbits)

convert bitmap to list or hex format ASCII string

Parameters

bool list
indicates whether the bitmap must be list

char *buf
page aligned buffer into which string is placed

const unsigned long *maskp
pointer to bitmap to convert

int nmaskbits
size of bitmap, in bits

Description

Output format is a comma-separated list of decimal numbers and ranges if list is specified or hex digits grouped into comma-separated sets of 8 digits/set. Returns the number of characters written to buf.

It is assumed that **buf** is a pointer into a PAGE_SIZE, page-aligned area and that sufficient storage remains at **buf** to accommodate the *bitmap_print_to_pagebuf()* output. Returns the number of characters actually printed to **buf**, excluding terminating '0'.

int **bitmap_parselist**(const char *buf, unsigned long *maskp, int nmaskbits)

convert list format ASCII string to bitmap

Parameters

const char *buf
read user string from this buffer; must be terminated with a 0 or n.

unsigned long *maskp
write resulting mask here

int nmaskbits
number of bits in mask to be written

Description

Input format is a comma-separated list of decimal numbers and ranges. Consecutively set bits are shown as two hyphen-separated decimal numbers, the smallest and largest bit numbers set in the range. Optionally each range can be postfixed to denote that only parts of it should be set. The range will divided to groups of specific size. From each group will be used only defined amount of bits. Syntax: range:used_size/group_size

Example

0-1023:2/256 ==> 0,1,256,257,512,513,768,769

Return

0 on success, -errno on invalid input strings. Error values:

- `-EINVAL`: wrong region format
- `-EINVAL`: invalid character in string
- `-ERANGE`: bit number specified too large for mask
- `-EOVERFLOW`: integer overflow in the input parameters

int **bitmap_parselist_user**(const char __user *ubuf, unsigned int ulen, unsigned long *maskp, int nmaskbits)

Parameters

const char __user *ubuf
pointer to user buffer containing string.

unsigned int ulen
buffer size in bytes. If string is smaller than this then it must be terminated with a 0.

`unsigned long *maskp`
pointer to bitmap array that will contain result.

`int nmaskbits`
size of bitmap, in bits.

Description

Wrapper for *`bitmap_parselist()`*, providing it with user buffer.

int **`bitmap_parse`**(const char *start, unsigned int buflen, unsigned long *maskp, int nmaskbits)

convert an ASCII hex string into a bitmap.

Parameters

`const char *start`
pointer to buffer containing string.

`unsigned int buflen`
buffer size in bytes. If string is smaller than this then it must be terminated with a 0 or n. In that case, UINT_MAX may be provided instead of string length.

`unsigned long *maskp`
pointer to bitmap array that will contain result.

`int nmaskbits`
size of bitmap, in bits.

Description

Commas group hex digits into chunks. Each chunk defines exactly 32 bits of the resultant bitmask. No chunk may specify a value larger than 32 bits (`-EOVERFLOW`), and if a chunk specifies a smaller value then leading 0-bits are prepended. `-EINVAL` is returned for illegal characters. Grouping such as “1„5” , “,44” , “,” or “” is allowed. Leading, embedded and trailing whitespace accepted.

int **`bitmap_find_free_region`**(unsigned long *bitmap, unsigned int bits, int order)

find a contiguous aligned mem region

Parameters

`unsigned long *bitmap`
array of unsigned longs corresponding to the bitmap

`unsigned int bits`
number of bits in the bitmap

`int order`
region size (log base 2 of number of bits) to find

Description

Find a region of free (zero) bits in a **bitmap** of **bits** bits and allocate them (set them to one). Only consider regions of length a power (**order**) of two, aligned to that power of two, which makes the search algorithm much faster.

Return the bit offset in bitmap of the allocated region, or -errno on failure.

void **bitmap_release_region**(unsigned long *bitmap, unsigned int pos, int order)

release allocated bitmap region

Parameters

unsigned long *bitmap
array of unsigned longs corresponding to the bitmap

unsigned int pos
beginning of bit region to release

int order
region size (log base 2 of number of bits) to release

Description

This is the complement to __bitmap_find_free_region() and releases the found region (by clearing it in the bitmap).

No return value.

int **bitmap_allocate_region**(unsigned long *bitmap, unsigned int pos, int order)

allocate bitmap region

Parameters

unsigned long *bitmap
array of unsigned longs corresponding to the bitmap

unsigned int pos
beginning of bit region to allocate

int order
region size (log base 2 of number of bits) to allocate

Description

Allocate (set bits in) a specified region of a bitmap.

Return 0 on success, or `-EBUSY` if specified region wasn't free (not all bits were zero).

void **bitmap_copy_le**(unsigned long *dst, const unsigned long *src, unsigned int nbits)

copy a bitmap, putting the bits into little-endian order.

Parameters

unsigned long *dst
destination buffer

const unsigned long *src
bitmap to copy

unsigned int nbits
number of bits in the bitmap

Description

Require nbits % BITS_PER_LONG == 0.

void **bitmap_from_arr32**(unsigned long *bitmap, const u32 *buf, unsigned int nbits)

copy the contents of u32 array of bits to bitmap

Parameters

unsigned long *bitmap
array of unsigned longs, the destination bitmap

const u32 *buf
array of u32 (in host byte order), the source bitmap

unsigned int nbits
number of bits in **bitmap**

void **bitmap_to_arr32**(u32 *buf, const unsigned long *bitmap, unsigned int nbits)

copy the contents of bitmap to a u32 array of bits

Parameters

u32 *buf
array of u32 (in host byte order), the dest bitmap

const unsigned long *bitmap
array of unsigned longs, the source bitmap

unsigned int nbits
number of bits in **bitmap**

int **bitmap_pos_to_ord**(const unsigned long *buf, unsigned int pos, unsigned int nbits)

find ordinal of set bit at given position in bitmap

Parameters

const unsigned long *buf
pointer to a bitmap

unsigned int pos
a bit position in **buf** (0 <= **pos** < **nbits**)

unsigned int nbits
number of valid bit positions in **buf**

Description

Map the bit at position **pos** in **buf** (of length **nbits**) to the ordinal of which set bit it is. If it is not set or if **pos** is not a valid bit position, map to -1.

If for example, just bits 4 through 7 are set in **buf**, then **pos** values 4 through 7 will get mapped to 0 through 3, respectively, and other **pos** values will get mapped to -1. When **pos** value 7 gets mapped to (returns) **ord** value 3 in this example, that means that bit 7 is the 3rd (starting with 0th) set bit in **buf**.

The bit positions 0 through **bits** are valid positions in **buf**.

unsigned int **bitmap_ord_to_pos**(const unsigned long *buf, unsigned int ord, unsigned int nbits)

find position of n-th set bit in bitmap

Parameters

const unsigned long *buf
pointer to bitmap

unsigned int ord
ordinal bit position (n-th set bit, n >= 0)

unsigned int nbits
number of valid bit positions in **buf**

Description

Map the ordinal offset of bit **ord** in **buf** to its position in **buf**. Value of **ord** should be in range 0 <= **ord** < weight(buf). If **ord** >= weight(buf), returns **nbits**.

If for example, just bits 4 through 7 are set in **buf**, then **ord** values 0 through 3 will get mapped to 4 through 7, respectively, and all other **ord** values returns **nbits**. When **ord** value 3 gets mapped to (returns) **pos** value 7 in this example, that means that the 3rd set bit (starting with 0th) is at position 7 in **buf**.

The bit positions 0 through **nbits**-1 are valid positions in **buf**.

void **bitmap_remap**(unsigned long *dst, const unsigned long *src, const unsigned long *old, const unsigned long *new, unsigned int nbits)

Apply map defined by a pair of bitmaps to another bitmap

Parameters

unsigned long *dst
remapped result

const unsigned long *src
subset to be remapped

const unsigned long *old
defines domain of map

const unsigned long *new
defines range of map

unsigned int nbits
number of bits in each of these bitmaps

Description

Let **old** and **new** define a mapping of bit positions, such that whatever position is held by the n-th set bit in **old** is mapped to the n-th set bit in **new**. In the more general case, allowing for the possibility that the weight 'w' of **new** is less than the weight of **old**, map the position of the n-th set bit in **old** to the position of the m-th set bit in **new**, where m == n % w.

If either of the **old** and **new** bitmaps are empty, or if **src** and **dst** point to the same location, then this routine copies **src** to **dst**.

The positions of unset bits in **old** are mapped to themselves (the identify map).

Apply the above specified mapping to **src**, placing the result in **dst**, clearing any bits previously set in **dst**.

For example, lets say that **old** has bits 4 through 7 set, and **new** has bits 12 through 15 set. This defines the mapping of bit position 4 to 12, 5 to 13, 6 to 14 and 7 to 15, and of all other bit positions unchanged. So if say **src** comes into this routine with bits 1, 5 and 7 set, then **dst** should leave with bits 1, 13 and 15 set.

int **bitmap_bitremap**(int oldbit, const unsigned long *old, const unsigned long *new, int bits)

Apply map defined by a pair of bitmaps to a single bit

Parameters

int oldbit
bit position to be mapped

const unsigned long *old
defines domain of map

const unsigned long *new
defines range of map

int bits
number of bits in each of these bitmaps

Description

Let **old** and **new** define a mapping of bit positions, such that whatever position is held by the n-th set bit in **old** is mapped to the n-th set bit in **new**. In the more general case, allowing for the possibility that the weight 'w' of **new** is less than the weight of **old**, map the position of the n-th set bit in **old** to the position of the m-th set bit in **new**, where m == n % w.

The positions of unset bits in **old** are mapped to themselves (the identify map).

Apply the above specified mapping to bit position **oldbit**, returning the new bit position.

For example, lets say that **old** has bits 4 through 7 set, and **new** has bits 12 through 15 set. This defines the mapping of bit position 4 to 12, 5 to 13, 6 to 14 and 7 to 15, and of all other bit positions unchanged. So if say **oldbit** is 5, then this routine returns 13.

void **bitmap_onto**(unsigned long *dst, const unsigned long *orig, const unsigned long *relmap, unsigned int bits)

translate one bitmap relative to another

Parameters

unsigned long *dst
resulting translated bitmap

const unsigned long *orig
original untranslated bitmap

const unsigned long *relmap
bitmap relative to which translated

unsigned int bits
number of bits in each of these bitmaps

Description

Set the n-th bit of **dst** iff there exists some m such that the n-th bit of **relmap** is set, the m-th bit of **orig** is set, and the n-th bit of **relmap** is also the m-th _set_ bit of **relmap**. (If you understood the previous sentence the first time your read it, you’ re overqualified for your current job.)

In other words, **orig** is mapped onto (surjectively) **dst**, using the map { <n, m> | the n-th bit of **relmap** is the m-th set bit of **relmap** }.

Any set bits in **orig** above bit number W, where W is the weight of (number of set bits in) **relmap** are mapped nowhere. In particular, if for all bits m set in **orig**, m >= W, then **dst** will end up empty. In situations where the possibility of such an empty result is not desired, one way to avoid it is to use the *bitmap_fold()* operator, below, to first fold the **orig** bitmap over itself so that all its set bits x are in the range 0 <= x < W. The *bitmap_fold()* operator does this by setting the bit (m % W) in **dst**, for each bit (m) set in **orig**.

Example [1] for bitmap_onto():

Let’ s say **relmap** has bits 30-39 set, and **orig** has bits 1, 3, 5, 7, 9 and 11 set. Then on return from this routine, **dst** will have bits 31, 33, 35, 37 and 39 set.

When bit 0 is set in **orig**, it means turn on the bit in **dst** corresponding to whatever is the first bit (if any) that is turned on in **relmap**. Since bit 0 was off in the above example, we leave off that bit (bit 30) in **dst**.

When bit 1 is set in **orig** (as in the above example), it means turn on the bit in **dst** corresponding to whatever is the second bit that is turned on in **relmap**. The second bit in **relmap** that was turned on in the above example was bit 31, so we turned on bit 31 in **dst**.

Similarly, we turned on bits 33, 35, 37 and 39 in **dst**, because they were the 4th, 6th, 8th and 10th set bits set in **relmap**, and the 4th, 6th, 8th and 10th bits of **orig** (i.e. bits 3, 5, 7 and 9) were also set.

When bit 11 is set in **orig**, it means turn on the bit in **dst** corresponding to whatever is the twelfth bit that is turned on in **relmap**. In the above example, there were only ten bits turned on in **relmap** (30..39), so that bit 11 was set in **orig** had no affect on **dst**.

Example [2] for bitmap_fold() + bitmap_onto():

Let’ s say **relmap** has these ten bits set:

```
40 41 42 43 45 48 53 61 74 95
```

(for the curious, that’ s 40 plus the first ten terms of the Fibonacci sequence.)

Further lets say we use the following code, invoking *bitmap_fold()* then bitmap_onto, as suggested above to avoid the possibility of an empty **dst** result:

```
unsigned long *tmp;     // a temporary bitmap's bits

bitmap_fold(tmp, orig, bitmap_weight(relmap, bits), bits);
bitmap_onto(dst, tmp, relmap, bits);
```

Then this table shows what various values of **dst** would be, for various **orig**' s. I list the zero-based positions of each set bit. The tmp column shows the intermediate result, as computed by using *bitmap_fold()* to fold the **orig** bitmap modulo ten (the weight of **relmap**):

orig	tmp	**dst**
0	0	40
1	1	41
9	9	95
10	0	40[1]
1 3 5 7	1 3 5 7	41 43 48 61
0 1 2 3 4	0 1 2 3 4	40 41 42 43 45
0 9 18 27	0 9 8 7	40 61 74 95
0 10 20 30	0	40
0 11 22 33	0 1 2 3	40 41 42 43
0 12 24 36	0 2 4 6	40 42 45 53
78 102 211	1 2 8	41 42 74[1]

If either of **orig** or **relmap** is empty (no set bits), then **dst** will be returned empty.

If (as explained above) the only set bits in **orig** are in positions m where m >= W, (where W is the weight of **relmap**) then **dst** will once again be returned empty.

All bits in **dst** not set by the above rule are cleared.

void **bitmap_fold**(unsigned long *dst, const unsigned long *orig, unsigned int sz, unsigned int nbits)

fold larger bitmap into smaller, modulo specified size

Parameters

unsigned long *dst
resulting smaller bitmap

const unsigned long *orig
original larger bitmap

unsigned int sz
specified size

unsigned int nbits
number of bits in each of these bitmaps

Description

For each bit oldbit in **orig**, set bit oldbit mod **sz** in **dst**. Clear all other bits in **dst**. See further the comment and Example [2] for *bitmap_onto()* for why and how to use this.

unsigned long **bitmap_find_next_zero_area**(unsigned long *map, unsigned long size, unsigned long start, unsigned int nr, unsigned long align_mask)

[1] For these marked lines, if we hadn' t first done *bitmap_fold()* into tmp, then the **dst** result would have been empty.

find a contiguous aligned zero area

Parameters

`unsigned long *map`
The address to base the search on

`unsigned long size`
The bitmap size in bits

`unsigned long start`
The bitnumber to start searching at

`unsigned int nr`
The number of zeroed bits we' re looking for

`unsigned long align_mask`
Alignment mask for zero area

Description

The **align_mask** should be one less than a power of 2; the effect is that the bit offset of all zero areas this function finds is multiples of that power of 2. A **align_mask** of 0 means no alignment is required.

bool **`bitmap_or_equal`**(const unsigned long *src1, const unsigned long *src2, const unsigned long *src3, unsigned int nbits)

Check whether the or of two bitmaps is equal to a third

Parameters

`const unsigned long *src1`
Pointer to bitmap 1

`const unsigned long *src2`
Pointer to bitmap 2 will be or' ed with bitmap 1

`const unsigned long *src3`
Pointer to bitmap 3. Compare to the result of ***src1** | ***src2**

`unsigned int nbits`
number of bits in each of these bitmaps

Return

True if (***src1** | ***src2**) == ***src3**, false otherwise

`BITMAP_FROM_U64`

`BITMAP_FROM_U64 (n)`

Represent u64 value in the format suitable for bitmap.

Parameters

`n`
u64 value

Description

Linux bitmaps are internally arrays of unsigned longs, i.e. 32-bit integers in 32-bit environment, and 64-bit integers in 64-bit one.

There are four combinations of endianness and length of the word in linux ABIs: LE64, BE64, LE32 and BE32.

On 64-bit kernels 64-bit LE and BE numbers are naturally ordered in bitmaps and therefore don't require any special handling.

On 32-bit kernels 32-bit LE ABI orders lo word of 64-bit number in memory prior to hi, and 32-bit BE orders hi word prior to lo. The bitmap on the other hand is represented as an array of 32-bit words and the position of bit N may therefore be calculated as: word #(N/32) and bit #(N``32``) in that word. For example, bit #42 is located at 10th position of 2nd word. It matches 32-bit LE ABI, and we can simply let the compiler store 64-bit values in memory as it usually does. But for BE we need to swap hi and lo words manually.

With all that, the macro *BITMAP_FROM_U64()* does explicit reordering of hi and lo parts of u64. For LE32 it does nothing, and for BE environment it swaps hi and lo words, as is expected by bitmap.

void **bitmap_from_u64**(unsigned long *dst, u64 mask)

Check and swap words within u64.

Parameters

unsigned long *dst
destination bitmap

u64 mask
source bitmap

Description

In 32-bit Big Endian kernel, when using `(u32 *)(:c:type:`val`)[*]` to read u64 mask, we will get the wrong word. That is `(u32 *)(:c:type:`val`)[0]` gets the upper 32 bits, but we expect the lower 32-bits of u64.

unsigned long **bitmap_get_value8**(const unsigned long *map, unsigned long start)

get an 8-bit value within a memory region

Parameters

const unsigned long *map
address to the bitmap memory region

unsigned long start
bit offset of the 8-bit value; must be a multiple of 8

Description

Returns the 8-bit value located at the **start** bit offset within the **src** memory region.

void **bitmap_set_value8**(unsigned long *map, unsigned long value, unsigned long start)

set an 8-bit value within a memory region

Parameters

unsigned long *map
address to the bitmap memory region

unsigned long value
the 8-bit value; values wider than 8 bits may clobber bitmap

unsigned long start
bit offset of the 8-bit value; must be a multiple of 8

Command-line Parsing

int **get_option**(char **str, int *pint)
Parse integer from an option string

Parameters

char **str
option string

int *pint
(output) integer value parsed from **str**

Read an int from an option string; if available accept a subsequent comma as well.

Return values: 0 - no int in string 1 - int found, no subsequent comma 2 - int found including a subsequent comma 3 - hyphen found to denote a range

char ***get_options**(const char *str, int nints, int *ints)
Parse a string into a list of integers

Parameters

const char *str
String to be parsed

int nints
size of integer array

int *ints
integer array

This function parses a string containing a comma-separated list of integers, a hyphen-separated range of _positive_ integers, or a combination of both. The parse halts when the array is full, or when no more numbers can be retrieved from the string.

Return value is the character in the string which caused the parse to end (typically a null terminator, if **str** is completely parseable).

unsigned long long **memparse**(const char *ptr, char **retptr)
parse a string with mem suffixes into a number

Parameters

const char *ptr
Where parse begins

char **retptr
(output) Optional pointer to next char after parse completes

Parses a string into a number. The number stored at **ptr** is potentially suffixed with K, M, G, T, P, E.

Sorting

void **sort_r**(void *base, size_t num, size_t size, cmp_r_func_t cmp_func, swap_func_t swap_func, const void *priv)

sort an array of elements

Parameters

void *base
pointer to data to sort

size_t num
number of elements

size_t size
size of each element

cmp_r_func_t cmp_func
pointer to comparison function

swap_func_t swap_func
pointer to swap function or NULL

const void *priv
third argument passed to comparison function

Description

This function does a heapsort on the given array. You may provide a swap_func function if you need to do something more than a memory copy (e.g. fix up pointers or auxiliary data), but the built-in swap avoids a slow retpoline and so is significantly faster.

Sorting time is O(n log n) both on average and worst-case. While quicksort is slightly faster on average, it suffers from exploitable O(n*n) worst-case behavior and extra memory requirements that make it less suitable for kernel use.

void **list_sort**(void *priv, struct list_head *head, list_cmp_func_t cmp)

sort a list

Parameters

void *priv
private data, opaque to *list_sort()*, passed to **cmp**

struct list_head *head
the list to sort

list_cmp_func_t cmp
the elements comparison function

Description

The comparison funtion **cmp** must return > 0 if **a** should sort after **b** (" **a** > **b**" if you want an ascending sort), and <= 0 if **a** should sort before **b** *or* their original order should be preserved. It is always called with the element that came first in the input in **a**, and list_sort is a stable sort, so it is not necessary to distinguish the **a** < **b** and **a** == **b** cases.

This is compatible with two styles of **cmp** function: - The traditional style which returns <0 / =0 / >0, or - Returning a boolean 0/1. The latter offers a chance to save a few cycles in the comparison (which is used by e.g. plug_ctx_cmp() in block/blk-mq.c).

A good way to write a multi-word comparison is:

```
if (a->high != b->high)
        return a->high > b->high;
if (a->middle != b->middle)
        return a->middle > b->middle;
return a->low > b->low;
```

This mergesort is as eager as possible while always performing at least 2:1 balanced merges. Given two pending sublists of size 2^k, they are merged to a size-2^(k+1) list as soon as we have 2^k following elements.

Thus, it will avoid cache thrashing as long as 3*2^k elements can fit into the cache. Not quite as good as a fully-eager bottom-up mergesort, but it does use 0.2*n fewer comparisons, so is faster in the common case that everything fits into L1.

The merging is controlled by "count", the number of elements in the pending lists. This is beautiully simple code, but rather subtle.

Each time we increment "count", we set one bit (bit k) and clear bits k-1 .. 0. Each time this happens (except the very first time for each bit, when count increments to 2^k), we merge two lists of size 2^k into one list of size 2^(k+1).

This merge happens exactly when the count reaches an odd multiple of 2^k, which is when we have 2^k elements pending in smaller lists, so it's safe to merge away two lists of size 2^k.

After this happens twice, we have created two lists of size 2^(k+1), which will be merged into a list of size 2^(k+2) before we create a third list of size 2^(k+1), so there are never more than two pending.

The number of pending lists of size 2^k is determined by the state of bit k of "count" plus two extra pieces of information:

- The state of bit k-1 (when k == 0, consider bit -1 always set), and
- Whether the higher-order bits are zero or non-zero (i.e. is count >= 2^(k+1)).

There are six states we distinguish. "x" represents some arbitrary bits, and "y" represents some arbitrary non-zero bits: 0: 00x: 0 pending of size 2^k; x pending of sizes < 2^k 1: 01x: 0 pending of size 2^k; 2^(k-1) + x pending of sizes < 2^k 2: x10x: 0 pending of size 2^k; 2^k + x pending of sizes < 2^k 3: x11x: 1 pending of size 2^k; 2^(k-1) + x pending of sizes < 2^k 4: y00x: 1 pending of size 2^k; 2^k

+ x pending of sizes < 2^k 5: y01x: 2 pending of size 2^k; 2^(k-1) + x pending of sizes < 2^k (merge and loop back to state 2)

We gain lists of size 2^k in the 2->3 and 4->5 transitions (because bit k-1 is set while the more significant bits are non-zero) and merge them away in the 5->2 transition. Note in particular that just before the 5->2 transition, all lower-order bits are 11 (state 3), so there is one list of each smaller size.

When we reach the end of the input, we merge all the pending lists, from smallest to largest. If you work through cases 2 to 5 above, you can see that the number of elements we merge with a list of size 2^k varies from 2^(k-1) (cases 3 and 5 when x == 0) to 2^(k+1) - 1 (second merge of case 5 when x == 2^(k-1) - 1).

Text Searching

INTRODUCTION

> The textsearch infrastructure provides text searching facilities for both linear and non-linear data. Individual search algorithms are implemented in modules and chosen by the user.

ARCHITECTURE

```
  User
  +----------------+
  |        finish()|<--------------(6)-----------------+
  |get_next_block()|<--------------(5)---------------+ |
  |                |                     Algorithm   | |
  |                |                    +---------------------------
↪---+
  |                |                    |  init()    find()   ␣
↪destroy() |
  |                |                    +---------------------------
↪---+
  |                |       Core API          ^       ^          ^
  |                |      +---------------+  (2)     (4)        (8)
  |             (1)|----->| prepare()     |---+       |          |
  |             (3)|----->| find()/next() |-----------+          |
  |             (7)|----->| destroy()     |----------------------+
  +----------------+      +---------------+

(1) User configures a search by calling textsearch_prepare()␣
↪specifying
    the search parameters such as the pattern and algorithm name.
(2) Core requests the algorithm to allocate and initialize a search
    configuration according to the specified parameters.
(3) User starts the search(es) by calling textsearch_find() or
    textsearch_next() to fetch subsequent occurrences. A state␣
↪variable
    is provided to the algorithm to store persistent variables.
(4) Core eventually resets the search offset and forwards the find()
    request to the algorithm.
```

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```
(5) Algorithm calls get_next_block() provided by the user␣
↪continuously
    to fetch the data to be searched in block by block.
(6) Algorithm invokes finish() after the last call to get_next_block
    to clean up any leftovers from get_next_block. (Optional)
(7) User destroys the configuration by calling textsearch_destroy().
(8) Core notifies the algorithm to destroy algorithm specific
    allocations. (Optional)
```

USAGE

Before a search can be performed, a configuration must be created by calling *textsearch_prepare()* specifying the searching algorithm, the pattern to look for and flags. As a flag, you can set TS_IGNORECASE to perform case insensitive matching. But it might slow down performance of algorithm, so you should use it at own your risk. The returned configuration may then be used for an arbitrary amount of times and even in parallel as long as a separate struct ts_state variable is provided to every instance.

The actual search is performed by either calling *textsearch_find_continuous()* for linear data or by providing an own get_next_block() implementation and calling *textsearch_find()*. Both functions return the position of the first occurrence of the pattern or UINT_MAX if no match was found. Subsequent occurrences can be found by calling *textsearch_next()* regardless of the linearity of the data.

Once you' re done using a configuration it must be given back via textsearch_destroy.

EXAMPLE:

```
int pos;
struct ts_config *conf;
struct ts_state state;
const char *pattern = "chicken";
const char *example = "We dance the funky chicken";

conf = textsearch_prepare("kmp", pattern, strlen(pattern),
                          GFP_KERNEL, TS_AUTOLOAD);
if (IS_ERR(conf)) {
    err = PTR_ERR(conf);
    goto errout;
}

pos = textsearch_find_continuous(conf, &state, example,␣
↪strlen(example));
if (pos != UINT_MAX)
    panic("Oh my god, dancing chickens at %d\n", pos);

textsearch_destroy(conf);
```

int **textsearch_register**(struct ts_ops *ops)
register a textsearch module

Parameters

struct ts_ops *ops
operations lookup table

Description

This function must be called by textsearch modules to announce their presence. The specified &**ops** must have `name` set to a unique identifier and the callbacks find(), init(), get_pattern(), and get_pattern_len() must be implemented.

Returns 0 or -EEXISTS if another module has already registered with same name.

int **textsearch_unregister**(struct ts_ops *ops)
unregister a textsearch module

Parameters

struct ts_ops *ops
operations lookup table

Description

This function must be called by textsearch modules to announce their disappearance for examples when the module gets unloaded. The `ops` parameter must be the same as the one during the registration.

Returns 0 on success or -ENOENT if no matching textsearch registration was found.

unsigned int **textsearch_find_continuous**(struct ts_config *conf, struct ts_state *state, const void *data, unsigned int len)
search a pattern in continuous/linear data

Parameters

struct ts_config *conf
search configuration

struct ts_state *state
search state

const void *data
data to search in

unsigned int len
length of data

Description

A simplified version of *textsearch_find()* for continuous/linear data. Call *textsearch_next()* to retrieve subsequent matches.

Returns the position of first occurrence of the pattern or `UINT_MAX` if no occurrence was found.

struct ts_config ***textsearch_prepare**(const char *algo, const void *pattern, unsigned int len, gfp_t gfp_mask, int flags)

Prepare a search

Parameters

const char *algo
name of search algorithm

const void *pattern
pattern data

unsigned int len
length of pattern

gfp_t gfp_mask
allocation mask

int flags
search flags

Description

Looks up the search algorithm module and creates a new textsearch configuration for the specified pattern.

Returns a new textsearch configuration according to the specified parameters or a ERR_PTR(). If a zero length pattern is passed, this function returns EINVAL.

Note

The format of the pattern may not be compatible between
the various search algorithms.

void **textsearch_destroy**(struct ts_config *conf)

destroy a search configuration

Parameters

struct ts_config *conf
search configuration

Description

Releases all references of the configuration and frees up the memory.

unsigned int **textsearch_next**(struct ts_config *conf, struct ts_state *state)

continue searching for a pattern

Parameters

struct ts_config *conf
search configuration

struct ts_state *state
search state

Description

Continues a search looking for more occurrences of the pattern. *textsearch_find()* must be called to find the first occurrence in order to reset the state.

Returns the position of the next occurrence of the pattern or UINT_MAX if not match was found.

unsigned int **textsearch_find**(struct ts_config *conf, struct ts_state *state)

start searching for a pattern

Parameters

struct ts_config *conf
search configuration

struct ts_state *state
search state

Description

Returns the position of first occurrence of the pattern or UINT_MAX if no match was found.

void ***textsearch_get_pattern**(struct ts_config *conf)

return head of the pattern

Parameters

struct ts_config *conf
search configuration

unsigned int **textsearch_get_pattern_len**(struct ts_config *conf)

return length of the pattern

Parameters

struct ts_config *conf
search configuration

1.1.4 CRC and Math Functions in Linux

CRC Functions

uint8_t **crc4**(uint8_t c, uint64_t x, int bits)

calculate the 4-bit crc of a value.

Parameters

uint8_t c
starting crc4

uint64_t x
value to checksum

int bits
number of bits in **x** to checksum

Description

Returns the crc4 value of **x**, using polynomial 0b10111.

The **x** value is treated as left-aligned, and bits above **bits** are ignored in the crc calculations.

u8 **crc7_be**(u8 crc, const u8 *buffer, size_t len)
update the CRC7 for the data buffer

Parameters

u8 crc
previous CRC7 value

const u8 *buffer
data pointer

size_t len
number of bytes in the buffer

Context

any

Description

Returns the updated CRC7 value. The CRC7 is left-aligned in the byte (the lsbit is always 0), as that makes the computation easier, and all callers want it in that form.

void **crc8_populate_msb**(u8 table[CRC8_TABLE_SIZE], u8 polynomial)
fill crc table for given polynomial in reverse bit order.

Parameters

u8 table[CRC8_TABLE_SIZE]
table to be filled.

u8 polynomial
polynomial for which table is to be filled.

void **crc8_populate_lsb**(u8 table[CRC8_TABLE_SIZE], u8 polynomial)
fill crc table for given polynomial in regular bit order.

Parameters

u8 table[CRC8_TABLE_SIZE]
table to be filled.

u8 polynomial
polynomial for which table is to be filled.

u8 **crc8**(const u8 table[CRC8_TABLE_SIZE], u8 *pdata, size_t nbytes, u8 crc)
calculate a crc8 over the given input data.

Parameters

const u8 table[CRC8_TABLE_SIZE]
crc table used for calculation.

u8 *pdata
pointer to data buffer.

size_t nbytes
number of bytes in data buffer.

u8 crc
previous returned crc8 value.

u16 **crc16**(u16 crc, u8 const *buffer, size_t len)
compute the CRC-16 for the data buffer

Parameters

u16 crc
previous CRC value

u8 const *buffer
data pointer

size_t len
number of bytes in the buffer

Description

Returns the updated CRC value.

u32 __pure **crc32_le_generic**(u32 crc, unsigned char const *p, size_t len, const u32 (*tab)[256], u32 polynomial)
Calculate bitwise little-endian Ethernet AUTODIN II CRC32/CRC32C

Parameters

u32 crc
seed value for computation. ~0 for Ethernet, sometimes 0 for other uses, or the previous crc32/crc32c value if computing incrementally.

unsigned char const *p
pointer to buffer over which CRC32/CRC32C is run

size_t len
length of buffer **p**

const u32 (*tab)[256]
little-endian Ethernet table

u32 polynomial
CRC32/CRC32c LE polynomial

u32 __attribute_const__ **crc32_generic_shift**(u32 crc, size_t len, u32 polynomial)
Append **len** 0 bytes to crc, in logarithmic time

Parameters

u32 crc
The original little-endian CRC (i.e. lsbit is x^31 coefficient)

size_t len
The number of bytes. **crc** is multiplied by x^(8***len**)

u32 polynomial
The modulus used to reduce the result to 32 bits.

Description

It's possible to parallelize CRC computations by computing a CRC over separate ranges of a buffer, then summing them. This shifts the given CRC by 8*len bits (i.e. produces the same effect as appending len bytes of zero to the data), in time proportional to log(len).

u32 __pure **crc32_be_generic**(u32 crc, unsigned char const *p, size_t len, const u32 (*tab)[256], u32 polynomial)

Calculate bitwise big-endian Ethernet AUTODIN II CRC32

Parameters

u32 crc
seed value for computation. ~0 for Ethernet, sometimes 0 for other uses, or the previous crc32 value if computing incrementally.

unsigned char const *p
pointer to buffer over which CRC32 is run

size_t len
length of buffer **p**

const u32 (*tab)[256]
big-endian Ethernet table

u32 polynomial
CRC32 BE polynomial

u16 **crc_ccitt**(u16 crc, u8 const *buffer, size_t len)

recompute the CRC (CRC-CCITT variant) for the data buffer

Parameters

u16 crc
previous CRC value

u8 const *buffer
data pointer

size_t len
number of bytes in the buffer

u16 **crc_ccitt_false**(u16 crc, u8 const *buffer, size_t len)

recompute the CRC (CRC-CCITT-FALSE variant) for the data buffer

Parameters

u16 crc
previous CRC value

u8 const *buffer
data pointer

size_t len
number of bytes in the buffer

u16 **crc_itu_t**(u16 crc, const u8 *buffer, size_t len)

Compute the CRC-ITU-T for the data buffer

Parameters

u16 crc
previous CRC value

const u8 *buffer
data pointer

size_t len
number of bytes in the buffer

Description

Returns the updated CRC value

Base 2 log and power Functions

bool **is_power_of_2**(unsigned long n)

check if a value is a power of two

Parameters

unsigned long n
the value to check

Description

Determine whether some value is a power of two, where zero is *not* considered a power of two.

Return

true if **n** is a power of 2, otherwise false.

unsigned long **__roundup_pow_of_two**(unsigned long n)

round up to nearest power of two

Parameters

unsigned long n
value to round up

unsigned long **__rounddown_pow_of_two**(unsigned long n)

round down to nearest power of two

Parameters

unsigned long n
value to round down

const_ilog2

`const_ilog2 (n)`

log base 2 of 32-bit or a 64-bit constant unsigned value

Parameters

n
    parameter

Description

Use this where sparse expects a true constant expression, e.g. for array indices.

ilog2

`ilog2 (n)`

    log base 2 of 32-bit or a 64-bit unsigned value

Parameters

n
    parameter

Description

constant-capable log of base 2 calculation - this can be used to initialise global variables from constant data, hence the massive ternary operator construction

selects the appropriately-sized optimised version depending on sizeof(n)

roundup_pow_of_two

`roundup_pow_of_two (n)`

    round the given value up to nearest power of two

Parameters

n
    parameter

Description

round the given value up to the nearest power of two - the result is undefined when n == 0 - this can be used to initialise global variables from constant data

rounddown_pow_of_two

`rounddown_pow_of_two (n)`

    round the given value down to nearest power of two

Parameters

n
    parameter

Description

round the given value down to the nearest power of two - the result is undefined when n == 0 - this can be used to initialise global variables from constant data

order_base_2

`order_base_2 (n)`

    calculate the (rounded up) base 2 order of the argument

Parameters

n
parameter

Description

The first few values calculated by this routine:
ob2(0) = 0 ob2(1) = 0 ob2(2) = 1 ob2(3) = 2 ob2(4) = 2 ob2(5) = 3 …and so on.

bits_per

`bits_per (n)`

calculate the number of bits required for the argument

Parameters

n
parameter

Description

This is constant-capable and can be used for compile time initializations, e.g bitfields.

The first few values calculated by this routine: bf(0) = 1 bf(1) = 1 bf(2) = 2 bf(3) = 2 bf(4) = 3 …and so on.

Integer power Functions

u64 **int_pow**(u64 base, unsigned int exp)
computes the exponentiation of the given base and exponent

Parameters

u64 base
base which will be raised to the given power

unsigned int exp
power to be raised to

Description

Computes: pow(base, exp), i.e. **base** raised to the **exp** power

unsigned long **int_sqrt**(unsigned long x)
computes the integer square root

Parameters

unsigned long x
integer of which to calculate the sqrt

Description

Computes: floor(sqrt(x))

u32 **int_sqrt64**(u64 x)
strongly typed int_sqrt function when minimum 64 bit input is expected.

Parameters

u64 x
64bit integer of which to calculate the sqrt

Division Functions

do_div

`do_div (n, base)`

returns 2 values: calculate remainder and update new dividend

Parameters

n
uint64_t dividend (will be updated)

base
uint32_t divisor

Description

Summary: `uint32_t remainder = n % base; n = n / base;`

Return

(uint32_t)remainder

NOTE

macro parameter **n** is evaluated multiple times, beware of side effects!

u64 **div_u64_rem**(u64 dividend, u32 divisor, u32 *remainder)
unsigned 64bit divide with 32bit divisor with remainder

Parameters

u64 dividend
unsigned 64bit dividend

u32 divisor
unsigned 32bit divisor

u32 *remainder
pointer to unsigned 32bit remainder

Return

sets `*remainder`, then returns dividend / divisor

Description

This is commonly provided by 32bit archs to provide an optimized 64bit divide.

u64 **div_u64**(u64 dividend, u32 divisor)
unsigned 64bit divide with 32bit divisor

Parameters

u64 dividend
unsigned 64bit dividend

u32 divisor
unsigned 32bit divisor

Description

This is the most common 64bit divide and should be used if possible, as many 32bit archs can optimize this variant better than a full 64bit divide.

s64 **div_s64**(s64 dividend, s32 divisor)
signed 64bit divide with 32bit divisor

Parameters

s64 dividend
signed 64bit dividend

s32 divisor
signed 32bit divisor

DIV64_U64_ROUND_CLOSEST

`DIV64_U64_ROUND_CLOSEST (dividend, divisor)`

unsigned 64bit divide with 64bit divisor rounded to nearest integer

Parameters

dividend
unsigned 64bit dividend

divisor
unsigned 64bit divisor

Description

Divide unsigned 64bit dividend by unsigned 64bit divisor and round to closest integer.

Return

dividend / divisor rounded to nearest integer

s64 **div_s64_rem**(s64 dividend, s32 divisor, s32 *remainder)
signed 64bit divide with 64bit divisor and remainder

Parameters

s64 dividend
64bit dividend

s32 divisor
64bit divisor

s32 *remainder
64bit remainder

u64 **div64_u64_rem**(u64 dividend, u64 divisor, u64 *remainder)
unsigned 64bit divide with 64bit divisor and remainder

Parameters

u64 dividend
64bit dividend

u64 divisor
64bit divisor

u64 *remainder
64bit remainder

Description

This implementation is a comparable to algorithm used by div64_u64. But this operation, which includes math for calculating the remainder, is kept distinct to avoid slowing down the div64_u64 operation on 32bit systems.

u64 **div64_u64**(u64 dividend, u64 divisor)
unsigned 64bit divide with 64bit divisor

Parameters

u64 dividend
64bit dividend

u64 divisor
64bit divisor

Description

This implementation is a modified version of the algorithm proposed by the book 'Hacker' s Delight' . The original source and full proof can be found here and is available for use without restriction.

'http://www.hackersdelight.org/hdcodetxt/divDouble.c.txt'

s64 **div64_s64**(s64 dividend, s64 divisor)
signed 64bit divide with 64bit divisor

Parameters

s64 dividend
64bit dividend

s64 divisor
64bit divisor

unsigned long **gcd**(unsigned long a, unsigned long b)
calculate and return the greatest common divisor of 2 unsigned longs

Parameters

unsigned long a
first value

unsigned long b
second value

UUID/GUID

void **generate_random_uuid**(unsigned char uuid[16])
    generate a random UUID

Parameters

unsigned char uuid[16]
    where to put the generated UUID

Description

Random UUID interface

Used to create a Boot ID or a filesystem UUID/GUID, but can be useful for other kernel drivers.

bool **uuid_is_valid**(const char *uuid)
    checks if a UUID string is valid

Parameters

const char *uuid
    UUID string to check

Description

It checks if the UUID string is following the format:
    xxxxxxxx-xxxx-xxxx-xxxx-xxxxxxxxxxxx

where x is a hex digit.

Return

true if input is valid UUID string.

1.1.5 Kernel IPC facilities

IPC utilities

int **ipc_init**(void)
    initialise ipc subsystem

Parameters

void
    no arguments

Description

The various sysv ipc resources (semaphores, messages and shared memory) are initialised.

A callback routine is registered into the memory hotplug notifier chain: since msgmni scales to lowmem this callback routine will be called upon successful memory add / remove to recompute msmgni.

void **ipc_init_ids**(struct ipc_ids *ids)

initialise ipc identifiers

Parameters

struct ipc_ids *ids
ipc identifier set

Description

Set up the sequence range to use for the ipc identifier range (limited below ipc_mni) then initialise the keys hashtable and ids idr.

void **ipc_init_proc_interface**(const char *path, const char *header, int ids, int (*show)(struct seq_file*, void*))

create a proc interface for sysipc types using a seq_file interface.

Parameters

const char *path
Path in procfs

const char *header
Banner to be printed at the beginning of the file.

int ids
ipc id table to iterate.

int (*show)(struct seq_file *, void *)
show routine.

struct kern_ipc_perm ***ipc_findkey**(struct ipc_ids *ids, key_t key)

find a key in an ipc identifier set

Parameters

struct ipc_ids *ids
ipc identifier set

key_t key
key to find

Description

Returns the locked pointer to the ipc structure if found or NULL otherwise. If key is found ipc points to the owning ipc structure

Called with writer ipc_ids.rwsem held.

int **ipc_addid**(struct ipc_ids *ids, struct kern_ipc_perm *new, int limit)

add an ipc identifier

Parameters

struct ipc_ids *ids
ipc identifier set

struct kern_ipc_perm *new
new ipc permission set

int limit
limit for the number of used ids

Description

Add an entry 'new' to the ipc ids idr. The permissions object is initialised and the first free entry is set up and the index assigned is returned. The 'new' entry is returned in a locked state on success.

On failure the entry is not locked and a negative err-code is returned. The caller must use ipc_rcu_putref() to free the identifier.

Called with writer ipc_ids.rwsem held.

int **ipcget_new**(struct ipc_namespace *ns, struct ipc_ids *ids, const struct ipc_ops *ops, struct ipc_params *params)

create a new ipc object

Parameters

struct ipc_namespace *ns
ipc namespace

struct ipc_ids *ids
ipc identifier set

const struct ipc_ops *ops
the actual creation routine to call

struct ipc_params *params
its parameters

Description

This routine is called by sys_msgget, sys_semget() and sys_shmget() when the key is IPC_PRIVATE.

int **ipc_check_perms**(struct ipc_namespace *ns, struct kern_ipc_perm *ipcp, const struct ipc_ops *ops, struct ipc_params *params)

check security and permissions for an ipc object

Parameters

struct ipc_namespace *ns
ipc namespace

struct kern_ipc_perm *ipcp
ipc permission set

const struct ipc_ops *ops
the actual security routine to call

struct ipc_params *params
its parameters

Description

This routine is called by sys_msgget(), sys_semget() and sys_shmget() when the key is not IPC_PRIVATE and that key already exists in the ds IDR.

On success, the ipc id is returned.

It is called with ipc_ids.rwsem and ipcp->lock held.

int **ipcget_public**(struct ipc_namespace *ns, struct ipc_ids *ids, const struct ipc_ops *ops, struct ipc_params *params)

get an ipc object or create a new one

Parameters

struct ipc_namespace *ns
ipc namespace

struct ipc_ids *ids
ipc identifier set

const struct ipc_ops *ops
the actual creation routine to call

struct ipc_params *params
its parameters

Description

This routine is called by sys_msgget, sys_semget() and sys_shmget() when the key is not IPC_PRIVATE. It adds a new entry if the key is not found and does some permission / security checkings if the key is found.

On success, the ipc id is returned.

void **ipc_kht_remove**(struct ipc_ids *ids, struct kern_ipc_perm *ipcp)

remove an ipc from the key hashtable

Parameters

struct ipc_ids *ids
ipc identifier set

struct kern_ipc_perm *ipcp
ipc perm structure containing the key to remove

Description

ipc_ids.rwsem (as a writer) and the spinlock for this ID are held before this function is called, and remain locked on the exit.

void **ipc_rmid**(struct ipc_ids *ids, struct kern_ipc_perm *ipcp)

remove an ipc identifier

Parameters

struct ipc_ids *ids
ipc identifier set

struct kern_ipc_perm *ipcp
ipc perm structure containing the identifier to remove

Description

ipc_ids.rwsem (as a writer) and the spinlock for this ID are held before this function is called, and remain locked on the exit.

void **ipc_set_key_private**(struct ipc_ids *ids, struct kern_ipc_perm *ipcp)
switch the key of an existing ipc to IPC_PRIVATE

Parameters

struct ipc_ids *ids
ipc identifier set

struct kern_ipc_perm *ipcp
ipc perm structure containing the key to modify

Description

ipc_ids.rwsem (as a writer) and the spinlock for this ID are held before this function is called, and remain locked on the exit.

int **ipcperms**(struct ipc_namespace *ns, struct kern_ipc_perm *ipcp, short flag)
check ipc permissions

Parameters

struct ipc_namespace *ns
ipc namespace

struct kern_ipc_perm *ipcp
ipc permission set

short flag
desired permission set

Description

Check user, group, other permissions for access to ipc resources. return 0 if allowed

flag will most probably be 0 or `S_...UGO` from <linux/stat.h>

void **kernel_to_ipc64_perm**(struct kern_ipc_perm *in, struct ipc64_perm *out)
convert kernel ipc permissions to user

Parameters

struct kern_ipc_perm *in
kernel permissions

struct ipc64_perm *out
new style ipc permissions

Description

Turn the kernel object **in** into a set of permissions descriptions for returning to userspace (**out**).

void **ipc64_perm_to_ipc_perm**(struct ipc64_perm *in, struct ipc_perm *out)
convert new ipc permissions to old

Parameters

struct ipc64_perm *in
new style ipc permissions

struct ipc_perm *out
old style ipc permissions

Description

Turn the new style permissions object **in** into a compatibility object and store it into the **out** pointer.

struct kern_ipc_perm ***ipc_obtain_object_idr**(struct ipc_ids *ids, int id)

Parameters

struct ipc_ids *ids
ipc identifier set

int id
ipc id to look for

Description

Look for an id in the ipc ids idr and return associated ipc object.

Call inside the RCU critical section. The ipc object is *not* locked on exit.

struct kern_ipc_perm ***ipc_obtain_object_check**(struct ipc_ids *ids, int id)

Parameters

struct ipc_ids *ids
ipc identifier set

int id
ipc id to look for

Description

Similar to *ipc_obtain_object_idr()* but also checks the ipc object sequence number.

Call inside the RCU critical section. The ipc object is *not* locked on exit.

int **ipcget**(struct ipc_namespace *ns, struct ipc_ids *ids, const struct ipc_ops *ops, struct ipc_params *params)

Common sys_*get() code

Parameters

struct ipc_namespace *ns
namespace

struct ipc_ids *ids
ipc identifier set

const struct ipc_ops *ops
operations to be called on ipc object creation, permission checks and further checks

struct ipc_params *params
the parameters needed by the previous operations.

Description

Common routine called by sys_msgget(), sys_semget() and sys_shmget().

int **ipc_update_perm**(struct ipc64_perm *in, struct kern_ipc_perm *out)
update the permissions of an ipc object

Parameters

struct ipc64_perm *in
the permission given as input.

struct kern_ipc_perm *out
the permission of the ipc to set.

struct kern_ipc_perm ***ipcctl_obtain_check**(struct ipc_namespace *ns, struct ipc_ids *ids, int id, int cmd, struct ipc64_perm *perm, int extra_perm)
retrieve an ipc object and check permissions

Parameters

struct ipc_namespace *ns
ipc namespace

struct ipc_ids *ids
the table of ids where to look for the ipc

int id
the id of the ipc to retrieve

int cmd
the cmd to check

struct ipc64_perm *perm
the permission to set

int extra_perm
one extra permission parameter used by msq

Description

This function does some common audit and permissions check for some IPC_XXX cmd and is called from semctl_down, shmctl_down and msgctl_down.

It:

- retrieves the ipc object with the given id in the given table.
- performs some audit and permission check, depending on the given cmd
- returns a pointer to the ipc object or otherwise, the corresponding error.

Call holding the both the rwsem and the rcu read lock.

int **ipc_parse_version**(int *cmd)
ipc call version

Parameters

int *cmd
pointer to command

Description

Return IPC_64 for new style IPC and IPC_OLD for old style IPC. The **cmd** value is turned from an encoding command and version into just the command code.

1.1.6 FIFO Buffer

kfifo interface

DECLARE_KFIFO_PTR

`DECLARE_KFIFO_PTR (fifo, type)`

macro to declare a fifo pointer object

Parameters

fifo
name of the declared fifo

type
type of the fifo elements

DECLARE_KFIFO

`DECLARE_KFIFO (fifo, type, size)`

macro to declare a fifo object

Parameters

fifo
name of the declared fifo

type
type of the fifo elements

size
the number of elements in the fifo, this must be a power of 2

INIT_KFIFO

`INIT_KFIFO (fifo)`

Initialize a fifo declared by DECLARE_KFIFO

Parameters

fifo
name of the declared fifo datatype

DEFINE_KFIFO

`DEFINE_KFIFO (fifo, type, size)`

macro to define and initialize a fifo

Parameters

fifo
name of the declared fifo datatype

type
type of the fifo elements

size
the number of elements in the fifo, this must be a power of 2

Note

the macro can be used for global and local fifo data type variables.

kfifo_initialized

`kfifo_initialized (fifo)`

Check if the fifo is initialized

Parameters

fifo
address of the fifo to check

Description

Return `true` if fifo is initialized, otherwise `false`. Assumes the fifo was 0 before.

kfifo_esize

`kfifo_esize (fifo)`

returns the size of the element managed by the fifo

Parameters

fifo
address of the fifo to be used

kfifo_recsize

`kfifo_recsize (fifo)`

returns the size of the record length field

Parameters

fifo
address of the fifo to be used

kfifo_size

`kfifo_size (fifo)`

returns the size of the fifo in elements

Parameters

fifo
address of the fifo to be used

kfifo_reset

`kfifo_reset (fifo)`

removes the entire fifo content

Parameters

fifo
address of the fifo to be used

Note

usage of *kfifo_reset()* is dangerous. It should be only called when the fifo is exclusived locked or when it is secured that no other thread is accessing the fifo.

kfifo_reset_out

`kfifo_reset_out (fifo)`

skip fifo content

Parameters

fifo
address of the fifo to be used

Note

The usage of *kfifo_reset_out()* is safe until it will be only called from the reader thread and there is only one concurrent reader. Otherwise it is dangerous and must be handled in the same way as *kfifo_reset()*.

kfifo_len

`kfifo_len (fifo)`

returns the number of used elements in the fifo

Parameters

fifo
address of the fifo to be used

kfifo_is_empty

`kfifo_is_empty (fifo)`

returns true if the fifo is empty

Parameters

fifo
address of the fifo to be used

kfifo_is_empty_spinlocked

`kfifo_is_empty_spinlocked (fifo, lock)`

returns true if the fifo is empty using a spinlock for locking

Parameters

fifo
address of the fifo to be used

lock
spinlock to be used for locking

kfifo_is_empty_spinlocked_noirqsave

`kfifo_is_empty_spinlocked_noirqsave (fifo, lock)`

returns true if the fifo is empty using a spinlock for locking, doesn't disable interrupts

Parameters

fifo
address of the fifo to be used

lock
spinlock to be used for locking

kfifo_is_full

`kfifo_is_full (fifo)`

returns true if the fifo is full

Parameters

fifo
address of the fifo to be used

kfifo_avail

`kfifo_avail (fifo)`

returns the number of unused elements in the fifo

Parameters

fifo
address of the fifo to be used

kfifo_skip

`kfifo_skip (fifo)`

skip output data

Parameters

fifo
address of the fifo to be used

kfifo_peek_len

`kfifo_peek_len (fifo)`

gets the size of the next fifo record

Parameters

fifo
address of the fifo to be used

Description

This function returns the size of the next fifo record in number of bytes.

kfifo_alloc

`kfifo_alloc (fifo, size, gfp_mask)`

dynamically allocates a new fifo buffer

Parameters

fifo
pointer to the fifo

size
the number of elements in the fifo, this must be a power of 2

gfp_mask
get_free_pages mask, passed to *kmalloc()*

Description

This macro dynamically allocates a new fifo buffer.

The number of elements will be rounded-up to a power of 2. The fifo will be release with *kfifo_free()*. Return 0 if no error, otherwise an error code.

kfifo_free

`kfifo_free (fifo)`

frees the fifo

Parameters

fifo
the fifo to be freed

kfifo_init

`kfifo_init (fifo, buffer, size)`

initialize a fifo using a preallocated buffer

Parameters

fifo
the fifo to assign the buffer

buffer
the preallocated buffer to be used

size
the size of the internal buffer, this have to be a power of 2

Description

This macro initializes a fifo using a preallocated buffer.

The number of elements will be rounded-up to a power of 2. Return 0 if no error, otherwise an error code.

kfifo_put

`kfifo_put (fifo, val)`

put data into the fifo

Parameters

fifo
address of the fifo to be used

val
the data to be added

Description

This macro copies the given value into the fifo. It returns 0 if the fifo was full. Otherwise it returns the number processed elements.

Note that with only one concurrent reader and one concurrent writer, you don't need extra locking to use these macro.

kfifo_get

`kfifo_get (fifo, val)`

get data from the fifo

Parameters

fifo
address of the fifo to be used

val
address where to store the data

Description

This macro reads the data from the fifo. It returns 0 if the fifo was empty. Otherwise it returns the number processed elements.

Note that with only one concurrent reader and one concurrent writer, you don't need extra locking to use these macro.

kfifo_peek

`kfifo_peek (fifo, val)`

get data from the fifo without removing

Parameters

fifo
address of the fifo to be used

val
address where to store the data

Description

This reads the data from the fifo without removing it from the fifo. It returns 0 if the fifo was empty. Otherwise it returns the number processed elements.

Note that with only one concurrent reader and one concurrent writer, you don't need extra locking to use these macro.

kfifo_in

`kfifo_in (fifo, buf, n)`

put data into the fifo

Parameters

fifo
address of the fifo to be used

buf
the data to be added

n
number of elements to be added

Description

This macro copies the given buffer into the fifo and returns the number of copied elements.

Note that with only one concurrent reader and one concurrent writer, you don't need extra locking to use these macro.

kfifo_in_spinlocked

`kfifo_in_spinlocked (fifo, buf, n, lock)`

put data into the fifo using a spinlock for locking

Parameters

fifo
address of the fifo to be used

buf
the data to be added

n
number of elements to be added

lock
pointer to the spinlock to use for locking

Description

This macro copies the given values buffer into the fifo and returns the number of copied elements.

kfifo_in_spinlocked_noirqsave

`kfifo_in_spinlocked_noirqsave (fifo, buf, n, lock)`

put data into fifo using a spinlock for locking, don't disable interrupts

Parameters

fifo
address of the fifo to be used

buf
the data to be added

n
number of elements to be added

lock
pointer to the spinlock to use for locking

Description

This is a variant of *kfifo_in_spinlocked()* but uses spin_lock/unlock() for locking and doesn't disable interrupts.

kfifo_out

`kfifo_out (fifo, buf, n)`

get data from the fifo

Parameters

fifo
address of the fifo to be used

buf
pointer to the storage buffer

n
max. number of elements to get

Description

This macro get some data from the fifo and return the numbers of elements copied.

Note that with only one concurrent reader and one concurrent writer, you don't need extra locking to use these macro.

kfifo_out_spinlocked

`kfifo_out_spinlocked (fifo, buf, n, lock)`

get data from the fifo using a spinlock for locking

Parameters

fifo
address of the fifo to be used

buf
pointer to the storage buffer

n
max. number of elements to get

lock
pointer to the spinlock to use for locking

Description

This macro get the data from the fifo and return the numbers of elements copied.

kfifo_out_spinlocked_noirqsave

`kfifo_out_spinlocked_noirqsave (fifo, buf, n, lock)`

get data from the fifo using a spinlock for locking, don't disable interrupts

Parameters

fifo
address of the fifo to be used

buf
pointer to the storage buffer

n
max. number of elements to get

lock
pointer to the spinlock to use for locking

Description

This is a variant of *kfifo_out_spinlocked()* which uses spin_lock/unlock() for locking and doesn't disable interrupts.

kfifo_from_user

`kfifo_from_user (fifo, from, len, copied)`

puts some data from user space into the fifo

Parameters

fifo
address of the fifo to be used

from
pointer to the data to be added

len
the length of the data to be added

copied
pointer to output variable to store the number of copied bytes

Description

This macro copies at most **len** bytes from the **from** into the fifo, depending of the available space and returns -EFAULT/0.

Note that with only one concurrent reader and one concurrent writer, you don't need extra locking to use these macro.

kfifo_to_user

`kfifo_to_user (fifo, to, len, copied)`

copies data from the fifo into user space

Parameters

fifo
address of the fifo to be used

to
where the data must be copied

len
the size of the destination buffer

copied
pointer to output variable to store the number of copied bytes

Description

This macro copies at most **len** bytes from the fifo into the **to** buffer and returns -EFAULT/0.

Note that with only one concurrent reader and one concurrent writer, you don't need extra locking to use these macro.

kfifo_dma_in_prepare

`kfifo_dma_in_prepare (fifo, sgl, nents, len)`

setup a scatterlist for DMA input

Parameters

fifo
address of the fifo to be used

sgl
pointer to the scatterlist array

nents
number of entries in the scatterlist array

len
number of elements to transfer

Description

This macro fills a scatterlist for DMA input. It returns the number entries in the scatterlist array.

Note that with only one concurrent reader and one concurrent writer, you don't need extra locking to use these macros.

kfifo_dma_in_finish

`kfifo_dma_in_finish (fifo, len)`

finish a DMA IN operation

Parameters

fifo
address of the fifo to be used

len
number of bytes to received

Description

This macro finish a DMA IN operation. The in counter will be updated by the len parameter. No error checking will be done.

Note that with only one concurrent reader and one concurrent writer, you don't need extra locking to use these macros.

kfifo_dma_out_prepare

`kfifo_dma_out_prepare (fifo, sgl, nents, len)`

setup a scatterlist for DMA output

Parameters

fifo
address of the fifo to be used

sgl
pointer to the scatterlist array

nents
number of entries in the scatterlist array

len
number of elements to transfer

Description

This macro fills a scatterlist for DMA output which at most **len** bytes to transfer. It returns the number entries in the scatterlist array. A zero means there is no space available and the scatterlist is not filled.

Note that with only one concurrent reader and one concurrent writer, you don't need extra locking to use these macros.

kfifo_dma_out_finish

`kfifo_dma_out_finish (fifo, len)`

finish a DMA OUT operation

Parameters

fifo
address of the fifo to be used

len
number of bytes transferred

Description

This macro finish a DMA OUT operation. The out counter will be updated by the len parameter. No error checking will be done.

Note that with only one concurrent reader and one concurrent writer, you don't need extra locking to use these macros.

kfifo_out_peek

`kfifo_out_peek (fifo, buf, n)`

gets some data from the fifo

Parameters

fifo
address of the fifo to be used

buf
pointer to the storage buffer

n
max. number of elements to get

Description

This macro get the data from the fifo and return the numbers of elements copied. The data is not removed from the fifo.

Note that with only one concurrent reader and one concurrent writer, you don't need extra locking to use these macro.

1.1.7 relay interface support

Relay interface support is designed to provide an efficient mechanism for tools and facilities to relay large amounts of data from kernel space to user space.

relay interface

int **relay_buf_full**(struct rchan_buf *buf)
boolean, is the channel buffer full?

Parameters

struct rchan_buf *buf
channel buffer

Returns 1 if the buffer is full, 0 otherwise.

void **relay_reset**(struct rchan *chan)
reset the channel

Parameters

struct rchan *chan
the channel

This has the effect of erasing all data from all channel buffers and restarting the channel in its initial state. The buffers are not freed, so any mappings are still in effect.

NOTE. Care should be taken that the channel isn't actually being used by anything when this call is made.

struct rchan ***relay_open**(const char *base_filename, struct dentry *parent, size_t subbuf_size, size_t n_subbufs, struct rchan_callbacks *cb, void *private_data)
create a new relay channel

Parameters

const char *base_filename
base name of files to create, `NULL` for buffering only

struct dentry *parent
dentry of parent directory, NULL for root directory or buffer

size_t subbuf_size
size of sub-buffers

size_t n_subbufs
number of sub-buffers

struct rchan_callbacks *cb
client callback functions

void *private_data
user-defined data

Returns channel pointer if successful, NULL otherwise.

Creates a channel buffer for each cpu using the sizes and attributes specified. The created channel buffer files will be named base_filename0… base_filenameN-1. File permissions will be S_IRUSR.

If opening a buffer (**parent** = NULL) that you later wish to register in a filesystem, call *relay_late_setup_files()* once the **parent** dentry is available.

int **relay_late_setup_files**(struct rchan *chan, const char *base_filename, struct dentry *parent)

triggers file creation

Parameters

struct rchan *chan
channel to operate on

const char *base_filename
base name of files to create

struct dentry *parent
dentry of parent directory, NULL for root directory

Returns 0 if successful, non-zero otherwise.

Use to setup files for a previously buffer-only channel created by *relay_open()* with a NULL parent dentry.

For example, this is useful for perfomring early tracing in kernel, before VFS is up and then exposing the early results once the dentry is available.

size_t **relay_switch_subbuf**(struct rchan_buf *buf, size_t length)

switch to a new sub-buffer

Parameters

struct rchan_buf *buf
channel buffer

size_t length
size of current event

Returns either the length passed in or 0 if full.

Performs sub-buffer-switch tasks such as invoking callbacks, updating padding counts, waking up readers, etc.

void **relay_subbufs_consumed**(struct rchan *chan, unsigned int cpu, size_t subbufs_consumed)

update the buffer's sub-buffers-consumed count

Parameters

struct rchan *chan
the channel

unsigned int cpu
the cpu associated with the channel buffer to update

size_t subbufs_consumed
number of sub-buffers to add to current buf's count

Adds to the channel buffer's consumed sub-buffer count. subbufs_consumed should be the number of sub-buffers newly consumed, not the total consumed.

NOTE. Kernel clients don't need to call this function if the channel mode is 'overwrite'.

void **relay_close**(struct rchan *chan)

close the channel

Parameters

struct rchan *chan
the channel

Closes all channel buffers and frees the channel.

void **relay_flush**(struct rchan *chan)

close the channel

Parameters

struct rchan *chan
the channel

Flushes all channel buffers, i.e. forces buffer switch.

int **relay_mmap_buf**(struct rchan_buf *buf, struct vm_area_struct *vma)

mmap channel buffer to process address space

Parameters

struct rchan_buf *buf
relay channel buffer

struct vm_area_struct *vma
vm_area_struct describing memory to be mapped

Returns 0 if ok, negative on error

Caller should already have grabbed mmap_lock.

void *`relay_alloc_buf`(struct rchan_buf *buf, size_t *size)
allocate a channel buffer

Parameters

struct rchan_buf *buf
the buffer struct

size_t *size
total size of the buffer

Returns a pointer to the resulting buffer, `NULL` if unsuccessful. The passed in size will get page aligned, if it isn't already.

struct rchan_buf *`relay_create_buf`(struct rchan *chan)
allocate and initialize a channel buffer

Parameters

struct rchan *chan
the relay channel

Returns channel buffer if successful, `NULL` otherwise.

void `relay_destroy_channel`(struct *kref* *kref)
free the channel struct

Parameters

struct kref *kref
target kernel reference that contains the relay channel

Should only be called from kref_put().

void `relay_destroy_buf`(struct rchan_buf *buf)
destroy an rchan_buf struct and associated buffer

Parameters

struct rchan_buf *buf
the buffer struct

void `relay_remove_buf`(struct *kref* *kref)
remove a channel buffer

Parameters

struct kref *kref
target kernel reference that contains the relay buffer

Removes the file from the filesystem, which also frees the rchan_buf_struct and the channel buffer. Should only be called from kref_put().

int `relay_buf_empty`(struct rchan_buf *buf)
boolean, is the channel buffer empty?

Parameters

struct rchan_buf *buf
channel buffer

Returns 1 if the buffer is empty, 0 otherwise.

void **wakeup_readers**(struct irq_work *work)

wake up readers waiting on a channel

Parameters

struct irq_work *work
contains the channel buffer

This is the function used to defer reader waking

void **__relay_reset**(struct rchan_buf *buf, unsigned int init)

reset a channel buffer

Parameters

struct rchan_buf *buf
the channel buffer

unsigned int init
1 if this is a first-time initialization

See *relay_reset()* for description of effect.

void **relay_close_buf**(struct rchan_buf *buf)

close a channel buffer

Parameters

struct rchan_buf *buf
channel buffer

Marks the buffer finalized and restores the default callbacks. The channel buffer and channel buffer data structure are then freed automatically when the last reference is given up.

int **relay_file_open**(struct *inode* *inode, struct file *filp)

open file op for relay files

Parameters

struct inode *inode
the inode

struct file *filp
the file

Increments the channel buffer refcount.

int **relay_file_mmap**(struct file *filp, struct vm_area_struct *vma)

mmap file op for relay files

Parameters

struct file *filp
the file

struct vm_area_struct *vma
the vma describing what to map

Calls upon *relay_mmap_buf()* to map the file into user space.

__poll_t **relay_file_poll**(struct file *filp, poll_table *wait)
poll file op for relay files

Parameters

struct file *filp
the file

poll_table *wait
poll table

Poll implemention.

int **relay_file_release**(struct *inode* *inode, struct file *filp)
release file op for relay files

Parameters

struct inode *inode
the inode

struct file *filp
the file

Decrements the channel refcount, as the filesystem is no longer using it.

size_t **relay_file_read_subbuf_avail**(size_t read_pos, struct rchan_buf *buf)
return bytes available in sub-buffer

Parameters

size_t read_pos
file read position

struct rchan_buf *buf
relay channel buffer

size_t **relay_file_read_start_pos**(struct rchan_buf *buf)
find the first available byte to read

Parameters

struct rchan_buf *buf
relay channel buffer

If the read_pos is in the middle of padding, return the position of the first actually available byte, otherwise return the original value.

size_t **relay_file_read_end_pos**(struct rchan_buf *buf, size_t read_pos, size_t count)
return the new read position

Parameters

struct rchan_buf *buf
relay channel buffer

size_t read_pos
file read position

size_t count
number of bytes to be read

1.1.8 Module Support

Module Loading

int **__request_module**(bool wait, const char *fmt, ...)
try to load a kernel module

Parameters

bool wait
wait (or not) for the operation to complete

const char *fmt
printf style format string for the name of the module

...
arguments as specified in the format string

Description

Load a module using the user mode module loader. The function returns zero on success or a negative errno code or positive exit code from "modprobe" on failure. Note that a successful module load does not mean the module did not then unload and exit on an error of its own. Callers must check that the service they requested is now available not blindly invoke it.

If module auto-loading support is disabled then this function simply returns -ENOENT.

Inter Module support

Refer to the file kernel/module.c for more information.

1.1.9 Hardware Interfaces

DMA Channels

int **request_dma**(unsigned int dmanr, const char *device_id)
request and reserve a system DMA channel

Parameters

unsigned int dmanr
DMA channel number

const char * device_id
reserving device ID string, used in /proc/dma

void **free_dma**(unsigned int dmanr)

free a reserved system DMA channel

Parameters

unsigned int dmanr
DMA channel number

Resources Management

struct resource ***request_resource_conflict**(struct resource *root, struct resource *new)

request and reserve an I/O or memory resource

Parameters

struct resource *root
root resource descriptor

struct resource *new
resource descriptor desired by caller

Description

Returns 0 for success, conflict resource on error.

int **find_next_iomem_res**(resource_size_t start, resource_size_t end, unsigned long flags, unsigned long desc, bool first_lvl, struct resource *res)

Parameters

resource_size_t start
start address of the resource searched for

resource_size_t end
end address of same resource

unsigned long flags
flags which the resource must have

unsigned long desc
descriptor the resource must have

bool first_lvl
walk only the first level children, if set

struct resource *res
return ptr, if resource found

Description

caller must specify **start**, **end**, **flags**, and **desc** (which may be IORES_DESC_NONE).

If a resource is found, returns 0 and *****res is overwritten with the part of the resource that' s within [**start**..**end**]; if none is found, returns -ENODEV. Returns -EINVAL for invalid parameters.

This function walks the whole tree and not just first level children unless **first_lvl** is true.

int **reallocate_resource**(struct resource *root, struct resource *old, resource_size_t newsize, struct resource_constraint *constraint)

allocate a slot in the resource tree given range & alignment. The resource will be relocated if the new size cannot be reallocated in the current location.

Parameters

struct resource *root
root resource descriptor

struct resource *old
resource descriptor desired by caller

resource_size_t newsize
new size of the resource descriptor

struct resource_constraint *constraint
the size and alignment constraints to be met.

struct resource ***lookup_resource**(struct resource *root, resource_size_t start)

find an existing resource by a resource start address

Parameters

struct resource *root
root resource descriptor

resource_size_t start
resource start address

Description

Returns a pointer to the resource if found, NULL otherwise

struct resource ***insert_resource_conflict**(struct resource *parent, struct resource *new)

Inserts resource in the resource tree

Parameters

struct resource *parent
parent of the new resource

struct resource *new
new resource to insert

Description

Returns 0 on success, conflict resource if the resource can’t be inserted.

This function is equivalent to request_resource_conflict when no conflict happens. If a conflict happens, and the conflicting resources entirely fit within the range of the new resource, then the new resource is inserted and the conflicting resources become children of the new resource.

This function is intended for producers of resources, such as FW modules and bus drivers.

void **insert_resource_expand_to_fit**(struct resource *root, struct resource *new)

Insert a resource into the resource tree

Parameters

struct resource *root
root resource descriptor

struct resource *new
new resource to insert

Description

Insert a resource into the resource tree, possibly expanding it in order to make it encompass any conflicting resources.

resource_size_t **resource_alignment**(struct resource *res)

calculate resource's alignment

Parameters

struct resource *res
resource pointer

Description

Returns alignment on success, 0 (invalid alignment) on failure.

void **release_mem_region_adjustable**(resource_size_t start, resource_size_t size)

release a previously reserved memory region

Parameters

resource_size_t start
resource start address

resource_size_t size
resource region size

Description

This interface is intended for memory hot-delete. The requested region is released from a currently busy memory resource. The requested region must either match exactly or fit into a single busy resource entry. In the latter case, the remaining resource is adjusted accordingly. Existing children of the busy memory resource must be immutable in the request.

Note

- Additional release conditions, such as overlapping region, can be supported after they are confirmed as valid cases.
- When a busy memory resource gets split into two entries, the code assumes that all children remain in the lower address entry for simplicity. Enhance this logic when necessary.

int **request_resource**(struct resource *root, struct resource *new)

request and reserve an I/O or memory resource

Parameters

struct resource *root
root resource descriptor

struct resource *new
resource descriptor desired by caller

Description

Returns 0 for success, negative error code on error.

int **release_resource**(struct resource *old)
release a previously reserved resource

Parameters

struct resource *old
resource pointer

int **walk_iomem_res_desc**(unsigned long desc, unsigned long flags, u64 start, u64 end, void *arg, int (*func)(struct resource*, void*))

Parameters

unsigned long desc
I/O resource descriptor. Use IORES_DESC_NONE to skip **desc** check.

unsigned long flags
I/O resource flags

u64 start
start addr

u64 end
end addr

void *arg
function argument for the callback **func**

int (*func)(struct resource *, void *)
callback function that is called for each qualifying resource area

Description

ranges. This walks through whole tree and not just first level children. All the memory ranges which overlap start,end and also match flags and desc are valid candidates.

NOTE

For a new descriptor search, define a new IORES_DESC in <linux/ioport.h> and set it in 'desc' of a target resource entry.

int **region_intersects**(resource_size_t start, size_t size, unsigned long flags, unsigned long desc)
determine intersection of region with known resources

Parameters

resource_size_t start
region start address

size_t size
size of region

unsigned long flags
flags of resource (in iomem_resource)

unsigned long desc
descriptor of resource (in iomem_resource) or IORES_DESC_NONE

Description

Check if the specified region partially overlaps or fully eclipses a resource identified by **flags** and **desc** (optional with IORES_DESC_NONE). Return REGION_DISJOINT if the region does not overlap **flags/desc**, return REGION_MIXED if the region overlaps **flags/desc** and another resource, and return REGION_INTERSECTS if the region overlaps **flags/desc** and no other defined resource. Note that REGION_INTERSECTS is also returned in the case when the specified region overlaps RAM and undefined memory holes.

region_intersect() is used by memory remapping functions to ensure the user is not remapping RAM and is a vast speed up over walking through the resource table page by page.

int **allocate_resource**(struct resource *root, struct resource *new, resource_size_t size, resource_size_t min, resource_size_t max, resource_size_t align, resource_size_t (*alignf)(void*, const struct resource*, resource_size_t, resource_size_t), void *alignf_data)

allocate empty slot in the resource tree given range & alignment. The resource will be reallocated with a new size if it was already allocated

Parameters

struct resource *root
root resource descriptor

struct resource *new
resource descriptor desired by caller

resource_size_t size
requested resource region size

resource_size_t min
minimum boundary to allocate

resource_size_t max
maximum boundary to allocate

resource_size_t align
alignment requested, in bytes

resource_size_t (*alignf)(void *, const struct resource *, resource_size_t, resource_size_t)
alignment function, optional, called if not NULL

void *alignf_data
arbitrary data to pass to the **alignf** function

int **insert_resource**(struct resource *parent, struct resource *new)
Inserts a resource in the resource tree

Parameters

struct resource *parent
parent of the new resource

struct resource *new
new resource to insert

Description

Returns 0 on success, -EBUSY if the resource can't be inserted.

This function is intended for producers of resources, such as FW modules and bus drivers.

int **remove_resource**(struct resource *old)
Remove a resource in the resource tree

Parameters

struct resource *old
resource to remove

Description

Returns 0 on success, -EINVAL if the resource is not valid.

This function removes a resource previously inserted by *insert_resource()* or *insert_resource_conflict()*, and moves the children (if any) up to where they were before. *insert_resource()* and *insert_resource_conflict()* insert a new resource, and move any conflicting resources down to the children of the new resource.

insert_resource(), *insert_resource_conflict()* and *remove_resource()* are intended for producers of resources, such as FW modules and bus drivers.

int **adjust_resource**(struct resource *res, resource_size_t start, resource_size_t size)
modify a resource's start and size

Parameters

struct resource *res
resource to modify

resource_size_t start
new start value

resource_size_t size
new size

Description

Given an existing resource, change its start and size to match the arguments. Returns 0 on success, -EBUSY if it can't fit. Existing children of the resource are assumed to be immutable.

struct resource ***__request_region**(struct resource *parent, resource_size_t start, resource_size_t n, const char *name, int flags)

create a new busy resource region

Parameters

struct resource *parent
parent resource descriptor

resource_size_t start
resource start address

resource_size_t n
resource region size

const char *name
reserving caller's ID string

int flags
IO resource flags

void **__release_region**(struct resource *parent, resource_size_t start, resource_size_t n)

release a previously reserved resource region

Parameters

struct resource *parent
parent resource descriptor

resource_size_t start
resource start address

resource_size_t n
resource region size

Description

The described resource region must match a currently busy region.

int **devm_request_resource**(struct device *dev, struct resource *root, struct resource *new)

request and reserve an I/O or memory resource

Parameters

struct device *dev
device for which to request the resource

struct resource *root
root of the resource tree from which to request the resource

struct resource *new
descriptor of the resource to request

Description

This is a device-managed version of *request_resource()*. There is usually no need to release resources requested by this function explicitly since that will be taken care of when the device is unbound from its driver. If for some reason the resource needs to be released explicitly, because of ordering issues for example, drivers must call *devm_release_resource()* rather than the regular *release_resource()*.

When a conflict is detected between any existing resources and the newly requested resource, an error message will be printed.

Returns 0 on success or a negative error code on failure.

void **devm_release_resource**(struct device *dev, struct resource *new)

release a previously requested resource

Parameters

struct device *dev
device for which to release the resource

struct resource *new
descriptor of the resource to release

Description

Releases a resource previously requested using *devm_request_resource()*.

struct resource ***devm_request_free_mem_region**(struct device *dev, struct resource *base, unsigned long size)

find free region for device private memory

Parameters

struct device *dev
device struct to bind the resource to

struct resource *base
resource tree to look in

unsigned long size
size in bytes of the device memory to add

Description

This function tries to find an empty range of physical address big enough to contain the new resource, so that it can later be hotplugged as ZONE_DEVICE memory, which in turn allocates struct pages.

MTRR Handling

int **arch_phys_wc_add**(unsigned long base, unsigned long size)
add a WC MTRR and handle errors if PAT is unavailable

Parameters

unsigned long base
Physical base address

unsigned long size
Size of region

Description

If PAT is available, this does nothing. If PAT is unavailable, it attempts to add a WC MTRR covering size bytes starting at base and logs an error if this fails.

The called should provide a power of two size on an equivalent power of two boundary.

Drivers must store the return value to pass to mtrr_del_wc_if_needed, but drivers should not try to interpret that return value.

1.1.10 Security Framework

int **security_init**(void)
initializes the security framework

Parameters

void
no arguments

Description

This should be called early in the kernel initialization sequence.

void **security_add_hooks**(struct security_hook_list *hooks, int count, char *lsm)
Add a modules hooks to the hook lists.

Parameters

struct security_hook_list *hooks
the hooks to add

int count
the number of hooks to add

char *lsm
the name of the security module

Description

Each LSM has to register its hooks with the infrastructure.

int **lsm_cred_alloc**(struct *cred* *cred, gfp_t gfp)
allocate a composite cred blob

Parameters

struct cred *cred
: the cred that needs a blob

gfp_t gfp
: allocation type

Description

Allocate the cred blob for all the modules

Returns 0, or -ENOMEM if memory can't be allocated.

void **lsm_early_cred**(struct *cred* *cred)
: during initialization allocate a composite cred blob

Parameters

struct cred *cred
: the cred that needs a blob

Description

Allocate the cred blob for all the modules

int **lsm_file_alloc**(struct *file* *file)
: allocate a composite file blob

Parameters

struct file *file
: the file that needs a blob

Description

Allocate the file blob for all the modules

Returns 0, or -ENOMEM if memory can't be allocated.

int **lsm_inode_alloc**(struct *inode* *inode)
: allocate a composite inode blob

Parameters

struct inode *inode
: the inode that needs a blob

Description

Allocate the inode blob for all the modules

Returns 0, or -ENOMEM if memory can't be allocated.

int **lsm_task_alloc**(struct task_struct *task)
: allocate a composite task blob

Parameters

struct task_struct *task
: the task that needs a blob

Description

Allocate the task blob for all the modules

Returns 0, or -ENOMEM if memory can't be allocated.

int **lsm_ipc_alloc**(struct kern_ipc_perm *kip)
allocate a composite ipc blob

Parameters

struct kern_ipc_perm *kip
the ipc that needs a blob

Description

Allocate the ipc blob for all the modules

Returns 0, or -ENOMEM if memory can't be allocated.

int **lsm_msg_msg_alloc**(struct msg_msg *mp)
allocate a composite msg_msg blob

Parameters

struct msg_msg *mp
the msg_msg that needs a blob

Description

Allocate the ipc blob for all the modules

Returns 0, or -ENOMEM if memory can't be allocated.

void **lsm_early_task**(struct task_struct *task)
during initialization allocate a composite task blob

Parameters

struct task_struct *task
the task that needs a blob

Description

Allocate the task blob for all the modules

struct dentry ***securityfs_create_file**(const char *name, umode_t mode, struct dentry *parent, void *data, const struct file_operations *fops)
create a file in the securityfs filesystem

Parameters

const char *name
a pointer to a string containing the name of the file to create.

umode_t mode
the permission that the file should have

struct dentry *parent
a pointer to the parent dentry for this file. This should be a directory dentry if set. If this parameter is NULL, then the file will be created in the root of the securityfs filesystem.

void *data
a pointer to something that the caller will want to get to later on. The inode.i_private pointer will point to this value on the open() call.

const struct file_operations *fops
a pointer to a struct file_operations that should be used for this file.

Description

This function creates a file in securityfs with the given **name**.

This function returns a pointer to a dentry if it succeeds. This pointer must be passed to the *securityfs_remove()* function when the file is to be removed (no automatic cleanup happens if your module is unloaded, you are responsible here). If an error occurs, the function will return the error value (via ERR_PTR).

If securityfs is not enabled in the kernel, the value `-ENODEV` is returned.

struct dentry ***securityfs_create_dir**(const char *name, struct dentry *parent)
create a directory in the securityfs filesystem

Parameters

const char *name
a pointer to a string containing the name of the directory to create.

struct dentry *parent
a pointer to the parent dentry for this file. This should be a directory dentry if set. If this parameter is `NULL`, then the directory will be created in the root of the securityfs filesystem.

Description

This function creates a directory in securityfs with the given **name**.

This function returns a pointer to a dentry if it succeeds. This pointer must be passed to the *securityfs_remove()* function when the file is to be removed (no automatic cleanup happens if your module is unloaded, you are responsible here). If an error occurs, the function will return the error value (via ERR_PTR).

If securityfs is not enabled in the kernel, the value `-ENODEV` is returned.

struct dentry ***securityfs_create_symlink**(const char *name, struct dentry *parent, const char *target, const struct inode_operations *iops)
create a symlink in the securityfs filesystem

Parameters

const char *name
a pointer to a string containing the name of the symlink to create.

struct dentry *parent
a pointer to the parent dentry for the symlink. This should be a directory dentry if set. If this parameter is `NULL`, then the directory will be created in the root of the securityfs filesystem.

const char *target
: a pointer to a string containing the name of the symlink's target. If this parameter is NULL, then the **iops** parameter needs to be setup to handle .readlink and .get_link inode_operations.

const struct inode_operations *iops
: a pointer to the struct inode_operations to use for the symlink. If this parameter is NULL, then the default simple_symlink_inode operations will be used.

Description

This function creates a symlink in securityfs with the given **name**.

This function returns a pointer to a dentry if it succeeds. This pointer must be passed to the *securityfs_remove()* function when the file is to be removed (no automatic cleanup happens if your module is unloaded, you are responsible here). If an error occurs, the function will return the error value (via ERR_PTR).

If securityfs is not enabled in the kernel, the value -ENODEV is returned.

void **securityfs_remove**(struct *dentry* *dentry)
: removes a file or directory from the securityfs filesystem

Parameters

struct dentry *dentry
: a pointer to a the dentry of the file or directory to be removed.

Description

This function removes a file or directory in securityfs that was previously created with a call to another securityfs function (like *securityfs_create_file()* or variants thereof.)

This function is required to be called in order for the file to be removed. No automatic cleanup of files will happen when a module is removed; you are responsible here.

1.1.11 Audit Interfaces

struct audit_buffer ***audit_log_start**(struct audit_context *ctx, gfp_t gfp_mask, int type)
: obtain an audit buffer

Parameters

struct audit_context *ctx
: audit_context (may be NULL)

gfp_t gfp_mask
: type of allocation

int type
: audit message type

Description

Returns audit_buffer pointer on success or NULL on error.

Obtain an audit buffer. This routine does locking to obtain the audit buffer, but then no locking is required for calls to audit_log_*format. If the task (ctx) is a task that is currently in a syscall, then the syscall is marked as auditable and an audit record will be written at syscall exit. If there is no associated task, then task context (ctx) should be NULL.

void **audit_log_format**(struct audit_buffer *ab, const char *fmt, ...)

format a message into the audit buffer.

Parameters

struct audit_buffer *ab
audit_buffer

const char *fmt
format string

...
optional parameters matching **fmt** string

Description

All the work is done in audit_log_vformat.

void **audit_log_end**(struct audit_buffer *ab)

end one audit record

Parameters

struct audit_buffer *ab
the audit_buffer

Description

We can not do a netlink send inside an irq context because it blocks (last arg, flags, is not set to MSG_DONTWAIT), so the audit buffer is placed on a queue and a tasklet is scheduled to remove them from the queue outside the irq context. May be called in any context.

void **audit_log**(struct audit_context *ctx, gfp_t gfp_mask, int type, const char *fmt, ...)

Log an audit record

Parameters

struct audit_context *ctx
audit context

gfp_t gfp_mask
type of allocation

int type
audit message type

const char *fmt
format string to use

...
variable parameters matching the format string

Description

This is a convenience function that calls audit_log_start, audit_log_vformat, and audit_log_end. It may be called in any context.

int **audit_alloc**(struct task_struct *tsk)

allocate an audit context block for a task

Parameters

struct task_struct *tsk
task

Description

Filter on the task information and allocate a per-task audit context if necessary. Doing so turns on system call auditing for the specified task. This is called from copy_process, so no lock is needed.

void **__audit_free**(struct task_struct *tsk)

free a per-task audit context

Parameters

struct task_struct *tsk
task whose audit context block to free

Description

Called from copy_process and do_exit

void **__audit_syscall_entry**(int major, unsigned long a1, unsigned long a2, unsigned long a3, unsigned long a4)

fill in an audit record at syscall entry

Parameters

int major
major syscall type (function)

unsigned long a1
additional syscall register 1

unsigned long a2
additional syscall register 2

unsigned long a3
additional syscall register 3

unsigned long a4
additional syscall register 4

Description

Fill in audit context at syscall entry. This only happens if the audit context was created when the task was created and the state or filters demand the audit context be built. If the state from the per-task filter or from the per-syscall filter is AUDIT_RECORD_CONTEXT, then the record will be written at syscall exit time (otherwise, it will only be written if another part of the kernel requests that it be written).

void **__audit_syscall_exit**(int success, long return_code)

deallocate audit context after a system call

Parameters

int success
success value of the syscall

long return_code
return value of the syscall

Description

Tear down after system call. If the audit context has been marked as auditable (either because of the AUDIT_RECORD_CONTEXT state from filtering, or because some other part of the kernel wrote an audit message), then write out the syscall information. In call cases, free the names stored from getname().

struct filename ***__audit_reusename**(__user const char *uptr)

fill out filename with info from existing entry

Parameters

const __user char *uptr
userland ptr to pathname

Description

Search the audit_names list for the current audit context. If there is an existing entry with a matching "uptr" then return the filename associated with that audit_name. If not, return NULL.

void **__audit_getname**(struct filename *name)

add a name to the list

Parameters

struct filename *name
name to add

Description

Add a name to the list of audit names for this context. Called from fs/namei.c:getname().

void **__audit_inode**(struct filename *name, const struct *dentry* *dentry, unsigned int flags)

store the inode and device from a lookup

Parameters

struct filename *name
name being audited

const struct dentry *dentry
dentry being audited

unsigned int flags
attributes for this particular entry

int **auditsc_get_stamp**(struct audit_context *ctx, struct timespec64 *t, unsigned int *serial)

get local copies of audit_context values

Parameters

struct audit_context *ctx
audit_context for the task

struct timespec64 *t
timespec64 to store time recorded in the audit_context

unsigned int *serial
serial value that is recorded in the audit_context

Description

Also sets the context as auditable.

void **__audit_mq_open**(int oflag, umode_t mode, struct mq_attr *attr)

record audit data for a POSIX MQ open

Parameters

int oflag
open flag

umode_t mode
mode bits

struct mq_attr *attr
queue attributes

void **__audit_mq_sendrecv**(mqd_t mqdes, size_t msg_len, unsigned int msg_prio, const struct timespec64 *abs_timeout)

record audit data for a POSIX MQ timed send/receive

Parameters

mqd_t mqdes
MQ descriptor

size_t msg_len
Message length

unsigned int msg_prio
Message priority

const struct timespec64 *abs_timeout
Message timeout in absolute time

void **__audit_mq_notify**(mqd_t mqdes, const struct sigevent *notification)

record audit data for a POSIX MQ notify

Parameters

mqd_t mqdes
MQ descriptor

const struct sigevent *notification
Notification event

void **__audit_mq_getsetattr**(mqd_t mqdes, struct mq_attr *mqstat)
record audit data for a POSIX MQ get/set attribute

Parameters

mqd_t mqdes
MQ descriptor

struct mq_attr *mqstat
MQ flags

void **__audit_ipc_obj**(struct kern_ipc_perm *ipcp)
record audit data for ipc object

Parameters

struct kern_ipc_perm *ipcp
ipc permissions

void **__audit_ipc_set_perm**(unsigned long qbytes, uid_t uid, gid_t gid, umode_t mode)
record audit data for new ipc permissions

Parameters

unsigned long qbytes
msgq bytes

uid_t uid
msgq user id

gid_t gid
msgq group id

umode_t mode
msgq mode (permissions)

Description

Called only after audit_ipc_obj().

int **__audit_socketcall**(int nargs, unsigned long *args)
record audit data for sys_socketcall

Parameters

int nargs
number of args, which should not be more than AUDITSC_ARGS.

unsigned long *args
args array

void **__audit_fd_pair**(int fd1, int fd2)
record audit data for pipe and socketpair

Parameters

int fd1
the first file descriptor

int fd2
the second file descriptor

int **__audit_sockaddr**(int len, void *a)
record audit data for sys_bind, sys_connect, sys_sendto

Parameters

int len
data length in user space

void *a
data address in kernel space

Description

Returns 0 for success or NULL context or < 0 on error.

int **audit_signal_info_syscall**(struct task_struct *t)
record signal info for syscalls

Parameters

struct task_struct *t
task being signaled

Description

If the audit subsystem is being terminated, record the task (pid) and uid that is doing that.

int **__audit_log_bprm_fcaps**(struct linux_binprm *bprm, const struct cred *new, const struct cred *old)
store information about a loading bprm and relevant fcaps

Parameters

struct linux_binprm *bprm
pointer to the bprm being processed

const struct cred *new
the proposed new credentials

const struct cred *old
the old credentials

Description

Simply check if the proc already has the caps given by the file and if not store the priv escalation info for later auditing at the end of the syscall

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void **__audit_log_capset**(const struct cred *new, const struct cred *old)
store information about the arguments to the capset syscall

Parameters

const struct cred *new
the new credentials

const struct cred *old
the old (current) credentials

Description

Record the arguments userspace sent to sys_capset for later printing by the audit system if applicable

void **audit_core_dumps**(long signr)
record information about processes that end abnormally

Parameters

long signr
signal value

Description

If a process ends with a core dump, something fishy is going on and we should record the event for investigation.

void **audit_seccomp**(unsigned long syscall, long signr, int code)
record information about a seccomp action

Parameters

unsigned long syscall
syscall number

long signr
signal value

int code
the seccomp action

Description

Record the information associated with a seccomp action. Event filtering for seccomp actions that are not to be logged is done in seccomp_log(). Therefore, this function forces auditing independent of the audit_enabled and dummy context state because seccomp actions should be logged even when audit is not in use.

int **audit_rule_change**(int type, int seq, void *data, size_t datasz)
apply all rules to the specified message type

Parameters

int type
audit message type

int seq
netlink audit message sequence (serial) number

void *data
payload data

size_t datasz
size of payload data

int **audit_list_rules_send**(struct sk_buff *request_skb, int seq)
list the audit rules

Parameters

struct sk_buff *request_skb
skb of request we are replying to (used to target the reply)

int seq
netlink audit message sequence (serial) number

int **parent_len**(const char *path)
find the length of the parent portion of a pathname

Parameters

const char *path
pathname of which to determine length

int **audit_compare_dname_path**(const struct qstr *dname, const char *path, int parentlen)
compare given dentry name with last component in given path. Return of 0 indicates a match.

Parameters

const struct qstr *dname
dentry name that we're comparing

const char *path
full pathname that we're comparing

int parentlen
length of the parent if known. Passing in AUDIT_NAME_FULL here indicates that we must compute this value.

1.1.12 Accounting Framework

long **sys_acct**(const char __user *name)
enable/disable process accounting

Parameters

const char __user * name
file name for accounting records or NULL to shutdown accounting

Description

sys_acct() is the only system call needed to implement process accounting. It takes the name of the file where accounting records should be written. If the filename is NULL, accounting will be shutdown.

Return

0 for success or negative errno values for failure.

void **acct_collect**(long exitcode, int group_dead)
collect accounting information into pacct_struct

Parameters

long exitcode
task exit code

int group_dead
not 0, if this thread is the last one in the process.

void **acct_process**(void)
handles process accounting for an exiting task

Parameters

void
no arguments

1.1.13 Block Devices

void **blk_queue_flag_set**(unsigned int flag, struct request_queue *q)
atomically set a queue flag

Parameters

unsigned int flag
flag to be set

struct request_queue *q
request queue

void **blk_queue_flag_clear**(unsigned int flag, struct request_queue *q)
atomically clear a queue flag

Parameters

unsigned int flag
flag to be cleared

struct request_queue *q
request queue

bool **blk_queue_flag_test_and_set**(unsigned int flag, struct request_queue *q)
atomically test and set a queue flag

Parameters

unsigned int flag
flag to be set

struct request_queue *q
request queue

Description

Returns the previous value of **flag** - 0 if the flag was not set and 1 if the flag was already set.

const char ***blk_op_str**(unsigned int op)

Return string XXX in the REQ_OP_XXX.

Parameters

unsigned int op
REQ_OP_XXX.

Description

Centralize block layer function to convert REQ_OP_XXX into string format. Useful in the debugging and tracing bio or request. For invalid REQ_OP_XXX it returns string "UNKNOWN".

void **blk_sync_queue**(struct request_queue *q)

cancel any pending callbacks on a queue

Parameters

struct request_queue *q
the queue

Description

The block layer may perform asynchronous callback activity on a queue, such as calling the unplug function after a timeout. A block device may call blk_sync_queue to ensure that any such activity is cancelled, thus allowing it to release resources that the callbacks might use. The caller must already have made sure that its ->submit_bio will not re-add plugging prior to calling this function.

This function does not cancel any asynchronous activity arising out of elevator or throttling code. That would require elevator_exit() and blkcg_exit_queue() to be called with queue lock initialized.

void **blk_set_pm_only**(struct request_queue *q)

increment pm_only counter

Parameters

struct request_queue *q
request queue pointer

void **blk_put_queue**(struct request_queue *q)

decrement the request_queue refcount

Parameters

struct request_queue *q
the request_queue structure to decrement the refcount for

Description

Decrements the refcount of the request_queue kobject. When this reaches 0 we'll have *blk_release_queue()* called.

Context

Any context, but the last reference must not be dropped from atomic context.

void **blk_cleanup_queue**(struct request_queue *q)

shutdown a request queue

Parameters

struct request_queue *q
request queue to shutdown

Description

Mark **q** DYING, drain all pending requests, mark **q** DEAD, destroy and put it. All future requests will be failed immediately with -ENODEV.

Context

can sleep

bool **blk_get_queue**(struct request_queue *q)

increment the request_queue refcount

Parameters

struct request_queue *q
the request_queue structure to increment the refcount for

Description

Increment the refcount of the request_queue kobject.

Context

Any context.

struct request ***blk_get_request**(struct request_queue *q, unsigned int op, blk_mq_req_flags_t flags)

allocate a request

Parameters

struct request_queue *q
request queue to allocate a request for

unsigned int op
operation (REQ_OP_*) and REQ_* flags, e.g. REQ_SYNC.

blk_mq_req_flags_t flags
BLK_MQ_REQ_* flags, e.g. BLK_MQ_REQ_NOWAIT.

blk_qc_t **submit_bio_noacct**(struct *bio* *bio)

re-submit a bio to the block device layer for I/O

Parameters

struct bio *bio
The bio describing the location in memory and on the device.

Description

This is a version of *submit_bio()* that shall only be used for I/O that is resubmitted to lower level drivers by stacking block drivers. All file systems and other upper level users of the block layer should use *submit_bio()* instead.

blk_qc_t **submit_bio**(struct *bio* *bio)

submit a bio to the block device layer for I/O

Parameters

struct bio *bio

The struct bio which describes the I/O

Description

submit_bio() is used to submit I/O requests to block devices. It is passed a fully set up struct bio that describes the I/O that needs to be done. The bio will be send to the device described by the bi_disk and bi_partno fields.

The success/failure status of the request, along with notification of completion, is delivered asynchronously through the ->bi_end_io() callback in **bio**. The bio must NOT be touched by thecaller until ->bi_end_io() has been called.

blk_status_t **blk_insert_cloned_request**(struct request_queue *q, struct request *rq)

Helper for stacking drivers to submit a request

Parameters

struct request_queue *q

the queue to submit the request

struct request *rq

the request being queued

unsigned int **blk_rq_err_bytes**(const struct request *rq)

determine number of bytes till the next failure boundary

Parameters

const struct request *rq

request to examine

Description

A request could be merge of IOs which require different failure handling. This function determines the number of bytes which can be failed from the beginning of the request without crossing into area which need to be retried further.

Return

The number of bytes to fail.

bool **blk_update_request**(struct request *req, blk_status_t error, unsigned int nr_bytes)

Special helper function for request stacking drivers

Parameters

struct request *req

the request being processed

blk_status_t error

block status code

unsigned int nr_bytes
number of bytes to complete **req**

Description

Ends I/O on a number of bytes attached to **req**, but doesn't complete the request structure even if **req** doesn't have leftover. If **req** has leftover, sets it up for the next range of segments.

This special helper function is only for request stacking drivers (e.g. request-based dm) so that they can handle partial completion. Actual device drivers should use blk_mq_end_request instead.

Passing the result of blk_rq_bytes() as **nr_bytes** guarantees `false` return from this function.

Note

The RQF_SPECIAL_PAYLOAD flag is ignored on purpose in both blk_rq_bytes() and in *blk_update_request()*.

Return

`false` - this request doesn't have any more data `true` - this request has more data

void **rq_flush_dcache_pages**(struct request *rq)
Helper function to flush all pages in a request

Parameters

struct request *rq
the request to be flushed

Description

Flush all pages in **rq**.

int **blk_lld_busy**(struct request_queue *q)
Check if underlying low-level drivers of a device are busy

Parameters

struct request_queue *q
the queue of the device being checked

Description

Check if underlying low-level drivers of a device are busy. If the drivers want to export their busy state, they must set own exporting function using blk_queue_lld_busy() first.

Basically, this function is used only by request stacking drivers to stop dispatching requests to underlying devices when underlying devices are busy. This behavior helps more I/O merging on the queue of the request stacking driver and prevents I/O throughput regression on burst I/O load.

Return

0 - Not busy (The request stacking driver should dispatch request) 1 - Busy (The request stacking driver should stop dispatching request)

void **blk_rq_unprep_clone**(struct request *rq)

Helper function to free all bios in a cloned request

Parameters

struct request *rq
the clone request to be cleaned up

Description

Free all bios in **rq** for a cloned request.

int **blk_rq_prep_clone**(struct request *rq, struct request *rq_src, struct bio_set *bs, gfp_t gfp_mask, int (*bio_ctr)(struct bio*, struct bio*, void*), void *data)

Helper function to setup clone request

Parameters

struct request *rq
the request to be setup

struct request *rq_src
original request to be cloned

struct bio_set *bs
bio_set that bios for clone are allocated from

gfp_t gfp_mask
memory allocation mask for bio

int (*bio_ctr)(struct bio *, struct bio *, void *)
setup function to be called for each clone bio. Returns `0` for success, non `0` for failure.

void *data
private data to be passed to **bio_ctr**

Description

Clones bios in **rq_src** to **rq**, and copies attributes of **rq_src** to **rq**. Also, pages which the original bios are pointing to are not copied and the cloned bios just point same pages. So cloned bios must be completed before original bios, which means the caller must complete **rq** before **rq_src**.

void **blk_start_plug**(struct blk_plug *plug)

initialize blk_plug and track it inside the task_struct

Parameters

struct blk_plug *plug
The `struct blk_plug` that needs to be initialized

Description

blk_start_plug() indicates to the block layer an intent by the caller to submit multiple I/O requests in a batch. The block layer may use this hint to defer submitting I/Os from the caller until *blk_finish_plug()* is called. However, the block layer may choose to submit requests before a call to *blk_finish_plug()* if the number of queued I/Os exceeds BLK_MAX_REQUEST_COUNT, or if the size of the I/O is larger than BLK_PLUG_FLUSH_SIZE. The queued I/Os may also be submitted early if the task schedules (see below).

Tracking blk_plug inside the task_struct will help with auto-flushing the pending I/O should the task end up blocking between *blk_start_plug()* and *blk_finish_plug()*. This is important from a performance perspective, but also ensures that we don't deadlock. For instance, if the task is blocking for a memory allocation, memory reclaim could end up wanting to free a page belonging to that request that is currently residing in our private plug. By flushing the pending I/O when the process goes to sleep, we avoid this kind of deadlock.

void **blk_finish_plug**(struct blk_plug *plug)

mark the end of a batch of submitted I/O

Parameters

struct blk_plug *plug
The `struct blk_plug` passed to *blk_start_plug()*

Description

Indicate that a batch of I/O submissions is complete. This function must be paired with an initial call to *blk_start_plug()*. The intent is to allow the block layer to optimize I/O submission. See the documentation for *blk_start_plug()* for more information.

int **blk_queue_enter**(struct request_queue *q, blk_mq_req_flags_t flags)

try to increase q->q_usage_counter

Parameters

struct request_queue *q
request queue pointer

blk_mq_req_flags_t flags
BLK_MQ_REQ_NOWAIT and/or BLK_MQ_REQ_PM

blk_status_t **blk_cloned_rq_check_limits**(struct request_queue *q, struct request *rq)

Helper function to check a cloned request for the new queue limits

Parameters

struct request_queue *q
the queue

struct request *rq
the request being checked

Description

rq may have been made based on weaker limitations of upper-level queues in request stacking drivers, and it may violate the limitation of **q**. Since the block layer and the underlying device driver trust **rq** after it is inserted to **q**, it should be checked against **q** before the insertion using this generic function.

Request stacking drivers like request-based dm may change the queue limits when retrying requests on other queues. Those requests need to be checked against the new queue limits again during dispatch.

int **blk_rq_map_user_iov**(struct request_queue *q, struct request *rq, struct rq_map_data *map_data, const struct iov_iter *iter, gfp_t gfp_mask)

map user data to a request, for passthrough requests

Parameters

struct request_queue *q
request queue where request should be inserted

struct request *rq
request to map data to

struct rq_map_data *map_data
pointer to the rq_map_data holding pages (if necessary)

const struct iov_iter *iter
iovec iterator

gfp_t gfp_mask
memory allocation flags

Description

Data will be mapped directly for zero copy I/O, if possible. Otherwise a kernel bounce buffer is used.

A matching *blk_rq_unmap_user()* must be issued at the end of I/O, while still in process context.

Note

The mapped bio may need to be bounced through blk_queue_bounce()
before being submitted to the device, as pages mapped may be out of reach. It's the callers responsibility to make sure this happens. The original bio must be passed back in to *blk_rq_unmap_user()* for proper unmapping.

int **blk_rq_unmap_user**(struct *bio* *bio)

unmap a request with user data

Parameters

struct bio *bio
start of bio list

Description

Unmap a rq previously mapped by blk_rq_map_user(). The caller must supply the original rq->bio from the blk_rq_map_user() return, since the I/O completion may have changed rq->bio.

int **blk_rq_map_kern**(struct request_queue *q, struct request *rq, void *kbuf, unsigned int len, gfp_t gfp_mask) map kernel data to a request, for passthrough requests

Parameters

struct request_queue *q
request queue where request should be inserted

struct request *rq
request to fill

void *kbuf
the kernel buffer

unsigned int len
length of user data

gfp_t gfp_mask
memory allocation flags

Description

Data will be mapped directly if possible. Otherwise a bounce buffer is used. Can be called multiple times to append multiple buffers.

void **blk_release_queue**(struct kobject *kobj)

releases all allocated resources of the request_queue

Parameters

struct kobject *kobj
pointer to a kobject, whose container is a request_queue

Description

This function releases all allocated resources of the request queue.

The struct request_queue refcount is incremented with *blk_get_queue()* and decremented with *blk_put_queue()*. Once the refcount reaches 0 this function is called.

For drivers that have a request_queue on a gendisk and added with *__device_add_disk()* the refcount to request_queue will reach 0 with the last *put_disk()* called by the driver. For drivers which don't use *__device_add_disk()* this happens with *blk_cleanup_queue()*.

Drivers exist which depend on the release of the request_queue to be synchronous, it should not be deferred.

Context

can sleep

void **blk_unregister_queue**(struct gendisk *disk)

counterpart of blk_register_queue()

Parameters

struct gendisk *disk
Disk of which the request queue should be unregistered from sysfs.

Note

the caller is responsible for guaranteeing that this function is called after blk_register_queue() has finished.

void **blk_set_default_limits**(struct queue_limits *lim)
reset limits to default values

Parameters

struct queue_limits *lim
the queue_limits structure to reset

Description

Returns a queue_limit struct to its default state.

void **blk_set_stacking_limits**(struct queue_limits *lim)
set default limits for stacking devices

Parameters

struct queue_limits *lim
the queue_limits structure to reset

Description

Returns a queue_limit struct to its default state. Should be used by stacking drivers like DM that have no internal limits.

void **blk_queue_bounce_limit**(struct request_queue *q, u64 max_addr)
set bounce buffer limit for queue

Parameters

struct request_queue *q
the request queue for the device

u64 max_addr
the maximum address the device can handle

Description

Different hardware can have different requirements as to what pages it can do I/O directly to. A low level driver can call blk_queue_bounce_limit to have lower memory pages allocated as bounce buffers for doing I/O to pages residing above **max_addr**.

void **blk_queue_max_hw_sectors**(struct request_queue *q, unsigned int max_hw_sectors)
set max sectors for a request for this queue

Parameters

struct request_queue *q
the request queue for the device

unsigned int max_hw_sectors
max hardware sectors in the usual 512b unit

Description

Enables a low level driver to set a hard upper limit, max_hw_sectors, on the size of requests. max_hw_sectors is set by the device driver based upon the capabilities of the I/O controller.

max_dev_sectors is a hard limit imposed by the storage device for READ/WRITE requests. It is set by the disk driver.

max_sectors is a soft limit imposed by the block layer for filesystem type requests. This value can be overridden on a per-device basis in /sys/block/<device>/queue/max_sectors_kb. The soft limit can not exceed max_hw_sectors.

void **blk_queue_chunk_sectors**(struct request_queue *q, unsigned int chunk_sectors)

set size of the chunk for this queue

Parameters

struct request_queue *q
the request queue for the device

unsigned int chunk_sectors
chunk sectors in the usual 512b unit

Description

If a driver doesn't want IOs to cross a given chunk size, it can set this limit and prevent merging across chunks. Note that the block layer must accept a page worth of data at any offset. So if the crossing of chunks is a hard limitation in the driver, it must still be prepared to split single page bios.

void **blk_queue_max_discard_sectors**(struct request_queue *q, unsigned int max_discard_sectors)

set max sectors for a single discard

Parameters

struct request_queue *q
the request queue for the device

unsigned int max_discard_sectors
maximum number of sectors to discard

void **blk_queue_max_write_same_sectors**(struct request_queue *q, unsigned int max_write_same_sectors)

set max sectors for a single write same

Parameters

struct request_queue *q
the request queue for the device

unsigned int max_write_same_sectors
maximum number of sectors to write per command

void **blk_queue_max_write_zeroes_sectors**(struct request_queue *q, unsigned int max_write_zeroes_sectors)

set max sectors for a single write zeroes

Parameters

struct request_queue *q
: the request queue for the device

unsigned int max_write_zeroes_sectors
: maximum number of sectors to write per command

void **blk_queue_max_zone_append_sectors**(struct request_queue *q, unsigned int max_zone_append_sectors)

set max sectors for a single zone append

Parameters

struct request_queue *q
: the request queue for the device

unsigned int max_zone_append_sectors
: maximum number of sectors to write per command

void **blk_queue_max_segments**(struct request_queue *q, unsigned short max_segments)

set max hw segments for a request for this queue

Parameters

struct request_queue *q
: the request queue for the device

unsigned short max_segments
: max number of segments

Description

Enables a low level driver to set an upper limit on the number of hw data segments in a request.

void **blk_queue_max_discard_segments**(struct request_queue *q, unsigned short max_segments)

set max segments for discard requests

Parameters

struct request_queue *q
: the request queue for the device

unsigned short max_segments
: max number of segments

Description

Enables a low level driver to set an upper limit on the number of segments in a discard request.

void **blk_queue_max_segment_size**(struct request_queue *q, unsigned int max_size)

set max segment size for blk_rq_map_sg

Parameters

struct request_queue *q
the request queue for the device

unsigned int max_size
max size of segment in bytes

Description

Enables a low level driver to set an upper limit on the size of a coalesced segment

void **blk_queue_logical_block_size**(struct request_queue *q, unsigned int size)

set logical block size for the queue

Parameters

struct request_queue *q
the request queue for the device

unsigned int size
the logical block size, in bytes

Description

This should be set to the lowest possible block size that the storage device can address. The default of 512 covers most hardware.

void **blk_queue_physical_block_size**(struct request_queue *q, unsigned int size)

set physical block size for the queue

Parameters

struct request_queue *q
the request queue for the device

unsigned int size
the physical block size, in bytes

Description

This should be set to the lowest possible sector size that the hardware can operate on without reverting to read-modify-write operations.

void **blk_queue_zone_write_granularity**(struct request_queue *q, unsigned int size)

set zone write granularity for the queue

Parameters

struct request_queue *q
the request queue for the zoned device

unsigned int size
the zone write granularity size, in bytes

Description

This should be set to the lowest possible size allowing to write in sequential zones of a zoned block device.

void **blk_queue_alignment_offset**(struct request_queue *q, unsigned int offset)

set physical block alignment offset

Parameters

struct request_queue *q
the request queue for the device

unsigned int offset
alignment offset in bytes

Description

Some devices are naturally misaligned to compensate for things like the legacy DOS partition table 63-sector offset. Low-level drivers should call this function for devices whose first sector is not naturally aligned.

void **blk_limits_io_min**(struct queue_limits *limits, unsigned int min)

set minimum request size for a device

Parameters

struct queue_limits *limits
the queue limits

unsigned int min
smallest I/O size in bytes

Description

Some devices have an internal block size bigger than the reported hardware sector size. This function can be used to signal the smallest I/O the device can perform without incurring a performance penalty.

void **blk_queue_io_min**(struct request_queue *q, unsigned int min)

set minimum request size for the queue

Parameters

struct request_queue *q
the request queue for the device

unsigned int min
smallest I/O size in bytes

Description

Storage devices may report a granularity or preferred minimum I/O size which is the smallest request the device can perform without incurring a performance penalty. For disk drives this is often the physical block size. For RAID arrays it is often the stripe chunk size. A properly aligned multiple of minimum_io_size is the preferred request size for workloads where a high number of I/O operations is desired.

void **blk_limits_io_opt**(struct queue_limits *limits, unsigned int opt)

set optimal request size for a device

Parameters

struct queue_limits *limits
: the queue limits

unsigned int opt
: smallest I/O size in bytes

Description

Storage devices may report an optimal I/O size, which is the device's preferred unit for sustained I/O. This is rarely reported for disk drives. For RAID arrays it is usually the stripe width or the internal track size. A properly aligned multiple of optimal_io_size is the preferred request size for workloads where sustained throughput is desired.

void **blk_queue_io_opt**(struct request_queue *q, unsigned int opt)

set optimal request size for the queue

Parameters

struct request_queue *q
: the request queue for the device

unsigned int opt
: optimal request size in bytes

Description

Storage devices may report an optimal I/O size, which is the device's preferred unit for sustained I/O. This is rarely reported for disk drives. For RAID arrays it is usually the stripe width or the internal track size. A properly aligned multiple of optimal_io_size is the preferred request size for workloads where sustained throughput is desired.

int **blk_stack_limits**(struct queue_limits *t, struct queue_limits *b, sector_t start)

adjust queue_limits for stacked devices

Parameters

struct queue_limits *t
: the stacking driver limits (top device)

struct queue_limits *b
: the underlying queue limits (bottom, component device)

sector_t start
: first data sector within component device

Description

This function is used by stacking drivers like MD and DM to ensure that all component devices have compatible block sizes and alignments. The stacking driver must provide a queue_limits struct (top) and then iteratively call the stacking function for all component (bottom) devices. The stacking function will attempt to combine the values and ensure proper alignment.

Returns 0 if the top and bottom queue_limits are compatible. The top device's block sizes and alignment offsets may be adjusted to ensure alignment with the bottom device. If no compatible sizes and alignments exist, -1 is returned and the resulting top queue_limits will have the misaligned flag set to indicate that the alignment_offset is undefined.

void **disk_stack_limits**(struct gendisk *disk, struct block_device *bdev, sector_t offset)

adjust queue limits for stacked drivers

Parameters

struct gendisk *disk
MD/DM gendisk (top)

struct block_device *bdev
the underlying block device (bottom)

sector_t offset
offset to beginning of data within component device

Description

Merges the limits for a top level gendisk and a bottom level block_device.

void **blk_queue_update_dma_pad**(struct request_queue *q, unsigned int mask)

update pad mask

Parameters

struct request_queue *q
the request queue for the device

unsigned int mask
pad mask

Description

Update dma pad mask.

Appending pad buffer to a request modifies the last entry of a scatter list such that it includes the pad buffer.

void **blk_queue_segment_boundary**(struct request_queue *q, unsigned long mask)

set boundary rules for segment merging

Parameters

struct request_queue *q
the request queue for the device

unsigned long mask
the memory boundary mask

void **blk_queue_virt_boundary**(struct request_queue *q, unsigned long mask)

set boundary rules for bio merging

Parameters

struct request_queue *q
the request queue for the device

unsigned long mask
the memory boundary mask

void **blk_queue_dma_alignment**(struct request_queue *q, int mask)
set dma length and memory alignment

Parameters

struct request_queue *q
the request queue for the device

int mask
alignment mask

Description

set required memory and length alignment for direct dma transactions. this is used when building direct io requests for the queue.

void **blk_queue_update_dma_alignment**(struct request_queue *q, int mask)
update dma length and memory alignment

Parameters

struct request_queue *q
the request queue for the device

int mask
alignment mask

Description

update required memory and length alignment for direct dma transactions. If the requested alignment is larger than the current alignment, then the current queue alignment is updated to the new value, otherwise it is left alone. The design of this is to allow multiple objects (driver, device, transport etc) to set their respective alignments without having them interfere.

void **blk_set_queue_depth**(struct request_queue *q, unsigned int depth)
tell the block layer about the device queue depth

Parameters

struct request_queue *q
the request queue for the device

unsigned int depth
queue depth

void **blk_queue_write_cache**(struct request_queue *q, bool wc, bool fua)
configure queue's write cache

Parameters

struct request_queue *q
the request queue for the device

bool wc
write back cache on or off

bool fua
device supports FUA writes, if true

Description

Tell the block layer about the write cache of **q**.

void **blk_queue_required_elevator_features**(struct request_queue *q, unsigned int features)
Set a queue required elevator features

Parameters

struct request_queue *q
the request queue for the target device

unsigned int features
Required elevator features OR'ed together

Description

Tell the block layer that for the device controlled through **q**, only the only elevators that can be used are those that implement at least the set of features specified by **features**.

bool **blk_queue_can_use_dma_map_merging**(struct request_queue *q, struct device *dev)
configure queue for merging segments.

Parameters

struct request_queue *q
the request queue for the device

struct device *dev
the device pointer for dma

Description

Tell the block layer about merging the segments by dma map of **q**.

void **blk_queue_set_zoned**(struct gendisk *disk, enum blk_zoned_model model)
configure a disk queue zoned model.

Parameters

struct gendisk *disk
the gendisk of the queue to configure

enum blk_zoned_model model
the zoned model to set

Description

Set the zoned model of the request queue of **disk** according to **model**. When **model** is BLK_ZONED_HM (host managed), this should be called only if zoned block device support is enabled (CONFIG_BLK_DEV_ZONED option). If **model** specifies BLK_ZONED_HA (host aware), the effective model used depends on CONFIG_BLK_DEV_ZONED settings and on the existence of partitions on the disk.

void **blk_execute_rq_nowait**(struct request_queue *q, struct gendisk *bd_disk, struct request *rq, int at_head, rq_end_io_fn *done)

insert a request into queue for execution

Parameters

struct request_queue *q
queue to insert the request in

struct gendisk *bd_disk
matching gendisk

struct request *rq
request to insert

int at_head
insert request at head or tail of queue

rq_end_io_fn *done
I/O completion handler

Description

Insert a fully prepared request at the back of the I/O scheduler queue for execution. Don't wait for completion.

Note

This function will invoke **done** directly if the queue is dead.

void **blk_execute_rq**(struct request_queue *q, struct gendisk *bd_disk, struct request *rq, int at_head)

insert a request into queue for execution

Parameters

struct request_queue *q
queue to insert the request in

struct gendisk *bd_disk
matching gendisk

struct request *rq
request to insert

int at_head
insert request at head or tail of queue

Description

Insert a fully prepared request at the back of the I/O scheduler queue for execution and wait for completion.

int **blkdev_issue_flush**(struct block_device *bdev, gfp_t gfp_mask)

queue a flush

Parameters

struct block_device *bdev
blockdev to issue flush for

gfp_t gfp_mask
memory allocation flags (for bio_alloc)

Description

Issue a flush for the block device in question.

int **blkdev_issue_discard**(struct block_device *bdev, sector_t sector, sector_t nr_sects, gfp_t gfp_mask, unsigned long flags)

queue a discard

Parameters

struct block_device *bdev
blockdev to issue discard for

sector_t sector
start sector

sector_t nr_sects
number of sectors to discard

gfp_t gfp_mask
memory allocation flags (for bio_alloc)

unsigned long flags
BLKDEV_DISCARD_* flags to control behaviour

Description

Issue a discard request for the sectors in question.

int **blkdev_issue_write_same**(struct block_device *bdev, sector_t sector, sector_t nr_sects, gfp_t gfp_mask, struct *page* *page)

queue a write same operation

Parameters

struct block_device *bdev
target blockdev

sector_t sector
start sector

sector_t nr_sects
number of sectors to write

gfp_t gfp_mask
memory allocation flags (for bio_alloc)

struct page *page
page containing data

Description

Issue a write same request for the sectors in question.

int **__blkdev_issue_zeroout**(struct block_device *bdev, sector_t sector, sector_t nr_sects, gfp_t gfp_mask, struct bio **biop, unsigned flags) generate number of zero filed write bios

Parameters

struct block_device *bdev
blockdev to issue

sector_t sector
start sector

sector_t nr_sects
number of sectors to write

gfp_t gfp_mask
memory allocation flags (for bio_alloc)

struct bio **biop
pointer to anchor bio

unsigned flags
controls detailed behavior

Description

Zero-fill a block range, either using hardware offload or by explicitly writing zeroes to the device.

If a device is using logical block provisioning, the underlying space will not be released if `flags` contains BLKDEV_ZERO_NOUNMAP.

If `flags` contains BLKDEV_ZERO_NOFALLBACK, the function will return -EOPNOTSUPP if no explicit hardware offload for zeroing is provided.

int **blkdev_issue_zeroout**(struct block_device *bdev, sector_t sector, sector_t nr_sects, gfp_t gfp_mask, unsigned flags)

zero-fill a block range

Parameters

struct block_device *bdev
blockdev to write

sector_t sector
start sector

sector_t nr_sects
number of sectors to write

gfp_t gfp_mask
memory allocation flags (for bio_alloc)

unsigned flags
controls detailed behavior

Description

Zero-fill a block range, either using hardware offload or by explicitly writing zeroes to the device. See *__blkdev_issue_zeroout()* for the valid values for `flags`.

int **blk_rq_count_integrity_sg**(struct request_queue *q, struct *bio* *bio)

Count number of integrity scatterlist elements

Parameters

struct request_queue *q
request queue

struct bio *bio
bio with integrity metadata attached

Description

Returns the number of elements required in a scatterlist corresponding to the integrity metadata in a bio.

int **blk_rq_map_integrity_sg**(struct request_queue *q, struct *bio* *bio, struct scatterlist *sglist)

Map integrity metadata into a scatterlist

Parameters

struct request_queue *q
request queue

struct bio *bio
bio with integrity metadata attached

struct scatterlist *sglist
target scatterlist

Description

Map the integrity vectors in request into a scatterlist. The scatterlist must be big enough to hold all elements. I.e. sized using *blk_rq_count_integrity_sg()*.

int **blk_integrity_compare**(struct gendisk *gd1, struct gendisk *gd2)

Compare integrity profile of two disks

Parameters

struct gendisk *gd1
Disk to compare

struct gendisk *gd2
Disk to compare

Description

Meta-devices like DM and MD need to verify that all sub-devices use the same integrity format before advertising to upper layers that they can send/receive integrity metadata. This function can be used to check whether two gendisk devices have compatible integrity formats.

void **blk_integrity_register**(struct gendisk *disk, struct blk_integrity *template)

Register a gendisk as being integrity-capable

Parameters

struct gendisk *disk
struct gendisk pointer to make integrity-aware

struct blk_integrity *template
block integrity profile to register

Description

When a device needs to advertise itself as being able to send/receive integrity metadata it must use this function to register the capability with the block layer. The template is a blk_integrity struct with values appropriate for the underlying hardware. See Documentation/block/data-integrity.rst.

void **blk_integrity_unregister**(struct gendisk *disk)
Unregister block integrity profile

Parameters

struct gendisk *disk
disk whose integrity profile to unregister

Description

This function unregisters the integrity capability from a block device.

int **blk_trace_ioctl**(struct block_device *bdev, unsigned cmd, char __user *arg)
handle the ioctls associated with tracing

Parameters

struct block_device *bdev
the block device

unsigned cmd
the ioctl cmd

char __user *arg
the argument data, if any

void **blk_trace_shutdown**(struct request_queue *q)
stop and cleanup trace structures

Parameters

struct request_queue *q
the request queue associated with the device

void **blk_add_trace_rq**(struct request *rq, int error, unsigned int nr_bytes, u32 what, u64 cgid)
Add a trace for a request oriented action

Parameters

struct request *rq
the source request

int error
return status to log

unsigned int nr_bytes
number of completed bytes

u32 what
the action

u64 cgid
the cgroup info

Description

Records an action against a request. Will log the bio offset + size.

void **blk_add_trace_bio**(struct request_queue *q, struct *bio* *bio, u32 what, int error)

Add a trace for a bio oriented action

Parameters

struct request_queue *q
queue the io is for

struct bio *bio
the source bio

u32 what
the action

int error
error, if any

Description

Records an action against a bio. Will log the bio offset + size.

void **blk_add_trace_bio_remap**(void *ignore, struct request_queue *q, struct *bio* *bio, dev_t dev, sector_t from)

Add a trace for a bio-remap operation

Parameters

void *ignore
trace callback data parameter (not used)

struct request_queue *q
queue the io is for

struct bio *bio
the source bio

dev_t dev
target device

sector_t from
source sector

Description

Device mapper or raid target sometimes need to split a bio because it spans a stripe (or similar). Add a trace for that action.

void **blk_add_trace_rq_remap**(void *ignore, struct request *rq, dev_t dev, sector_t from)

Add a trace for a request-remap operation

Parameters

void *ignore
trace callback data parameter (not used)

struct request *rq
the source request

dev_t dev
target device

sector_t from
source sector

Description

Device mapper remaps request to other devices. Add a trace for that action.

struct hd_struct ***disk_get_part**(struct gendisk *disk, int partno)
get partition

Parameters

struct gendisk *disk
disk to look partition from

int partno
partition number

Description

Look for partition **partno** from **disk**. If found, increment reference count and return it.

Context

Don't care.

Return

Pointer to the found partition on success, NULL if not found.

struct hd_struct ***disk_map_sector_rcu**(struct gendisk *disk, sector_t sector)
map sector to partition

Parameters

struct gendisk *disk
gendisk of interest

sector_t sector
sector to map

Description

Find out which partition **sector** maps to on **disk**. This is primarily used for stats accounting.

Context

RCU read locked. The returned partition pointer is always valid because its refcount is grabbed except for part0, which lifetime is same with the disk.

Return

Found partition on success, part0 is returned if no partition matches or the matched partition is being deleted.

int **blk_mangle_minor**(int minor)
scatter minor numbers apart

Parameters

int minor
minor number to mangle

Description

Scatter consecutively allocated **minor** number apart if MANGLE_DEVT is enabled. Mangling twice gives the original value.

Return

Mangled value.

Context

Don't care.

int **blk_alloc_devt**(struct hd_struct *part, dev_t *devt)
allocate a dev_t for a partition

Parameters

struct hd_struct *part
partition to allocate dev_t for

dev_t *devt
out parameter for resulting dev_t

Description

Allocate a dev_t for block device.

Return

0 on success, allocated dev_t is returned in ***devt**. -errno on failure.

Context

Might sleep.

void **blk_free_devt**(dev_t devt)
free a dev_t

Parameters

dev_t devt
dev_t to free

Description

Free **devt** which was allocated using *blk_alloc_devt()*.

Context

Might sleep.

void **__device_add_disk**(struct device *parent, struct gendisk *disk, const struct attribute_group **groups, bool register_queue)

add disk information to kernel list

Parameters

struct device *parent
parent device for the disk

struct gendisk *disk
per-device partitioning information

const struct attribute_group **groups
Additional per-device sysfs groups

bool register_queue
register the queue if set to true

Description

This function registers the partitioning information in **disk** with the kernel.

FIXME: error handling

struct gendisk ***get_gendisk**(dev_t devt, int *partno)

get partitioning information for a given device

Parameters

dev_t devt
device to get partitioning information for

int *partno
returned partition index

Description

This function gets the structure containing partitioning information for the given device **devt**.

Context

can sleep

void **disk_replace_part_tbl**(struct gendisk *disk, struct disk_part_tbl *new_ptbl)

replace disk->part_tbl in RCU-safe way

Parameters

struct gendisk *disk
disk to replace part_tbl for

struct disk_part_tbl *new_ptbl
new part_tbl to install

Description

Replace disk->part_tbl with **new_ptbl** in RCU-safe way. The original ptbl is freed using RCU callback.

LOCKING: Matching bd_mutex locked or the caller is the only user of **disk**.

int **disk_expand_part_tbl**(struct gendisk *disk, int partno)
expand disk->part_tbl

Parameters

struct gendisk *disk
disk to expand part_tbl for

int partno
expand such that this partno can fit in

Description

Expand disk->part_tbl such that **partno** can fit in. disk->part_tbl uses RCU to allow unlocked dereferencing for stats and other stuff.

LOCKING: Matching bd_mutex locked or the caller is the only user of **disk**. Might sleep.

Return

0 on success, -errno on failure.

void **disk_release**(struct device *dev)
releases all allocated resources of the gendisk

Parameters

struct device *dev
the device representing this disk

Description

This function releases all allocated resources of the gendisk.

The struct gendisk refcount is incremented with *get_gendisk()* or *get_disk_and_module()*, and its refcount is decremented with *put_disk_and_module()* or *put_disk()*. Once the refcount reaches 0 this function is called.

Drivers which used *__device_add_disk()* have a gendisk with a request_queue assigned. Since the request_queue sits on top of the gendisk for these drivers we also call *blk_put_queue()* for them, and we expect the request_queue refcount to reach 0 at this point, and so the request_queue will also be freed prior to the disk.

Context

can sleep

void **disk_block_events**(struct gendisk *disk)
block and flush disk event checking

Parameters

struct gendisk *disk
disk to block events for

Description

On return from this function, it is guaranteed that event checking isn't in progress and won't happen until unblocked by *disk_unblock_events()*. Events blocking is counted and the actual unblocking happens after the matching number of unblocks are done.

Note that this intentionally does not block event checking from *disk_clear_events()*.

Context

Might sleep.

void **disk_unblock_events**(struct gendisk *disk)
unblock disk event checking

Parameters

struct gendisk *disk
disk to unblock events for

Description

Undo *disk_block_events()*. When the block count reaches zero, it starts events polling if configured.

Context

Don't care. Safe to call from irq context.

void **disk_flush_events**(struct gendisk *disk, unsigned int mask)
schedule immediate event checking and flushing

Parameters

struct gendisk *disk
disk to check and flush events for

unsigned int mask
events to flush

Description

Schedule immediate event checking on **disk** if not blocked. Events in **mask** are scheduled to be cleared from the driver. Note that this doesn't clear the events from **disk->ev**.

Context

If **mask** is non-zero must be called with bdev->bd_mutex held.

unsigned int **disk_clear_events**(struct gendisk *disk, unsigned int mask)
synchronously check, clear and return pending events

Parameters

struct gendisk *disk
disk to fetch and clear events from

unsigned int mask
mask of events to be fetched and cleared

Description

Disk events are synchronously checked and pending events in **mask** are cleared and returned. This ignores the block count.

Context

Might sleep.

void **disk_part_iter_init**(struct disk_part_iter *piter, struct gendisk *disk, unsigned int flags)

initialize partition iterator

Parameters

struct disk_part_iter *piter
iterator to initialize

struct gendisk *disk
disk to iterate over

unsigned int flags
DISK_PITER_* flags

Description

Initialize **piter** so that it iterates over partitions of **disk**.

Context

Don't care.

struct hd_struct ***disk_part_iter_next**(struct disk_part_iter *piter)

proceed iterator to the next partition and return it

Parameters

struct disk_part_iter *piter
iterator of interest

Description

Proceed **piter** to the next partition and return it.

Context

Don't care.

void **disk_part_iter_exit**(struct disk_part_iter *piter)

finish up partition iteration

Parameters

struct disk_part_iter *piter
iter of interest

Description

Called when iteration is over. Cleans up **piter**.

Context

Don't care.

bool **disk_has_partitions**(struct gendisk *disk)

Parameters

struct gendisk *disk
gendisk of interest

Description

Walk through the partition table and check if valid partition exists.

Context

Don't care.

Return

True if the gendisk has at least one valid non-zero size partition. Otherwise false.

int **register_blkdev**(unsigned int major, const char *name)
register a new block device

Parameters

unsigned int major
the requested major device number [1..BLKDEV_MAJOR_MAX-1]. If **major** = 0, try to allocate any unused major number.

const char *name
the name of the new block device as a zero terminated string

Description

The **name** must be unique within the system.

The return value depends on the **major** input parameter:

- if a major device number was requested in range [1..BLKDEV_MAJOR_MAX-1] then the function returns zero on success, or a negative error code
- if any unused major number was requested with **major** = 0 parameter then the return value is the allocated major number in range [1..BLKDEV_MAJOR_MAX-1] or a negative error code otherwise

See Documentation/admin-guide/devices.txt for the list of allocated major numbers.

void **del_gendisk**(struct gendisk *disk)
remove the gendisk

Parameters

struct gendisk *disk
the struct gendisk to remove

Description

Removes the gendisk and all its associated resources. This deletes the partitions associated with the gendisk, and unregisters the associated request_queue.

This is the counter to the respective *__device_add_disk()* call.

The final removal of the struct gendisk happens when its refcount reaches 0 with *put_disk()*, which should be called after *del_gendisk()*, if *__device_add_disk()* was used.

Drivers exist which depend on the release of the gendisk to be synchronous, it should not be deferred.

Context

can sleep

struct block_device ***bdget_disk**(struct gendisk *disk, int partno)

do bdget() by gendisk and partition number

Parameters

struct gendisk *disk
gendisk of interest

int partno
partition number

Description

Find partition **partno** from **disk**, do bdget() on it.

Context

Don't care.

Return

Resulting block_device on success, NULL on failure.

struct kobject ***get_disk_and_module**(struct gendisk *disk)

increments the gendisk and gendisk fops module refcount

Parameters

struct gendisk *disk
the struct gendisk to increment the refcount for

Description

This increments the refcount for the struct gendisk, and the gendisk's fops module owner.

Context

Any context.

void **put_disk**(struct gendisk *disk)

decrements the gendisk refcount

Parameters

struct gendisk *disk
the struct gendisk to decrement the refcount for

Description

This decrements the refcount for the struct gendisk. When this reaches 0 we'll have *disk_release()* called.

Context

Any context, but the last reference must not be dropped from atomic context.

void **put_disk_and_module**(struct gendisk *disk)
decrements the module and gendisk refcount

Parameters

struct gendisk *disk
the struct gendisk to decrement the refcount for

Description

This is a counterpart of *get_disk_and_module()* and thus also of *get_gendisk()*.

Context

Any context, but the last reference must not be dropped from atomic context.

bool **bdev_check_media_change**(struct block_device *bdev)
check if a removable media has been changed

Parameters

struct block_device *bdev
block device to check

Description

Check whether a removable media has been changed, and attempt to free all dentries and inodes and invalidates all block device page cache entries in that case.

Returns `true` if the block device changed, or `false` if not.

1.1.14 Char devices

int **register_chrdev_region**(dev_t from, unsigned count, const char *name)
register a range of device numbers

Parameters

dev_t from
the first in the desired range of device numbers; must include the major number.

unsigned count
the number of consecutive device numbers required

const char *name
the name of the device or driver.

Description

Return value is zero on success, a negative error code on failure.

int **alloc_chrdev_region**(dev_t *dev, unsigned baseminor, unsigned count, const char *name)
register a range of char device numbers

Parameters

dev_t *dev
output parameter for first assigned number

unsigned baseminor
first of the requested range of minor numbers

unsigned count
the number of minor numbers required

const char *name
the name of the associated device or driver

Description

Allocates a range of char device numbers. The major number will be chosen dynamically, and returned (along with the first minor number) in **dev**. Returns zero or a negative error code.

int **__register_chrdev**(unsigned int major, unsigned int baseminor, unsigned int count, const char *name, const struct file_operations *fops)

create and register a cdev occupying a range of minors

Parameters

unsigned int major
major device number or 0 for dynamic allocation

unsigned int baseminor
first of the requested range of minor numbers

unsigned int count
the number of minor numbers required

const char *name
name of this range of devices

const struct file_operations *fops
file operations associated with this devices

Description

If **major** == 0 this functions will dynamically allocate a major and return its number.

If **major** > 0 this function will attempt to reserve a device with the given major number and will return zero on success.

Returns a -ve errno on failure.

The name of this device has nothing to do with the name of the device in /dev. It only helps to keep track of the different owners of devices. If your module name has only one type of devices it's ok to use e.g. the name of the module here.

void **unregister_chrdev_region**(dev_t from, unsigned count)

unregister a range of device numbers

Parameters

dev_t from
the first in the range of numbers to unregister

unsigned count
the number of device numbers to unregister

Description

This function will unregister a range of **count** device numbers, starting with **from**. The caller should normally be the one who allocated those numbers in the first place…

void **__unregister_chrdev**(unsigned int major, unsigned int baseminor, unsigned int count, const char *name)

unregister and destroy a cdev

Parameters

unsigned int major
major device number

unsigned int baseminor
first of the range of minor numbers

unsigned int count
the number of minor numbers this cdev is occupying

const char *name
name of this range of devices

Description

Unregister and destroy the cdev occupying the region described by **major**, **baseminor** and **count**. This function undoes what *__register_chrdev()* did.

int **cdev_add**(struct cdev *p, dev_t dev, unsigned count)

add a char device to the system

Parameters

struct cdev *p
the cdev structure for the device

dev_t dev
the first device number for which this device is responsible

unsigned count
the number of consecutive minor numbers corresponding to this device

Description

cdev_add() adds the device represented by **p** to the system, making it live immediately. A negative error code is returned on failure.

void **cdev_set_parent**(struct cdev *p, struct kobject *kobj)

set the parent kobject for a char device

Parameters

struct cdev *p
the cdev structure

struct kobject *kobj
the kobject to take a reference to

Description

cdev_set_parent() sets a parent kobject which will be referenced appropriately so the parent is not freed before the cdev. This should be called before cdev_add.

int **cdev_device_add**(struct *cdev* *cdev, struct device *dev)

add a char device and it's corresponding struct device, linkink

Parameters

struct cdev *cdev
the cdev structure

struct device *dev
the device structure

Description

cdev_device_add() adds the char device represented by **cdev** to the system, just as cdev_add does. It then adds **dev** to the system using device_add The dev_t for the char device will be taken from the struct device which needs to be initialized first. This helper function correctly takes a reference to the parent device so the parent will not get released until all references to the cdev are released.

This helper uses dev->devt for the device number. If it is not set it will not add the cdev and it will be equivalent to device_add.

This function should be used whenever the struct cdev and the struct device are members of the same structure whose lifetime is managed by the struct device.

NOTE

Callers must assume that userspace was able to open the cdev and can call cdev fops callbacks at any time, even if this function fails.

void **cdev_device_del**(struct *cdev* *cdev, struct device *dev)

inverse of cdev_device_add

Parameters

struct cdev *cdev
the cdev structure

struct device *dev
the device structure

Description

cdev_device_del() is a helper function to call cdev_del and device_del. It should be used whenever cdev_device_add is used.

If dev->devt is not set it will not remove the cdev and will be equivalent to device_del.

NOTE

This guarantees that associated sysfs callbacks are not running or runnable, however any cdevs already open will remain and their fops will still be callable even after this function returns.

void **cdev_del**(struct cdev *p)

remove a cdev from the system

Parameters

struct cdev *p
the cdev structure to be removed

Description

cdev_del() removes **p** from the system, possibly freeing the structure itself.

NOTE

This guarantees that cdev device will no longer be able to be opened, however any cdevs already open will remain and their fops will still be callable even after cdev_del returns.

struct cdev ***cdev_alloc**(void)
allocate a cdev structure

Parameters

void
no arguments

Description

Allocates and returns a cdev structure, or NULL on failure.

void **cdev_init**(struct *cdev* *cdev, const struct file_operations *fops)
initialize a cdev structure

Parameters

struct cdev *cdev
the structure to initialize

const struct file_operations *fops
the file_operations for this device

Description

Initializes **cdev**, remembering **fops**, making it ready to add to the system with *cdev_add()*.

1.1.15 Clock Framework

The clock framework defines programming interfaces to support software management of the system clock tree. This framework is widely used with System-On-Chip (SOC) platforms to support power management and various devices which may need custom clock rates. Note that these "clocks" don't relate to timekeeping or real time clocks (RTCs), each of which have separate frameworks. These `struct clk` instances may be used to manage for example a 96 MHz signal that is used to shift bits into and out of peripherals or busses, or otherwise trigger synchronous state machine transitions in system hardware.

Power management is supported by explicit software clock gating: unused clocks are disabled, so the system doesn't waste power changing the state of transistors that aren't in active use. On some systems this may be backed by hardware clock gating, where clocks are gated without being disabled in software. Sections of chips that are powered but not clocked may be able to retain their last state. This low power state is often called a *retention mode*. This mode still incurs leakage currents, especially with finer circuit geometries, but for CMOS circuits power is mostly used by clocked state changes.

Power-aware drivers only enable their clocks when the device they manage is in active use. Also, system sleep states often differ according to which clock domains are active: while a "standby" state may allow wakeup from several active domains, a "mem" (suspend-to-RAM) state may require a more wholesale shutdown of clocks derived from higher speed PLLs and oscillators, limiting the number of possible wakeup event sources. A driver's suspend method may need to be aware of system-specific clock constraints on the target sleep state.

Some platforms support programmable clock generators. These can be used by external chips of various kinds, such as other CPUs, multimedia codecs, and devices with strict requirements for interface clocking.

struct **clk_notifier**

associate a clk with a notifier

Definition

```
struct clk_notifier {
  struct clk                        *clk;
  struct srcu_notifier_head         notifier_head;
  struct list_head                  node;
};
```

Members

clk
struct clk * to associate the notifier with

notifier_head
a blocking_notifier_head for this clk

node
linked list pointers

Description

A list of *struct clk_notifier* is maintained by the notifier code. An entry is created whenever code registers the first notifier on a particular **clk**. Future notifiers on that **clk** are added to the **notifier_head**.

struct **clk_notifier_data**

rate data to pass to the notifier callback

Definition

```
struct clk_notifier_data {
  struct clk              *clk;
  unsigned long           old_rate;
  unsigned long           new_rate;
};
```

Members

clk
  struct clk * being changed

old_rate
  previous rate of this clk

new_rate
  new rate of this clk

Description

For a pre-notifier, old_rate is the clk's rate before this rate change, and new_rate is what the rate will be in the future. For a post-notifier, old_rate and new_rate are both set to the clk's current rate (this was done to optimize the implementation).

struct **clk_bulk_data**
  Data used for bulk clk operations.

Definition

```
struct clk_bulk_data {
  const char              *id;
  struct clk              *clk;
};
```

Members

id
  clock consumer ID

clk
  struct clk * to store the associated clock

Description

The CLK APIs provide a series of clk_bulk_() API calls as a convenience to consumers which require multiple clks. This structure is used to manage data for these calls.

int **clk_notifier_register**(struct *clk* *clk, struct notifier_block *nb)
  change notifier callback

Parameters

struct clk *clk
  clock whose rate we are interested in

struct notifier_block *nb
  notifier block with callback function pointer

Description

ProTip: debugging across notifier chains can be frustrating. Make sure that your notifier callback function prints a nice big warning in case of failure.

int **clk_notifier_unregister**(struct *clk* *clk, struct notifier_block *nb)
  change notifier callback

Parameters

struct clk *clk
clock whose rate we are no longer interested in

struct notifier_block *nb
notifier block which will be unregistered

long **clk_get_accuracy**(struct *clk* *clk)
obtain the clock accuracy in ppb (parts per billion) for a clock source.

Parameters

struct clk *clk
clock source

Description

This gets the clock source accuracy expressed in ppb. A perfect clock returns 0.

int **clk_set_phase**(struct *clk* *clk, int degrees)
adjust the phase shift of a clock signal

Parameters

struct clk *clk
clock signal source

int degrees
number of degrees the signal is shifted

Description

Shifts the phase of a clock signal by the specified degrees. Returns 0 on success, -EERROR otherwise.

int **clk_get_phase**(struct *clk* *clk)
return the phase shift of a clock signal

Parameters

struct clk *clk
clock signal source

Description

Returns the phase shift of a clock node in degrees, otherwise returns -EERROR.

int **clk_set_duty_cycle**(struct *clk* *clk, unsigned int num, unsigned int den)
adjust the duty cycle ratio of a clock signal

Parameters

struct clk *clk
clock signal source

unsigned int num
numerator of the duty cycle ratio to be applied

unsigned int den
denominator of the duty cycle ratio to be applied

Description

Adjust the duty cycle of a clock signal by the specified ratio. Returns 0 on success, -EERROR otherwise.

int **clk_get_scaled_duty_cycle**(struct *clk* *clk, unsigned int scale)

return the duty cycle ratio of a clock signal

Parameters

struct clk *clk
clock signal source

unsigned int scale
scaling factor to be applied to represent the ratio as an integer

Description

Returns the duty cycle ratio multiplied by the scale provided, otherwise returns -EERROR.

bool **clk_is_match**(const struct clk *p, const struct clk *q)

check if two clk' s point to the same hardware clock

Parameters

const struct clk *p
clk compared against q

const struct clk *q
clk compared against p

Description

Returns true if the two struct clk pointers both point to the same hardware clock node. Put differently, returns true if **p** and **q** share the same `struct clk_core` object.

Returns false otherwise. Note that two NULL clks are treated as matching.

int **clk_rate_exclusive_get**(struct *clk* *clk)

get exclusivity over the rate control of a producer

Parameters

struct clk *clk
clock source

Description

This function allows drivers to get exclusive control over the rate of a provider. It prevents any other consumer to execute, even indirectly, opereation which could alter the rate of the provider or cause glitches

If exlusivity is claimed more than once on clock, even by the same driver, the rate effectively gets locked as exclusivity can' t be preempted.

Must not be called from within atomic context.

Returns success (0) or negative errno.

void **clk_rate_exclusive_put**(struct *clk* *clk)
release exclusivity over the rate control of a producer

Parameters

struct clk *clk
clock source

Description

This function allows drivers to release the exclusivity it previously got from *clk_rate_exclusive_get()*

The caller must balance the number of *clk_rate_exclusive_get()* and *clk_rate_exclusive_put()* calls.

Must not be called from within atomic context.

int **clk_prepare**(struct *clk* *clk)
prepare a clock source

Parameters

struct clk *clk
clock source

Description

This prepares the clock source for use.

Must not be called from within atomic context.

void **clk_unprepare**(struct *clk* *clk)
undo preparation of a clock source

Parameters

struct clk *clk
clock source

Description

This undoes a previously prepared clock. The caller must balance the number of prepare and unprepare calls.

Must not be called from within atomic context.

struct clk ***clk_get**(struct device *dev, const char *id)
lookup and obtain a reference to a clock producer.

Parameters

struct device *dev
device for clock "consumer"

const char *id
clock consumer ID

Description

Returns a struct clk corresponding to the clock producer, or valid IS_ERR() condition containing errno. The implementation uses **dev** and **id** to determine the clock consumer, and thereby the clock producer. (IOW, **id** may be identical strings, but clk_get may return different clock producers depending on **dev**.)

Drivers must assume that the clock source is not enabled.

clk_get should not be called from within interrupt context.

int **clk_bulk_get**(struct device *dev, int num_clks, struct *clk_bulk_data* *clks)
lookup and obtain a number of references to clock producer.

Parameters

struct device *dev
device for clock "consumer"

int num_clks
the number of clk_bulk_data

struct clk_bulk_data *clks
the clk_bulk_data table of consumer

Description

This helper function allows drivers to get several clk consumers in one operation. If any of the clk cannot be acquired then any clks that were obtained will be freed before returning to the caller.

Returns 0 if all clocks specified in clk_bulk_data table are obtained successfully, or valid IS_ERR() condition containing errno. The implementation uses **dev** and **clk_bulk_data.id** to determine the clock consumer, and thereby the clock producer. The clock returned is stored in each **clk_bulk_data.clk** field.

Drivers must assume that the clock source is not enabled.

clk_bulk_get should not be called from within interrupt context.

int **clk_bulk_get_all**(struct device *dev, struct *clk_bulk_data* **clks)
lookup and obtain all available references to clock producer.

Parameters

struct device *dev
device for clock "consumer"

struct clk_bulk_data **clks
pointer to the clk_bulk_data table of consumer

Description

This helper function allows drivers to get all clk consumers in one operation. If any of the clk cannot be acquired then any clks that were obtained will be freed before returning to the caller.

Returns a positive value for the number of clocks obtained while the clock references are stored in the clk_bulk_data table in **clks** field. Returns 0 if there're none and a negative value if something failed.

Drivers must assume that the clock source is not enabled.

clk_bulk_get should not be called from within interrupt context.

int **clk_bulk_get_optional**(struct device *dev, int num_clks, struct *clk_bulk_data* *clks)

lookup and obtain a number of references to clock producer

Parameters

struct device *dev
device for clock "consumer"

int num_clks
the number of clk_bulk_data

struct clk_bulk_data *clks
the clk_bulk_data table of consumer

Description

Behaves the same as *clk_bulk_get()* except where there is no clock producer. In this case, instead of returning -ENOENT, the function returns 0 and NULL for a clk for which a clock producer could not be determined.

int **devm_clk_bulk_get**(struct device *dev, int num_clks, struct *clk_bulk_data* *clks)

managed get multiple clk consumers

Parameters

struct device *dev
device for clock "consumer"

int num_clks
the number of clk_bulk_data

struct clk_bulk_data *clks
the clk_bulk_data table of consumer

Description

Return 0 on success, an errno on failure.

This helper function allows drivers to get several clk consumers in one operation with management, the clks will automatically be freed when the device is unbound.

int **devm_clk_bulk_get_optional**(struct device *dev, int num_clks, struct *clk_bulk_data* *clks)

managed get multiple optional consumer clocks

Parameters

struct device *dev
device for clock "consumer"

int num_clks
the number of clk_bulk_data

struct clk_bulk_data *clks
pointer to the clk_bulk_data table of consumer

Description

Behaves the same as *devm_clk_bulk_get()* except where there is no clock producer. In this case, instead of returning -ENOENT, the function returns NULL for given clk. It is assumed all clocks in clk_bulk_data are optional.

Returns 0 if all clocks specified in clk_bulk_data table are obtained successfully or for any clk there was no clk provider available, otherwise returns valid IS_ERR() condition containing errno. The implementation uses **dev** and **clk_bulk_data.id** to determine the clock consumer, and thereby the clock producer. The clock returned is stored in each **clk_bulk_data.clk** field.

Drivers must assume that the clock source is not enabled.

clk_bulk_get should not be called from within interrupt context.

int **devm_clk_bulk_get_all**(struct device *dev, struct *clk_bulk_data* **clks)

managed get multiple clk consumers

Parameters

struct device *dev
device for clock "consumer"

struct clk_bulk_data **clks
pointer to the clk_bulk_data table of consumer

Description

Returns a positive value for the number of clocks obtained while the clock references are stored in the clk_bulk_data table in **clks** field. Returns 0 if there' re none and a negative value if something failed.

This helper function allows drivers to get several clk consumers in one operation with management, the clks will automatically be freed when the device is unbound.

struct clk ***devm_clk_get**(struct device *dev, const char *id)

lookup and obtain a managed reference to a clock producer.

Parameters

struct device *dev
device for clock "consumer"

const char *id
clock consumer ID

Description

Returns a struct clk corresponding to the clock producer, or valid IS_ERR() condition containing errno. The implementation uses **dev** and **id** to determine the clock consumer, and thereby the clock producer. (IOW, **id** may be identical strings, but clk_get may return different clock producers depending on **dev**.)

Drivers must assume that the clock source is not enabled.

devm_clk_get should not be called from within interrupt context.

The clock will automatically be freed when the device is unbound from the bus.

struct clk ***devm_clk_get_prepared**(struct device *dev, const char *id)

devm_clk_get() + *clk_prepare()*

Parameters

struct device *dev
device for clock "consumer"

const char *id
clock consumer ID

Context

May sleep.

Return

a struct clk corresponding to the clock producer, or valid IS_ERR() condition containing errno. The implementation uses **dev** and **id** to determine the clock consumer, and thereby the clock producer. (IOW, **id** may be identical strings, but clk_get may return different clock producers depending on **dev**.)

Description

The returned clk (if valid) is prepared. Drivers must however assume that the clock is not enabled.

The clock will automatically be unprepared and freed when the device is unbound from the bus.

struct clk ***devm_clk_get_enabled**(struct device *dev, const char *id)

devm_clk_get() + clk_prepare_enable()

Parameters

struct device *dev
device for clock "consumer"

const char *id
clock consumer ID

Context

May sleep.

Return

a struct clk corresponding to the clock producer, or valid IS_ERR() condition containing errno. The implementation uses **dev** and **id** to determine the clock consumer, and thereby the clock producer. (IOW, **id** may be identical strings, but clk_get may return different clock producers depending on **dev**.)

Description

The returned clk (if valid) is prepared and enabled.

The clock will automatically be disabled, unprepared and freed when the device is unbound from the bus.

struct clk ***devm_clk_get_optional**(struct device *dev, const char *id)

lookup and obtain a managed reference to an optional clock producer.

Parameters

struct device *dev
device for clock "consumer"

const char *id
clock consumer ID

Description

Behaves the same as *devm_clk_get()* except where there is no clock producer. In this case, instead of returning -ENOENT, the function returns NULL.

struct clk ***devm_clk_get_optional_prepared**(struct device *dev, const char *id)

devm_clk_get_optional() + *clk_prepare()*

Parameters

struct device *dev
device for clock "consumer"

const char *id
clock consumer ID

Context

May sleep.

Return

a struct clk corresponding to the clock producer, or valid IS_ERR() condition containing errno. The implementation uses **dev** and **id** to determine the clock consumer, and thereby the clock producer. If no such clk is found, it returns NULL which serves as a dummy clk. That's the only difference compared to *devm_clk_get_prepared()*.

Description

The returned clk (if valid) is prepared. Drivers must however assume that the clock is not enabled.

The clock will automatically be unprepared and freed when the device is unbound from the bus.

struct clk ***devm_clk_get_optional_enabled**(struct device *dev, const char *id)

devm_clk_get_optional() + clk_prepare_enable()

Parameters

struct device *dev
device for clock "consumer"

const char *id
clock consumer ID

Context

May sleep.

Return

a struct clk corresponding to the clock producer, or valid IS_ERR() condition containing errno. The implementation uses **dev** and **id** to determine the clock consumer, and thereby the clock producer. If no such clk is found, it returns NULL which serves as a dummy clk. That's the only difference compared to *devm_clk_get_enabled()*.

Description

The returned clk (if valid) is prepared and enabled.

The clock will automatically be disabled, unprepared and freed when the device is unbound from the bus.

struct clk ***devm_get_clk_from_child**(struct device *dev, struct device_node *np, const char *con_id)

lookup and obtain a managed reference to a clock producer from child node.

Parameters

struct device *dev
device for clock "consumer"

struct device_node *np
pointer to clock consumer node

const char *con_id
clock consumer ID

Description

This function parses the clocks, and uses them to look up the struct clk from the registered list of clock providers by using **np** and **con_id**

The clock will automatically be freed when the device is unbound from the bus.

int **clk_enable**(struct *clk* *clk)

inform the system when the clock source should be running.

Parameters

struct clk *clk
clock source

Description

If the clock can not be enabled/disabled, this should return success.

May be called from atomic contexts.

Returns success (0) or negative errno.

int **clk_bulk_enable**(int num_clks, const struct *clk_bulk_data* *clks)

inform the system when the set of clks should be running.

Parameters

int num_clks
the number of clk_bulk_data

const struct clk_bulk_data *clks
the clk_bulk_data table of consumer

Description

May be called from atomic contexts.

Returns success (0) or negative errno.

void **clk_disable**(struct *clk* *clk)
: inform the system when the clock source is no longer required.

Parameters

struct clk *clk
: clock source

Description

Inform the system that a clock source is no longer required by a driver and may be shut down.

May be called from atomic contexts.

Implementation detail: if the clock source is shared between multiple drivers, *clk_enable()* calls must be balanced by the same number of *clk_disable()* calls for the clock source to be disabled.

void **clk_bulk_disable**(int num_clks, const struct *clk_bulk_data* *clks)
: inform the system when the set of clks is no longer required.

Parameters

int num_clks
: the number of clk_bulk_data

const struct clk_bulk_data *clks
: the clk_bulk_data table of consumer

Description

Inform the system that a set of clks is no longer required by a driver and may be shut down.

May be called from atomic contexts.

Implementation detail: if the set of clks is shared between multiple drivers, *clk_bulk_enable()* calls must be balanced by the same number of *clk_bulk_disable()* calls for the clock source to be disabled.

unsigned long **clk_get_rate**(struct *clk* *clk)
: obtain the current clock rate (in Hz) for a clock source. This is only valid once the clock source has been enabled.

Parameters

struct clk *clk
: clock source

void **clk_put**(struct *clk* *clk)
: "free" the clock source

Parameters

struct clk *clk
clock source

Note

drivers must ensure that all clk_enable calls made on this clock source are balanced by clk_disable calls prior to calling this function.

Description

clk_put should not be called from within interrupt context.

void **clk_bulk_put**(int num_clks, struct *clk_bulk_data* *clks)
"free" the clock source

Parameters

int num_clks
the number of clk_bulk_data

struct clk_bulk_data *clks
the clk_bulk_data table of consumer

Note

drivers must ensure that all clk_bulk_enable calls made on this clock source are balanced by clk_bulk_disable calls prior to calling this function.

Description

clk_bulk_put should not be called from within interrupt context.

void **clk_bulk_put_all**(int num_clks, struct *clk_bulk_data* *clks)
"free" all the clock source

Parameters

int num_clks
the number of clk_bulk_data

struct clk_bulk_data *clks
the clk_bulk_data table of consumer

Note

drivers must ensure that all clk_bulk_enable calls made on this clock source are balanced by clk_bulk_disable calls prior to calling this function.

Description

clk_bulk_put_all should not be called from within interrupt context.

void **devm_clk_put**(struct device *dev, struct *clk* *clk)
"free" a managed clock source

Parameters

struct device *dev
device used to acquire the clock

struct clk *clk
clock source acquired with *devm_clk_get()*

Note

drivers must ensure that all clk_enable calls made on this clock source are balanced by clk_disable calls prior to calling this function.

Description

clk_put should not be called from within interrupt context.

long **clk_round_rate**(struct *clk* *clk, unsigned long rate)
adjust a rate to the exact rate a clock can provide

Parameters

struct clk *clk
clock source

unsigned long rate
desired clock rate in Hz

Description

This answers the question "if I were to pass **rate** to *clk_set_rate()*, what clock rate would I end up with?" without changing the hardware in any way. In other words:

rate = clk_round_rate(clk, r);

and:

clk_set_rate(clk, r); rate = clk_get_rate(clk);

are equivalent except the former does not modify the clock hardware in any way.

Returns rounded clock rate in Hz, or negative errno.

int **clk_set_rate**(struct *clk* *clk, unsigned long rate)
set the clock rate for a clock source

Parameters

struct clk *clk
clock source

unsigned long rate
desired clock rate in Hz

Description

Updating the rate starts at the top-most affected clock and then walks the tree down to the bottom-most clock that needs updating.

Returns success (0) or negative errno.

int **clk_set_rate_exclusive**(struct *clk* *clk, unsigned long rate)
set the clock rate and claim exclusivity over clock source

Parameters

struct clk *clk
clock source

unsigned long rate
desired clock rate in Hz

Description

This helper function allows drivers to atomically set the rate of a producer and claim exclusivity over the rate control of the producer.

It is essentially a combination of *clk_set_rate()* and clk_rate_exclusite_get(). Caller must balance this call with a call to *clk_rate_exclusive_put()*

Returns success (0) or negative errno.

bool **clk_has_parent**(struct *clk* *clk, struct *clk* *parent)
check if a clock is a possible parent for another

Parameters

struct clk *clk
clock source

struct clk *parent
parent clock source

Description

This function can be used in drivers that need to check that a clock can be the parent of another without actually changing the parent.

Returns true if **parent** is a possible parent for **clk**, false otherwise.

int **clk_set_rate_range**(struct *clk* *clk, unsigned long min, unsigned long max)
set a rate range for a clock source

Parameters

struct clk *clk
clock source

unsigned long min
desired minimum clock rate in Hz, inclusive

unsigned long max
desired maximum clock rate in Hz, inclusive

Description

Returns success (0) or negative errno.

int **clk_set_min_rate**(struct *clk* *clk, unsigned long rate)
set a minimum clock rate for a clock source

Parameters

struct clk *clk
clock source

unsigned long rate
desired minimum clock rate in Hz, inclusive

Description

Returns success (0) or negative errno.

int **clk_set_max_rate**(struct *clk* *clk, unsigned long rate)
set a maximum clock rate for a clock source

Parameters

struct clk *clk
clock source

unsigned long rate
desired maximum clock rate in Hz, inclusive

Description

Returns success (0) or negative errno.

int **clk_set_parent**(struct *clk* *clk, struct *clk* *parent)
set the parent clock source for this clock

Parameters

struct clk *clk
clock source

struct clk *parent
parent clock source

Description

Returns success (0) or negative errno.

struct *clk* ***clk_get_parent**(struct *clk* *clk)
get the parent clock source for this clock

Parameters

struct clk *clk
clock source

Description

Returns struct clk corresponding to parent clock source, or valid IS_ERR() condition containing errno.

struct clk ***clk_get_sys**(const char *dev_id, const char *con_id)
get a clock based upon the device name

Parameters

const char *dev_id
device name

const char *con_id
connection ID

Description

Returns a struct clk corresponding to the clock producer, or valid IS_ERR() condition containing errno. The implementation uses **dev_id** and **con_id** to determine the clock consumer, and thereby the clock producer. In contrast to `clk_get()` this function takes the device name instead of the device itself for identification.

Drivers must assume that the clock source is not enabled.

clk_get_sys should not be called from within interrupt context.

int **clk_save_context**(void)

save clock context for poweroff

Parameters

void
no arguments

Description

Saves the context of the clock register for powerstates in which the contents of the registers will be lost. Occurs deep within the suspend code so locking is not necessary.

void **clk_restore_context**(void)

restore clock context after poweroff

Parameters

void
no arguments

Description

This occurs with all clocks enabled. Occurs deep within the resume code so locking is not necessary.

struct clk ***clk_get_optional**(struct device *dev, const char *id)

lookup and obtain a reference to an optional clock producer.

Parameters

struct device *dev
device for clock "consumer"

const char *id
clock consumer ID

Description

Behaves the same as *clk_get()* except where there is no clock producer. In this case, instead of returning -ENOENT, the function returns NULL.

1.1.16 Synchronization Primitives

Read-Copy Update (RCU)

RCU_NONIDLE

`RCU_NONIDLE (a)`

Indicate idle-loop code that needs RCU readers

Parameters

a
Code that RCU needs to pay attention to.

Description

RCU read-side critical sections are forbidden in the inner idle loop, that is, between the *rcu_idle_enter()* and the *rcu_idle_exit()* – RCU will happily ignore any such read-side critical sections. However, things like powertop need tracepoints in the inner idle loop.

This macro provides the way out: RCU_NONIDLE(do_something_with_RCU()) will tell RCU that it needs to pay attention, invoke its argument (in this example, calling the do_something_with_RCU() function), and then tell RCU to go back to ignoring this CPU. It is permissible to nest *RCU_NONIDLE()* wrappers, but not indefinitely (but the limit is on the order of a million or so, even on 32-bit systems). It is not legal to block within *RCU_NONIDLE()*, nor is it permissible to transfer control either into or out of *RCU_NONIDLE()*' s statement.

bool **rcu_trace_implies_rcu_gp**(void)

does an RCU Tasks Trace grace period imply an RCU grace period?

Parameters

void
no arguments

Description

As an accident of implementation, an RCU Tasks Trace grace period also acts as an RCU grace period. However, this could change at any time. Code relying on this accident must call this function to verify that this accident is still happening.

You have been warned!

cond_resched_tasks_rcu_qs

`cond_resched_tasks_rcu_qs ()`

Report potential quiescent states to RCU

Parameters

Description

This macro resembles cond_resched(), except that it is defined to report potential quiescent states to RCU-tasks even if the cond_resched() machinery were to be shut off, as some advocate for PREEMPTION kernels.

rcu_softirq_qs_periodic

`rcu_softirq_qs_periodic (old_ts)`

Report RCU and RCU-Tasks quiescent states

Parameters

old_ts
jiffies at start of processing.

Description

This helper is for long-running softirq handlers, such as NAPI threads in networking. The caller should initialize the variable passed in as **old_ts** at the beginning of the softirq handler. When invoked frequently, this macro will invoke rcu_softirq_qs() every 100 milliseconds thereafter, which will provide both RCU and RCU-Tasks quiescent states. Note that this macro modifies its old_ts argument.

Because regions of code that have disabled softirq act as RCU read-side critical sections, this macro should be invoked with softirq (and preemption) enabled.

The macro is not needed when CONFIG_PREEMPT_RT is defined. RT kernels would have more chance to invoke schedule() calls and provide necessary quiescent states. As a contrast, calling cond_resched() only won't achieve the same effect because cond_resched() does not provide RCU-Tasks quiescent states.

RCU_LOCKDEP_WARN

`RCU_LOCKDEP_WARN (c, s)`

emit lockdep splat if specified condition is met

Parameters

c
condition to check

s
informative message

Description

This checks debug_lockdep_rcu_enabled() before checking (c) to prevent early boot splats due to lockdep not yet being initialized, and rechecks it after checking (c) to prevent false-positive splats due to races with lockdep being disabled. See commit 3066820034b5dd ("rcu: Reject *RCU_LOCKDEP_WARN()* false positives") for more detail.

unrcu_pointer

`unrcu_pointer (p)`

mark a pointer as not being RCU protected

Parameters

p
pointer needing to lose its __rcu property

Description

Converts **p** from an __rcu pointer to a __kernel pointer. This allows an __rcu pointer to be used with xchg() and friends.

RCU_INITIALIZER

`RCU_INITIALIZER (v)`

statically initialize an RCU-protected global variable

Parameters

v
The value to statically initialize with.

rcu_assign_pointer

`rcu_assign_pointer (p, v)`

assign to RCU-protected pointer

Parameters

p
pointer to assign to

v
value to assign (publish)

Description

Assigns the specified value to the specified RCU-protected pointer, ensuring that any concurrent RCU readers will see any prior initialization.

Inserts memory barriers on architectures that require them (which is most of them), and also prevents the compiler from reordering the code that initializes the structure after the pointer assignment. More importantly, this call documents which pointers will be dereferenced by RCU read-side code.

In some special cases, you may use *RCU_INIT_POINTER()* instead of *rcu_assign_pointer()*. *RCU_INIT_POINTER()* is a bit faster due to the fact that it does not constrain either the CPU or the compiler. That said, using *RCU_INIT_POINTER()* when you should have used *rcu_assign_pointer()* is a very bad thing that results in impossible-to-diagnose memory corruption. So please be careful. See the *RCU_INIT_POINTER()* comment header for details.

Note that *rcu_assign_pointer()* evaluates each of its arguments only once, appearances notwithstanding. One of the "extra" evaluations is in typeof() and the other visible only to sparse (__CHECKER__), neither of which actually execute the argument. As with most cpp macros, this execute-arguments-only-once property is important, so please be careful when making changes to *rcu_assign_pointer()* and the other macros that it invokes.

rcu_replace_pointer

`rcu_replace_pointer (rcu_ptr, ptr, c)`

replace an RCU pointer, returning its old value

Parameters

rcu_ptr
RCU pointer, whose old value is returned

ptr
regular pointer

c
the lockdep conditions under which the dereference will take place

Description

Perform a replacement, where **rcu_ptr** is an RCU-annotated pointer and **c** is the lockdep argument that is passed to the *rcu_dereference_protected()* call used to read that pointer. The old value of **rcu_ptr** is returned, and **rcu_ptr** is set to **ptr**.

rcu_access_pointer

`rcu_access_pointer (p)`

fetch RCU pointer with no dereferencing

Parameters

p
The pointer to read

Description

Return the value of the specified RCU-protected pointer, but omit the lockdep checks for being in an RCU read-side critical section. This is useful when the value of this pointer is accessed, but the pointer is not dereferenced, for example, when testing an RCU-protected pointer against NULL. Although *rcu_access_pointer()* may also be used in cases where update-side locks prevent the value of the pointer from changing, you should instead use *rcu_dereference_protected()* for this use case.

It is also permissible to use *rcu_access_pointer()* when read-side access to the pointer was removed at least one grace period ago, as is the case in the context of the RCU callback that is freeing up the data, or after a *synchronize_rcu()* returns. This can be useful when tearing down multi-linked structures after a grace period has elapsed.

rcu_dereference_check

`rcu_dereference_check (p, c)`

rcu_dereference with debug checking

Parameters

p
The pointer to read, prior to dereferencing

c
The conditions under which the dereference will take place

Description

Do an *rcu_dereference()*, but check that the conditions under which the dereference will take place are correct. Typically the conditions indicate the various locking conditions that should be held at that point. The check should return true if the conditions are satisfied. An implicit check for being in an RCU read-side critical section (*rcu_read_lock()*) is included.

For example:

bar = rcu_dereference_check(foo->bar, lockdep_is_held(`foo->lock`));

could be used to indicate to lockdep that foo->bar may only be dereferenced if either *rcu_read_lock()* is held, or that the lock required to replace the bar struct at foo->bar is held.

Note that the list of conditions may also include indications of when a lock need not be held, for example during initialisation or destruction of the target struct:

bar = rcu_dereference_check(foo->bar, lockdep_is_held(foo->lock) ||
atomic_read(foo->usage) == 0);

Inserts memory barriers on architectures that require them (currently only the Alpha), prevents the compiler from refetching (and from merging fetches), and, more importantly, documents exactly which pointers are protected by RCU and checks that the pointer is annotated as __rcu.

rcu_dereference_bh_check

`rcu_dereference_bh_check (p, c)`

rcu_dereference_bh with debug checking

Parameters

p
The pointer to read, prior to dereferencing

c
The conditions under which the dereference will take place

Description

This is the RCU-bh counterpart to *rcu_dereference_check()*.

rcu_dereference_sched_check

`rcu_dereference_sched_check (p, c)`

rcu_dereference_sched with debug checking

Parameters

p
The pointer to read, prior to dereferencing

c
The conditions under which the dereference will take place

Description

This is the RCU-sched counterpart to *rcu_dereference_check()*.

rcu_dereference_protected

`rcu_dereference_protected (p, c)`

fetch RCU pointer when updates prevented

Parameters

p
The pointer to read, prior to dereferencing

c
The conditions under which the dereference will take place

Description

Return the value of the specified RCU-protected pointer, but omit the READ_ONCE(). This is useful in cases where update-side locks prevent the value of the pointer from changing. Please note that this primitive does *not* prevent the compiler from repeating this reference or combining it with other references, so it should not be used without protection of appropriate locks.

This function is only for update-side use. Using this function when protected only by *rcu_read_lock()* will result in infrequent but very ugly failures.

rcu_dereference

`rcu_dereference (p)`

fetch RCU-protected pointer for dereferencing

Parameters

p
The pointer to read, prior to dereferencing

Description

This is a simple wrapper around *rcu_dereference_check()*.

rcu_dereference_bh

`rcu_dereference_bh (p)`

fetch an RCU-bh-protected pointer for dereferencing

Parameters

p
The pointer to read, prior to dereferencing

Description

Makes *rcu_dereference_check()* do the dirty work.

rcu_dereference_sched

`rcu_dereference_sched (p)`

fetch RCU-sched-protected pointer for dereferencing

Parameters

p
The pointer to read, prior to dereferencing

Description

Makes *rcu_dereference_check()* do the dirty work.

rcu_pointer_handoff

`rcu_pointer_handoff (p)`

Hand off a pointer from RCU to other mechanism

Parameters

p
The pointer to hand off

Description

This is simply an identity function, but it documents where a pointer is handed off from RCU to some other synchronization mechanism, for example, reference counting or locking. In C11, it would map to kill_dependency(). It could be used as follows:

```
rcu_read_lock();
p = rcu_dereference(gp);
long_lived = is_long_lived(p);
if (long_lived) {
        if (!atomic_inc_not_zero(p->refcnt))
                long_lived = false;
        else
                p = rcu_pointer_handoff(p);
}
rcu_read_unlock();
```

void **rcu_read_lock**(void)
mark the beginning of an RCU read-side critical section

Parameters

void
no arguments

Description

When *synchronize_rcu()* is invoked on one CPU while other CPUs are within RCU read-side critical sections, then the *synchronize_rcu()* is guaranteed to block until after all the other CPUs exit their critical sections. Similarly, if *call_rcu()* is invoked on one CPU while other CPUs are within RCU read-side critical sections, invocation of the corresponding RCU callback is deferred until after the all the other CPUs exit their critical sections.

Note, however, that RCU callbacks are permitted to run concurrently with new RCU read-side critical sections. One way that this can happen is via the following sequence of events: (1) CPU 0 enters an RCU read-side critical section, (2) CPU 1 invokes *call_rcu()* to register an RCU callback, (3) CPU 0 exits the RCU read-side critical section, (4) CPU 2 enters a RCU read-side critical section, (5) the RCU callback is invoked. This is legal, because the RCU read-side critical section that was running concurrently with the *call_rcu()* (and which therefore might be referencing something that the corresponding RCU callback would free up) has completed before the corresponding RCU callback is invoked.

RCU read-side critical sections may be nested. Any deferred actions will be deferred until the outermost RCU read-side critical section completes.

You can avoid reading and understanding the next paragraph by following this rule: don't put anything in an *rcu_read_lock()* RCU read-side critical section that would block in a !PREEMPTION kernel. But if you want the full story, read on!

In non-preemptible RCU implementations (pure TREE_RCU and TINY_RCU), it is illegal to block while in an RCU read-side critical section. In preemptible RCU implementations (PREEMPT_RCU) in CONFIG_PREEMPTION kernel builds, RCU read-side critical sections may be preempted, but explicit blocking is illegal. Finally, in preemptible RCU implementations in real-time (with -rt patchset) kernel builds, RCU read-side critical sections may be preempted and they may also block, but only when acquiring spinlocks that are subject to priority inheritance.

void **rcu_read_unlock**(void)

marks the end of an RCU read-side critical section.

Parameters

void
no arguments

Description

In most situations, *rcu_read_unlock()* is immune from deadlock. However, in kernels built with CONFIG_RCU_BOOST, *rcu_read_unlock()* is responsible for deboosting, which it does via rt_mutex_unlock(). Unfortunately, this function acquires the scheduler's runqueue and priority-inheritance spinlocks. This means that deadlock could result if the caller of *rcu_read_unlock()* already holds one of these locks or any lock that is ever acquired while holding them.

That said, RCU readers are never priority boosted unless they were preempted. Therefore, one way to avoid deadlock is to make sure that preemption never happens within any RCU read-side critical section whose outermost *rcu_read_unlock()* is called with one of rt_mutex_unlock()'s locks held. Such preemption can be avoided in a number of ways, for example, by invoking preempt_disable() before critical section's outermost *rcu_read_lock()*.

Given that the set of locks acquired by rt_mutex_unlock() might change at any time, a somewhat more future-proofed approach is to make sure that that preemption never happens within any RCU read-side critical section whose outermost *rcu_read_unlock()* is called with irqs disabled. This approach relies on the fact that rt_mutex_unlock() currently only acquires irq-disabled locks.

The second of these two approaches is best in most situations, however, the first approach can also be useful, at least to those developers willing to keep abreast of the set of locks acquired by rt_mutex_unlock().

See *rcu_read_lock()* for more information.

void **rcu_read_lock_bh**(void)

mark the beginning of an RCU-bh critical section

Parameters

void
no arguments

Description

This is equivalent of *rcu_read_lock()*, but also disables softirqs. Note that anything else that disables softirqs can also serve as an RCU read-side critical section.

Note that *rcu_read_lock_bh()* and the matching *rcu_read_unlock_bh()* must occur in the same context, for example, it is illegal to invoke *rcu_read_unlock_bh()* from one task if the matching *rcu_read_lock_bh()* was invoked from some other task.

void **rcu_read_unlock_bh**(void)

marks the end of a softirq-only RCU critical section

Parameters

void
no arguments

Description

See *rcu_read_lock_bh()* for more information.

void **rcu_read_lock_sched**(void)

mark the beginning of a RCU-sched critical section

Parameters

void
no arguments

Description

This is equivalent of *rcu_read_lock()*, but disables preemption. Read-side critical sections can also be introduced by anything else that disables preemption, including local_irq_disable() and friends.

Note that *rcu_read_lock_sched()* and the matching *rcu_read_unlock_sched()* must occur in the same context, for example, it is illegal to invoke *rcu_read_unlock_sched()* from process context if the matching *rcu_read_lock_sched()* was invoked from an NMI handler.

void **rcu_read_unlock_sched**(void)

marks the end of a RCU-classic critical section

Parameters

void
no arguments

Description

See *rcu_read_lock_sched()* for more information.

RCU_INIT_POINTER

RCU_INIT_POINTER (p, v)

initialize an RCU protected pointer

Parameters

p
The pointer to be initialized.

v
The value to initialized the pointer to.

Description

Initialize an RCU-protected pointer in special cases where readers do not need ordering constraints on the CPU or the compiler. These special cases are:

1. This use of `RCU_INIT_POINTER()` is NULLing out the pointer *or*
2. The caller has taken whatever steps are required to prevent RCU readers from concurrently accessing this pointer *or*
3. The referenced data structure has already been exposed to readers either at compile time or via `rcu_assign_pointer()` *and*

   a. You have not made *any* reader-visible changes to this structure since then *or*

   b. It is OK for readers accessing this structure from its new location to see the old state of the structure. (For example, the changes were to statistical counters or to other state where exact synchronization is not required.)

Failure to follow these rules governing use of `RCU_INIT_POINTER()` will result in impossible-to-diagnose memory corruption. As in the structures will look OK in crash dumps, but any concurrent RCU readers might see pre-initialized values of the referenced data structure. So please be very careful how you use `RCU_INIT_POINTER()`!!!

If you are creating an RCU-protected linked structure that is accessed by a single external-to-structure RCU-protected pointer, then you may use `RCU_INIT_POINTER()` to initialize the internal RCU-protected pointers, but you must use `rcu_assign_pointer()` to initialize the external-to-structure pointer *after* you have completely initialized the reader-accessible portions of the linked structure.

Note that unlike `rcu_assign_pointer()`, `RCU_INIT_POINTER()` provides no ordering guarantees for either the CPU or the compiler.

RCU_POINTER_INITIALIZER

`RCU_POINTER_INITIALIZER (p, v)`

statically initialize an RCU protected pointer

Parameters

p
The pointer to be initialized.

v
The value to initialized the pointer to.

Description

GCC-style initialization for an RCU-protected pointer in a structure field.

kfree_rcu

`kfree_rcu (ptr, rhf)`

kfree an object after a grace period.

Parameters

ptr
pointer to kfree

rhf
the name of the struct rcu_head within the type of **ptr**.

Description

Many rcu callbacks functions just call *kfree()* on the base structure. These functions are trivial, but their size adds up, and furthermore when they are used in a kernel module, that module must invoke the high-latency *rcu_barrier()* function at module-unload time.

The *kfree_rcu()* function handles this issue. Rather than encoding a function address in the embedded rcu_head structure, *kfree_rcu()* instead encodes the offset of the rcu_head structure within the base structure. Because the functions are not allowed in the low-order 4096 bytes of kernel virtual memory, offsets up to 4095 bytes can be accommodated. If the offset is larger than 4095 bytes, a compile-time error will be generated in __kvfree_rcu(). If this error is triggered, you can either fall back to use of *call_rcu()* or rearrange the structure to position the rcu_head structure into the first 4096 bytes.

Note that the allowable offset might decrease in the future, for example, to allow something like kmem_cache_free_rcu().

The BUILD_BUG_ON check must not involve any function calls, hence the checks are done in macros here.

kvfree_rcu

`kvfree_rcu (...)`

kvfree an object after a grace period.

Parameters

...
variable arguments

Description

This macro consists of one or two arguments and it is based on whether an object is head-less or not. If it has a head then a semantic stays the same as it used to be before:

kvfree_rcu(ptr, rhf);

where **ptr** is a pointer to *kvfree()*, **rhf** is the name of the rcu_head structure within the type of **ptr**.

When it comes to head-less variant, only one argument is passed and that is just a pointer which has to be freed after a grace period. Therefore the semantic is

kvfree_rcu(ptr);

where **ptr** is a pointer to *kvfree()*.

Please note, head-less way of freeing is permitted to use from a context that has to follow might_sleep() annotation. Otherwise, please switch and embed the rcu_head structure within the type of **ptr**.

void **rcu_head_init**(struct rcu_head *rhp)
Initialize rcu_head for *rcu_head_after_call_rcu()*

Parameters

struct rcu_head *rhp
The rcu_head structure to initialize.

Description

If you intend to invoke *rcu_head_after_call_rcu()* to test whether a given rcu_head structure has already been passed to *call_rcu()*, then you must also invoke this *rcu_head_init()* function on it just after allocating that structure. Calls to this function must not race with calls to *call_rcu()*, *rcu_head_after_call_rcu()*, or callback invocation.

bool **rcu_head_after_call_rcu**(struct rcu_head *rhp, rcu_callback_t f)
Has this rcu_head been passed to *call_rcu()*?

Parameters

struct rcu_head *rhp
The rcu_head structure to test.

rcu_callback_t f
The function passed to *call_rcu()* along with **rhp**.

Description

Returns **true** if the **rhp** has been passed to *call_rcu()* with **func**, and **false** otherwise. Emits a warning in any other case, including the case where **rhp** has already been invoked after a grace period. Calls to this function must not race with callback invocation. One way to avoid such races is to enclose the call to *rcu_head_after_call_rcu()* in an RCU read-side critical section that includes a read-side fetch of the pointer to the structure containing **rhp**.

int **rcu_is_cpu_rrupt_from_idle**(void)
see if 'interrupted' from idle

Parameters

void
no arguments

Description

If the current CPU is idle and running at a first-level (not nested) interrupt, or directly, from idle, return true.

The caller must have at least disabled IRQs.

void **rcu_idle_enter**(void)
inform RCU that current CPU is entering idle

Parameters

void
no arguments

Description

Enter idle mode, in other words, -leave- the mode in which RCU read-side critical sections can occur. (Though RCU read-side critical sections can occur in irq handlers in idle, a possibility handled by irq_enter() and irq_exit().)

If you add or remove a call to *rcu_idle_enter()*, be sure to test with CONFIG_RCU_EQS_DEBUG=y.

noinstr void **rcu_user_enter**(void)
inform RCU that we are resuming userspace.

Parameters

void
no arguments

Description

Enter RCU idle mode right before resuming userspace. No use of RCU is permitted between this call and *rcu_user_exit()*. This way the CPU doesn't need to maintain the tick for RCU maintenance purposes when the CPU runs in userspace.

If you add or remove a call to *rcu_user_enter()*, be sure to test with CONFIG_RCU_EQS_DEBUG=y.

noinstr void **rcu_nmi_exit**(void)
inform RCU of exit from NMI context

Parameters

void
no arguments

Description

If we are returning from the outermost NMI handler that interrupted an RCU-idle period, update rdp->dynticks and rdp->dynticks_nmi_nesting to let the RCU grace-period handling know that the CPU is back to being RCU-idle.

If you add or remove a call to *rcu_nmi_exit()*, be sure to test with CONFIG_RCU_EQS_DEBUG=y.

void noinstr **rcu_irq_exit**(void)
inform RCU that current CPU is exiting irq towards idle

Parameters

void
no arguments

Description

Exit from an interrupt handler, which might possibly result in entering idle mode, in other words, leaving the mode in which read-side critical sections can occur. The caller must have disabled interrupts.

This code assumes that the idle loop never does anything that might result in unbalanced calls to irq_enter() and irq_exit(). If your architecture's idle loop violates this assumption, RCU will give you what you deserve, good and hard. But very infrequently and irreproducibly.

Use things like work queues to work around this limitation.

You have been warned.

If you add or remove a call to *rcu_irq_exit()*, be sure to test with CONFIG_RCU_EQS_DEBUG=y.

void **rcu_irq_exit_preempt**(void)

Inform RCU that current CPU is exiting irq towards in kernel preemption

Parameters

void
no arguments

Description

Same as *rcu_irq_exit()* but has a sanity check that scheduling is safe from RCU point of view. Invoked from return from interrupt before kernel preemption.

void **rcu_irq_exit_check_preempt**(void)

Validate that scheduling is possible

Parameters

void
no arguments

void **rcu_idle_exit**(void)

inform RCU that current CPU is leaving idle

Parameters

void
no arguments

Description

Exit idle mode, in other words, -enter- the mode in which RCU read-side critical sections can occur.

If you add or remove a call to *rcu_idle_exit()*, be sure to test with CONFIG_RCU_EQS_DEBUG=y.

void noinstr **rcu_user_exit**(void)

inform RCU that we are exiting userspace.

Parameters

void
no arguments

Description

Exit RCU idle mode while entering the kernel because it can run a RCU read side critical section anytime.

If you add or remove a call to *rcu_user_exit()*, be sure to test with CONFIG_RCU_EQS_DEBUG=y.

void **__rcu_irq_enter_check_tick**(void)

Enable scheduler tick on CPU if RCU needs it.

Parameters

void
no arguments

Description

The scheduler tick is not normally enabled when CPUs enter the kernel from nohz_full userspace execution. After all, nohz_full userspace execution is an RCU quiescent state and the time executing in the kernel is quite short. Except of course when it isn't. And it is not hard to cause a large system to spend tens of seconds or even minutes looping in the kernel, which can cause a number of problems, include RCU CPU stall warnings.

Therefore, if a nohz_full CPU fails to report a quiescent state in a timely manner, the RCU grace-period kthread sets that CPU's ->rcu_urgent_qs flag with the expectation that the next interrupt or exception will invoke this function, which will turn on the scheduler tick, which will enable RCU to detect that CPU's quiescent states, for example, due to cond_resched() calls in CONFIG_PREEMPT=n kernels. The tick will be disabled once a quiescent state is reported for this CPU.

Of course, in carefully tuned systems, there might never be an interrupt or exception. In that case, the RCU grace-period kthread will eventually cause one to happen. However, in less carefully controlled environments, this function allows RCU to get what it needs without creating otherwise useless interruptions.

noinstr void **rcu_nmi_enter**(void)

inform RCU of entry to NMI context

Parameters

void
no arguments

Description

If the CPU was idle from RCU's viewpoint, update rdp->dynticks and rdp->dynticks_nmi_nesting to let the RCU grace-period handling know that the CPU is active. This implementation permits nested NMIs, as long as the nesting level does not overflow an int. (You will probably run out of stack space first.)

If you add or remove a call to *rcu_nmi_enter()*, be sure to test with CONFIG_RCU_EQS_DEBUG=y.

noinstr void **rcu_irq_enter**(void)

inform RCU that current CPU is entering irq away from idle

Parameters

void
no arguments

Description

Enter an interrupt handler, which might possibly result in exiting idle mode, in other words, entering the mode in which read-side critical sections can occur. The caller must have disabled interrupts.

Note that the Linux kernel is fully capable of entering an interrupt handler that it never exits, for example when doing upcalls to user mode! This code assumes that the idle loop never does upcalls to user mode. If your architecture's idle loop does do upcalls to user mode (or does anything else that results in unbalanced calls to the irq_enter() and irq_exit() functions), RCU will give you what you deserve, good and hard. But very infrequently and irreproducibly.

Use things like work queues to work around this limitation.

You have been warned.

If you add or remove a call to *rcu_irq_enter()*, be sure to test with CONFIG_RCU_EQS_DEBUG=y.

notrace bool **rcu_is_watching**(void)

see if RCU thinks that the current CPU is not idle

Parameters

void
no arguments

Description

Return true if RCU is watching the running CPU, which means that this CPU can safely enter RCU read-side critical sections. In other words, if the current CPU is not in its idle loop or is in an interrupt or NMI handler, return true.

Make notrace because it can be called by the internal functions of ftrace, and making this notrace removes unnecessary recursion calls.

void **call_rcu**(struct rcu_head *head, rcu_callback_t func)

Queue an RCU callback for invocation after a grace period.

Parameters

struct rcu_head *head
structure to be used for queueing the RCU updates.

rcu_callback_t func
actual callback function to be invoked after the grace period

Description

The callback function will be invoked some time after a full grace period elapses, in other words after all pre-existing RCU read-side critical sections have completed. However, the callback function might well execute concurrently with RCU read-side critical sections that started after *call_rcu()* was invoked. RCU read-side critical sections are delimited by *rcu_read_lock()* and *rcu_read_unlock()*, and may be nested. In addition, regions of code across which interrupts, preemption, or softirqs have been disabled also serve as RCU read-side critical sections. This includes hardware interrupt handlers, softirq handlers, and NMI handlers.

Note that all CPUs must agree that the grace period extended beyond all pre-existing RCU read-side critical section. On systems with more than one CPU, this means that when "func()" is invoked, each CPU is guaranteed to have executed a full memory barrier since the end of its last RCU read-side critical section whose beginning preceded the call to *call_rcu()*. It also means that each CPU executing an RCU read-side critical section that continues beyond the start of "func()" must have executed a memory barrier after the *call_rcu()* but before the beginning of that RCU read-side critical section. Note that these guarantees include CPUs that are offline, idle, or executing in user mode, as well as CPUs that are executing in the kernel.

Furthermore, if CPU A invoked *call_rcu()* and CPU B invoked the resulting RCU callback function "func()", then both CPU A and CPU B are guaranteed to execute a full memory barrier during the time interval between the call to *call_rcu()* and the invocation of "func()" – even if CPU A and CPU B are the same CPU (but again only if the system has more than one CPU).

struct **kvfree_rcu_bulk_data**

single block to store *kvfree_rcu()* pointers

Definition

```
struct kvfree_rcu_bulk_data {
  unsigned long nr_records;
  struct kvfree_rcu_bulk_data *next;
  void *records[];
};
```

Members

nr_records
Number of active pointers in the array

next
Next bulk object in the block chain

records
Array of the *kvfree_rcu()* pointers

struct **kfree_rcu_cpu_work**

single batch of *kfree_rcu()* requests

Definition

```
struct kfree_rcu_cpu_work {
  struct rcu_work rcu_work;
  struct rcu_head *head_free;
  struct kvfree_rcu_bulk_data *bkvhead_free[FREE_N_CHANNELS];
  struct kfree_rcu_cpu *krcp;
};
```

Members

rcu_work
Let *queue_rcu_work()* invoke workqueue handler after grace period

head_free
List of *kfree_rcu()* objects waiting for a grace period

bkvhead_free
Bulk-List of *kvfree_rcu()* objects waiting for a grace period

krcp
Pointer to **kfree_rcu_cpu** structure

struct **kfree_rcu_cpu**
batch up *kfree_rcu()* requests for RCU grace period

Definition

```
struct kfree_rcu_cpu {
  struct rcu_head *head;
  struct kvfree_rcu_bulk_data *bkvhead[FREE_N_CHANNELS];
  struct kfree_rcu_cpu_work krw_arr[KFREE_N_BATCHES];
  raw_spinlock_t lock;
  struct delayed_work monitor_work;
  bool monitor_todo;
  bool initialized;
  int count;
  struct work_struct page_cache_work;
  atomic_t work_in_progress;
  struct hrtimer hrtimer;
  struct llist_head bkvcache;
  int nr_bkv_objs;
};
```

Members

head
List of *kfree_rcu()* objects not yet waiting for a grace period

bkvhead
Bulk-List of *kvfree_rcu()* objects not yet waiting for a grace period

krw_arr
Array of batches of *kfree_rcu()* objects waiting for a grace period

lock
Synchronize access to this structure

monitor_work
Promote **head** to **head_free** after KFREE_DRAIN_JIFFIES

monitor_todo
Tracks whether a **monitor_work** delayed work is pending

initialized
The **rcu_work** fields have been initialized

count
Number of objects for which GP not started

page_cache_work
A work to refill the cache when it is empty

work_in_progress
Indicates that page_cache_work is running

hrtimer
A hrtimer for scheduling a page_cache_work

bkvcache
A simple cache list that contains objects for reuse purpose. In order to save some per-cpu space the list is singular. Even though it is lockless an access has to be protected by the per-cpu lock.

nr_bkv_objs
number of allocated objects at **bkvcache**.

Description

This is a per-CPU structure. The reason that it is not included in the rcu_data structure is to permit this code to be extracted from the RCU files. Such extraction could allow further optimization of the interactions with the slab allocators.

void **synchronize_rcu**(void)

wait until a grace period has elapsed.

Parameters

void
no arguments

Description

Control will return to the caller some time after a full grace period has elapsed, in other words after all currently executing RCU read-side critical sections have completed. Note, however, that upon return from *synchronize_rcu()*, the caller might well be executing concurrently with new RCU read-side critical sections that began while *synchronize_rcu()* was waiting. RCU read-side critical sections are delimited by *rcu_read_lock()* and *rcu_read_unlock()*, and may be nested. In addition, regions of code across which interrupts, preemption, or softirqs have been disabled also serve as RCU read-side critical sections. This includes hardware interrupt handlers, softirq handlers, and NMI handlers.

Note that this guarantee implies further memory-ordering guarantees. On systems with more than one CPU, when *synchronize_rcu()* returns, each CPU is guaranteed to have executed a full memory barrier since the end of its last RCU read-side critical section whose beginning preceded the call to *synchronize_rcu()*. In addition, each CPU having an RCU read-side critical section that extends beyond the return from *synchronize_rcu()* is guaranteed to have executed a full memory barrier after the beginning of *synchronize_rcu()* and before the beginning of that RCU read-side critical section. Note that these guarantees include CPUs that are offline, idle, or executing in user mode, as well as CPUs that are executing in the kernel.

Furthermore, if CPU A invoked *synchronize_rcu()*, which returned to its caller on CPU B, then both CPU A and CPU B are guaranteed to have executed a full memory barrier during the execution of *synchronize_rcu()* – even if CPU A and CPU B are the same CPU (but again only if the system has more than one CPU).

unsigned long **get_state_synchronize_rcu**(void)

Snapshot current RCU state

Parameters

void
no arguments

Description

Returns a cookie that is used by a later call to *cond_synchronize_rcu()* to determine whether or not a full grace period has elapsed in the meantime.

void **cond_synchronize_rcu**(unsigned long oldstate)

Conditionally wait for an RCU grace period

Parameters

unsigned long oldstate
return value from earlier call to *get_state_synchronize_rcu()*

Description

If a full RCU grace period has elapsed since the earlier call to *get_state_synchronize_rcu()*, just return. Otherwise, invoke *synchronize_rcu()* to wait for a full grace period.

Yes, this function does not take counter wrap into account. But counter wrap is harmless. If the counter wraps, we have waited for more than 2 billion grace periods (and way more on a 64-bit system!), so waiting for one additional grace period should be just fine.

void **rcu_barrier**(void)

Wait until all in-flight *call_rcu()* callbacks complete.

Parameters

void
no arguments

Description

Note that this primitive does not necessarily wait for an RCU grace period to complete. For example, if there are no RCU callbacks queued anywhere in the system, then *rcu_barrier()* is within its rights to return immediately, without waiting for anything, much less an RCU grace period.

void **synchronize_rcu_expedited**(void)

Brute-force RCU grace period

Parameters

void
no arguments

Description

Wait for an RCU grace period, but expedite it. The basic idea is to IPI all non-idle non-nohz online CPUs. The IPI handler checks whether the CPU is in an RCU critical section, and if so, it sets a flag that causes the outermost *rcu_read_unlock()*

to report the quiescent state for RCU-preempt or asks the scheduler for help for RCU-sched. On the other hand, if the CPU is not in an RCU read-side critical section, the IPI handler reports the quiescent state immediately.

Although this is a great improvement over previous expedited implementations, it is still unfriendly to real-time workloads, so is thus not recommended for any sort of common-case code. In fact, if you are using `synchronize_rcu_expedited()` in a loop, please restructure your code to batch your updates, and then use a single `synchronize_rcu()` instead.

This has the same semantics as (but is more brutal than) `synchronize_rcu()`.

bool **rcu_read_lock_held_common**(bool *ret)

might we be in RCU-sched read-side critical section?

Parameters

bool *ret
Best guess answer if lockdep cannot be relied on

Description

Returns true if lockdep must be ignored, in which case `*ret` contains the best guess described below. Otherwise returns false, in which case `*ret` tells the caller nothing and the caller should instead consult lockdep.

If CONFIG_DEBUG_LOCK_ALLOC is selected, set `*ret` to nonzero iff in an RCU-sched read-side critical section. In absence of CONFIG_DEBUG_LOCK_ALLOC, this assumes we are in an RCU-sched read-side critical section unless it can prove otherwise. Note that disabling of preemption (including disabling irqs) counts as an RCU-sched read-side critical section. This is useful for debug checks in functions that required that they be called within an RCU-sched read-side critical section.

Check debug_lockdep_rcu_enabled() to prevent false positives during boot and while lockdep is disabled.

Note that if the CPU is in the idle loop from an RCU point of view (ie: that we are in the section between `rcu_idle_enter()` and `rcu_idle_exit()`) then `rcu_read_lock_held()` sets `*ret` to false even if the CPU did an `rcu_read_lock()`. The reason for this is that RCU ignores CPUs that are in such a section, considering these as in extended quiescent state, so such a CPU is effectively never in an RCU read-side critical section regardless of what RCU primitives it invokes. This state of affairs is required —we need to keep an RCU-free window in idle where the CPU may possibly enter into low power mode. This way we can notice an extended quiescent state to other CPUs that started a grace period. Otherwise we would delay any grace period as long as we run in the idle task.

Similarly, we avoid claiming an RCU read lock held if the current CPU is offline.

void **rcu_expedite_gp**(void)

Expedite future RCU grace periods

Parameters

void
no arguments

Description

After a call to this function, future calls to *synchronize_rcu()* and friends act as the corresponding *synchronize_rcu_expedited()* function had instead been called.

void **rcu_unexpedite_gp**(void)

Cancel prior *rcu_expedite_gp()* invocation

Parameters

void
no arguments

Description

Undo a prior call to *rcu_expedite_gp()*. If all prior calls to *rcu_expedite_gp()* are undone by a subsequent call to *rcu_unexpedite_gp()*, and if the rcu_expedited sysfs/boot parameter is not set, then all subsequent calls to *synchronize_rcu()* and friends will return to their normal non-expedited behavior.

int **rcu_read_lock_held**(void)

might we be in RCU read-side critical section?

Parameters

void
no arguments

Description

If CONFIG_DEBUG_LOCK_ALLOC is selected, returns nonzero iff in an RCU read-side critical section. In absence of CONFIG_DEBUG_LOCK_ALLOC, this assumes we are in an RCU read-side critical section unless it can prove otherwise. This is useful for debug checks in functions that require that they be called within an RCU read-side critical section.

Checks debug_lockdep_rcu_enabled() to prevent false positives during boot and while lockdep is disabled.

Note that *rcu_read_lock()* and the matching *rcu_read_unlock()* must occur in the same context, for example, it is illegal to invoke *rcu_read_unlock()* in process context if the matching *rcu_read_lock()* was invoked from within an irq handler.

Note that *rcu_read_lock()* is disallowed if the CPU is either idle or offline from an RCU perspective, so check for those as well.

int **rcu_read_lock_bh_held**(void)

might we be in RCU-bh read-side critical section?

Parameters

void
no arguments

Description

Check for bottom half being disabled, which covers both the CONFIG_PROVE_RCU and not cases. Note that if someone uses *rcu_read_lock_bh()*, but then later enables BH, lockdep (if enabled) will show the situation. This is useful for debug checks in functions that require that they be called within an RCU read-side critical section.

Check debug_lockdep_rcu_enabled() to prevent false positives during boot.

Note that *rcu_read_lock_bh()* is disallowed if the CPU is either idle or offline from an RCU perspective, so check for those as well.

void **wakeme_after_rcu**(struct rcu_head *head)

Callback function to awaken a task after grace period

Parameters

struct rcu_head *head
Pointer to rcu_head member within rcu_synchronize structure

Description

Awaken the corresponding task now that a grace period has elapsed.

void **init_rcu_head_on_stack**(struct rcu_head *head)

initialize on-stack rcu_head for debugobjects

Parameters

struct rcu_head *head
pointer to rcu_head structure to be initialized

Description

This function informs debugobjects of a new rcu_head structure that has been allocated as an auto variable on the stack. This function is not required for rcu_head structures that are statically defined or that are dynamically allocated on the heap. This function has no effect for !CONFIG_DEBUG_OBJECTS_RCU_HEAD kernel builds.

void **destroy_rcu_head_on_stack**(struct rcu_head *head)

destroy on-stack rcu_head for debugobjects

Parameters

struct rcu_head *head
pointer to rcu_head structure to be initialized

Description

This function informs debugobjects that an on-stack rcu_head structure is about to go out of scope. As with *init_rcu_head_on_stack()*, this function is not required for rcu_head structures that are statically defined or that are dynamically allocated on the heap. Also as with *init_rcu_head_on_stack()*, this function has no effect for !CONFIG_DEBUG_OBJECTS_RCU_HEAD kernel builds.

int **srcu_read_lock_held**(const struct srcu_struct *ssp)

might we be in SRCU read-side critical section?

Parameters

const struct srcu_struct *ssp
The srcu_struct structure to check

Description

If CONFIG_DEBUG_LOCK_ALLOC is selected, returns nonzero iff in an SRCU read-side critical section. In absence of CONFIG_DEBUG_LOCK_ALLOC, this assumes we are in an SRCU read-side critical section unless it can prove otherwise.

Checks debug_lockdep_rcu_enabled() to prevent false positives during boot and while lockdep is disabled.

Note that SRCU is based on its own statemachine and it doesn't relies on normal RCU, it can be called from the CPU which is in the idle loop from an RCU point of view or offline.

srcu_dereference_check

`srcu_dereference_check (p, ssp, c)`

fetch SRCU-protected pointer for later dereferencing

Parameters

p
: the pointer to fetch and protect for later dereferencing

ssp
: pointer to the srcu_struct, which is used to check that we really are in an SRCU read-side critical section.

c
: condition to check for update-side use

Description

If PROVE_RCU is enabled, invoking this outside of an RCU read-side critical section will result in an RCU-lockdep splat, unless **c** evaluates to 1. The **c** argument will normally be a logical expression containing lockdep_is_held() calls.

srcu_dereference

`srcu_dereference (p, ssp)`

fetch SRCU-protected pointer for later dereferencing

Parameters

p
: the pointer to fetch and protect for later dereferencing

ssp
: pointer to the srcu_struct, which is used to check that we really are in an SRCU read-side critical section.

Description

Makes *rcu_dereference_check()* do the dirty work. If PROVE_RCU is enabled, invoking this outside of an RCU read-side critical section will result in an RCU-lockdep splat.

srcu_dereference_notrace

`srcu_dereference_notrace (p, ssp)`

no tracing and no lockdep calls from here

Parameters

p
the pointer to fetch and protect for later dereferencing

ssp
pointer to the srcu_struct, which is used to check that we really are in an SRCU read-side critical section.

int **srcu_read_lock**(struct srcu_struct *ssp)
register a new reader for an SRCU-protected structure.

Parameters

struct srcu_struct *ssp
srcu_struct in which to register the new reader.

Description

Enter an SRCU read-side critical section. Note that SRCU read-side critical sections may be nested. However, it is illegal to call anything that waits on an SRCU grace period for the same srcu_struct, whether directly or indirectly. Please note that one way to indirectly wait on an SRCU grace period is to acquire a mutex that is held elsewhere while calling *synchronize_srcu()* or *synchronize_srcu_expedited()*.

Note that *srcu_read_lock()* and the matching *srcu_read_unlock()* must occur in the same context, for example, it is illegal to invoke *srcu_read_unlock()* in an irq handler if the matching *srcu_read_lock()* was invoked in process context.

void **srcu_read_unlock**(struct srcu_struct *ssp, int idx)
unregister a old reader from an SRCU-protected structure.

Parameters

struct srcu_struct *ssp
srcu_struct in which to unregister the old reader.

int idx
return value from corresponding *srcu_read_lock()*.

Description

Exit an SRCU read-side critical section.

void **smp_mb__after_srcu_read_unlock**(void)
ensure full ordering after srcu_read_unlock

Parameters

void
no arguments

Description

Converts the preceding srcu_read_unlock into a two-way memory barrier.

Call this after srcu_read_unlock, to guarantee that all memory operations that occur after smp_mb__after_srcu_read_unlock will appear to happen after the preceding srcu_read_unlock.

int **init_srcu_struct**(struct srcu_struct *ssp)

initialize a sleep-RCU structure

Parameters

struct srcu_struct *ssp
structure to initialize.

Description

Must invoke this on a given srcu_struct before passing that srcu_struct to any other function. Each srcu_struct represents a separate domain of SRCU protection.

bool **srcu_readers_active**(struct srcu_struct *ssp)

returns true if there are readers. and false otherwise

Parameters

struct srcu_struct *ssp
which srcu_struct to count active readers (holding srcu_read_lock).

Description

Note that this is not an atomic primitive, and can therefore suffer severe errors when invoked on an active srcu_struct. That said, it can be useful as an error check at cleanup time.

void **cleanup_srcu_struct**(struct srcu_struct *ssp)

deconstruct a sleep-RCU structure

Parameters

struct srcu_struct *ssp
structure to clean up.

Description

Must invoke this after you are finished using a given srcu_struct that was initialized via *init_srcu_struct()*, else you leak memory.

void **call_srcu**(struct srcu_struct *ssp, struct rcu_head *rhp, rcu_callback_t func)

Queue a callback for invocation after an SRCU grace period

Parameters

struct srcu_struct *ssp
srcu_struct in queue the callback

struct rcu_head *rhp
structure to be used for queueing the SRCU callback.

rcu_callback_t func
function to be invoked after the SRCU grace period

Description

The callback function will be invoked some time after a full SRCU grace period elapses, in other words after all pre-existing SRCU read-side critical sections have completed. However, the callback function might well execute concurrently with other SRCU read-side critical sections that started after *call_srcu()* was invoked. SRCU read-side critical sections are delimited by *srcu_read_lock()* and *srcu_read_unlock()*, and may be nested.

The callback will be invoked from process context, but must nevertheless be fast and must not block.

void **synchronize_srcu_expedited**(struct srcu_struct *ssp)

Brute-force SRCU grace period

Parameters

struct srcu_struct *ssp
srcu_struct with which to synchronize.

Description

Wait for an SRCU grace period to elapse, but be more aggressive about spinning rather than blocking when waiting.

Note that *synchronize_srcu_expedited()* has the same deadlock and memory-ordering properties as does *synchronize_srcu()*.

void **synchronize_srcu**(struct srcu_struct *ssp)

wait for prior SRCU read-side critical-section completion

Parameters

struct srcu_struct *ssp
srcu_struct with which to synchronize.

Description

Wait for the count to drain to zero of both indexes. To avoid the possible starvation of *synchronize_srcu()*, it waits for the count of the index=((->srcu_idx & 1) ^ 1) to drain to zero at first, and then flip the srcu_idx and wait for the count of the other index.

Can block; must be called from process context.

Note that it is illegal to call *synchronize_srcu()* from the corresponding SRCU read-side critical section; doing so will result in deadlock. However, it is perfectly legal to call *synchronize_srcu()* on one srcu_struct from some other srcu_struct's read-side critical section, as long as the resulting graph of srcu_structs is acyclic.

There are memory-ordering constraints implied by *synchronize_srcu()*. On systems with more than one CPU, when *synchronize_srcu()* returns, each CPU is guaranteed to have executed a full memory barrier since the end of its last corresponding SRCU read-side critical section whose beginning preceded the call to *synchronize_srcu()*. In addition, each CPU having an SRCU read-side critical section that extends beyond the return from *synchronize_srcu()* is guaranteed to have executed a full memory barrier after the beginning of *synchronize_srcu()* and before the beginning of that SRCU read-side critical section. Note that these guarantees include CPUs that are offline, idle, or executing in user mode, as well as CPUs that are executing in the kernel.

Furthermore, if CPU A invoked *synchronize_srcu()*, which returned to its caller on CPU B, then both CPU A and CPU B are guaranteed to have executed a full memory barrier during the execution of *synchronize_srcu()*. This guarantee applies even if CPU A and CPU B are the same CPU, but again only if the system has more than one CPU.

Of course, these memory-ordering guarantees apply only when *synchronize_srcu()*, *srcu_read_lock()*, and *srcu_read_unlock()* are passed the same srcu_struct structure.

If SRCU is likely idle, expedite the first request. This semantic was provided by Classic SRCU, and is relied upon by its users, so TREE SRCU must also provide it. Note that detecting idleness is heuristic and subject to both false positives and negatives.

unsigned long **get_state_synchronize_srcu**(struct srcu_struct *ssp)

Provide an end-of-grace-period cookie

Parameters

struct srcu_struct *ssp
srcu_struct to provide cookie for.

Description

This function returns a cookie that can be passed to *poll_state_synchronize_srcu()*, which will return true if a full grace period has elapsed in the meantime. It is the caller's responsibility to make sure that grace period happens, for example, by invoking *call_srcu()* after return from *get_state_synchronize_srcu()*.

unsigned long **start_poll_synchronize_srcu**(struct srcu_struct *ssp)

Provide cookie and start grace period

Parameters

struct srcu_struct *ssp
srcu_struct to provide cookie for.

Description

This function returns a cookie that can be passed to *poll_state_synchronize_srcu()*, which will return true if a full grace period has elapsed in the meantime. Unlike *get_state_synchronize_srcu()*, this function also ensures that any needed SRCU grace period will be started. This convenience does come at a cost in terms of CPU overhead.

bool **poll_state_synchronize_srcu**(struct srcu_struct *ssp, unsigned long cookie)

Has cookie's grace period ended?

Parameters

struct srcu_struct *ssp
srcu_struct to provide cookie for.

unsigned long cookie
Return value from *get_state_synchronize_srcu()* or *start_poll_synchronize_srcu()*.

Description

This function takes the cookie that was returned from either *get_state_synchronize_srcu()* or *start_poll_synchronize_srcu()*, and returns **true** if an SRCU grace period elapsed since the time that the cookie was created.

void **srcu_barrier**(struct srcu_struct *ssp)

Wait until all in-flight *call_srcu()* callbacks complete.

Parameters

struct srcu_struct *ssp
srcu_struct on which to wait for in-flight callbacks.

unsigned long **srcu_batches_completed**(struct srcu_struct *ssp)

return batches completed.

Parameters

struct srcu_struct *ssp
srcu_struct on which to report batch completion.

Description

Report the number of batches, correlated with, but not necessarily precisely the same as, the number of grace periods that have elapsed.

void **hlist_bl_del_rcu**(struct hlist_bl_node *n)

deletes entry from hash list without re-initialization

Parameters

struct hlist_bl_node *n
the element to delete from the hash list.

Note

hlist_bl_unhashed() on entry does not return true after this, the entry is in an undefined state. It is useful for RCU based lockfree traversal.

Description

In particular, it means that we can not poison the forward pointers that may still be used for walking the hash list.

The caller must take whatever precautions are necessary (such as holding appropriate locks) to avoid racing with another list-mutation primitive, such as *hlist_bl_add_head_rcu()* or *hlist_bl_del_rcu()*, running on this same list. However, it is perfectly legal to run concurrently with the _rcu list-traversal primitives, such as hlist_bl_for_each_entry().

void **hlist_bl_add_head_rcu**(struct hlist_bl_node *n, struct hlist_bl_head *h)

Parameters

struct hlist_bl_node *n
the element to add to the hash list.

struct hlist_bl_head *h
the list to add to.

Description

Adds the specified element to the specified hlist_bl, while permitting racing traversals.

The caller must take whatever precautions are necessary (such as holding appropriate locks) to avoid racing with another list-mutation primitive, such as *hlist_bl_add_head_rcu()* or *hlist_bl_del_rcu()*, running on this same list. However, it is perfectly legal to run concurrently with the _rcu list-traversal primitives, such as *hlist_bl_for_each_entry_rcu()*, used to prevent memory-consistency problems on Alpha CPUs. Regardless of the type of CPU, the list-traversal primitive must be guarded by *rcu_read_lock()*.

hlist_bl_for_each_entry_rcu

`hlist_bl_for_each_entry_rcu (tpos, pos, head, member)`

iterate over rcu list of given type

Parameters

tpos
the type * to use as a loop cursor.

pos
the `struct hlist_bl_node` to use as a loop cursor.

head
the head for your list.

member
the name of the hlist_bl_node within the struct.

list_tail_rcu

`list_tail_rcu (head)`

returns the prev pointer of the head of the list

Parameters

head
the head of the list

Note

This should only be used with the list header, and even then only if *list_del()* and similar primitives are not also used on the list header.

void **list_add_rcu**(struct list_head *new, struct list_head *head)

add a new entry to rcu-protected list

Parameters

struct list_head *new
new entry to be added

struct list_head *head
list head to add it after

Description

Insert a new entry after the specified head. This is good for implementing stacks.

The caller must take whatever precautions are necessary (such as holding appropriate locks) to avoid racing with another list-mutation primitive, such as *list_add_rcu()* or *list_del_rcu()*, running on this same list. However, it is perfectly legal to run concurrently with the _rcu list-traversal primitives, such as *list_for_each_entry_rcu()*.

void **list_add_tail_rcu**(struct list_head *new, struct list_head *head)

add a new entry to rcu-protected list

Parameters

struct list_head *new
new entry to be added

struct list_head *head
list head to add it before

Description

Insert a new entry before the specified head. This is useful for implementing queues.

The caller must take whatever precautions are necessary (such as holding appropriate locks) to avoid racing with another list-mutation primitive, such as *list_add_tail_rcu()* or *list_del_rcu()*, running on this same list. However, it is perfectly legal to run concurrently with the _rcu list-traversal primitives, such as *list_for_each_entry_rcu()*.

void **list_del_rcu**(struct list_head *entry)

deletes entry from list without re-initialization

Parameters

struct list_head *entry
the element to delete from the list.

Note

list_empty() on entry does not return true after this, the entry is in an undefined state. It is useful for RCU based lockfree traversal.

Description

In particular, it means that we can not poison the forward pointers that may still be used for walking the list.

The caller must take whatever precautions are necessary (such as holding appropriate locks) to avoid racing with another list-mutation primitive, such as *list_del_rcu()* or *list_add_rcu()*, running on this same list. However, it is perfectly legal to run concurrently with the _rcu list-traversal primitives, such as *list_for_each_entry_rcu()*.

Note that the caller is not permitted to immediately free the newly deleted entry. Instead, either *synchronize_rcu()* or *call_rcu()* must be used to defer freeing until an RCU grace period has elapsed.

void **hlist_del_init_rcu**(struct hlist_node *n)

deletes entry from hash list with re-initialization

Parameters

struct hlist_node *n
the element to delete from the hash list.

Note

list_unhashed() on the node return true after this. It is useful for RCU based read lockfree traversal if the writer side must know if the list entry is still hashed or already unhashed.

Description

In particular, it means that we can not poison the forward pointers that may still be used for walking the hash list and we can only zero the pprev pointer so list_unhashed() will return true after this.

The caller must take whatever precautions are necessary (such as holding appropriate locks) to avoid racing with another list-mutation primitive, such as *hlist_add_head_rcu()* or *hlist_del_rcu()*, running on this same list. However, it is perfectly legal to run concurrently with the _rcu list-traversal primitives, such as *hlist_for_each_entry_rcu()*.

void **list_replace_rcu**(struct list_head *old, struct list_head *new)

replace old entry by new one

Parameters

struct list_head *old
the element to be replaced

struct list_head *new
the new element to insert

Description

The **old** entry will be replaced with the **new** entry atomically.

Note

old should not be empty.

void **__list_splice_init_rcu**(struct list_head *list, struct list_head *prev, struct list_head *next, void (*sync)(void))

join an RCU-protected list into an existing list.

Parameters

struct list_head *list
the RCU-protected list to splice

struct list_head *prev
points to the last element of the existing list

struct list_head *next
points to the first element of the existing list

void (*sync)(void)
synchronize_rcu, synchronize_rcu_expedited, ⋯

Description

The list pointed to by **prev** and **next** can be RCU-read traversed concurrently with this function.

Note that this function blocks.

Important note: the caller must take whatever action is necessary to prevent any other updates to the existing list. In principle, it is possible to modify the list as soon as sync() begins execution. If this sort of thing becomes necessary, an alternative version based on *call_rcu()* could be created. But only if -really-needed – there is no shortage of RCU API members.

void **list_splice_init_rcu**(struct list_head *list, struct list_head *head, void (*sync)(void))

splice an RCU-protected list into an existing list, designed for stacks.

Parameters

struct list_head *list
the RCU-protected list to splice

struct list_head *head
the place in the existing list to splice the first list into

void (*sync)(void)
synchronize_rcu, synchronize_rcu_expedited, ⋯

void **list_splice_tail_init_rcu**(struct list_head *list, struct list_head *head, void (*sync)(void))

splice an RCU-protected list into an existing list, designed for queues.

Parameters

struct list_head *list
the RCU-protected list to splice

struct list_head *head
the place in the existing list to splice the first list into

void (*sync)(void)
synchronize_rcu, synchronize_rcu_expedited, ⋯

list_entry_rcu

`list_entry_rcu (ptr, type, member)`

get the struct for this entry

Parameters

ptr
the `struct list_head` pointer.

type
the type of the struct this is embedded in.

member
the name of the list_head within the struct.

Description

This primitive may safely run concurrently with the _rcu list-mutation primitives such as *list_add_rcu()* as long as it's guarded by *rcu_read_lock()*.

list_first_or_null_rcu

`list_first_or_null_rcu (ptr, type, member)`

get the first element from a list

Parameters

ptr
the list head to take the element from.

type
the type of the struct this is embedded in.

member
the name of the list_head within the struct.

Description

Note that if the list is empty, it returns NULL.

This primitive may safely run concurrently with the _rcu list-mutation primitives such as *list_add_rcu()* as long as it's guarded by *rcu_read_lock()*.

list_next_or_null_rcu

`list_next_or_null_rcu (head, ptr, type, member)`

get the first element from a list

Parameters

head
the head for the list.

ptr
the list head to take the next element from.

type
the type of the struct this is embedded in.

member
the name of the list_head within the struct.

Description

Note that if the ptr is at the end of the list, NULL is returned.

This primitive may safely run concurrently with the _rcu list-mutation primitives such as *list_add_rcu()* as long as it's guarded by *rcu_read_lock()*.

list_for_each_entry_rcu

`list_for_each_entry_rcu (pos, head, member, cond...)`

iterate over rcu list of given type

Parameters

pos
the type * to use as a loop cursor.

head
the head for your list.

member
the name of the list_head within the struct.

cond...
optional lockdep expression if called from non-RCU protection.

Description

This list-traversal primitive may safely run concurrently with the _rcu list-mutation primitives such as *list_add_rcu()* as long as the traversal is guarded by *rcu_read_lock()*.

list_for_each_entry_srcu

`list_for_each_entry_srcu (pos, head, member, cond)`

iterate over rcu list of given type

Parameters

pos
the type * to use as a loop cursor.

head
the head for your list.

member
the name of the list_head within the struct.

cond
lockdep expression for the lock required to traverse the list.

Description

This list-traversal primitive may safely run concurrently with the _rcu list-mutation primitives such as *list_add_rcu()* as long as the traversal is guarded by *srcu_read_lock()*. The lockdep expression *srcu_read_lock_held()* can be passed as the cond argument from read side.

list_entry_lockless

`list_entry_lockless (ptr, type, member)`

get the struct for this entry

Parameters

ptr
the `struct list_head` pointer.

type
the type of the struct this is embedded in.

member
the name of the list_head within the struct.

Description

This primitive may safely run concurrently with the _rcu list-mutation primitives such as *list_add_rcu()*, but requires some implicit RCU read-side guarding. One example is running within a special exception-time environment where preemption is disabled and where lockdep cannot be invoked. Another example is when items are added to the list, but never deleted.

list_for_each_entry_lockless

`list_for_each_entry_lockless (pos, head, member)`

iterate over rcu list of given type

Parameters

pos
the type * to use as a loop cursor.

head
the head for your list.

member
the name of the list_struct within the struct.

Description

This primitive may safely run concurrently with the _rcu list-mutation primitives such as *list_add_rcu()*, but requires some implicit RCU read-side guarding. One example is running within a special exception-time environment where preemption is disabled and where lockdep cannot be invoked. Another example is when items are added to the list, but never deleted.

list_for_each_entry_continue_rcu

`list_for_each_entry_continue_rcu (pos, head, member)`

continue iteration over list of given type

Parameters

pos
the type * to use as a loop cursor.

head
the head for your list.

member
the name of the list_head within the struct.

Description

Continue to iterate over list of given type, continuing after the current position which must have been in the list when the RCU read lock was taken. This would typically require either that you obtained the node from a previous walk of the list in the same RCU read-side critical section, or that you held some sort of non-RCU reference (such as a reference count) to keep the node alive *and* in the list.

This iterator is similar to *list_for_each_entry_from_rcu()* except this starts after the given position and that one starts at the given position.

list_for_each_entry_from_rcu

`list_for_each_entry_from_rcu (pos, head, member)`

iterate over a list from current point

Parameters

pos
the type * to use as a loop cursor.

head
the head for your list.

member
the name of the list_node within the struct.

Description

Iterate over the tail of a list starting from a given position, which must have been in the list when the RCU read lock was taken. This would typically require either that you obtained the node from a previous walk of the list in the same RCU read-side critical section, or that you held some sort of non-RCU reference (such as a reference count) to keep the node alive *and* in the list.

This iterator is similar to *list_for_each_entry_continue_rcu()* except this starts from the given position and that one starts from the position after the given position.

void **hlist_del_rcu**(struct hlist_node *n)

deletes entry from hash list without re-initialization

Parameters

struct hlist_node *n
the element to delete from the hash list.

Note

list_unhashed() on entry does not return true after this, the entry is in an undefined state. It is useful for RCU based lockfree traversal.

Description

In particular, it means that we can not poison the forward pointers that may still be used for walking the hash list.

The caller must take whatever precautions are necessary (such as holding appropriate locks) to avoid racing with another list-mutation primitive, such as *hlist_add_head_rcu()* or *hlist_del_rcu()*, running on this same list. However, it is perfectly legal to run concurrently with the _rcu list-traversal primitives, such as *hlist_for_each_entry()*.

void **hlist_replace_rcu**(struct hlist_node *old, struct hlist_node *new)

replace old entry by new one

Parameters

struct hlist_node *old
the element to be replaced

struct hlist_node *new
the new element to insert

Description

The **old** entry will be replaced with the **new** entry atomically.

void **hlists_swap_heads_rcu**(struct hlist_head *left, struct hlist_head *right)
swap the lists the hlist heads point to

Parameters

struct hlist_head *left
The hlist head on the left

struct hlist_head *right
The hlist head on the right

Description

The lists start out as [left][node1 ⋯] and
[**right**][node2 ⋯]

The lists end up as [left][node2 ⋯]
[**right**][node1 ⋯]

void **hlist_add_head_rcu**(struct hlist_node *n, struct hlist_head *h)

Parameters

struct hlist_node *n
the element to add to the hash list.

struct hlist_head *h
the list to add to.

Description

Adds the specified element to the specified hlist, while permitting racing traversals.

The caller must take whatever precautions are necessary (such as holding appropriate locks) to avoid racing with another list-mutation primitive, such as *hlist_add_head_rcu()* or *hlist_del_rcu()*, running on this same list. However, it is perfectly legal to run concurrently with the _rcu list-traversal primitives, such as *hlist_for_each_entry_rcu()*, used to prevent memory-consistency problems on Alpha CPUs. Regardless of the type of CPU, the list-traversal primitive must be guarded by *rcu_read_lock()*.

void **hlist_add_tail_rcu**(struct hlist_node *n, struct hlist_head *h)

Parameters

struct hlist_node *n
the element to add to the hash list.

struct hlist_head *h
the list to add to.

Description

Adds the specified element to the specified hlist, while permitting racing traversals.

The caller must take whatever precautions are necessary (such as holding appropriate locks) to avoid racing with another list-mutation primitive, such as *hlist_add_head_rcu()* or *hlist_del_rcu()*, running on this same list. However, it is perfectly legal to run concurrently with the _rcu list-traversal primitives, such as *hlist_for_each_entry_rcu()*, used to prevent memory-consistency problems on Alpha CPUs. Regardless of the type of CPU, the list-traversal primitive must be guarded by *rcu_read_lock()*.

void **hlist_add_before_rcu**(struct hlist_node *n, struct hlist_node *next)

Parameters

struct hlist_node *n
the new element to add to the hash list.

struct hlist_node *next
the existing element to add the new element before.

Description

Adds the specified element to the specified hlist before the specified node while permitting racing traversals.

The caller must take whatever precautions are necessary (such as holding appropriate locks) to avoid racing with another list-mutation primitive, such as *hlist_add_head_rcu()* or *hlist_del_rcu()*, running on this same list. However, it is perfectly legal to run concurrently with the _rcu list-traversal primitives, such as *hlist_for_each_entry_rcu()*, used to prevent memory-consistency problems on Alpha CPUs.

void **hlist_add_behind_rcu**(struct hlist_node *n, struct hlist_node *prev)

Parameters

struct hlist_node *n
the new element to add to the hash list.

struct hlist_node *prev
the existing element to add the new element after.

Description

Adds the specified element to the specified hlist after the specified node while permitting racing traversals.

The caller must take whatever precautions are necessary (such as holding appropriate locks) to avoid racing with another list-mutation primitive, such as *hlist_add_head_rcu()* or *hlist_del_rcu()*, running on this same list. However, it is perfectly legal to run concurrently with the _rcu list-traversal primitives, such as *hlist_for_each_entry_rcu()*, used to prevent memory-consistency problems on Alpha CPUs.

hlist_for_each_entry_rcu

`hlist_for_each_entry_rcu (pos, head, member, cond...)`

iterate over rcu list of given type

Parameters

pos
the type * to use as a loop cursor.

head
the head for your list.

member
the name of the hlist_node within the struct.

cond...
optional lockdep expression if called from non-RCU protection.

Description

This list-traversal primitive may safely run concurrently with the _rcu list-mutation primitives such as *hlist_add_head_rcu()* as long as the traversal is guarded by *rcu_read_lock()*.

hlist_for_each_entry_srcu

`hlist_for_each_entry_srcu (pos, head, member, cond)`

iterate over rcu list of given type

Parameters

pos
the type * to use as a loop cursor.

head
the head for your list.

member
the name of the hlist_node within the struct.

cond
lockdep expression for the lock required to traverse the list.

Description

This list-traversal primitive may safely run concurrently with the _rcu list-mutation primitives such as *hlist_add_head_rcu()* as long as the traversal is guarded by *srcu_read_lock()*. The lockdep expression *srcu_read_lock_held()* can be passed as the cond argument from read side.

hlist_for_each_entry_rcu_notrace

`hlist_for_each_entry_rcu_notrace (pos, head, member)`

iterate over rcu list of given type (for tracing)

Parameters

pos
the type * to use as a loop cursor.

head
the head for your list.

member
the name of the hlist_node within the struct.

Description

This list-traversal primitive may safely run concurrently with the _rcu list-mutation primitives such as *hlist_add_head_rcu()* as long as the traversal is guarded by *rcu_read_lock()*.

This is the same as *hlist_for_each_entry_rcu()* except that it does not do any RCU debugging or tracing.

hlist_for_each_entry_rcu_bh

`hlist_for_each_entry_rcu_bh (pos, head, member)`

iterate over rcu list of given type

Parameters

pos
the type * to use as a loop cursor.

head
the head for your list.

member
the name of the hlist_node within the struct.

Description

This list-traversal primitive may safely run concurrently with the _rcu list-mutation primitives such as *hlist_add_head_rcu()* as long as the traversal is guarded by *rcu_read_lock()*.

hlist_for_each_entry_continue_rcu

`hlist_for_each_entry_continue_rcu (pos, member)`

iterate over a hlist continuing after current point

Parameters

pos
the type * to use as a loop cursor.

member
the name of the hlist_node within the struct.

hlist_for_each_entry_continue_rcu_bh

`hlist_for_each_entry_continue_rcu_bh (pos, member)`

iterate over a hlist continuing after current point

Parameters

pos
the type * to use as a loop cursor.

member
the name of the hlist_node within the struct.

hlist_for_each_entry_from_rcu

`hlist_for_each_entry_from_rcu (pos, member)`

iterate over a hlist continuing from current point

Parameters

pos
the type * to use as a loop cursor.

member
the name of the hlist_node within the struct.

void **hlist_nulls_del_init_rcu**(struct hlist_nulls_node *n)

deletes entry from hash list with re-initialization

Parameters

struct hlist_nulls_node *n
the element to delete from the hash list.

Note

hlist_nulls_unhashed() on the node return true after this. It is useful for RCU based read lockfree traversal if the writer side must know if the list entry is still hashed or already unhashed.

Description

In particular, it means that we can not poison the forward pointers that may still be used for walking the hash list and we can only zero the pprev pointer so list_unhashed() will return true after this.

The caller must take whatever precautions are necessary (such as holding appropriate locks) to avoid racing with another list-mutation primitive, such as *hlist_nulls_add_head_rcu()* or *hlist_nulls_del_rcu()*, running on this same list. However, it is perfectly legal to run concurrently with the _rcu list-traversal primitives, such as *hlist_nulls_for_each_entry_rcu()*.

hlist_nulls_first_rcu

`hlist_nulls_first_rcu (head)`

returns the first element of the hash list.

Parameters

head
the head of the list.

hlist_nulls_next_rcu

`hlist_nulls_next_rcu (node)`

returns the element of the list after **node**.

Parameters

node
element of the list.

void **hlist_nulls_del_rcu**(struct hlist_nulls_node *n)
deletes entry from hash list without re-initialization

Parameters

struct hlist_nulls_node *n
the element to delete from the hash list.

Note

hlist_nulls_unhashed() on entry does not return true after this, the entry is in an undefined state. It is useful for RCU based lockfree traversal.

Description

In particular, it means that we can not poison the forward pointers that may still be used for walking the hash list.

The caller must take whatever precautions are necessary (such as holding appropriate locks) to avoid racing with another list-mutation primitive, such as *hlist_nulls_add_head_rcu()* or *hlist_nulls_del_rcu()*, running on this same list. However, it is perfectly legal to run concurrently with the _rcu list-traversal primitives, such as hlist_nulls_for_each_entry().

void **hlist_nulls_add_head_rcu**(struct hlist_nulls_node *n, struct hlist_nulls_head *h)

Parameters

struct hlist_nulls_node *n
the element to add to the hash list.

struct hlist_nulls_head *h
the list to add to.

Description

Adds the specified element to the specified hlist_nulls, while permitting racing traversals.

The caller must take whatever precautions are necessary (such as holding appropriate locks) to avoid racing with another list-mutation primitive, such as *hlist_nulls_add_head_rcu()* or *hlist_nulls_del_rcu()*, running on this same list. However, it is perfectly legal to run concurrently with the _rcu list-traversal primitives, such as *hlist_nulls_for_each_entry_rcu()*, used to prevent memory-consistency problems on Alpha CPUs. Regardless of the type of CPU, the list-traversal primitive must be guarded by *rcu_read_lock()*.

void **hlist_nulls_add_tail_rcu**(struct hlist_nulls_node *n, struct hlist_nulls_head *h)

Parameters

struct hlist_nulls_node *n
the element to add to the hash list.

struct hlist_nulls_head *h
the list to add to.

Description

Adds the specified element to the specified hlist_nulls, while permitting racing traversals.

The caller must take whatever precautions are necessary (such as holding appropriate locks) to avoid racing with another list-mutation primitive, such as *hlist_nulls_add_head_rcu()* or *hlist_nulls_del_rcu()*, running on this same list. However, it is perfectly legal to run concurrently with the _rcu list-traversal primitives, such as *hlist_nulls_for_each_entry_rcu()*, used to prevent memory-consistency problems on Alpha CPUs. Regardless of the type of CPU, the list-traversal primitive must be guarded by *rcu_read_lock()*.

hlist_nulls_for_each_entry_rcu

`hlist_nulls_for_each_entry_rcu (tpos, pos, head, member)`

iterate over rcu list of given type

Parameters

tpos
the type * to use as a loop cursor.

pos
the `struct hlist_nulls_node` to use as a loop cursor.

head
the head of the list.

member
the name of the hlist_nulls_node within the struct.

Description

The barrier() is needed to make sure compiler doesn't cache first element [1], as this loop can be restarted [2] [1] *Semantics and Behavior of Atomic and Bitmask Operations* around line 114 [2] *Using RCU hlist_nulls to protect list and objects* around line 146

hlist_nulls_for_each_entry_safe

`hlist_nulls_for_each_entry_safe (tpos, pos, head, member)`

iterate over list of given type safe against removal of list entry

Parameters

tpos
the type * to use as a loop cursor.

pos
the `struct hlist_nulls_node` to use as a loop cursor.

head
the head of the list.

member
the name of the hlist_nulls_node within the struct.

bool **rcu_sync_is_idle**(struct rcu_sync *rsp)

Are readers permitted to use their fastpaths?

Parameters

struct rcu_sync *rsp
Pointer to rcu_sync structure to use for synchronization

Description

Returns true if readers are permitted to use their fastpaths. Must be invoked within some flavor of RCU read-side critical section.

void **rcu_sync_init**(struct rcu_sync *rsp)

Initialize an rcu_sync structure

Parameters

struct rcu_sync *rsp
Pointer to rcu_sync structure to be initialized

void **rcu_sync_enter_start**(struct rcu_sync *rsp)

Force readers onto slow path for multiple updates

Parameters

struct rcu_sync *rsp
Pointer to rcu_sync structure to use for synchronization

Description

Must be called after *rcu_sync_init()* and before first use.

Ensures *rcu_sync_is_idle()* returns false and rcu_sync_{enter,exit}() pairs turn into NO-OPs.

void **rcu_sync_func**(struct rcu_head *rhp)

Callback function managing reader access to fastpath

Parameters

struct rcu_head *rhp
Pointer to rcu_head in rcu_sync structure to use for synchronization

Description

This function is passed to *call_rcu()* function by *rcu_sync_enter()* and *rcu_sync_exit()*, so that it is invoked after a grace period following the that invocation of enter/exit.

If it is called by *rcu_sync_enter()* it signals that all the readers were switched onto slow path.

If it is called by *rcu_sync_exit()* it takes action based on events that have taken place in the meantime, so that closely spaced *rcu_sync_enter()* and *rcu_sync_exit()* pairs need not wait for a grace period.

If another *rcu_sync_enter()* is invoked before the grace period ended, reset state to allow the next *rcu_sync_exit()* to let the readers back onto their fastpaths (after a grace period). If both another *rcu_sync_enter()* and its matching *rcu_sync_exit()* are invoked before the grace period ended, re-invoke *call_rcu()* on behalf of that *rcu_sync_exit()*. Otherwise, set all state back to idle so that readers can again use their fastpaths.

void **rcu_sync_enter**(struct rcu_sync *rsp)

Force readers onto slowpath

Parameters

struct rcu_sync *rsp
Pointer to rcu_sync structure to use for synchronization

Description

This function is used by updaters who need readers to make use of a slowpath during the update. After this function returns, all subsequent calls to *rcu_sync_is_idle()* will return false, which tells readers to stay off their fastpaths. A later call to *rcu_sync_exit()* re-enables reader slowpaths.

When called in isolation, *rcu_sync_enter()* must wait for a grace period, however, closely spaced calls to *rcu_sync_enter()* can optimize away the grace-period wait via a state machine implemented by *rcu_sync_enter()*, *rcu_sync_exit()*, and *rcu_sync_func()*.

void **rcu_sync_exit**(struct rcu_sync *rsp)

Allow readers back onto fast path after grace period

Parameters

struct rcu_sync *rsp
Pointer to rcu_sync structure to use for synchronization

Description

This function is used by updaters who have completed, and can therefore now allow readers to make use of their fastpaths after a grace period has elapsed. After this grace period has completed, all subsequent calls to *rcu_sync_is_idle()* will return true, which tells readers that they can once again use their fastpaths.

void **rcu_sync_dtor**(struct rcu_sync *rsp)

Clean up an rcu_sync structure

Parameters

struct rcu_sync *rsp
Pointer to rcu_sync structure to be cleaned up

1.2 Concurrency Managed Workqueue (cmwq)

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1.2.1 Introduction

There are many cases where an asynchronous process execution context is needed and the workqueue (wq) API is the most commonly used mechanism for such cases.

When such an asynchronous execution context is needed, a work item describing which function to execute is put on a queue. An independent thread serves as the asynchronous execution context. The queue is called workqueue and the thread is called worker.

While there are work items on the workqueue the worker executes the functions associated with the work items one after the other. When there is no work item left on the workqueue the worker becomes idle. When a new work item gets queued, the worker begins executing again.

1.2.2 Why cmwq?

In the original wq implementation, a multi threaded (MT) wq had one worker thread per CPU and a single threaded (ST) wq had one worker thread system-wide. A single MT wq needed to keep around the same number of workers as the number of CPUs. The kernel grew a lot of MT wq users over the years and with the number of CPU cores continuously rising, some systems saturated the default 32k PID space just booting up.

Although MT wq wasted a lot of resource, the level of concurrency provided was unsatisfactory. The limitation was common to both ST and MT wq albeit less severe on MT. Each wq maintained its own separate worker pool. An MT wq could provide only one execution context per CPU while an ST wq one for the whole system. Work items had to compete for those very limited execution contexts leading to various problems including proneness to deadlocks around the single execution context.

The tension between the provided level of concurrency and resource usage also forced its users to make unnecessary tradeoffs like libata choosing to use ST wq for polling PIOs and accepting an unnecessary limitation that no two polling PIOs can progress at the same time. As MT wq don't provide much better concurrency, users which require higher level of concurrency, like async or fscache, had to implement their own thread pool.

Concurrency Managed Workqueue (cmwq) is a reimplementation of wq with focus on the following goals.

- Maintain compatibility with the original workqueue API.
- Use per-CPU unified worker pools shared by all wq to provide flexible level of concurrency on demand without wasting a lot of resource.
- Automatically regulate worker pool and level of concurrency so that the API users don't need to worry about such details.

1.2.3 The Design

In order to ease the asynchronous execution of functions a new abstraction, the work item, is introduced.

A work item is a simple struct that holds a pointer to the function that is to be executed asynchronously. Whenever a driver or subsystem wants a function to be executed asynchronously it has to set up a work item pointing to that function and queue that work item on a workqueue.

Special purpose threads, called worker threads, execute the functions off of the queue, one after the other. If no work is queued, the worker threads become idle. These worker threads are managed in so called worker-pools.

The cmwq design differentiates between the user-facing workqueues that subsystems and drivers queue work items on and the backend mechanism which manages worker-pools and processes the queued work items.

There are two worker-pools, one for normal work items and the other for high priority ones, for each possible CPU and some extra worker-pools to serve work items queued on unbound workqueues - the number of these backing pools is dynamic.

Subsystems and drivers can create and queue work items through special workqueue API functions as they see fit. They can influence some aspects of the way the work items are executed by setting flags on the workqueue they are putting the work item on. These flags include things like CPU locality, concurrency limits, priority and more. To get a detailed overview refer to the API description of `alloc_workqueue()` below.

When a work item is queued to a workqueue, the target worker-pool is determined according to the queue parameters and workqueue attributes and appended on the shared worklist of the worker-pool. For example, unless specifically overridden, a work item of a bound workqueue will be queued on the worklist of either normal or highpri worker-pool that is associated to the CPU the issuer is running on.

For any worker pool implementation, managing the concurrency level (how many execution contexts are active) is an important issue. cmwq tries to keep the concurrency at a minimal but sufficient level. Minimal to save resources and sufficient in that the system is used at its full capacity.

Each worker-pool bound to an actual CPU implements concurrency management by hooking into the scheduler. The worker-pool is notified whenever an active worker wakes up or sleeps and keeps track of the number of the currently runnable workers. Generally, work items are not expected to hog a CPU and consume many cycles. That means maintaining just enough concurrency to prevent work processing from stalling should be optimal. As long as there are one or more runnable workers on the CPU, the worker-pool doesn't start execution of a new work, but, when the last running worker goes to sleep, it immediately schedules a new worker so that the CPU doesn't sit idle while there are pending work items. This allows using a minimal number of workers without losing execution bandwidth.

Keeping idle workers around doesn't cost other than the memory space for kthreads, so cmwq holds onto idle ones for a while before killing them.

For unbound workqueues, the number of backing pools is dynamic. Unbound workqueue can be assigned custom attributes using `apply_workqueue_attrs()`

and workqueue will automatically create backing worker pools matching the attributes. The responsibility of regulating concurrency level is on the users. There is also a flag to mark a bound wq to ignore the concurrency management. Please refer to the API section for details.

Forward progress guarantee relies on that workers can be created when more execution contexts are necessary, which in turn is guaranteed through the use of rescue workers. All work items which might be used on code paths that handle memory reclaim are required to be queued on wq's that have a rescue-worker reserved for execution under memory pressure. Else it is possible that the worker-pool deadlocks waiting for execution contexts to free up.

1.2.4 Application Programming Interface (API)

`alloc_workqueue()` allocates a wq. The original `create_*workqueue()` functions are deprecated and scheduled for removal. `alloc_workqueue()` takes three arguments - `@name`, `@flags` and `@max_active`. `@name` is the name of the wq and also used as the name of the rescuer thread if there is one.

A wq no longer manages execution resources but serves as a domain for forward progress guarantee, flush and work item attributes. `@flags` and `@max_active` control how work items are assigned execution resources, scheduled and executed.

flags

WQ_UNBOUND
: Work items queued to an unbound wq are served by the special worker-pools which host workers which are not bound to any specific CPU. This makes the wq behave as a simple execution context provider without concurrency management. The unbound worker-pools try to start execution of work items as soon as possible. Unbound wq sacrifices locality but is useful for the following cases.

  - Wide fluctuation in the concurrency level requirement is expected and using bound wq may end up creating large number of mostly unused workers across different CPUs as the issuer hops through different CPUs.
  - Long running CPU intensive workloads which can be better managed by the system scheduler.

WQ_FREEZABLE
: A freezable wq participates in the freeze phase of the system suspend operations. Work items on the wq are drained and no new work item starts execution until thawed.

WQ_MEM_RECLAIM
: All wq which might be used in the memory reclaim paths **MUST** have this flag set. The wq is guaranteed to have at least one execution context regardless of memory pressure.

WQ_HIGHPRI
: Work items of a highpri wq are queued to the highpri worker-pool of the target

cpu. Highpri worker-pools are served by worker threads with elevated nice level.

Note that normal and highpri worker-pools don't interact with each other. Each maintains its separate pool of workers and implements concurrency management among its workers.

WQ_CPU_INTENSIVE
Work items of a CPU intensive wq do not contribute to the concurrency level. In other words, runnable CPU intensive work items will not prevent other work items in the same worker-pool from starting execution. This is useful for bound work items which are expected to hog CPU cycles so that their execution is regulated by the system scheduler.

Although CPU intensive work items don't contribute to the concurrency level, start of their executions is still regulated by the concurrency management and runnable non-CPU-intensive work items can delay execution of CPU intensive work items.

This flag is meaningless for unbound wq.

Note that the flag `WQ_NON_REENTRANT` no longer exists as all workqueues are now non-reentrant - any work item is guaranteed to be executed by at most one worker system-wide at any given time.

max_active

`@max_active` determines the maximum number of execution contexts per CPU which can be assigned to the work items of a wq. For example, with `@max_active` of 16, at most 16 work items of the wq can be executing at the same time per CPU.

Currently, for a bound wq, the maximum limit for `@max_active` is 512 and the default value used when 0 is specified is 256. For an unbound wq, the limit is higher of 512 and 4 * `num_possible_cpus()`. These values are chosen sufficiently high such that they are not the limiting factor while providing protection in runaway cases.

The number of active work items of a wq is usually regulated by the users of the wq, more specifically, by how many work items the users may queue at the same time. Unless there is a specific need for throttling the number of active work items, specifying '0' is recommended.

Some users depend on the strict execution ordering of ST wq. The combination of `@max_active` of 1 and `WQ_UNBOUND` used to achieve this behavior. Work items on such wq were always queued to the unbound worker-pools and only one work item could be active at any given time thus achieving the same ordering property as ST wq.

In the current implementation the above configuration only guarantees ST behavior within a given NUMA node. Instead `alloc_ordered_queue()` should be used to achieve system-wide ST behavior.

1.2.5 Example Execution Scenarios

The following example execution scenarios try to illustrate how cmwq behave under different configurations.

> Work items w0, w1, w2 are queued to a bound wq q0 on the same CPU. w0 burns CPU for 5ms then sleeps for 10ms then burns CPU for 5ms again before finishing. w1 and w2 burn CPU for 5ms then sleep for 10ms.

Ignoring all other tasks, works and processing overhead, and assuming simple FIFO scheduling, the following is one highly simplified version of possible sequences of events with the original wq.

```
TIME IN MSECS  EVENT
0              w0 starts and burns CPU
5              w0 sleeps
15             w0 wakes up and burns CPU
20             w0 finishes
20             w1 starts and burns CPU
25             w1 sleeps
35             w1 wakes up and finishes
35             w2 starts and burns CPU
40             w2 sleeps
50             w2 wakes up and finishes
```

And with cmwq with `@max_active` >= 3,

```
TIME IN MSECS  EVENT
0              w0 starts and burns CPU
5              w0 sleeps
5              w1 starts and burns CPU
10             w1 sleeps
10             w2 starts and burns CPU
15             w2 sleeps
15             w0 wakes up and burns CPU
20             w0 finishes
20             w1 wakes up and finishes
25             w2 wakes up and finishes
```

If `@max_active` == 2,

```
TIME IN MSECS  EVENT
0              w0 starts and burns CPU
5              w0 sleeps
5              w1 starts and burns CPU
10             w1 sleeps
15             w0 wakes up and burns CPU
20             w0 finishes
20             w1 wakes up and finishes
20             w2 starts and burns CPU
25             w2 sleeps
35             w2 wakes up and finishes
```

Now, let's assume w1 and w2 are queued to a different wq q1 which has WQ_CPU_INTENSIVE set,

```
TIME IN MSECS  EVENT
0              w0 starts and burns CPU
5              w0 sleeps
5              w1 and w2 start and burn CPU
10             w1 sleeps
15             w2 sleeps
15             w0 wakes up and burns CPU
20             w0 finishes
20             w1 wakes up and finishes
25             w2 wakes up and finishes
```

1.2.6 Guidelines

- Do not forget to use WQ_MEM_RECLAIM if a wq may process work items which are used during memory reclaim. Each wq with WQ_MEM_RECLAIM set has an execution context reserved for it. If there is dependency among multiple work items used during memory reclaim, they should be queued to separate wq each with WQ_MEM_RECLAIM.
- Unless strict ordering is required, there is no need to use ST wq.
- Unless there is a specific need, using 0 for @max_active is recommended. In most use cases, concurrency level usually stays well under the default limit.
- A wq serves as a domain for forward progress guarantee (WQ_MEM_RECLAIM, flush and work item attributes. Work items which are not involved in memory reclaim and don't need to be flushed as a part of a group of work items, and don't require any special attribute, can use one of the system wq. There is no difference in execution characteristics between using a dedicated wq and a system wq.
- Unless work items are expected to consume a huge amount of CPU cycles, using a bound wq is usually beneficial due to the increased level of locality in wq operations and work item execution.

1.2.7 Debugging

Because the work functions are executed by generic worker threads there are a few tricks needed to shed some light on misbehaving workqueue users.

Worker threads show up in the process list as:

```
root      5671  0.0  0.0      0     0 ?        S    12:07   0:00␣
↪[kworker/0:1]
root      5672  0.0  0.0      0     0 ?        S    12:07   0:00␣
↪[kworker/1:2]
root      5673  0.0  0.0      0     0 ?        S    12:12   0:00␣
↪[kworker/0:0]
```

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```
root       5674  0.0  0.0      0     0 ?        S    12:13   0:00␣
↪[kworker/1:0]
```

If kworkers are going crazy (using too much cpu), there are two types of possible problems:

1. Something being scheduled in rapid succession
2. A single work item that consumes lots of cpu cycles

The first one can be tracked using tracing:

```
$ echo workqueue:workqueue_queue_work > /sys/kernel/debug/tracing/
↪set_event
$ cat /sys/kernel/debug/tracing/trace_pipe > out.txt
(wait a few secs)
^C
```

If something is busy looping on work queueing, it would be dominating the output and the offender can be determined with the work item function.

For the second type of problems it should be possible to just check the stack trace of the offending worker thread.

```
$ cat /proc/THE_OFFENDING_KWORKER/stack
```

The work item's function should be trivially visible in the stack trace.

1.2.8 Kernel Inline Documentations Reference

struct **workqueue_attrs**

A struct for workqueue attributes.

Definition

```
struct workqueue_attrs {
  int nice;
  cpumask_var_t cpumask;
  bool no_numa;
};
```

Members

nice
nice level

cpumask
allowed CPUs

no_numa
disable NUMA affinity

Unlike other fields, `no_numa` isn't a property of a worker_pool. It only modifies how *apply_workqueue_attrs()* select pools and thus doesn' t participate in pool hash calculations or equality comparisons.

Description

This can be used to change attributes of an unbound workqueue.

work_pending

`work_pending (work)`

Find out whether a work item is currently pending

Parameters

work
The work item in question

delayed_work_pending

`delayed_work_pending (w)`

Find out whether a delayable work item is currently pending

Parameters

w
The work item in question

struct workqueue_struct ***alloc_workqueue**(const char *fmt, unsigned int flags, int max_active, ...)

allocate a workqueue

Parameters

const char *fmt
printf format for the name of the workqueue

unsigned int flags
WQ_* flags

int max_active
max in-flight work items, 0 for default remaining args: args for **fmt**

...
variable arguments

Description

Allocate a workqueue with the specified parameters. For detailed information on WQ_* flags, please refer to *Concurrency Managed Workqueue (cmwq)*.

Return

Pointer to the allocated workqueue on success, `NULL` on failure.

alloc_ordered_workqueue

`alloc_ordered_workqueue (fmt, flags, args...)`

allocate an ordered workqueue

Parameters

fmt
printf format for the name of the workqueue

flags
WQ_* flags (only WQ_FREEZABLE and WQ_MEM_RECLAIM are meaningful)

args...
args for **fmt**

Description

Allocate an ordered workqueue. An ordered workqueue executes at most one work item at any given time in the queued order. They are implemented as unbound workqueues with **max_active** of one.

Return

Pointer to the allocated workqueue on success, `NULL` on failure.

bool **queue_work**(struct workqueue_struct *wq, struct work_struct *work)
queue work on a workqueue

Parameters

struct workqueue_struct *wq
workqueue to use

struct work_struct *work
work to queue

Description

Returns `false` if **work** was already on a queue, `true` otherwise.

We queue the work to the CPU on which it was submitted, but if the CPU dies it can be processed by another CPU.

Memory-ordering properties: If it returns `true`, guarantees that all stores preceding the call to *queue_work()* in the program order will be visible from the CPU which will execute **work** by the time such work executes, e.g.,

{ x is initially 0 }

CPU0 CPU1

WRITE_ONCE(x, 1); [**work** is being executed] r0 = queue_work(wq, work); r1 = READ_ONCE(x);

Forbids: r0 == true && r1 == 0

bool **queue_delayed_work**(struct workqueue_struct *wq, struct delayed_work *dwork, unsigned long delay)
queue work on a workqueue after delay

Parameters

struct workqueue_struct *wq
workqueue to use

struct delayed_work *dwork
delayable work to queue

unsigned long delay
number of jiffies to wait before queueing

Description

Equivalent to *queue_delayed_work_on()* but tries to use the local CPU.

bool **mod_delayed_work**(struct workqueue_struct *wq, struct delayed_work *dwork, unsigned long delay)

modify delay of or queue a delayed work

Parameters

struct workqueue_struct *wq
workqueue to use

struct delayed_work *dwork
work to queue

unsigned long delay
number of jiffies to wait before queueing

Description

mod_delayed_work_on() on local CPU.

bool **schedule_work_on**(int cpu, struct work_struct *work)

put work task on a specific cpu

Parameters

int cpu
cpu to put the work task on

struct work_struct *work
job to be done

Description

This puts a job on a specific cpu

bool **schedule_work**(struct work_struct *work)

put work task in global workqueue

Parameters

struct work_struct *work
job to be done

Description

Returns `false` if **work** was already on the kernel-global workqueue and `true` otherwise.

This puts a job in the kernel-global workqueue if it was not already queued and leaves it in the same position on the kernel-global workqueue otherwise.

Shares the same memory-ordering properties of *queue_work()*, cf. the DocBook header of *queue_work()*.

void **flush_scheduled_work**(void)
ensure that any scheduled work has run to completion.

Parameters

void
no arguments

Description

Forces execution of the kernel-global workqueue and blocks until its completion.

Think twice before calling this function! It's very easy to get into trouble if you don't take great care. Either of the following situations will lead to deadlock:

One of the work items currently on the workqueue needs to acquire a lock held by your code or its caller.

Your code is running in the context of a work routine.

They will be detected by lockdep when they occur, but the first might not occur very often. It depends on what work items are on the workqueue and what locks they need, which you have no control over.

In most situations flushing the entire workqueue is overkill; you merely need to know that a particular work item isn't queued and isn't running. In such cases you should use *cancel_delayed_work_sync()* or *cancel_work_sync()* instead.

bool **schedule_delayed_work_on**(int cpu, struct delayed_work *dwork, unsigned long delay)
queue work in global workqueue on CPU after delay

Parameters

int cpu
cpu to use

struct delayed_work *dwork
job to be done

unsigned long delay
number of jiffies to wait

Description

After waiting for a given time this puts a job in the kernel-global workqueue on the specified CPU.

bool **schedule_delayed_work**(struct delayed_work *dwork, unsigned long delay)
put work task in global workqueue after delay

Parameters

struct delayed_work *dwork
job to be done

unsigned long delay
number of jiffies to wait or 0 for immediate execution

Description

After waiting for a given time this puts a job in the kernel-global workqueue.

for_each_pool

`for_each_pool (pool, pi)`

iterate through all worker_pools in the system

Parameters

pool
iteration cursor

pi
integer used for iteration

Description

This must be called either with wq_pool_mutex held or RCU read locked. If the pool needs to be used beyond the locking in effect, the caller is responsible for guaranteeing that the pool stays online.

The if/else clause exists only for the lockdep assertion and can be ignored.

for_each_pool_worker

`for_each_pool_worker (worker, pool)`

iterate through all workers of a worker_pool

Parameters

worker
iteration cursor

pool
worker_pool to iterate workers of

Description

This must be called with wq_pool_attach_mutex.

The if/else clause exists only for the lockdep assertion and can be ignored.

for_each_pwq

`for_each_pwq (pwq, wq)`

iterate through all pool_workqueues of the specified workqueue

Parameters

pwq
iteration cursor

wq
the target workqueue

Description

This must be called either with wq->mutex held or RCU read locked. If the pwq needs to be used beyond the locking in effect, the caller is responsible for guaranteeing that the pwq stays online.

The if/else clause exists only for the lockdep assertion and can be ignored.

int **worker_pool_assign_id**(struct worker_pool *pool)
allocate ID and assing it to **pool**

Parameters

struct worker_pool *pool
the pool pointer of interest

Description

Returns 0 if ID in [0, WORK_OFFQ_POOL_NONE) is allocated and assigned successfully, -errno on failure.

struct pool_workqueue ***unbound_pwq_by_node**(struct workqueue_struct *wq, int node)
return the unbound pool_workqueue for the given node

Parameters

struct workqueue_struct *wq
the target workqueue

int node
the node ID

Description

This must be called with any of wq_pool_mutex, wq->mutex or RCU read locked. If the pwq needs to be used beyond the locking in effect, the caller is responsible for guaranteeing that the pwq stays online.

Return

The unbound pool_workqueue for **node**.

struct worker_pool ***get_work_pool**(struct work_struct *work)
return the worker_pool a given work was associated with

Parameters

struct work_struct *work
the work item of interest

Description

Pools are created and destroyed under wq_pool_mutex, and allows read access under RCU read lock. As such, this function should be called under wq_pool_mutex or inside of a `rcu_read_lock()` region.

All fields of the returned pool are accessible as long as the above mentioned locking is in effect. If the returned pool needs to be used beyond the critical section, the caller is responsible for ensuring the returned pool is and stays online.

Return

The worker_pool **work** was last associated with. `NULL` if none.

int **get_work_pool_id**(struct work_struct *work)
return the worker pool ID a given work is associated with

Parameters

struct work_struct *work
the work item of interest

Return

The worker_pool ID **work** was last associated with. `WORK_OFFQ_POOL_NONE` if none.

void **wake_up_worker**(struct worker_pool *pool)
wake up an idle worker

Parameters

struct worker_pool *pool
worker pool to wake worker from

Description

Wake up the first idle worker of **pool**.

Context

raw_spin_lock_irq(pool->lock).

void **wq_worker_running**(struct task_struct *task)
a worker is running again

Parameters

struct task_struct *task
task waking up

Description

This function is called when a worker returns from schedule()

void **wq_worker_sleeping**(struct task_struct *task)
a worker is going to sleep

Parameters

struct task_struct *task
task going to sleep

Description

This function is called from schedule() when a busy worker is going to sleep. Preemption needs to be disabled to protect ->sleeping assignment.

work_func_t **wq_worker_last_func**(struct task_struct *task)
retrieve worker's last work function

Parameters

struct task_struct *task
Task to retrieve last work function of.

Description

Determine the last function a worker executed. This is called from the scheduler to get a worker's last known identity.

This function is called during schedule() when a kworker is going to sleep. It's used by psi to identify aggregation workers during dequeuing, to allow periodic aggregation to shut-off when that worker is the last task in the system or cgroup to go to sleep.

As this function doesn't involve any workqueue-related locking, it only returns stable values when called from inside the scheduler's queuing and dequeuing paths, when **task**, which must be a kworker, is guaranteed to not be processing any works.

Context

raw_spin_lock_irq(rq->lock)

Return

The last work function `current` executed as a worker, NULL if it hasn't executed any work yet.

void **worker_set_flags**(struct *worker* *worker, unsigned int flags)

set worker flags and adjust nr_running accordingly

Parameters

struct worker *worker
self

unsigned int flags
flags to set

Description

Set **flags** in **worker->flags** and adjust nr_running accordingly.

Context

raw_spin_lock_irq(pool->lock)

void **worker_clr_flags**(struct *worker* *worker, unsigned int flags)

clear worker flags and adjust nr_running accordingly

Parameters

struct worker *worker
self

unsigned int flags
flags to clear

Description

Clear **flags** in **worker->flags** and adjust nr_running accordingly.

Context

raw_spin_lock_irq(pool->lock)

struct worker ***find_worker_executing_work**(struct worker_pool *pool, struct work_struct *work)

find worker which is executing a work

Parameters

struct worker_pool *pool
pool of interest

struct work_struct *work
work to find worker for

Description

Find a worker which is executing **work** on **pool** by searching **pool->busy_hash** which is keyed by the address of **work**. For a worker to match, its current execution should match the address of **work** and its work function. This is to avoid unwanted dependency between unrelated work executions through a work item being recycled while still being executed.

This is a bit tricky. A work item may be freed once its execution starts and nothing prevents the freed area from being recycled for another work item. If the same work item address ends up being reused before the original execution finishes, workqueue will identify the recycled work item as currently executing and make it wait until the current execution finishes, introducing an unwanted dependency.

This function checks the work item address and work function to avoid false positives. Note that this isn't complete as one may construct a work function which can introduce dependency onto itself through a recycled work item. Well, if somebody wants to shoot oneself in the foot that badly, there's only so much we can do, and if such deadlock actually occurs, it should be easy to locate the culprit work function.

Context

raw_spin_lock_irq(pool->lock).

Return

Pointer to worker which is executing **work** if found, `NULL` otherwise.

void **move_linked_works**(struct work_struct *work, struct list_head *head, struct work_struct **nextp)

move linked works to a list

Parameters

struct work_struct *work
start of series of works to be scheduled

struct list_head *head
target list to append **work** to

struct work_struct **nextp
out parameter for nested worklist walking

Description

Schedule linked works starting from **work** to **head**. Work series to be scheduled starts at **work** and includes any consecutive work with WORK_STRUCT_LINKED set in its predecessor.

If **nextp** is not NULL, it's updated to point to the next work of the last scheduled work. This allows *move_linked_works()* to be nested inside outer *list_for_each_entry_safe()*.

Context

raw_spin_lock_irq(pool->lock).

void **get_pwq**(struct pool_workqueue *pwq)

get an extra reference on the specified pool_workqueue

Parameters

struct pool_workqueue *pwq
pool_workqueue to get

Description

Obtain an extra reference on **pwq**. The caller should guarantee that **pwq** has positive refcnt and be holding the matching pool->lock.

void **put_pwq**(struct pool_workqueue *pwq)

put a pool_workqueue reference

Parameters

struct pool_workqueue *pwq
pool_workqueue to put

Description

Drop a reference of **pwq**. If its refcnt reaches zero, schedule its destruction. The caller should be holding the matching pool->lock.

void **put_pwq_unlocked**(struct pool_workqueue *pwq)

put_pwq() with surrounding pool lock/unlock

Parameters

struct pool_workqueue *pwq
pool_workqueue to put (can be NULL)

Description

put_pwq() with locking. This function also allows NULL **pwq**.

void **pwq_dec_nr_in_flight**(struct pool_workqueue *pwq, int color)

decrement pwq's nr_in_flight

Parameters

struct pool_workqueue *pwq
pwq of interest

int color
color of work which left the queue

Description

A work either has completed or is removed from pending queue, decrement nr_in_flight of its pwq and handle workqueue flushing.

Context

raw_spin_lock_irq(pool->lock).

int **try_to_grab_pending**(struct work_struct *work, bool is_dwork, unsigned long *flags)

steal work item from worklist and disable irq

Parameters

struct work_struct *work
work item to steal

bool is_dwork
work is a delayed_work

unsigned long *flags
place to store irq state

Description

Try to grab PENDING bit of **work**. This function can handle **work** in any stable state - idle, on timer or on worklist.

On successful return, >= 0, irq is disabled and the caller is responsible for releasing it using local_irq_restore(***flags**).

This function is safe to call from any context including IRQ handler.

Return

1	if **work** was pending and we successfully stole PENDING
0	if **work** was idle and we claimed PENDING
-EAGAIN	if PENDING couldn't be grabbed at the moment, safe to busy-retry
-ENOENT	if someone else is canceling **work**, this state may persist for arbitrarily long

Note

On >= 0 return, the caller owns **work**'s PENDING bit. To avoid getting interrupted while holding PENDING and **work** off queue, irq must be disabled on entry. This, combined with delayed_work->timer being irqsafe, ensures that we return -EAGAIN for finite short period of time.

void **insert_work**(struct pool_workqueue *pwq, struct work_struct *work, struct list_head *head, unsigned int extra_flags)

insert a work into a pool

Parameters

struct pool_workqueue *pwq
pwq **work** belongs to

struct work_struct *work
work to insert

struct list_head *head
insertion point

unsigned int extra_flags
extra WORK_STRUCT_* flags to set

Description

Insert **work** which belongs to **pwq** after **head**. **extra_flags** is or'd to work_struct flags.

Context

raw_spin_lock_irq(pool->lock).

bool **queue_work_on**(int cpu, struct workqueue_struct *wq, struct work_struct *work)
queue work on specific cpu

Parameters

int cpu
CPU number to execute work on

struct workqueue_struct *wq
workqueue to use

struct work_struct *work
work to queue

Description

We queue the work to a specific CPU, the caller must ensure it can't go away.

Return

`false` if **work** was already on a queue, `true` otherwise.

int **workqueue_select_cpu_near**(int node)
Select a CPU based on NUMA node

Parameters

int node
NUMA node ID that we want to select a CPU from

Description

This function will attempt to find a "random" cpu available on a given node. If there are no CPUs available on the given node it will return WORK_CPU_UNBOUND indicating that we should just schedule to any available CPU if we need to schedule this work.

bool **queue_work_node**(int node, struct workqueue_struct *wq, struct work_struct *work)
queue work on a "random" cpu for a given NUMA node

Parameters

int node
NUMA node that we are targeting the work for

struct workqueue_struct *wq
workqueue to use

struct work_struct *work
work to queue

Description

We queue the work to a "random" CPU within a given NUMA node. The basic idea here is to provide a way to somehow associate work with a given NUMA node.

This function will only make a best effort attempt at getting this onto the right NUMA node. If no node is requested or the requested node is offline then we just fall back to standard queue_work behavior.

Currently the "random" CPU ends up being the first available CPU in the intersection of cpu_online_mask and the cpumask of the node, unless we are running on the node. In that case we just use the current CPU.

Return

`false` if **work** was already on a queue, `true` otherwise.

bool **queue_delayed_work_on**(int cpu, struct workqueue_struct *wq, struct delayed_work *dwork, unsigned long delay)

queue work on specific CPU after delay

Parameters

int cpu
CPU number to execute work on

struct workqueue_struct *wq
workqueue to use

struct delayed_work *dwork
work to queue

unsigned long delay
number of jiffies to wait before queueing

Return

`false` if **work** was already on a queue, `true` otherwise. If **delay** is zero and **dwork** is idle, it will be scheduled for immediate execution.

bool **mod_delayed_work_on**(int cpu, struct workqueue_struct *wq, struct delayed_work *dwork, unsigned long delay)

modify delay of or queue a delayed work on specific CPU

Parameters

int cpu
CPU number to execute work on

struct workqueue_struct *wq
workqueue to use

struct delayed_work *dwork
work to queue

unsigned long delay
number of jiffies to wait before queueing

Description

If **dwork** is idle, equivalent to *queue_delayed_work_on()*; otherwise, modify **dwork**' s timer so that it expires after **delay**. If **delay** is zero, **work** is guaranteed to be scheduled immediately regardless of its current state.

This function is safe to call from any context including IRQ handler. See *try_to_grab_pending()* for details.

Return

`false` if **dwork** was idle and queued, `true` if **dwork** was pending and its timer was modified.

bool **queue_rcu_work**(struct workqueue_struct *wq, struct rcu_work *rwork)

queue work after a RCU grace period

Parameters

struct workqueue_struct *wq
workqueue to use

struct rcu_work *rwork
work to queue

Return

`false` if **rwork** was already pending, `true` otherwise. Note that a full RCU grace period is guaranteed only after a `true` return. While **rwork** is guaranteed to be executed after a `false` return, the execution may happen before a full RCU grace period has passed.

void **worker_enter_idle**(struct *worker* *worker)

enter idle state

Parameters

struct worker *worker
worker which is entering idle state

Description

worker is entering idle state. Update stats and idle timer if necessary.

LOCKING: raw_spin_lock_irq(pool->lock).

void **worker_leave_idle**(struct *worker* *worker)

leave idle state

Parameters

struct worker *worker
worker which is leaving idle state

Description

worker is leaving idle state. Update stats.

LOCKING: raw_spin_lock_irq(pool->lock).

void **worker_attach_to_pool**(struct *worker* *worker, struct worker_pool *pool)
attach a worker to a pool

Parameters

struct worker *worker
worker to be attached

struct worker_pool *pool
the target pool

Description

Attach **worker** to **pool**. Once attached, the `WORKER_UNBOUND` flag and cpu-binding of **worker** are kept coordinated with the pool across cpu-[un]hotplugs.

void **worker_detach_from_pool**(struct *worker* *worker)
detach a worker from its pool

Parameters

struct worker *worker
worker which is attached to its pool

Description

Undo the attaching which had been done in *worker_attach_to_pool()*. The caller worker shouldn't access to the pool after detached except it has other reference to the pool.

struct worker ***create_worker**(struct worker_pool *pool)
create a new workqueue worker

Parameters

struct worker_pool *pool
pool the new worker will belong to

Description

Create and start a new worker which is attached to **pool**.

Context

Might sleep. Does GFP_KERNEL allocations.

Return

Pointer to the newly created worker.

void **destroy_worker**(struct *worker* *worker)
destroy a workqueue worker

Parameters

struct worker *worker
worker to be destroyed

Description

Destroy **worker** and adjust **pool** stats accordingly. The worker should be idle.

Context

raw_spin_lock_irq(pool->lock).

void **maybe_create_worker**(struct worker_pool *pool)

create a new worker if necessary

Parameters

struct worker_pool *pool
pool to create a new worker for

Description

Create a new worker for **pool** if necessary. **pool** is guaranteed to have at least one idle worker on return from this function. If creating a new worker takes longer than MAYDAY_INTERVAL, mayday is sent to all rescuers with works scheduled on **pool** to resolve possible allocation deadlock.

On return, need_to_create_worker() is guaranteed to be `false` and may_start_working() `true`.

LOCKING: raw_spin_lock_irq(pool->lock) which may be released and regrabbed multiple times. Does GFP_KERNEL allocations. Called only from manager.

bool **manage_workers**(struct *worker* *worker)

manage worker pool

Parameters

struct worker *worker
self

Description

Assume the manager role and manage the worker pool **worker** belongs to. At any given time, there can be only zero or one manager per pool. The exclusion is handled automatically by this function.

The caller can safely start processing works on false return. On true return, it's guaranteed that need_to_create_worker() is false and may_start_working() is true.

Context

raw_spin_lock_irq(pool->lock) which may be released and regrabbed multiple times. Does GFP_KERNEL allocations.

Return

`false` if the pool doesn't need management and the caller can safely start processing works, `true` if management function was performed and the conditions that the caller verified before calling the function may no longer be true.

void **process_one_work**(struct *worker* *worker, struct work_struct *work)

process single work

Parameters

struct worker *worker
self

struct work_struct *work
work to process

Description

Process **work**. This function contains all the logics necessary to process a single work including synchronization against and interaction with other workers on the same cpu, queueing and flushing. As long as context requirement is met, any worker can call this function to process a work.

Context

raw_spin_lock_irq(pool->lock) which is released and regrabbed.

void **process_scheduled_works**(struct *worker* *worker)

process scheduled works

Parameters

struct worker *worker
self

Description

Process all scheduled works. Please note that the scheduled list may change while processing a work, so this function repeatedly fetches a work from the top and executes it.

Context

raw_spin_lock_irq(pool->lock) which may be released and regrabbed multiple times.

int **worker_thread**(void *__worker)

the worker thread function

Parameters

void *__worker
self

Description

The worker thread function. All workers belong to a worker_pool - either a per-cpu one or dynamic unbound one. These workers process all work items regardless of their specific target workqueue. The only exception is work items which belong to workqueues with a rescuer which will be explained in *rescuer_thread()*.

Return

0

int **rescuer_thread**(void *__rescuer)

the rescuer thread function

Parameters

void *__rescuer
self

Description

Workqueue rescuer thread function. There's one rescuer for each workqueue which has WQ_MEM_RECLAIM set.

Regular work processing on a pool may block trying to create a new worker which uses GFP_KERNEL allocation which has slight chance of developing into deadlock if some works currently on the same queue need to be processed to satisfy the GFP_KERNEL allocation. This is the problem rescuer solves.

When such condition is possible, the pool summons rescuers of all workqueues which have works queued on the pool and let them process those works so that forward progress can be guaranteed.

This should happen rarely.

Return

0

void **check_flush_dependency**(struct workqueue_struct *target_wq, struct work_struct *target_work)

check for flush dependency sanity

Parameters

struct workqueue_struct *target_wq
workqueue being flushed

struct work_struct *target_work
work item being flushed (NULL for workqueue flushes)

Description

`current` is trying to flush the whole **target_wq** or **target_work** on it. If **target_wq** doesn't have `WQ_MEM_RECLAIM`, verify that `current` is not reclaiming memory or running on a workqueue which doesn't have `WQ_MEM_RECLAIM` as that can break forward-progress guarantee leading to a deadlock.

void **insert_wq_barrier**(struct pool_workqueue *pwq, struct wq_barrier *barr, struct work_struct *target, struct *worker* *worker)

insert a barrier work

Parameters

struct pool_workqueue *pwq
pwq to insert barrier into

struct wq_barrier *barr
wq_barrier to insert

struct work_struct *target
target work to attach **barr** to

struct worker *worker
worker currently executing **target**, NULL if **target** is not executing

Description

barr is linked to **target** such that **barr** is completed only after **target** finishes execution. Please note that the ordering guarantee is observed only with respect to **target** and on the local cpu.

Currently, a queued barrier can't be canceled. This is because *try_to_grab_pending()* can't determine whether the work to be grabbed is at the head of the queue and thus can't clear LINKED flag of the previous work while there must be a valid next work after a work with LINKED flag set.

Note that when **worker** is non-NULL, **target** may be modified underneath us, so we can't reliably determine pwq from **target**.

Context

raw_spin_lock_irq(pool->lock).

bool **`flush_workqueue_prep_pwqs`**(struct workqueue_struct *wq, int flush_color, int work_color)

prepare pwqs for workqueue flushing

Parameters

`struct workqueue_struct *wq`
workqueue being flushed

`int flush_color`
new flush color, < 0 for no-op

`int work_color`
new work color, < 0 for no-op

Description

Prepare pwqs for workqueue flushing.

If **flush_color** is non-negative, flush_color on all pwqs should be -1. If no pwq has in-flight commands at the specified color, all pwq->flush_color's stay at -1 and `false` is returned. If any pwq has in flight commands, its pwq->flush_color is set to **flush_color**, **wq->nr_pwqs_to_flush** is updated accordingly, pwq wakeup logic is armed and `true` is returned.

The caller should have initialized **wq->first_flusher** prior to calling this function with non-negative **flush_color**. If **flush_color** is negative, no flush color update is done and `false` is returned.

If **work_color** is non-negative, all pwqs should have the same work_color which is previous to **work_color** and all will be advanced to **work_color**.

Context

mutex_lock(wq->mutex).

Return

`true` if **flush_color** >= 0 and there's something to flush. `false` otherwise.

void **`flush_workqueue`**(struct workqueue_struct *wq)

ensure that any scheduled work has run to completion.

Parameters

`struct workqueue_struct *wq`
workqueue to flush

Description

This function sleeps until all work items which were queued on entry have finished execution, but it is not livelocked by new incoming ones.

void **drain_workqueue**(struct workqueue_struct *wq)
drain a workqueue

Parameters

struct workqueue_struct *wq
workqueue to drain

Description

Wait until the workqueue becomes empty. While draining is in progress, only chain queueing is allowed. IOW, only currently pending or running work items on **wq** can queue further work items on it. **wq** is flushed repeatedly until it becomes empty. The number of flushing is determined by the depth of chaining and should be relatively short. Whine if it takes too long.

bool **flush_work**(struct work_struct *work)
wait for a work to finish executing the last queueing instance

Parameters

struct work_struct *work
the work to flush

Description

Wait until **work** has finished execution. **work** is guaranteed to be idle on return if it hasn't been requeued since flush started.

Return

`true` if *flush_work()* waited for the work to finish execution, `false` if it was already idle.

bool **cancel_work_sync**(struct work_struct *work)
cancel a work and wait for it to finish

Parameters

struct work_struct *work
the work to cancel

Description

Cancel **work** and wait for its execution to finish. This function can be used even if the work re-queues itself or migrates to another workqueue. On return from this function, **work** is guaranteed to be not pending or executing on any CPU.

cancel_work_sync(`delayed_work->work`) must not be used for delayed_work's. Use *cancel_delayed_work_sync()* instead.

The caller must ensure that the workqueue on which **work** was last queued can't be destroyed before this function returns.

Return

`true` if **work** was pending, `false` otherwise.

bool **flush_delayed_work**(struct delayed_work *dwork)
wait for a dwork to finish executing the last queueing

Parameters

struct delayed_work *dwork
the delayed work to flush

Description

Delayed timer is cancelled and the pending work is queued for immediate execution. Like *flush_work()*, this function only considers the last queueing instance of **dwork**.

Return

true if *flush_work()* waited for the work to finish execution, false if it was already idle.

bool **flush_rcu_work**(struct rcu_work *rwork)
wait for a rwork to finish executing the last queueing

Parameters

struct rcu_work *rwork
the rcu work to flush

Return

true if *flush_rcu_work()* waited for the work to finish execution, false if it was already idle.

bool **cancel_delayed_work**(struct delayed_work *dwork)
cancel a delayed work

Parameters

struct delayed_work *dwork
delayed_work to cancel

Description

Kill off a pending delayed_work.

This function is safe to call from any context including IRQ handler.

Return

true if **dwork** was pending and canceled; false if it wasn't pending.

Note

The work callback function may still be running on return, unless it returns true and the work doesn't re-arm itself. Explicitly flush or use *cancel_delayed_work_sync()* to wait on it.

bool **cancel_delayed_work_sync**(struct delayed_work *dwork)
cancel a delayed work and wait for it to finish

Parameters

struct delayed_work *dwork
the delayed work cancel

Description

This is *cancel_work_sync()* for delayed works.

Return

`true` if **dwork** was pending, `false` otherwise.

int **schedule_on_each_cpu**(work_func_t func)

execute a function synchronously on each online CPU

Parameters

work_func_t func
the function to call

Description

schedule_on_each_cpu() executes **func** on each online CPU using the system workqueue and blocks until all CPUs have completed. *schedule_on_each_cpu()* is very slow.

Return

0 on success, -errno on failure.

int **execute_in_process_context**(work_func_t fn, struct execute_work *ew)

reliably execute the routine with user context

Parameters

work_func_t fn
the function to execute

struct execute_work *ew
guaranteed storage for the execute work structure (must be available when the work executes)

Description

Executes the function immediately if process context is available, otherwise schedules the function for delayed execution.

Return

0 - function was executed
1 - function was scheduled for execution

void **free_workqueue_attrs**(struct *workqueue_attrs* *attrs)

free a workqueue_attrs

Parameters

struct workqueue_attrs *attrs
workqueue_attrs to free

Description

Undo *alloc_workqueue_attrs()*.

struct *workqueue_attrs* ***alloc_workqueue_attrs**(void)
allocate a workqueue_attrs

Parameters

void
no arguments

Description

Allocate a new workqueue_attrs, initialize with default settings and return it.

Return

The allocated new workqueue_attr on success. NULL on failure.

int **init_worker_pool**(struct worker_pool *pool)
initialize a newly zalloc'd worker_pool

Parameters

struct worker_pool *pool
worker_pool to initialize

Description

Initialize a newly zalloc'd **pool**. It also allocates **pool->attrs**.

Return

0 on success, -errno on failure. Even on failure, all fields inside **pool** proper are initialized and *put_unbound_pool()* can be called on **pool** safely to release it.

void **put_unbound_pool**(struct worker_pool *pool)
put a worker_pool

Parameters

struct worker_pool *pool
worker_pool to put

Description

Put **pool**. If its refcnt reaches zero, it gets destroyed in RCU safe manner. *get_unbound_pool()* calls this function on its failure path and this function should be able to release pools which went through, successfully or not, *init_worker_pool()*.

Should be called with wq_pool_mutex held.

struct worker_pool ***get_unbound_pool**(const struct *workqueue_attrs* *attrs)
get a worker_pool with the specified attributes

Parameters

const struct workqueue_attrs *attrs
the attributes of the worker_pool to get

Description

Obtain a worker_pool which has the same attributes as **attrs**, bump the reference count and return it. If there already is a matching worker_pool, it will be used; otherwise, this function attempts to create a new one.

Should be called with wq_pool_mutex held.

Return

On success, a worker_pool with the same attributes as **attrs**. On failure, `NULL`.

void **pwq_adjust_max_active**(struct pool_workqueue *pwq)
update a pwq' s max_active to the current setting

Parameters

struct pool_workqueue *pwq
target pool_workqueue

Description

If **pwq** isn' t freezing, set **pwq->max_active** to the associated workqueue' s saved_max_active and activate inactive work items accordingly. If **pwq** is freezing, clear **pwq->max_active** to zero.

bool **wq_calc_node_cpumask**(const struct *workqueue_attrs* *attrs, int node, int cpu_going_down, cpumask_t *cpumask)
calculate a wq_attrs' cpumask for the specified node

Parameters

const struct workqueue_attrs *attrs
the wq_attrs of the default pwq of the target workqueue

int node
the target NUMA node

int cpu_going_down
if >= 0, the CPU to consider as offline

cpumask_t *cpumask
outarg, the resulting cpumask

Description

Calculate the cpumask a workqueue with **attrs** should use on **node**. If **cpu_going_down** is >= 0, that cpu is considered offline during calculation. The result is stored in **cpumask**.

If NUMA affinity is not enabled, **attrs->cpumask** is always used. If enabled and **node** has online CPUs requested by **attrs**, the returned cpumask is the intersection of the possible CPUs of **node** and **attrs->cpumask**.

The caller is responsible for ensuring that the cpumask of **node** stays stable.

Return

`true` if the resulting **cpumask** is different from **attrs->cpumask**, `false` if equal.

int **apply_workqueue_attrs**(struct workqueue_struct *wq, const struct *workqueue_attrs* *attrs)
apply new workqueue_attrs to an unbound workqueue

Parameters

struct workqueue_struct *wq
: the target workqueue

const struct workqueue_attrs *attrs
: the workqueue_attrs to apply, allocated with *alloc_workqueue_attrs()*

Description

Apply **attrs** to an unbound workqueue **wq**. Unless disabled, on NUMA machines, this function maps a separate pwq to each NUMA node with possibles CPUs in **attrs->cpumask** so that work items are affine to the NUMA node it was issued on. Older pwqs are released as in-flight work items finish. Note that a work item which repeatedly requeues itself back-to-back will stay on its current pwq.

Performs GFP_KERNEL allocations.

Assumes caller has CPU hotplug read exclusion, i.e. get_online_cpus().

Return

0 on success and -errno on failure.

void **wq_update_unbound_numa**(struct workqueue_struct *wq, int cpu, bool online)

update NUMA affinity of a wq for CPU hot[un]plug

Parameters

struct workqueue_struct *wq
: the target workqueue

int cpu
: the CPU coming up or going down

bool online
: whether **cpu** is coming up or going down

Description

This function is to be called from `CPU_DOWN_PREPARE`, `CPU_ONLINE` and `CPU_DOWN_FAILED`. **cpu** is being hot[un]plugged, update NUMA affinity of **wq** accordingly.

If NUMA affinity can't be adjusted due to memory allocation failure, it falls back to **wq->dfl_pwq** which may not be optimal but is always correct.

Note that when the last allowed CPU of a NUMA node goes offline for a workqueue with a cpumask spanning multiple nodes, the workers which were already executing the work items for the workqueue will lose their CPU affinity and may execute on any CPU. This is similar to how per-cpu workqueues behave on CPU_DOWN. If a workqueue user wants strict affinity, it's the user's responsibility to flush the work item from CPU_DOWN_PREPARE.

void **destroy_workqueue**(struct workqueue_struct *wq)

safely terminate a workqueue

Parameters

struct workqueue_struct *wq
: target workqueue

Description

Safely destroy a workqueue. All work currently pending will be done first.

void **workqueue_set_max_active**(struct workqueue_struct *wq, int max_active)
adjust max_active of a workqueue

Parameters

struct workqueue_struct *wq
target workqueue

int max_active
new max_active value.

Description

Set max_active of **wq** to **max_active**.

Context

Don't call from IRQ context.

struct work_struct ***current_work**(void)
retrieve `current` task's work struct

Parameters

void
no arguments

Description

Determine if `current` task is a workqueue worker and what it's working on. Useful to find out the context that the `current` task is running in.

Return

work struct if `current` task is a workqueue worker, `NULL` otherwise.

bool **current_is_workqueue_rescuer**(void)
is `current` workqueue rescuer?

Parameters

void
no arguments

Description

Determine whether `current` is a workqueue rescuer. Can be used from work functions to determine whether it's being run off the rescuer task.

Return

`true` if `current` is a workqueue rescuer. `false` otherwise.

bool **workqueue_congested**(int cpu, struct workqueue_struct *wq)
test whether a workqueue is congested

Parameters

int cpu
CPU in question

struct workqueue_struct *wq
target workqueue

Description

Test whether **wq**' s cpu workqueue for **cpu** is congested. There is no synchronization around this function and the test result is unreliable and only useful as advisory hints or for debugging.

If **cpu** is WORK_CPU_UNBOUND, the test is performed on the local CPU. Note that both per-cpu and unbound workqueues may be associated with multiple pool_workqueues which have separate congested states. A workqueue being congested on one CPU doesn' t mean the workqueue is also contested on other CPUs / NUMA nodes.

Return

`true` if congested, `false` otherwise.

unsigned int **work_busy**(struct work_struct *work)
test whether a work is currently pending or running

Parameters

struct work_struct *work
the work to be tested

Description

Test whether **work** is currently pending or running. There is no synchronization around this function and the test result is unreliable and only useful as advisory hints or for debugging.

Return

OR' d bitmask of WORK_BUSY_* bits.

void **set_worker_desc**(const char *fmt, ...)
set description for the current work item

Parameters

const char *fmt
printf-style format string

...
arguments for the format string

Description

This function can be called by a running work function to describe what the work item is about. If the worker task gets dumped, this information will be printed out together to help debugging. The description can be at most WORKER_DESC_LEN including the trailing '0' .

void **print_worker_info**(const char *log_lvl, struct task_struct *task)
print out worker information and description

Parameters

const char *log_lvl
: the log level to use when printing

struct task_struct *task
: target task

Description

If **task** is a worker and currently executing a work item, print out the name of the workqueue being serviced and worker description set with `set_worker_desc()` by the currently executing work item.

This function can be safely called on any task as long as the task_struct itself is accessible. While safe, this function isn't synchronized and may print out mixups or garbages of limited length.

void **show_workqueue_state**(void)
: dump workqueue state

Parameters

void
: no arguments

Description

Called from a sysrq handler or try_to_freeze_tasks() and prints out all busy workqueues and pools.

void **rebind_workers**(struct worker_pool *pool)
: rebind all workers of a pool to the associated CPU

Parameters

struct worker_pool *pool
: pool of interest

Description

pool->cpu is coming online. Rebind all workers to the CPU.

void **restore_unbound_workers_cpumask**(struct worker_pool *pool, int cpu)
: restore cpumask of unbound workers

Parameters

struct worker_pool *pool
: unbound pool of interest

int cpu
: the CPU which is coming up

Description

An unbound pool may end up with a cpumask which doesn't have any online CPUs. When a worker of such pool get scheduled, the scheduler resets its cpus_allowed. If **cpu** is in **pool**'s cpumask which didn't have any online CPU before, cpus_allowed of all its workers should be restored.

long **work_on_cpu**(int cpu, long (*fn)(void*), void *arg)
run a function in thread context on a particular cpu

Parameters

int cpu
the cpu to run on

long (*fn)(void *)
the function to run

void *arg
the function arg

Description

It is up to the caller to ensure that the cpu doesn't go offline. The caller must not hold any locks which would prevent **fn** from completing.

Return

The value **fn** returns.

long **work_on_cpu_safe**(int cpu, long (*fn)(void*), void *arg)
run a function in thread context on a particular cpu

Parameters

int cpu
the cpu to run on

long (*fn)(void *)
the function to run

void *arg
the function argument

Description

Disables CPU hotplug and calls *work_on_cpu()*. The caller must not hold any locks which would prevent **fn** from completing.

Return

The value **fn** returns.

void **freeze_workqueues_begin**(void)
begin freezing workqueues

Parameters

void
no arguments

Description

Start freezing workqueues. After this function returns, all freezable workqueues will queue new works to their inactive_works list instead of pool->worklist.

Context

Grabs and releases wq_pool_mutex, wq->mutex and pool->lock's.

bool **freeze_workqueues_busy**(void)

are freezable workqueues still busy?

Parameters

void
no arguments

Description

Check whether freezing is complete. This function must be called between *freeze_workqueues_begin()* and *thaw_workqueues()*.

Context

Grabs and releases wq_pool_mutex.

Return

`true` if some freezable workqueues are still busy. `false` if freezing is complete.

void **thaw_workqueues**(void)

thaw workqueues

Parameters

void
no arguments

Description

Thaw workqueues. Normal queueing is restored and all collected frozen works are transferred to their respective pool worklists.

Context

Grabs and releases wq_pool_mutex, wq->mutex and pool->lock's.

int **workqueue_set_unbound_cpumask**(cpumask_var_t cpumask)

Set the low-level unbound cpumask

Parameters

cpumask_var_t cpumask
the cpumask to set

The low-level workqueues cpumask is a global cpumask that limits the affinity of all unbound workqueues. This function check the **cpumask** and apply it to all unbound workqueues and updates all pwqs of them.

Retun: 0 - Success
-EINVAL - Invalid **cpumask** -ENOMEM - Failed to allocate memory for attrs or pwqs.

int **workqueue_sysfs_register**(struct workqueue_struct *wq)

make a workqueue visible in sysfs

Parameters

struct workqueue_struct *wq
the workqueue to register

Description

Expose **wq** in sysfs under /sys/bus/workqueue/devices. alloc_workqueue*() automatically calls this function if WQ_SYSFS is set which is the preferred method.

Workqueue user should use this function directly iff it wants to apply workqueue_attrs before making the workqueue visible in sysfs; otherwise, *apply_workqueue_attrs()* may race against userland updating the attributes.

Return

0 on success, -errno on failure.

void **workqueue_sysfs_unregister**(struct workqueue_struct *wq)

undo *workqueue_sysfs_register()*

Parameters

struct workqueue_struct *wq
the workqueue to unregister

Description

If **wq** is registered to sysfs by *workqueue_sysfs_register()*, unregister.

void **workqueue_init_early**(void)

early init for workqueue subsystem

Parameters

void
no arguments

Description

This is the first half of two-staged workqueue subsystem initialization and invoked as soon as the bare basics - memory allocation, cpumasks and idr are up. It sets up all the data structures and system workqueues and allows early boot code to create workqueues and queue/cancel work items. Actual work item execution starts only after kthreads can be created and scheduled right before early initcalls.

void **workqueue_init**(void)

bring workqueue subsystem fully online

Parameters

void
no arguments

Description

This is the latter half of two-staged workqueue subsystem initialization and invoked as soon as kthreads can be created and scheduled. Workqueues have been created and work items queued on them, but there are no kworkers executing the work items yet. Populate the worker pools with the initial workers and enable future kworker creations.

1.3 Message logging with printk

printk() is one of the most widely known functions in the Linux kernel. It' s the standard tool we have for printing messages and usually the most basic way of tracing and debugging. If you' re familiar with printf(3) you can tell *printk()* is based on it, although it has some functional differences:

- *printk()* messages can specify a log level.
- the format string, while largely compatible with C99, doesn't follow the exact same specification. It has some extensions and a few limitations (no `%n` or floating point conversion specifiers). See *How to get printk format specifiers right*.

All *printk()* messages are printed to the kernel log buffer, which is a ring buffer exported to userspace through /dev/kmsg. The usual way to read it is using `dmesg`.

printk() is typically used like this:

```
printk(KERN_INFO "Message: %s\n", arg);
```

where `KERN_INFO` is the log level (note that it' s concatenated to the format string, the log level is not a separate argument). The available log levels are:

Name	String	Alias function
KERN_EMERG	"0"	*pr_emerg()*
KERN_ALERT	"1"	*pr_alert()*
KERN_CRIT	"2"	*pr_crit()*
KERN_ERR	"3"	*pr_err()*
KERN_WARNING	"4"	*pr_warn()*
KERN_NOTICE	"5"	*pr_notice()*
KERN_INFO	"6"	*pr_info()*
KERN_DEBUG	"7"	*pr_debug()* and *pr_devel()* if DEBUG is defined
KERN_DEFAULT	""	
KERN_CONT	"c"	*pr_cont()*

The log level specifies the importance of a message. The kernel decides whether to show the message immediately (printing it to the current console) depending on its log level and the current *console_loglevel* (a kernel variable). If the message priority is higher (lower log level value) than the *console_loglevel* the message will be printed to the console.

If the log level is omitted, the message is printed with `KERN_DEFAULT` level.

You can check the current *console_loglevel* with:

```
$ cat /proc/sys/kernel/printk
4        4        1        7
```

The result shows the *current*, *default*, *minimum* and *boot-time-default* log levels.

To change the current console_loglevel simply write the desired level to `/proc/sys/kernel/printk`. For example, to print all messages to the console:

```
# echo 8 > /proc/sys/kernel/printk
```

Another way, using `dmesg`:

```
# dmesg -n 5
```

sets the console_loglevel to print KERN_WARNING (4) or more severe messages to console. See `dmesg(1)` for more information.

As an alternative to *printk()* you can use the `pr_*()` aliases for logging. This family of macros embed the log level in the macro names. For example:

```
pr_info("Info message no. %d\n", msg_num);
```

prints a `KERN_INFO` message.

Besides being more concise than the equivalent *printk()* calls, they can use a common definition for the format string through the *pr_fmt()* macro. For instance, defining this at the top of a source file (before any `#include` directive):

```
#define pr_fmt(fmt) "%s:%s: " fmt, KBUILD_MODNAME, __func__
```

would prefix every pr_*() message in that file with the module and function name that originated the message.

For debugging purposes there are also two conditionally-compiled macros: *pr_debug()* and *pr_devel()*, which are compiled-out unless `DEBUG` (or also `CONFIG_DYNAMIC_DEBUG` in the case of *pr_debug()*) is defined.

1.3.1 Function reference

__visible int **printk**(const char *fmt, ...)

print a kernel message

Parameters

const char *fmt
format string

...
variable arguments

Description

This is *printk()*. It can be called from any context. We want it to work.

We try to grab the console_lock. If we succeed, it's easy - we log the output and call the console drivers. If we fail to get the semaphore, we place the output into the log buffer and return. The current holder of the console_sem will notice the new output in console_unlock(); and will send it to the consoles before releasing the lock.

One effect of this deferred printing is that code which calls *printk()* and then changes console_loglevel may break. This is because console_loglevel is inspected when the actual printing occurs.

See also: printf(3)

See the *vsnprintf()* documentation for format string extensions over C99.

pr_fmt

`pr_fmt (fmt)`

used by the pr_*() macros to generate the printk format string

Parameters

fmt
format string passed from a pr_*() macro

Description

This macro can be used to generate a unified format string for pr_*() macros. A common use is to prefix all pr_*() messages in a file with a common string. For example, defining this at the top of a source file:

#define pr_fmt(fmt) KBUILD_MODNAME " : " fmt

would prefix all pr_info, pr_emerg…messages in the file with the module name.

pr_emerg

`pr_emerg (fmt, ...)`

Print an emergency-level message

Parameters

fmt
format string

...
arguments for the format string

Description

This macro expands to a printk with KERN_EMERG loglevel. It uses *pr_fmt()* to generate the format string.

pr_alert

`pr_alert (fmt, ...)`

Print an alert-level message

Parameters

fmt
format string

...
arguments for the format string

Description

This macro expands to a printk with KERN_ALERT loglevel. It uses *pr_fmt()* to generate the format string.

pr_crit

`pr_crit (fmt, ...)`

Print a critical-level message

Parameters

fmt
format string

...
arguments for the format string

Description

This macro expands to a printk with KERN_CRIT loglevel. It uses *pr_fmt()* to generate the format string.

pr_err

`pr_err (fmt, ...)`

Print an error-level message

Parameters

fmt
format string

...
arguments for the format string

Description

This macro expands to a printk with KERN_ERR loglevel. It uses *pr_fmt()* to generate the format string.

pr_warn

`pr_warn (fmt, ...)`

Print a warning-level message

Parameters

fmt
format string

...
arguments for the format string

Description

This macro expands to a printk with KERN_WARNING loglevel. It uses *pr_fmt()* to generate the format string.

pr_notice

`pr_notice (fmt, ...)`

Print a notice-level message

Parameters

fmt
    format string

...
    arguments for the format string

Description

This macro expands to a printk with KERN_NOTICE loglevel. It uses *pr_fmt()* to generate the format string.

pr_info

`pr_info (fmt, ...)`

    Print an info-level message

Parameters

fmt
    format string

...
    arguments for the format string

Description

This macro expands to a printk with KERN_INFO loglevel. It uses *pr_fmt()* to generate the format string.

pr_cont

`pr_cont (fmt, ...)`

    Continues a previous log message in the same line.

Parameters

fmt
    format string

...
    arguments for the format string

Description

This macro expands to a printk with KERN_CONT loglevel. It should only be used when continuing a log message with no newline (' n') enclosed. Otherwise it defaults back to KERN_DEFAULT loglevel.

pr_devel

`pr_devel (fmt, ...)`

    Print a debug-level message conditionally

Parameters

fmt
    format string

...
    arguments for the format string

Description

This macro expands to a printk with KERN_DEBUG loglevel if DEBUG is defined. Otherwise it does nothing.

It uses *pr_fmt()* to generate the format string.

pr_debug

`pr_debug (fmt, ...)`

Print a debug-level message conditionally

Parameters

fmt
format string

...
arguments for the format string

Description

This macro expands to dynamic_pr_debug() if CONFIG_DYNAMIC_DEBUG is set. Otherwise, if DEBUG is defined, it's equivalent to a printk with KERN_DEBUG loglevel. If DEBUG is not defined it does nothing.

It uses *pr_fmt()* to generate the format string (dynamic_pr_debug() uses *pr_fmt()* internally).

1.4 How to get printk format specifiers right

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1.4.1 Integer types

```
If variable is of Type,         use printk format specifier:
------------------------------------------------------------
        char                    %d or %x
        unsigned char           %u or %x
        short int               %d or %x
        unsigned short int      %u or %x
        int                     %d or %x
        unsigned int            %u or %x
        long                    %ld or %lx
        unsigned long           %lu or %lx
        long long               %lld or %llx
        unsigned long long      %llu or %llx
        size_t                  %zu or %zx
        ssize_t                 %zd or %zx
```

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```
        s8                      %d or %x
        u8                      %u or %x
        s16                     %d or %x
        u16                     %u or %x
        s32                     %d or %x
        u32                     %u or %x
        s64                     %lld or %llx
        u64                     %llu or %llx
```

If <type> is dependent on a config option for its size (e.g., sector_t, blkcnt_t) or is architecture-dependent for its size (e.g., tcflag_t), use a format specifier of its largest possible type and explicitly cast to it.

Example:

```
printk("test: sector number/total blocks: %llu/%llu\n",
        (unsigned long long)sector, (unsigned long long)blockcount);
```

Reminder: sizeof() returns type size_t.

The kernel's printf does not support %n. Floating point formats (%e, %f, %g, %a) are also not recognized, for obvious reasons. Use of any unsupported specifier or length qualifier results in a WARN and early return from *vsnprintf()*.

1.4.2 Pointer types

A raw pointer value may be printed with %p which will hash the address before printing. The kernel also supports extended specifiers for printing pointers of different types.

Some of the extended specifiers print the data on the given address instead of printing the address itself. In this case, the following error messages might be printed instead of the unreachable information:

```
(null)   data on plain NULL address
(efault) data on invalid address
(einval) invalid data on a valid address
```

Plain Pointers

```
%p      abcdef12 or 00000000abcdef12
```

Pointers printed without a specifier extension (i.e unadorned %p) are hashed to prevent leaking information about the kernel memory layout. This has the added benefit of providing a unique identifier. On 64-bit machines the first 32 bits are zeroed. The kernel will print `(ptrval)` until it gathers enough entropy. If you *really* want the address see %px below.

Error Pointers

```
%pe     -ENOSPC
```

For printing error pointers (i.e. a pointer for which IS_ERR() is true) as a symbolic error name. Error values for which no symbolic name is known are printed in decimal, while a non-ERR_PTR passed as the argument to %pe gets treated as ordinary %p.

Symbols/Function Pointers

```
%pS     versatile_init+0x0/0x110
%ps     versatile_init
%pSR    versatile_init+0x9/0x110
        (with __builtin_extract_return_addr() translation)
%pB     prev_fn_of_versatile_init+0x88/0x88
```

The `S` and `s` specifiers are used for printing a pointer in symbolic format. They result in the symbol name with (S) or without (s) offsets. If KALLSYMS are disabled then the symbol address is printed instead.

The `B` specifier results in the symbol name with offsets and should be used when printing stack backtraces. The specifier takes into consideration the effect of compiler optimisations which may occur when tail-calls are used and marked with the noreturn GCC attribute.

Probed Pointers from BPF / tracing

```
%pks    kernel string
%pus    user string
```

The `k` and `u` specifiers are used for printing prior probed memory from either kernel memory (k) or user memory (u). The subsequent `s` specifier results in printing a string. For direct use in regular *vsnprintf()* the (k) and (u) annotation is ignored, however, when used out of BPF's bpf_trace_printk(), for example, it reads the memory it is pointing to without faulting.

Kernel Pointers

```
%pK     01234567 or 0123456789abcdef
```

For printing kernel pointers which should be hidden from unprivileged users. The behaviour of %pK depends on the kptr_restrict sysctl - see Documentation/admin-guide/sysctl/kernel.rst for more details.

Unmodified Addresses

```
%px     01234567 or 0123456789abcdef
```

For printing pointers when you *really* want to print the address. Please consider whether or not you are leaking sensitive information about the kernel memory layout before printing pointers with %px. %px is functionally equivalent to %lx (or %lu). %px is preferred because it is more uniquely grep' able. If in the future we need to modify the way the kernel handles printing pointers we will be better equipped to find the call sites.

Pointer Differences

```
%td     2560
%tx     a00
```

For printing the pointer differences, use the %t modifier for ptrdiff_t.

Example:

```
printk("test: difference between pointers: %td\n", ptr2 - ptr1);
```

Struct Resources

```
%pr     [mem 0x60000000-0x6fffffff flags 0x2200] or
        [mem 0x0000000060000000-0x000000006fffffff flags 0x2200]
%pR     [mem 0x60000000-0x6fffffff pref] or
        [mem 0x0000000060000000-0x000000006fffffff pref]
```

For printing struct resources. The R and r specifiers result in a printed resource with (R) or without (r) a decoded flags member.

Passed by reference.

Physical address types phys_addr_t

```
%pa[p]  0x01234567 or 0x0123456789abcdef
```

For printing a phys_addr_t type (and its derivatives, such as resource_size_t) which can vary based on build options, regardless of the width of the CPU data path.

Passed by reference.

DMA address types dma_addr_t

```
%pad    0x01234567 or 0x0123456789abcdef
```

For printing a dma_addr_t type which can vary based on build options, regardless of the width of the CPU data path.

Passed by reference.

Raw buffer as an escaped string

```
%*pE[achnops]
```

For printing raw buffer as an escaped string. For the following buffer:

```
1b 62 20 5c 43 07 22 90 0d 5d
```

A few examples show how the conversion would be done (excluding surrounding quotes):

```
%*pE            "\eb \C\a"\220\r]"
%*pEhp          "\x1bb \C\x07"\x90\x0d]"
%*pEa           "\e\142\040\\\103\a\042\220\r\135"
```

The conversion rules are applied according to an optional combination of flags (see *string_escape_mem()* kernel documentation for the details):

- a - ESCAPE_ANY
- c - ESCAPE_SPECIAL
- h - ESCAPE_HEX
- n - ESCAPE_NULL
- o - ESCAPE_OCTAL
- p - ESCAPE_NP
- s - ESCAPE_SPACE

By default ESCAPE_ANY_NP is used.

ESCAPE_ANY_NP is the sane choice for many cases, in particularly for printing SSIDs.

If field width is omitted then 1 byte only will be escaped.

Raw buffer as a hex string

```
%*ph    00 01 02  ...  3f
%*phC   00:01:02: ... :3f
%*phD   00-01-02- ... -3f
%*phN   000102 ... 3f
```

For printing small buffers (up to 64 bytes long) as a hex string with a certain separator. For larger buffers consider using `print_hex_dump()`.

MAC/FDDI addresses

```
%pM     00:01:02:03:04:05
%pMR    05:04:03:02:01:00
%pMF    00-01-02-03-04-05
%pm     000102030405
%pmR    050403020100
```

For printing 6-byte MAC/FDDI addresses in hex notation. The `M` and `m` specifiers result in a printed address with (M) or without (m) byte separators. The default byte separator is the colon (:).

Where FDDI addresses are concerned the `F` specifier can be used after the `M` specifier to use dash (-) separators instead of the default separator.

For Bluetooth addresses the `R` specifier shall be used after the `M` specifier to use reversed byte order suitable for visual interpretation of Bluetooth addresses which are in the little endian order.

Passed by reference.

IPv4 addresses

```
%pI4    1.2.3.4
%pi4    001.002.003.004
%p[Ii]4[hnbl]
```

For printing IPv4 dot-separated decimal addresses. The `I4` and `i4` specifiers result in a printed address with (i4) or without (I4) leading zeros.

The additional `h`, `n`, `b`, and `l` specifiers are used to specify host, network, big or little endian order addresses respectively. Where no specifier is provided the default network/big endian order is used.

Passed by reference.

IPv6 addresses

```
%pI6    0001:0002:0003:0004:0005:0006:0007:0008
%pi6    00010002000300040005000600070008
%pI6c   1:2:3:4:5:6:7:8
```

For printing IPv6 network-order 16-bit hex addresses. The `I6` and `i6` specifiers result in a printed address with (I6) or without (i6) colon-separators. Leading zeros are always used.

The additional `c` specifier can be used with the `I` specifier to print a compressed IPv6 address as described by https://tools.ietf.org/html/rfc5952

Passed by reference.

IPv4/IPv6 addresses (generic, with port, flowinfo, scope)

```
%pIS    1.2.3.4         or 0001:0002:0003:0004:0005:0006:0007:0008
%piS    001.002.003.004 or 00010002000300040005000600070008
%pISc   1.2.3.4         or 1:2:3:4:5:6:7:8
%pISpc  1.2.3.4:12345   or [1:2:3:4:5:6:7:8]:12345
%p[Ii]S[pfschnbl]
```

For printing an IP address without the need to distinguish whether it's of type AF_INET or AF_INET6. A pointer to a valid struct sockaddr, specified through `IS` or `iS`, can be passed to this format specifier.

The additional `p`, `f`, and `s` specifiers are used to specify port (IPv4, IPv6), flowinfo (IPv6) and scope (IPv6). Ports have a `:` prefix, flowinfo a `/` and scope a `%`, each followed by the actual value.

In case of an IPv6 address the compressed IPv6 address as described by https://tools.ietf.org/html/rfc5952 is being used if the additional specifier `c` is given. The IPv6 address is surrounded by `[`, `]` in case of additional specifiers `p`, `f` or `s` as suggested by https://tools.ietf.org/html/draft-ietf-6man-text-addr-representation-07

In case of IPv4 addresses, the additional `h`, `n`, `b`, and `l` specifiers can be used as well and are ignored in case of an IPv6 address.

Passed by reference.

Further examples:

```
%pISfc          1.2.3.4         or [1:2:3:4:5:6:7:8]/123456789
%pISsc          1.2.3.4         or [1:2:3:4:5:6:7:8]%1234567890
%pISpfc         1.2.3.4:12345   or [1:2:3:4:5:6:7:8]:12345/123456789
```

UUID/GUID addresses

```
%pUb    00010203-0405-0607-0809-0a0b0c0d0e0f
%pUB    00010203-0405-0607-0809-0A0B0C0D0E0F
%pUl    03020100-0504-0706-0809-0a0b0c0e0e0f
%pUL    03020100-0504-0706-0809-0A0B0C0E0E0F
```

For printing 16-byte UUID/GUIDs addresses. The additional `l`, `L`, `b` and `B` specifiers are used to specify a little endian order in lower (l) or upper case (L) hex notation - and big endian order in lower (b) or upper case (B) hex notation.

Where no additional specifiers are used the default big endian order with lower case hex notation will be printed.

Passed by reference.

dentry names

```
%pd{,2,3,4}
%pD{,2,3,4}
```

For printing dentry name; if we race with `d_move()`, the name might be a mix of old and new ones, but it won' t oops. %pd dentry is a safer equivalent of %s dentry->d_name.name we used to use, %pd<n> prints `n` last components. %pD does the same thing for struct file.

Passed by reference.

block_device names

```
%pg     sda, sda1 or loop0p1
```

For printing name of block_device pointers.

struct va_format

```
%pV
```

For printing struct va_format structures. These contain a format string and va_list as follows:

```
struct va_format {
        const char *fmt;
        va_list *va;
};
```

Implements a "recursive vsnprintf" .

Do not use this feature without some mechanism to verify the correctness of the format string and va_list arguments.

Passed by reference.

Device tree nodes

```
%pOF[fnpPcCF]
```

For printing device tree node structures. Default behaviour is equivalent to %pOFf.

- f - device node full_name
- n - device node name
- p - device node phandle
- P - device node path spec (name + @unit)
- F - device node flags
- c - major compatible string
- C - full compatible string

The separator when using multiple arguments is ':'

Examples:

```
%pOF    /foo/bar@0                      - Node full name
%pOFf   /foo/bar@0                      - Same as above
%pOFfp  /foo/bar@0:10                   - Node full name + phandle
%pOFfcF /foo/bar@0:foo,device:--P-      - Node full name +
                                          major compatible string +
                                          node flags
                                                D - dynamic
                                                d - detached
                                                P - Populated
                                                B - Populated bus
```

Passed by reference.

Fwnode handles

```
%pfw[fP]
```

For printing information on fwnode handles. The default is to print the full node name, including the path. The modifiers are functionally equivalent to %pOF above.

- f - full name of the node, including the path
- P - the name of the node including an address (if there is one)

Examples (ACPI):

```
%pfwf   \_SB.PCI0.CIO2.port@1.endpoint@0        - Full node name
%pfwP   endpoint@0                              - Node name
```

Examples (OF):

```
%pfwf   /ocp@68000000/i2c@48072000/camera@10/port/endpoint - Full␣
↪name
%pfwP   endpoint                                        - Node name
```

Time and date

```
%pt[RT]                 YYYY-mm-ddTHH:MM:SS
%pt[RT]d                YYYY-mm-dd
%pt[RT]t                HH:MM:SS
%pt[RT][dt][r]
```

For printing date and time as represented by:

```
R  struct rtc_time structure
T  time64_t type
```

in human readable format.

By default year will be incremented by 1900 and month by 1. Use %pt[RT]r (raw) to suppress this behaviour.

Passed by reference.

struct clk

```
%pC     pll1
%pCn    pll1
```

For printing struct clk structures. %pC and %pCn print the name of the clock (Common Clock Framework) or a unique 32-bit ID (legacy clock framework).

Passed by reference.

bitmap and its derivatives such as cpumask and nodemask

```
%*pb    0779
%*pbl   0,3-6,8-10
```

For printing bitmap and its derivatives such as cpumask and nodemask, %*pb outputs the bitmap with field width as the number of bits and %*pbl output the bitmap as range list with field width as the number of bits.

Passed by reference.

Flags bitfields such as page flags, gfp_flags

```
%pGp    referenced|uptodate|lru|active|private
%pGg    GFP_USER|GFP_DMA32|GFP_NOWARN
%pGv    read|exec|mayread|maywrite|mayexec|denywrite
```

For printing flags bitfields as a collection of symbolic constants that would construct the value. The type of flags is given by the third character. Currently supported are [p]age flags, [v]ma_flags (both expect `unsigned long *`) and [g]fp_flags (expects `gfp_t *`). The flag names and print order depends on the particular type.

Note that this format should not be used directly in the `TP_printk()` part of a tracepoint. Instead, use the show_*_flags() functions from <trace/events/mmflags.h>.

Passed by reference.

Network device features

```
%pNF    0x000000000000c000
```

For printing netdev_features_t.

Passed by reference.

1.4.3 Thanks

If you add other %p extensions, please extend <lib/test_printf.c> with one or more test cases, if at all feasible.

Thank you for your cooperation and attention.

1.5 Symbol Namespaces

The following document describes how to use Symbol Namespaces to structure the export surface of in-kernel symbols exported through the family of EXPORT_SYMBOL() macros.

1.5.1 1. Introduction

Symbol Namespaces have been introduced as a means to structure the export surface of the in-kernel API. It allows subsystem maintainers to partition their exported symbols into separate namespaces. That is useful for documentation purposes (think of the SUBSYSTEM_DEBUG namespace) as well as for limiting the availability of a set of symbols for use in other parts of the kernel. As of today, modules that make use of symbols exported into namespaces, are required to import the namespace. Otherwise the kernel will, depending on its configuration, reject loading the module or warn about a missing import.

1.5.2 2. How to define Symbol Namespaces

Symbols can be exported into namespace using different methods. All of them are changing the way EXPORT_SYMBOL and friends are instrumented to create ksymtab entries.

1.5.3 2.1 Using the EXPORT_SYMBOL macros

In addition to the macros EXPORT_SYMBOL() and EXPORT_SYMBOL_GPL(), that allow exporting of kernel symbols to the kernel symbol table, variants of these are available to export symbols into a certain namespace: EXPORT_SYMBOL_NS() and EXPORT_SYMBOL_NS_GPL(). They take one additional argument: the namespace. Please note that due to macro expansion that argument needs to be a preprocessor symbol. E.g. to export the symbol *usb_stor_suspend* into the namespace *USB_STORAGE*, use:

```
EXPORT_SYMBOL_NS(usb_stor_suspend, USB_STORAGE);
```

The corresponding ksymtab entry struct *kernel_symbol* will have the member *namespace* set accordingly. A symbol that is exported without a namespace will refer to *NULL*. There is no default namespace if none is defined. *modpost* and kernel/module.c make use the namespace at build time or module load time, respectively.

1.5.4 2.2 Using the DEFAULT_SYMBOL_NAMESPACE define

Defining namespaces for all symbols of a subsystem can be very verbose and may become hard to maintain. Therefore a default define (DEFAULT_SYMBOL_NAMESPACE) is been provided, that, if set, will become the default for all EXPORT_SYMBOL() and EXPORT_SYMBOL_GPL() macro expansions that do not specify a namespace.

There are multiple ways of specifying this define and it depends on the subsystem and the maintainer's preference, which one to use. The first option is to define the default namespace in the *Makefile* of the subsystem. E.g. to export all symbols defined in usb-common into the namespace USB_COMMON, add a line like this to drivers/usb/common/Makefile:

```
ccflags-y += -DDEFAULT_SYMBOL_NAMESPACE=USB_COMMON
```

That will affect all EXPORT_SYMBOL() and EXPORT_SYMBOL_GPL() statements. A symbol exported with EXPORT_SYMBOL_NS() while this definition is present, will still be exported into the namespace that is passed as the namespace argument as this argument has preference over a default symbol namespace.

A second option to define the default namespace is directly in the compilation unit as preprocessor statement. The above example would then read:

```
#undef  DEFAULT_SYMBOL_NAMESPACE
#define DEFAULT_SYMBOL_NAMESPACE USB_COMMON
```

within the corresponding compilation unit before any EXPORT_SYMBOL macro is used.

1.5.5 3. How to use Symbols exported in Namespaces

In order to use symbols that are exported into namespaces, kernel modules need to explicitly import these namespaces. Otherwise the kernel might reject to load the module. The module code is required to use the macro MODULE_IMPORT_NS for the namespaces it uses symbols from. E.g. a module using the usb_stor_suspend symbol from above, needs to import the namespace USB_STORAGE using a statement like:

```
MODULE_IMPORT_NS(USB_STORAGE);
```

This will create a *modinfo* tag in the module for each imported namespace. This has the side effect, that the imported namespaces of a module can be inspected with modinfo:

```
$ modinfo drivers/usb/storage/ums-karma.ko
[...]
import_ns:      USB_STORAGE
[...]
```

It is advisable to add the MODULE_IMPORT_NS() statement close to other module metadata definitions like MODULE_AUTHOR() or MODULE_LICENSE(). Refer to section 5. for a way to create missing import statements automatically.

1.5.6 4. Loading Modules that use namespaced Symbols

At module loading time (e.g. *insmod*), the kernel will check each symbol referenced from the module for its availability and whether the namespace it might be exported to has been imported by the module. The default behaviour of the kernel is to reject loading modules that don't specify sufficient imports. An error will be logged and loading will be failed with EINVAL. In order to allow loading of modules that don't satisfy this precondition, a configuration option is available: Setting MODULE_ALLOW_MISSING_NAMESPACE_IMPORTS=y will enable loading regardless, but will emit a warning.

1.5.7 5. Automatically creating MODULE_IMPORT_NS statements

Missing namespaces imports can easily be detected at build time. In fact, modpost will emit a warning if a module uses a symbol from a namespace without importing it. MODULE_IMPORT_NS() statements will usually be added at a definite location (along with other module meta data). To make the life of module authors (and subsystem maintainers) easier, a script and make target is available to fixup missing imports. Fixing missing imports can be done with:

```
$ make nsdeps
```

A typical scenario for module authors would be:

```
- write code that depends on a symbol from a not imported namespace
- `make`
- notice the warning of modpost telling about a missing import
- run `make nsdeps` to add the import to the correct code location
```

For subsystem maintainers introducing a namespace, the steps are very similar. Again, *make nsdeps* will eventually add the missing namespace imports for in-tree modules:

```
- move or add symbols to a namespace (e.g. with EXPORT_SYMBOL_NS())
- `make` (preferably with an allmodconfig to cover all in-kernel
  modules)
- notice the warning of modpost telling about a missing import
- run `make nsdeps` to add the import to the correct code location
```

You can also run nsdeps for external module builds. A typical usage is:

```
$ make -C <path_to_kernel_src> M=$PWD nsdeps
```

CHAPTER

TWO

DATA STRUCTURES AND LOW-LEVEL UTILITIES

Library functionality that is used throughout the kernel.

2.1 Everything you never wanted to know about kobjects, ksets, and ktypes

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Part of the difficulty in understanding the driver model - and the kobject abstraction upon which it is built - is that there is no obvious starting place. Dealing with kobjects requires understanding a few different types, all of which make reference to each other. In an attempt to make things easier, we'll take a multi-pass approach, starting with vague terms and adding detail as we go. To that end, here are some quick definitions of some terms we will be working with.

- A kobject is an object of type struct kobject. Kobjects have a name and a reference count. A kobject also has a parent pointer (allowing objects to be arranged into hierarchies), a specific type, and, usually, a representation in the sysfs virtual filesystem.

  Kobjects are generally not interesting on their own; instead, they are usually embedded within some other structure which contains the stuff the code is really interested in.

  No structure should **EVER** have more than one kobject embedded within it. If it does, the reference counting for the object is sure to be messed up and incorrect, and your code will be buggy. So do not do this.

- A ktype is the type of object that embeds a kobject. Every structure that embeds a kobject needs a corresponding ktype. The ktype controls what happens to the kobject when it is created and destroyed.

- A kset is a group of kobjects. These kobjects can be of the same ktype or belong to different ktypes. The kset is the basic container type for collections of kobjects. Ksets contain their own kobjects, but you can safely ignore that implementation detail as the kset core code handles this kobject automatically.

When you see a sysfs directory full of other directories, generally each of those directories corresponds to a kobject in the same kset.

We'll look at how to create and manipulate all of these types. A bottom-up approach will be taken, so we' ll go back to kobjects.

2.1.1 Embedding kobjects

It is rare for kernel code to create a standalone kobject, with one major exception explained below. Instead, kobjects are used to control access to a larger, domain-specific object. To this end, kobjects will be found embedded in other structures. If you are used to thinking of things in object-oriented terms, kobjects can be seen as a top-level, abstract class from which other classes are derived. A kobject implements a set of capabilities which are not particularly useful by themselves, but are nice to have in other objects. The C language does not allow for the direct expression of inheritance, so other techniques - such as structure embedding - must be used.

(As an aside, for those familiar with the kernel linked list implementation, this is analogous as to how "list_head" structs are rarely useful on their own, but are invariably found embedded in the larger objects of interest.)

So, for example, the UIO code in `drivers/uio/uio.c` has a structure that defines the memory region associated with a uio device:

```
struct uio_map {
        struct kobject kobj;
        struct uio_mem *mem;
};
```

If you have a struct uio_map structure, finding its embedded kobject is just a matter of using the kobj member. Code that works with kobjects will often have the opposite problem, however: given a struct kobject pointer, what is the pointer to the containing structure? You must avoid tricks (such as assuming that the kobject is at the beginning of the structure) and, instead, use the container_of() macro, found in `<linux/kernel.h>`:

```
container_of(ptr, type, member)
```

where:

- `ptr` is the pointer to the embedded kobject,
- `type` is the type of the containing structure, and
- `member` is the name of the structure field to which `pointer` points.

The return value from container_of() is a pointer to the corresponding container type. So, for example, a pointer `kp` to a struct kobject embedded **within** a struct uio_map could be converted to a pointer to the **containing** uio_map structure with:

```
struct uio_map *u_map = container_of(kp, struct uio_map, kobj);
```

For convenience, programmers often define a simple macro for **back-casting** kobject pointers to the containing type. Exactly this happens in the earlier `drivers/uio/uio.c`, as you can see here:

```
struct uio_map {
        struct kobject kobj;
        struct uio_mem *mem;
};

#define to_map(map) container_of(map, struct uio_map, kobj)
```

where the macro argument "map" is a pointer to the struct kobject in question. That macro is subsequently invoked with:

```
struct uio_map *map = to_map(kobj);
```

2.1.2 Initialization of kobjects

Code which creates a kobject must, of course, initialize that object. Some of the internal fields are setup with a (mandatory) call to kobject_init():

```
void kobject_init(struct kobject *kobj, struct kobj_type *ktype);
```

The ktype is required for a kobject to be created properly, as every kobject must have an associated kobj_type. After calling kobject_init(), to register the kobject with sysfs, the function kobject_add() must be called:

```
int kobject_add(struct kobject *kobj, struct kobject *parent,
                const char *fmt, ...);
```

This sets up the parent of the kobject and the name for the kobject properly. If the kobject is to be associated with a specific kset, kobj->kset must be assigned before calling kobject_add(). If a kset is associated with a kobject, then the parent for the kobject can be set to NULL in the call to kobject_add() and then the kobject's parent will be the kset itself.

As the name of the kobject is set when it is added to the kernel, the name of the kobject should never be manipulated directly. If you must change the name of the kobject, call kobject_rename():

```
int kobject_rename(struct kobject *kobj, const char *new_name);
```

kobject_rename() does not perform any locking or have a solid notion of what names are valid so the caller must provide their own sanity checking and serialization.

There is a function called kobject_set_name() but that is legacy cruft and is being removed. If your code needs to call this function, it is incorrect and needs to be fixed.

To properly access the name of the kobject, use the function kobject_name():

```
const char *kobject_name(const struct kobject * kobj);
```

There is a helper function to both initialize and add the kobject to the kernel at the same time, called surprisingly enough kobject_init_and_add():

```
int kobject_init_and_add(struct kobject *kobj, struct kobj_type␣
↪*ktype,
                         struct kobject *parent, const char *fmt, ..
↪.);
```

The arguments are the same as the individual kobject_init() and kobject_add() functions described above.

2.1.3 Uevents

After a kobject has been registered with the kobject core, you need to announce to the world that it has been created. This can be done with a call to kobject_uevent():

```
int kobject_uevent(struct kobject *kobj, enum kobject_action␣
↪action);
```

Use the **KOBJ_ADD** action for when the kobject is first added to the kernel. This should be done only after any attributes or children of the kobject have been initialized properly, as userspace will instantly start to look for them when this call happens.

When the kobject is removed from the kernel (details on how to do that are below), the uevent for **KOBJ_REMOVE** will be automatically created by the kobject core, so the caller does not have to worry about doing that by hand.

2.1.4 Reference counts

One of the key functions of a kobject is to serve as a reference counter for the object in which it is embedded. As long as references to the object exist, the object (and the code which supports it) must continue to exist. The low-level functions for manipulating a kobject's reference counts are:

```
struct kobject *kobject_get(struct kobject *kobj);
void kobject_put(struct kobject *kobj);
```

A successful call to kobject_get() will increment the kobject's reference counter and return the pointer to the kobject.

When a reference is released, the call to kobject_put() will decrement the reference count and, possibly, free the object. Note that kobject_init() sets the reference count to one, so the code which sets up the kobject will need to do a kobject_put() eventually to release that reference.

Because kobjects are dynamic, they must not be declared statically or on the stack, but instead, always allocated dynamically. Future versions of the kernel will contain a run-time check for kobjects that are created statically and will warn the developer of this improper usage.

If all that you want to use a kobject for is to provide a reference counter for your structure, please use the struct kref instead; a kobject would be overkill. For more information on how to use struct kref, please see the file *Adding reference counters (krefs) to kernel objects* in the Linux kernel source tree.

2.1.5 Creating "simple" kobjects

Sometimes all that a developer wants is a way to create a simple directory in the sysfs hierarchy, and not have to mess with the whole complication of ksets, show and store functions, and other details. This is the one exception where a single kobject should be created. To create such an entry, use the function:

```
struct kobject *kobject_create_and_add(const char *name, struct␣
↪kobject *parent);
```

This function will create a kobject and place it in sysfs in the location underneath the specified parent kobject. To create simple attributes associated with this kobject, use:

```
int sysfs_create_file(struct kobject *kobj, const struct attribute␣
↪*attr);
```

or:

```
int sysfs_create_group(struct kobject *kobj, const struct attribute_
↪group *grp);
```

Both types of attributes used here, with a kobject that has been created with the kobject_create_and_add(), can be of type kobj_attribute, so no special custom attribute is needed to be created.

See the example module, `samples/kobject/kobject-example.c` for an implementation of a simple kobject and attributes.

2.1.6 ktypes and release methods

One important thing still missing from the discussion is what happens to a kobject when its reference count reaches zero. The code which created the kobject generally does not know when that will happen; if it did, there would be little point in using a kobject in the first place. Even predictable object lifecycles become more complicated when sysfs is brought in as other portions of the kernel can get a reference on any kobject that is registered in the system.

The end result is that a structure protected by a kobject cannot be freed before its reference count goes to zero. The reference count is not under the direct control of the code which created the kobject. So that code must be notified asynchronously whenever the last reference to one of its kobjects goes away.

Once you registered your kobject via kobject_add(), you must never use *kfree()* to free it directly. The only safe way is to use kobject_put(). It is good practice to always use kobject_put() after kobject_init() to avoid errors creeping in.

This notification is done through a kobject's release() method. Usually such a method has a form like:

```
void my_object_release(struct kobject *kobj)
{
        struct my_object *mine = container_of(kobj, struct my_
↪object, kobj);

        /* Perform any additional cleanup on this object, then... */
        kfree(mine);
}
```

One important point cannot be overstated: every kobject must have a release() method, and the kobject must persist (in a consistent state) until that method is called. If these constraints are not met, the code is flawed. Note that the kernel will warn you if you forget to provide a release() method. Do not try to get rid of this warning by providing an "empty" release function.

If all your cleanup function needs to do is call *kfree()*, then you must create a wrapper function which uses container_of() to upcast to the correct type (as shown in the example above) and then calls *kfree()* on the overall structure.

Note, the name of the kobject is available in the release function, but it must NOT be changed within this callback. Otherwise there will be a memory leak in the kobject core, which makes people unhappy.

Interestingly, the release() method is not stored in the kobject itself; instead, it is associated with the ktype. So let us introduce struct kobj_type:

```
struct kobj_type {
        void (*release)(struct kobject *kobj);
        const struct sysfs_ops *sysfs_ops;
        struct attribute **default_attrs;
        const struct attribute_group **default_groups;
        const struct kobj_ns_type_operations *(*child_ns_
↪type)(struct kobject *kobj);
        const void *(*namespace)(struct kobject *kobj);
        void (*get_ownership)(struct kobject *kobj, kuid_t *uid,␣
↪kgid_t *gid);
};
```

This structure is used to describe a particular type of kobject (or, more correctly, of containing object). Every kobject needs to have an associated kobj_type structure; a pointer to that structure must be specified when you call kobject_init() or kobject_init_and_add().

The release field in struct kobj_type is, of course, a pointer to the release() method for this type of kobject. The other two fields (sysfs_ops and default_attrs) control how objects of this type are represented in sysfs; they are beyond the scope of this document.

The default_attrs pointer is a list of default attributes that will be automatically created for any kobject that is registered with this ktype.

2.1.7 ksets

A kset is merely a collection of kobjects that want to be associated with each other. There is no restriction that they be of the same ktype, but be very careful if they are not.

A kset serves these functions:

- It serves as a bag containing a group of objects. A kset can be used by the kernel to track "all block devices" or "all PCI device drivers."
- A kset is also a subdirectory in sysfs, where the associated kobjects with the kset can show up. Every kset contains a kobject which can be set up to be the parent of other kobjects; the top-level directories of the sysfs hierarchy are constructed in this way.
- Ksets can support the "hotplugging" of kobjects and influence how uevent events are reported to user space.

In object-oriented terms, "kset" is the top-level container class; ksets contain their own kobject, but that kobject is managed by the kset code and should not be manipulated by any other user.

A kset keeps its children in a standard kernel linked list. Kobjects point back to their containing kset via their kset field. In almost all cases, the kobjects belonging to a kset have that kset (or, strictly, its embedded kobject) in their parent.

As a kset contains a kobject within it, it should always be dynamically created and never declared statically or on the stack. To create a new kset use:

```
struct kset *kset_create_and_add(const char *name,
                                 const struct kset_uevent_ops␣
↪*uevent_ops,
                                 struct kobject *parent_kobj);
```

When you are finished with the kset, call:

```
void kset_unregister(struct kset *k);
```

to destroy it. This removes the kset from sysfs and decrements its reference count. When the reference count goes to zero, the kset will be released. Because other references to the kset may still exist, the release may happen after kset_unregister() returns.

An example of using a kset can be seen in the `samples/kobject/kset-example.c` file in the kernel tree.

If a kset wishes to control the uevent operations of the kobjects associated with it, it can use the struct kset_uevent_ops to handle it:

```
struct kset_uevent_ops {
        int (* const filter)(struct kset *kset, struct kobject␣
```

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```
↪*kobj);
        const char *(* const name)(struct kset *kset, struct␣
↪kobject *kobj);
        int (* const uevent)(struct kset *kset, struct kobject␣
↪*kobj,
                      struct kobj_uevent_env *env);
};
```

The filter function allows a kset to prevent a uevent from being emitted to userspace for a specific kobject. If the function returns 0, the uevent will not be emitted.

The name function will be called to override the default name of the kset that the uevent sends to userspace. By default, the name will be the same as the kset itself, but this function, if present, can override that name.

The uevent function will be called when the uevent is about to be sent to userspace to allow more environment variables to be added to the uevent.

One might ask how, exactly, a kobject is added to a kset, given that no functions which perform that function have been presented. The answer is that this task is handled by kobject_add(). When a kobject is passed to kobject_add(), its kset member should point to the kset to which the kobject will belong. kobject_add() will handle the rest.

If the kobject belonging to a kset has no parent kobject set, it will be added to the kset's directory. Not all members of a kset do necessarily live in the kset directory. If an explicit parent kobject is assigned before the kobject is added, the kobject is registered with the kset, but added below the parent kobject.

2.1.8 Kobject removal

After a kobject has been registered with the kobject core successfully, it must be cleaned up when the code is finished with it. To do that, call kobject_put(). By doing this, the kobject core will automatically clean up all of the memory allocated by this kobject. If a `KOBJ_ADD` uevent has been sent for the object, a corresponding `KOBJ_REMOVE` uevent will be sent, and any other sysfs housekeeping will be handled for the caller properly.

If you need to do a two-stage delete of the kobject (say you are not allowed to sleep when you need to destroy the object), then call kobject_del() which will unregister the kobject from sysfs. This makes the kobject "invisible", but it is not cleaned up, and the reference count of the object is still the same. At a later time call kobject_put() to finish the cleanup of the memory associated with the kobject.

kobject_del() can be used to drop the reference to the parent object, if circular references are constructed. It is valid in some cases, that a parent objects references a child. Circular references _must_ be broken with an explicit call to kobject_del(), so that a release functions will be called, and the objects in the former circle release each other.

2.1.9 Example code to copy from

For a more complete example of using ksets and kobjects properly, see the example programs `samples/kobject/{kobject-example.c,kset-example.c}`, which will be built as loadable modules if you select `CONFIG_SAMPLE_KOBJECT`.

2.2 Adding reference counters (krefs) to kernel objects

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A lot of this was lifted from Greg Kroah-Hartman's 2004 OLS paper and presentation on krefs, which can be found at:

- http://www.kroah.com/linux/talks/ols_2004_kref_paper/Reprint-Kroah-Hartman-OLS2004.pdf
- http://www.kroah.com/linux/talks/ols_2004_kref_talk/

2.2.1 Introduction

krefs allow you to add reference counters to your objects. If you have objects that are used in multiple places and passed around, and you don't have refcounts, your code is almost certainly broken. If you want refcounts, krefs are the way to go.

To use a kref, add one to your data structures like:

```
struct my_data
{
    .
    .
    struct kref refcount;
    .
    .
};
```

The kref can occur anywhere within the data structure.

2.2.2 Initialization

You must initialize the kref after you allocate it. To do this, call kref_init as so:

```
struct my_data *data;

data = kmalloc(sizeof(*data), GFP_KERNEL);
if (!data)
       return -ENOMEM;
kref_init(&data->refcount);
```

This sets the refcount in the kref to 1.

2.2.3 Kref rules

Once you have an initialized kref, you must follow the following rules:

1) If you make a non-temporary copy of a pointer, especially if it can be passed to another thread of execution, you must increment the refcount with kref_get() before passing it off:

   ```
   kref_get(&data->refcount);
   ```

   If you already have a valid pointer to a kref-ed structure (the refcount cannot go to zero) you may do this without a lock.

2) When you are done with a pointer, you must call kref_put():

   ```
   kref_put(&data->refcount, data_release);
   ```

   If this is the last reference to the pointer, the release routine will be called. If the code never tries to get a valid pointer to a kref-ed structure without already holding a valid pointer, it is safe to do this without a lock.

3) If the code attempts to gain a reference to a kref-ed structure without already holding a valid pointer, it must serialize access where a kref_put() cannot occur during the kref_get(), and the structure must remain valid during the kref_get().

For example, if you allocate some data and then pass it to another thread to process:

```
void data_release(struct kref *ref)
{
    struct my_data *data = container_of(ref, struct my_data,␣
↪refcount);
    kfree(data);
}

void more_data_handling(void *cb_data)
{
    struct my_data *data = cb_data;
    .
    . do stuff with data here
    .
    kref_put(&data->refcount, data_release);
}

int my_data_handler(void)
{
    int rv = 0;
    struct my_data *data;
    struct task_struct *task;
```

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```
    data = kmalloc(sizeof(*data), GFP_KERNEL);
    if (!data)
            return -ENOMEM;
    kref_init(&data->refcount);

    kref_get(&data->refcount);
    task = kthread_run(more_data_handling, data, "more_data_handling
↪");
    if (task == ERR_PTR(-ENOMEM)) {
            rv = -ENOMEM;
            kref_put(&data->refcount, data_release);
            goto out;
    }

    .
    . do stuff with data here
    .
out:
    kref_put(&data->refcount, data_release);
    return rv;
}
```

This way, it doesn't matter what order the two threads handle the data, the kref_put() handles knowing when the data is not referenced any more and releasing it. The kref_get() does not require a lock, since we already have a valid pointer that we own a refcount for. The put needs no lock because nothing tries to get the data without already holding a pointer.

In the above example, kref_put() will be called 2 times in both success and error paths. This is necessary because the reference count got incremented 2 times by kref_init() and kref_get().

Note that the "before" in rule 1 is very important. You should never do something like:

```
task = kthread_run(more_data_handling, data, "more_data_handling");
if (task == ERR_PTR(-ENOMEM)) {
        rv = -ENOMEM;
        goto out;
} else
        /* BAD BAD BAD - get is after the handoff */
        kref_get(&data->refcount);
```

Don't assume you know what you are doing and use the above construct. First of all, you may not know what you are doing. Second, you may know what you are doing (there are some situations where locking is involved where the above may be legal) but someone else who doesn't know what they are doing may change the code or copy the code. It's bad style. Don't do it.

There are some situations where you can optimize the gets and puts. For instance, if you are done with an object and enqueuing it for something else or passing it off to something else, there is no reason to do a get then a put:

```
/* Silly extra get and put */
kref_get(&obj->ref);
enqueue(obj);
kref_put(&obj->ref, obj_cleanup);
```

Just do the enqueue. A comment about this is always welcome:

```
enqueue(obj);
/* We are done with obj, so we pass our refcount off
   to the queue.  DON'T TOUCH obj AFTER HERE! */
```

The last rule (rule 3) is the nastiest one to handle. Say, for instance, you have a list of items that are each kref-ed, and you wish to get the first one. You can't just pull the first item off the list and kref_get() it. That violates rule 3 because you are not already holding a valid pointer. You must add a mutex (or some other lock). For instance:

```
static DEFINE_MUTEX(mutex);
static LIST_HEAD(q);
struct my_data
{
        struct kref      refcount;
        struct list_head link;
};

static struct my_data *get_entry()
{
        struct my_data *entry = NULL;
        mutex_lock(&mutex);
        if (!list_empty(&q)) {
                entry = container_of(q.next, struct my_data, link);
                kref_get(&entry->refcount);
        }
        mutex_unlock(&mutex);
        return entry;
}

static void release_entry(struct kref *ref)
{
        struct my_data *entry = container_of(ref, struct my_data,␣
↪refcount);

        list_del(&entry->link);
        kfree(entry);
}

static void put_entry(struct my_data *entry)
{
        mutex_lock(&mutex);
        kref_put(&entry->refcount, release_entry);
```

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```
        mutex_unlock(&mutex);
}
```

The kref_put() return value is useful if you do not want to hold the lock during the whole release operation. Say you didn't want to call *kfree()* with the lock held in the example above (since it is kind of pointless to do so). You could use kref_put() as follows:

```
static void release_entry(struct kref *ref)
{
        /* All work is done after the return from kref_put(). */
}

static void put_entry(struct my_data *entry)
{
        mutex_lock(&mutex);
        if (kref_put(&entry->refcount, release_entry)) {
                list_del(&entry->link);
                mutex_unlock(&mutex);
                kfree(entry);
        } else
                mutex_unlock(&mutex);
}
```

This is really more useful if you have to call other routines as part of the free operations that could take a long time or might claim the same lock. Note that doing everything in the release routine is still preferred as it is a little neater.

The above example could also be optimized using kref_get_unless_zero() in the following way:

```
static struct my_data *get_entry()
{
        struct my_data *entry = NULL;
        mutex_lock(&mutex);
        if (!list_empty(&q)) {
                entry = container_of(q.next, struct my_data, link);
                if (!kref_get_unless_zero(&entry->refcount))
                        entry = NULL;
        }
        mutex_unlock(&mutex);
        return entry;
}

static void release_entry(struct kref *ref)
{
        struct my_data *entry = container_of(ref, struct my_data,␣
↪refcount);

        mutex_lock(&mutex);
```

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```
        list_del(&entry->link);
        mutex_unlock(&mutex);
        kfree(entry);
}

static void put_entry(struct my_data *entry)
{
        kref_put(&entry->refcount, release_entry);
}
```

Which is useful to remove the mutex lock around kref_put() in put_entry(), but it's important that kref_get_unless_zero is enclosed in the same critical section that finds the entry in the lookup table, otherwise kref_get_unless_zero may reference already freed memory. Note that it is illegal to use kref_get_unless_zero without checking its return value. If you are sure (by already having a valid pointer) that kref_get_unless_zero() will return true, then use kref_get() instead.

2.2.4 Krefs and RCU

The function kref_get_unless_zero also makes it possible to use rcu locking for lookups in the above example:

```
struct my_data
{
        struct rcu_head rhead;
        .
        struct kref refcount;
        .
        .
};

static struct my_data *get_entry_rcu()
{
        struct my_data *entry = NULL;
        rcu_read_lock();
        if (!list_empty(&q)) {
                entry = container_of(q.next, struct my_data, link);
                if (!kref_get_unless_zero(&entry->refcount))
                        entry = NULL;
        }
        rcu_read_unlock();
        return entry;
}

static void release_entry_rcu(struct kref *ref)
{
        struct my_data *entry = container_of(ref, struct my_data,
 ↪refcount);
```

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```
        mutex_lock(&mutex);
        list_del_rcu(&entry->link);
        mutex_unlock(&mutex);
        kfree_rcu(entry, rhead);
}

static void put_entry(struct my_data *entry)
{
        kref_put(&entry->refcount, release_entry_rcu);
}
```

But note that the struct kref member needs to remain in valid memory for a rcu grace period after release_entry_rcu was called. That can be accomplished by using kfree_rcu(entry, rhead) as done above, or by calling *synchronize_rcu()* before using kfree, but note that *synchronize_rcu()* may sleep for a substantial amount of time.

2.3 Generic Associative Array Implementation

2.3.1 Overview

This associative array implementation is an object container with the following properties:

1. Objects are opaque pointers. The implementation does not care where they point (if anywhere) or what they point to (if anything).

   Note: Pointers to objects _must_ be zero in the least significant bit.

2. Objects do not need to contain linkage blocks for use by the array. This permits an object to be located in multiple arrays simultaneously. Rather, the array is made up of metadata blocks that point to objects.
3. Objects require index keys to locate them within the array.
4. Index keys must be unique. Inserting an object with the same key as one already in the array will replace the old object.
5. Index keys can be of any length and can be of different lengths.
6. Index keys should encode the length early on, before any variation due to length is seen.
7. Index keys can include a hash to scatter objects throughout the array.
8. The array can iterated over. The objects will not necessarily come out in key order.
9. The array can be iterated over while it is being modified, provided the RCU readlock is being held by the iterator. Note, however, under these circumstances, some objects may be seen more than once. If this is a problem, the

iterator should lock against modification. Objects will not be missed, however, unless deleted.

10. Objects in the array can be looked up by means of their index key.
11. Objects can be looked up while the array is being modified, provided the RCU readlock is being held by the thread doing the look up.

The implementation uses a tree of 16-pointer nodes internally that are indexed on each level by nibbles from the index key in the same manner as in a radix tree. To improve memory efficiency, shortcuts can be emplaced to skip over what would otherwise be a series of single-occupancy nodes. Further, nodes pack leaf object pointers into spare space in the node rather than making an extra branch until as such time an object needs to be added to a full node.

2.3.2 The Public API

The public API can be found in `<linux/assoc_array.h>`. The associative array is rooted on the following structure:

```
struct assoc_array {
        ...
};
```

The code is selected by enabling `CONFIG_ASSOCIATIVE_ARRAY` with:

```
./script/config -e ASSOCIATIVE_ARRAY
```

Edit Script

The insertion and deletion functions produce an 'edit script' that can later be applied to effect the changes without risking `ENOMEM`. This retains the preallocated metadata blocks that will be installed in the internal tree and keeps track of the metadata blocks that will be removed from the tree when the script is applied.

This is also used to keep track of dead blocks and dead objects after the script has been applied so that they can be freed later. The freeing is done after an RCU grace period has passed - thus allowing access functions to proceed under the RCU read lock.

The script appears as outside of the API as a pointer of the type:

```
struct assoc_array_edit;
```

There are two functions for dealing with the script:

1. Apply an edit script:

   ```
   void assoc_array_apply_edit(struct assoc_array_edit *edit);
   ```

This will perform the edit functions, interpolating various write barriers to permit accesses under the RCU read lock to continue. The edit script will then be passed to `call_rcu()` to free it and any dead stuff it points to.

2. Cancel an edit script:

```
void assoc_array_cancel_edit(struct assoc_array_edit *edit);
```

This frees the edit script and all preallocated memory immediately. If this was for insertion, the new object is _not_ released by this function, but must rather be released by the caller.

These functions are guaranteed not to fail.

Operations Table

Various functions take a table of operations:

```
struct assoc_array_ops {
        ...
};
```

This points to a number of methods, all of which need to be provided:

1. Get a chunk of index key from caller data:

```
unsigned long (*get_key_chunk)(const void *index_key, int␣
↪level);
```

This should return a chunk of caller-supplied index key starting at the *bit* position given by the level argument. The level argument will be a multiple of `ASSOC_ARRAY_KEY_CHUNK_SIZE` and the function should return `ASSOC_ARRAY_KEY_CHUNK_SIZE bits`. No error is possible.

2. Get a chunk of an object's index key:

```
unsigned long (*get_object_key_chunk)(const void *object, int␣
↪level);
```

As the previous function, but gets its data from an object in the array rather than from a caller-supplied index key.

3. See if this is the object we're looking for:

```
bool (*compare_object)(const void *object, const void *index_
↪key);
```

Compare the object against an index key and return `true` if it matches and `false` if it doesn't.

4. Diff the index keys of two objects:

```
int (*diff_objects)(const void *object, const void *index_key);
```

Return the bit position at which the index key of the specified object differs from the given index key or -1 if they are the same.

5. Free an object:

```
void (*free_object)(void *object);
```

Free the specified object. Note that this may be called an RCU grace period after `assoc_array_apply_edit()` was called, so `synchronize_rcu()` may be necessary on module unloading.

Manipulation Functions

There are a number of functions for manipulating an associative array:

1. Initialise an associative array:

```
void assoc_array_init(struct assoc_array *array);
```

This initialises the base structure for an associative array. It can't fail.

2. Insert/replace an object in an associative array:

```
struct assoc_array_edit *
assoc_array_insert(struct assoc_array *array,
                   const struct assoc_array_ops *ops,
                   const void *index_key,
                   void *object);
```

This inserts the given object into the array. Note that the least significant bit of the pointer must be zero as it's used to type-mark pointers internally.

If an object already exists for that key then it will be replaced with the new object and the old one will be freed automatically.

The `index_key` argument should hold index key information and is passed to the methods in the ops table when they are called.

This function makes no alteration to the array itself, but rather returns an edit script that must be applied. `-ENOMEM` is returned in the case of an out-of-memory error.

The caller should lock exclusively against other modifiers of the array.

3. Delete an object from an associative array:

```
struct assoc_array_edit *
assoc_array_delete(struct assoc_array *array,
                   const struct assoc_array_ops *ops,
                   const void *index_key);
```

This deletes an object that matches the specified data from the array.

The `index_key` argument should hold index key information and is passed to the methods in the ops table when they are called.

This function makes no alteration to the array itself, but rather returns an edit script that must be applied. `-ENOMEM` is returned in the case of an out-of-memory error. `NULL` will be returned if the specified object is not found within the array.

The caller should lock exclusively against other modifiers of the array.

4. Delete all objects from an associative array:

```
struct assoc_array_edit *
assoc_array_clear(struct assoc_array *array,
                  const struct assoc_array_ops *ops);
```

This deletes all the objects from an associative array and leaves it completely empty.

This function makes no alteration to the array itself, but rather returns an edit script that must be applied. `-ENOMEM` is returned in the case of an out-of-memory error.

The caller should lock exclusively against other modifiers of the array.

5. Destroy an associative array, deleting all objects:

```
void assoc_array_destroy(struct assoc_array *array,
                         const struct assoc_array_ops *ops);
```

This destroys the contents of the associative array and leaves it completely empty. It is not permitted for another thread to be traversing the array under the RCU read lock at the same time as this function is destroying it as no RCU deferral is performed on memory release - something that would require memory to be allocated.

The caller should lock exclusively against other modifiers and accessors of the array.

6. Garbage collect an associative array:

```
int assoc_array_gc(struct assoc_array *array,
                   const struct assoc_array_ops *ops,
                   bool (*iterator)(void *object, void␣
↪*iterator_data),
                   void *iterator_data);
```

This iterates over the objects in an associative array and passes each one to `iterator()`. If `iterator()` returns `true`, the object is kept. If it returns `false`, the object will be freed. If the `iterator()` function returns `true`, it must perform any appropriate refcount incrementing on the object before returning.

The internal tree will be packed down if possible as part of the iteration to reduce the number of nodes in it.

The `iterator_data` is passed directly to `iterator()` and is otherwise ignored by the function.

The function will return `0` if successful and `-ENOMEM` if there wasn't enough memory.

It is possible for other threads to iterate over or search the array under the RCU read lock while this function is in progress. The caller should lock exclusively against other modifiers of the array.

Access Functions

There are two functions for accessing an associative array:

1. Iterate over all the objects in an associative array:

```
int assoc_array_iterate(const struct assoc_array *array,
                        int (*iterator)(const void *object,
                                        void *iterator_data),
                        void *iterator_data);
```

This passes each object in the array to the iterator callback function. `iterator_data` is private data for that function.

This may be used on an array at the same time as the array is being modified, provided the RCU read lock is held. Under such circumstances, it is possible for the iteration function to see some objects twice. If this is a problem, then modification should be locked against. The iteration algorithm should not, however, miss any objects.

The function will return `0` if no objects were in the array or else it will return the result of the last iterator function called. Iteration stops immediately if any call to the iteration function results in a non-zero return.

2. Find an object in an associative array:

```
void *assoc_array_find(const struct assoc_array *array,
                       const struct assoc_array_ops *ops,
                       const void *index_key);
```

This walks through the array's internal tree directly to the object specified by the index key..

This may be used on an array at the same time as the array is being modified, provided the RCU read lock is held.

The function will return the object if found (and set `*_type` to the object type) or will return `NULL` if the object was not found.

Index Key Form

The index key can be of any form, but since the algorithms aren't told how long the key is, it is strongly recommended that the index key includes its length very early on before any variation due to the length would have an effect on comparisons.

This will cause leaves with different length keys to scatter away from each other - and those with the same length keys to cluster together.

It is also recommended that the index key begin with a hash of the rest of the key to maximise scattering throughout keyspace.

The better the scattering, the wider and lower the internal tree will be.

Poor scattering isn't too much of a problem as there are shortcuts and nodes can contain mixtures of leaves and metadata pointers.

The index key is read in chunks of machine word. Each chunk is subdivided into one nibble (4 bits) per level, so on a 32-bit CPU this is good for 8 levels and on a 64-bit CPU, 16 levels. Unless the scattering is really poor, it is unlikely that more than one word of any particular index key will have to be used.

2.3.3 Internal Workings

The associative array data structure has an internal tree. This tree is constructed of two types of metadata blocks: nodes and shortcuts.

A node is an array of slots. Each slot can contain one of four things:

- A NULL pointer, indicating that the slot is empty.
- A pointer to an object (a leaf).
- A pointer to a node at the next level.
- A pointer to a shortcut.

Basic Internal Tree Layout

Ignoring shortcuts for the moment, the nodes form a multilevel tree. The index key space is strictly subdivided by the nodes in the tree and nodes occur on fixed levels. For example:

```
Level: 0               1               2               3
       =============== =============== =============== ===============
                                                       NODE D
                       NODE B          NODE C  +------>+---+
               +------>+---+   +------>+---+   |       | 0 |
       NODE A  |       | 0 |   |       | 0 |   |       +---+
       +---+   |       +---+   |       +---+   |       :   :
       | 0 |   |       :   :   |       :   :   |       +---+
       +---+   |       +---+   |       +---+   |       | f |
       | 1 |---+       | 3 |---+       | 7 |---+       +---+
       +---+           +---+           +---+
       :   :           :   :           | 8 |---+
       +---+           +---+           +---+   |       NODE E
       | e |---+       | f |           :   :   +------>+---+
       +---+   |       +---+           +---+           | 0 |
       | f |   |                       | f |           +---+
       +---+   |                       +---+           :   :
               |       NODE F                          +---+
               +------>+---+                           | f |
                       | 0 |           NODE G          +---+
                       +---+   +------>+---+
                       :   :   |       | 0 |
                       +---+   |       +---+
                       | 6 |---+       :   :
                       +---+           +---+
```

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```
                      :   :           | f |
                      +---+           +---+
                      | f |
                      +---+
```

In the above example, there are 7 nodes (A-G), each with 16 slots (0-f). Assuming no other meta data nodes in the tree, the key space is divided thusly:

```
KEY PREFIX      NODE
==========      ====
137*            D
138*            E
13[0-69-f]*     C
1[0-24-f]*      B
e6*             G
e[0-57-f]*      F
[02-df]*        A
```

So, for instance, keys with the following example index keys will be found in the appropriate nodes:

```
INDEX KEY       PREFIX  NODE
=============== ======= ====
13694892892489  13      C
13795289025897  137     D
13889dde88793   138     E
138bbb89003093  138     E
1394879524789   12      C
1458952489      1       B
9431809de993ba  -       A
b4542910809cd   -       A
e5284310def98   e       F
e68428974237    e6      G
e7fffcbd443     e       F
f3842239082     -       A
```

To save memory, if a node can hold all the leaves in its portion of keyspace, then the node will have all those leaves in it and will not have any metadata pointers - even if some of those leaves would like to be in the same slot.

A node can contain a heterogeneous mix of leaves and metadata pointers. Metadata pointers must be in the slots that match their subdivisions of key space. The leaves can be in any slot not occupied by a metadata pointer. It is guaranteed that none of the leaves in a node will match a slot occupied by a metadata pointer. If the metadata pointer is there, any leaf whose key matches the metadata key prefix must be in the subtree that the metadata pointer points to.

In the above example list of index keys, node A will contain:

```
SLOT    CONTENT         INDEX KEY (PREFIX)
====    =============== ==================
```

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```
1       PTR TO NODE B   1*
any     LEAF            9431809de993ba
any     LEAF            b4542910809cd
e       PTR TO NODE F   e*
any     LEAF            f3842239082
```

and node B:

```
3   PTR TO NODE C   13*
any LEAF            1458952489
```

Shortcuts

Shortcuts are metadata records that jump over a piece of keyspace. A shortcut is a replacement for a series of single-occupancy nodes ascending through the levels. Shortcuts exist to save memory and to speed up traversal.

It is possible for the root of the tree to be a shortcut - say, for example, the tree contains at least 17 nodes all with key prefix `1111`. The insertion algorithm will insert a shortcut to skip over the `1111` keyspace in a single bound and get to the fourth level where these actually become different.

Splitting And Collapsing Nodes

Each node has a maximum capacity of 16 leaves and metadata pointers. If the insertion algorithm finds that it is trying to insert a 17th object into a node, that node will be split such that at least two leaves that have a common key segment at that level end up in a separate node rooted on that slot for that common key segment.

If the leaves in a full node and the leaf that is being inserted are sufficiently similar, then a shortcut will be inserted into the tree.

When the number of objects in the subtree rooted at a node falls to 16 or fewer, then the subtree will be collapsed down to a single node - and this will ripple towards the root if possible.

Non-Recursive Iteration

Each node and shortcut contains a back pointer to its parent and the number of slot in that parent that points to it. None-recursive iteration uses these to proceed rootwards through the tree, going to the parent node, slot N + 1 to make sure progress is made without the need for a stack.

The backpointers, however, make simultaneous alteration and iteration tricky.

Simultaneous Alteration And Iteration

There are a number of cases to consider:

1. Simple insert/replace. This involves simply replacing a NULL or old matching leaf pointer with the pointer to the new leaf after a barrier. The metadata blocks don't change otherwise. An old leaf won't be freed until after the RCU grace period.
2. Simple delete. This involves just clearing an old matching leaf. The metadata blocks don't change otherwise. The old leaf won't be freed until after the RCU grace period.
3. Insertion replacing part of a subtree that we haven't yet entered. This may involve replacement of part of that subtree - but that won't affect the iteration as we won't have reached the pointer to it yet and the ancestry blocks are not replaced (the layout of those does not change).
4. Insertion replacing nodes that we're actively processing. This isn't a problem as we've passed the anchoring pointer and won't switch onto the new layout until we follow the back pointers - at which point we've already examined the leaves in the replaced node (we iterate over all the leaves in a node before following any of its metadata pointers).

   We might, however, re-see some leaves that have been split out into a new branch that's in a slot further along than we were at.
5. Insertion replacing nodes that we're processing a dependent branch of. This won't affect us until we follow the back pointers. Similar to (4).
6. Deletion collapsing a branch under us. This doesn't affect us because the back pointers will get us back to the parent of the new node before we could see the new node. The entire collapsed subtree is thrown away unchanged - and will still be rooted on the same slot, so we shouldn't process it a second time as we'll go back to slot + 1.

Note: Under some circumstances, we need to simultaneously change the parent pointer and the parent slot pointer on a node (say, for example, we inserted another node before it and moved it up a level). We cannot do this without locking against a read - so we have to replace that node too.

However, when we're changing a shortcut into a node this isn't a problem as shortcuts only have one slot and so the parent slot number isn't used when traversing backwards over one. This means that it's okay to change the slot number first - provided suitable barriers are used to make sure the parent slot number is read after the back pointer.

Obsolete blocks and leaves are freed up after an RCU grace period has passed, so as long as anyone doing walking or iteration holds the RCU read lock, the old superstructure should not go away on them.

2.4 XArray

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2.4.1 Overview

The XArray is an abstract data type which behaves like a very large array of pointers. It meets many of the same needs as a hash or a conventional resizable array. Unlike a hash, it allows you to sensibly go to the next or previous entry in a cache-efficient manner. In contrast to a resizable array, there is no need to copy data or change MMU mappings in order to grow the array. It is more memory-efficient, parallelisable and cache friendly than a doubly-linked list. It takes advantage of RCU to perform lookups without locking.

The XArray implementation is efficient when the indices used are densely clustered; hashing the object and using the hash as the index will not perform well. The XArray is optimised for small indices, but still has good performance with large indices. If your index can be larger than `ULONG_MAX` then the XArray is not the data type for you. The most important user of the XArray is the page cache.

Normal pointers may be stored in the XArray directly. They must be 4-byte aligned, which is true for any pointer returned from *kmalloc()* and alloc_page(). It isn't true for arbitrary user-space pointers, nor for function pointers. You can store pointers to statically allocated objects, as long as those objects have an alignment of at least 4.

You can also store integers between 0 and `LONG_MAX` in the XArray. You must first convert it into an entry using *xa_mk_value()*. When you retrieve an entry from the XArray, you can check whether it is a value entry by calling *xa_is_value()*, and convert it back to an integer by calling *xa_to_value()*.

Some users want to tag the pointers they store in the XArray. You can call *xa_tag_pointer()* to create an entry with a tag, *xa_untag_pointer()* to turn a tagged entry back into an untagged pointer and *xa_pointer_tag()* to retrieve the tag of an entry. Tagged pointers use the same bits that are used to distinguish value entries from normal pointers, so you must decide whether they want to store value entries or tagged pointers in any particular XArray.

The XArray does not support storing IS_ERR() pointers as some conflict with value entries or internal entries.

An unusual feature of the XArray is the ability to create entries which occupy a range of indices. Once stored to, looking up any index in the range will return the same entry as looking up any other index in the range. Storing to any index will store to all of them. Multi-index entries can be explicitly split into smaller entries, or storing `NULL` into any entry will cause the XArray to forget about the range.

2.4.2 Normal API

Start by initialising an XArray, either with *DEFINE_XARRAY()* for statically allocated XArrays or *xa_init()* for dynamically allocated ones. A freshly-initialised XArray contains a NULL pointer at every index.

You can then set entries using *xa_store()* and get entries using *xa_load()*. xa_store will overwrite any entry with the new entry and return the previous entry stored at that index. You can use *xa_erase()* instead of calling *xa_store()* with a NULL entry. There is no difference between an entry that has never been stored to, one that has been erased and one that has most recently had NULL stored to it.

You can conditionally replace an entry at an index by using *xa_cmpxchg()*. Like cmpxchg(), it will only succeed if the entry at that index has the 'old' value. It also returns the entry which was at that index; if it returns the same entry which was passed as 'old', then *xa_cmpxchg()* succeeded.

If you want to only store a new entry to an index if the current entry at that index is NULL, you can use *xa_insert()* which returns -EBUSY if the entry is not empty.

You can copy entries out of the XArray into a plain array by calling *xa_extract()*. Or you can iterate over the present entries in the XArray by calling *xa_for_each()*, *xa_for_each_start()* or *xa_for_each_range()*. You may prefer to use *xa_find()* or *xa_find_after()* to move to the next present entry in the XArray.

Calling *xa_store_range()* stores the same entry in a range of indices. If you do this, some of the other operations will behave in a slightly odd way. For example, marking the entry at one index may result in the entry being marked at some, but not all of the other indices. Storing into one index may result in the entry retrieved by some, but not all of the other indices changing.

Sometimes you need to ensure that a subsequent call to *xa_store()* will not need to allocate memory. The *xa_reserve()* function will store a reserved entry at the indicated index. Users of the normal API will see this entry as containing NULL. If you do not need to use the reserved entry, you can call *xa_release()* to remove the unused entry. If another user has stored to the entry in the meantime, *xa_release()* will do nothing; if instead you want the entry to become NULL, you should use *xa_erase()*. Using *xa_insert()* on a reserved entry will fail.

If all entries in the array are NULL, the *xa_empty()* function will return true.

Finally, you can remove all entries from an XArray by calling *xa_destroy()*. If the XArray entries are pointers, you may wish to free the entries first. You can do this by iterating over all present entries in the XArray using the *xa_for_each()* iterator.

Search Marks

Each entry in the array has three bits associated with it called marks. Each mark may be set or cleared independently of the others. You can iterate over marked entries by using the *xa_for_each_marked()* iterator.

You can enquire whether a mark is set on an entry by using *xa_get_mark()*. If the entry is not NULL, you can set a mark on it by using *xa_set_mark()* and remove the mark from an entry by calling *xa_clear_mark()*. You can ask whether any entry in the XArray has a particular mark set by calling *xa_marked()*. Erasing an entry from the XArray causes all marks associated with that entry to be cleared.

Setting or clearing a mark on any index of a multi-index entry will affect all indices covered by that entry. Querying the mark on any index will return the same result.

There is no way to iterate over entries which are not marked; the data structure does not allow this to be implemented efficiently. There are not currently iterators to search for logical combinations of bits (eg iterate over all entries which have both XA_MARK_1 and XA_MARK_2 set, or iterate over all entries which have XA_MARK_0 or XA_MARK_2 set). It would be possible to add these if a user arises.

Allocating XArrays

If you use *DEFINE_XARRAY_ALLOC()* to define the XArray, or initialise it by passing XA_FLAGS_ALLOC to *xa_init_flags()*, the XArray changes to track whether entries are in use or not.

You can call *xa_alloc()* to store the entry at an unused index in the XArray. If you need to modify the array from interrupt context, you can use *xa_alloc_bh()* or *xa_alloc_irq()* to disable interrupts while allocating the ID.

Using *xa_store()*, *xa_cmpxchg()* or *xa_insert()* will also mark the entry as being allocated. Unlike a normal XArray, storing NULL will mark the entry as being in use, like *xa_reserve()*. To free an entry, use *xa_erase()* (or *xa_release()* if you only want to free the entry if it's NULL).

By default, the lowest free entry is allocated starting from 0. If you want to allocate entries starting at 1, it is more efficient to use *DEFINE_XARRAY_ALLOC1()* or XA_FLAGS_ALLOC1. If you want to allocate IDs up to a maximum, then wrap back around to the lowest free ID, you can use *xa_alloc_cyclic()*.

You cannot use XA_MARK_0 with an allocating XArray as this mark is used to track whether an entry is free or not. The other marks are available for your use.

Memory allocation

The *xa_store()*, *xa_cmpxchg()*, *xa_alloc()*, *xa_reserve()* and *xa_insert()* functions take a gfp_t parameter in case the XArray needs to allocate memory to store this entry. If the entry is being deleted, no memory allocation needs to be performed, and the GFP flags specified will be ignored.

It is possible for no memory to be allocatable, particularly if you pass a restrictive set of GFP flags. In that case, the functions return a special value which can be turned into an errno using *xa_err()*. If you don't need to know exactly which error occurred, using *xa_is_err()* is slightly more efficient.

Locking

When using the Normal API, you do not have to worry about locking. The XArray uses RCU and an internal spinlock to synchronise access:

No lock needed:

- *xa_empty()*
- *xa_marked()*

Takes RCU read lock:

- *xa_load()*
- *xa_for_each()*
- *xa_for_each_start()*
- *xa_for_each_range()*
- *xa_find()*
- *xa_find_after()*
- *xa_extract()*
- *xa_get_mark()*

Takes xa_lock internally:

- *xa_store()*
- *xa_store_bh()*
- *xa_store_irq()*
- *xa_insert()*
- *xa_insert_bh()*
- *xa_insert_irq()*
- *xa_erase()*
- *xa_erase_bh()*
- *xa_erase_irq()*
- *xa_cmpxchg()*
- *xa_cmpxchg_bh()*
- *xa_cmpxchg_irq()*
- *xa_store_range()*
- *xa_alloc()*
- *xa_alloc_bh()*
- *xa_alloc_irq()*

- *xa_reserve()*
- *xa_reserve_bh()*
- *xa_reserve_irq()*
- *xa_destroy()*
- *xa_set_mark()*
- *xa_clear_mark()*

Assumes xa_lock held on entry:

- *__xa_store()*
- *__xa_insert()*
- *__xa_erase()*
- *__xa_cmpxchg()*
- *__xa_alloc()*
- *__xa_set_mark()*
- *__xa_clear_mark()*

If you want to take advantage of the lock to protect the data structures that you are storing in the XArray, you can call xa_lock() before calling *xa_load()*, then take a reference count on the object you have found before calling xa_unlock(). This will prevent stores from removing the object from the array between looking up the object and incrementing the refcount. You can also use RCU to avoid dereferencing freed memory, but an explanation of that is beyond the scope of this document.

The XArray does not disable interrupts or softirqs while modifying the array. It is safe to read the XArray from interrupt or softirq context as the RCU lock provides enough protection.

If, for example, you want to store entries in the XArray in process context and then erase them in softirq context, you can do that this way:

```
void foo_init(struct foo *foo)
{
    xa_init_flags(&foo->array, XA_FLAGS_LOCK_BH);
}

int foo_store(struct foo *foo, unsigned long index, void *entry)
{
    int err;

    xa_lock_bh(&foo->array);
    err = xa_err(__xa_store(&foo->array, index, entry, GFP_KERNEL));
    if (!err)
        foo->count++;
    xa_unlock_bh(&foo->array);
    return err;
}
```

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```
/* foo_erase() is only called from softirq context */
void foo_erase(struct foo *foo, unsigned long index)
{
    xa_lock(&foo->array);
    __xa_erase(&foo->array, index);
    foo->count--;
    xa_unlock(&foo->array);
}
```

If you are going to modify the XArray from interrupt or softirq context, you need to initialise the array using *xa_init_flags()*, passing `XA_FLAGS_LOCK_IRQ` or `XA_FLAGS_LOCK_BH`.

The above example also shows a common pattern of wanting to extend the coverage of the xa_lock on the store side to protect some statistics associated with the array.

Sharing the XArray with interrupt context is also possible, either using xa_lock_irqsave() in both the interrupt handler and process context, or xa_lock_irq() in process context and xa_lock() in the interrupt handler. Some of the more common patterns have helper functions such as *xa_store_bh()*, *xa_store_irq()*, *xa_erase_bh()*, *xa_erase_irq()*, *xa_cmpxchg_bh()* and *xa_cmpxchg_irq()*.

Sometimes you need to protect access to the XArray with a mutex because that lock sits above another mutex in the locking hierarchy. That does not entitle you to use functions like *__xa_erase()* without taking the xa_lock; the xa_lock is used for lockdep validation and will be used for other purposes in the future.

The *__xa_set_mark()* and *__xa_clear_mark()* functions are also available for situations where you look up an entry and want to atomically set or clear a mark. It may be more efficient to use the advanced API in this case, as it will save you from walking the tree twice.

2.4.3 Advanced API

The advanced API offers more flexibility and better performance at the cost of an interface which can be harder to use and has fewer safeguards. No locking is done for you by the advanced API, and you are required to use the xa_lock while modifying the array. You can choose whether to use the xa_lock or the RCU lock while doing read-only operations on the array. You can mix advanced and normal operations on the same array; indeed the normal API is implemented in terms of the advanced API. The advanced API is only available to modules with a GPL-compatible license.

The advanced API is based around the xa_state. This is an opaque data structure which you declare on the stack using the *XA_STATE()* macro. This macro initialises the xa_state ready to start walking around the XArray. It is used as a cursor to maintain the position in the XArray and let you compose various operations together without having to restart from the top every time.

The xa_state is also used to store errors. You can call *xas_error()* to retrieve the error. All operations check whether the xa_state is in an error state before proceeding, so there's no need for you to check for an error after each call; you can make multiple calls in succession and only check at a convenient point. The only errors currently generated by the XArray code itself are ENOMEM and EINVAL, but it supports arbitrary errors in case you want to call *xas_set_err()* yourself.

If the xa_state is holding an ENOMEM error, calling *xas_nomem()* will attempt to allocate more memory using the specified gfp flags and cache it in the xa_state for the next attempt. The idea is that you take the xa_lock, attempt the operation and drop the lock. The operation attempts to allocate memory while holding the lock, but it is more likely to fail. Once you have dropped the lock, *xas_nomem()* can try harder to allocate more memory. It will return true if it is worth retrying the operation (i.e. that there was a memory error *and* more memory was allocated). If it has previously allocated memory, and that memory wasn't used, and there is no error (or some error that isn't ENOMEM), then it will free the memory previously allocated.

Internal Entries

The XArray reserves some entries for its own purposes. These are never exposed through the normal API, but when using the advanced API, it's possible to see them. Usually the best way to handle them is to pass them to *xas_retry()*, and retry the operation if it returns true.

Nan	Test	Usage
Nod	xa_is_r	An XArray node. May be visible when using a multi-index xa_state.
Sib-ling	*xa_is_*	A non-canonical entry for a multi-index entry. The value indicates which slot in this node has the canonical entry.
Retı	*xa_is_*	This entry is currently being modified by a thread which has the xa_lock. The node containing this entry may be freed at the end of this RCU period. You should restart the lookup from the head of the array.
Zerc	*xa_is_*	Zero entries appear as NULL through the Normal API, but occupy an entry in the XArray which can be used to reserve the index for future use. This is used by allocating XArrays for allocated entries which are NULL.

Other internal entries may be added in the future. As far as possible, they will be handled by *xas_retry()*.

Additional functionality

The *xas_create_range()* function allocates all the necessary memory to store every entry in a range. It will set ENOMEM in the xa_state if it cannot allocate memory.

You can use *xas_init_marks()* to reset the marks on an entry to their default state. This is usually all marks clear, unless the XArray is marked with XA_FLAGS_TRACK_FREE, in which case mark 0 is set and all other marks are clear.

Replacing one entry with another using *xas_store()* will not reset the marks on that entry; if you want the marks reset, you should do that explicitly.

The *xas_load()* will walk the xa_state as close to the entry as it can. If you know the xa_state has already been walked to the entry and need to check that the entry hasn't changed, you can use *xas_reload()* to save a function call.

If you need to move to a different index in the XArray, call *xas_set()*. This resets the cursor to the top of the tree, which will generally make the next operation walk the cursor to the desired spot in the tree. If you want to move to the next or previous index, call *xas_next()* or *xas_prev()*. Setting the index does not walk the cursor around the array so does not require a lock to be held, while moving to the next or previous index does.

You can search for the next present entry using *xas_find()*. This is the equivalent of both *xa_find()* and *xa_find_after()*; if the cursor has been walked to an entry, then it will find the next entry after the one currently referenced. If not, it will return the entry at the index of the xa_state. Using *xas_next_entry()* to move to the next present entry instead of *xas_find()* will save a function call in the majority of cases at the expense of emitting more inline code.

The *xas_find_marked()* function is similar. If the xa_state has not been walked, it will return the entry at the index of the xa_state, if it is marked. Otherwise, it will return the first marked entry after the entry referenced by the xa_state. The *xas_next_marked()* function is the equivalent of *xas_next_entry()*.

When iterating over a range of the XArray using *xas_for_each()* or *xas_for_each_marked()*, it may be necessary to temporarily stop the iteration. The *xas_pause()* function exists for this purpose. After you have done the necessary work and wish to resume, the xa_state is in an appropriate state to continue the iteration after the entry you last processed. If you have interrupts disabled while iterating, then it is good manners to pause the iteration and reenable interrupts every `XA_CHECK_SCHED` entries.

The *xas_get_mark()*, *xas_set_mark()* and *xas_clear_mark()* functions require the xa_state cursor to have been moved to the appropriate location in the XArray; they will do nothing if you have called *xas_pause()* or *xas_set()* immediately before.

You can call *xas_set_update()* to have a callback function called each time the XArray updates a node. This is used by the page cache workingset code to maintain its list of nodes which contain only shadow entries.

Multi-Index Entries

The XArray has the ability to tie multiple indices together so that operations on one index affect all indices. For example, storing into any index will change the value of the entry retrieved from any index. Setting or clearing a mark on any index will set or clear the mark on every index that is tied together. The current implementation only allows tying ranges which are aligned powers of two together; eg indices 64-127 may be tied together, but 2-6 may not be. This may save substantial quantities of memory; for example tying 512 entries together will save over 4kB.

You can create a multi-index entry by using *XA_STATE_ORDER()* or *xas_set_order()* followed by a call to *xas_store()*. Calling *xas_load()* with a multi-index xa_state will walk the xa_state to the right location in the tree, but the return value is not meaningful, potentially being an internal entry or `NULL` even when there is an entry stored within the range. Calling *xas_find_conflict()* will return the first entry within the range or `NULL` if there are no entries in the range. The *xas_for_each_conflict()* iterator will iterate over every entry which overlaps the specified range.

If *xas_load()* encounters a multi-index entry, the xa_index in the xa_state will not be changed. When iterating over an XArray or calling *xas_find()*, if the initial index is in the middle of a multi-index entry, it will not be altered. Subsequent calls or iterations will move the index to the first index in the range. Each entry will only be returned once, no matter how many indices it occupies.

Using *xas_next()* or *xas_prev()* with a multi-index xa_state is not supported. Using either of these functions on a multi-index entry will reveal sibling entries; these should be skipped over by the caller.

Storing `NULL` into any index of a multi-index entry will set the entry at every index to `NULL` and dissolve the tie. A multi-index entry can be split into entries occupying smaller ranges by calling *xas_split_alloc()* without the xa_lock held, followed by taking the lock and calling *xas_split()*.

2.4.4 Functions and structures

void *__xa_mk_value__(unsigned long v)

Create an XArray entry from an integer.

Parameters

unsigned long v
Value to store in XArray.

Context

Any context.

Return

An entry suitable for storing in the XArray.

unsigned long **xa_to_value**(const void *entry)

Get value stored in an XArray entry.

Parameters

const void *entry
XArray entry.

Context

Any context.

Return

The value stored in the XArray entry.

bool **xa_is_value**(const void *entry)

Determine if an entry is a value.

Parameters

const void *entry
XArray entry.

Context

Any context.

Return

True if the entry is a value, false if it is a pointer.

void ***xa_tag_pointer**(void *p, unsigned long tag)
Create an XArray entry for a tagged pointer.

Parameters

void *p
Plain pointer.

unsigned long tag
Tag value (0, 1 or 3).

Description

If the user of the XArray prefers, they can tag their pointers instead of storing value entries. Three tags are available (0, 1 and 3). These are distinct from the xa_mark_t as they are not replicated up through the array and cannot be searched for.

Context

Any context.

Return

An XArray entry.

void ***xa_untag_pointer**(void *entry)
Turn an XArray entry into a plain pointer.

Parameters

void *entry
XArray entry.

Description

If you have stored a tagged pointer in the XArray, call this function to get the untagged version of the pointer.

Context

Any context.

Return

A pointer.

unsigned int **xa_pointer_tag**(void *entry)
Get the tag stored in an XArray entry.

Parameters

void *entry
XArray entry.

Description

If you have stored a tagged pointer in the XArray, call this function to get the tag of that pointer.

Context

Any context.

Return

A tag.

bool **xa_is_zero**(const void *entry)
Is the entry a zero entry?

Parameters

const void *entry
Entry retrieved from the XArray

Description

The normal API will return NULL as the contents of a slot containing a zero entry. You can only see zero entries by using the advanced API.

Return

`true` if the entry is a zero entry.

bool **xa_is_err**(const void *entry)
Report whether an XArray operation returned an error

Parameters

const void *entry
Result from calling an XArray function

Description

If an XArray operation cannot complete an operation, it will return a special value indicating an error. This function tells you whether an error occurred; *xa_err()* tells you which error occurred.

Context

Any context.

Return

`true` if the entry indicates an error.

int **xa_err**(void *entry)
Turn an XArray result into an errno.

Parameters

void *entry
Result from calling an XArray function.

Description

If an XArray operation cannot complete an operation, it will return a special pointer value which encodes an errno. This function extracts the errno from the pointer value, or returns 0 if the pointer does not represent an errno.

Context

Any context.

Return

A negative errno or 0.

struct **xa_limit**

Represents a range of IDs.

Definition

```
struct xa_limit {
  u32 max;
  u32 min;
};
```

Members

max
The maximum ID to allocate (inclusive).

min
The lowest ID to allocate (inclusive).

Description

This structure is used either directly or via the XA_LIMIT() macro to communicate the range of IDs that are valid for allocation. Two common ranges are predefined for you: * xa_limit_32b - [0 - UINT_MAX] * xa_limit_31b - [0 - INT_MAX]

struct **xarray**

The anchor of the XArray.

Definition

```
struct xarray {
  spinlock_t xa_lock;
};
```

Members

xa_lock
Lock that protects the contents of the XArray.

Description

To use the xarray, define it statically or embed it in your data structure. It is a very small data structure, so it does not usually make sense to allocate it separately and keep a pointer to it in your data structure.

You may use the xa_lock to protect your own data structures as well.

DEFINE_XARRAY_FLAGS

`DEFINE_XARRAY_FLAGS (name, flags)`

Define an XArray with custom flags.

Parameters

name
A string that names your XArray.

flags
XA_FLAG values.

Description

This is intended for file scope definitions of XArrays. It declares and initialises an empty XArray with the chosen name and flags. It is equivalent to calling *xa_init_flags()* on the array, but it does the initialisation at compiletime instead of runtime.

DEFINE_XARRAY

`DEFINE_XARRAY (name)`

Define an XArray.

Parameters

name
A string that names your XArray.

Description

This is intended for file scope definitions of XArrays. It declares and initialises an empty XArray with the chosen name. It is equivalent to calling *xa_init()* on the array, but it does the initialisation at compiletime instead of runtime.

DEFINE_XARRAY_ALLOC

`DEFINE_XARRAY_ALLOC (name)`

Define an XArray which allocates IDs starting at 0.

Parameters

name
A string that names your XArray.

Description

This is intended for file scope definitions of allocating XArrays. See also *DEFINE_XARRAY()*.

DEFINE_XARRAY_ALLOC1

`DEFINE_XARRAY_ALLOC1 (name)`

Define an XArray which allocates IDs starting at 1.

Parameters

name
A string that names your XArray.

Description

This is intended for file scope definitions of allocating XArrays. See also *DEFINE_XARRAY()*.

void **xa_init_flags**(struct *xarray* *xa, gfp_t flags)
Initialise an empty XArray with flags.

Parameters

struct xarray *xa
XArray.

gfp_t flags
XA_FLAG values.

Description

If you need to initialise an XArray with special flags (eg you need to take the lock from interrupt context), use this function instead of *xa_init()*.

Context

Any context.

void **xa_init**(struct *xarray* *xa)
Initialise an empty XArray.

Parameters

struct xarray *xa
XArray.

Description

An empty XArray is full of NULL entries.

Context

Any context.

bool **xa_empty**(const struct *xarray* *xa)
Determine if an array has any present entries.

Parameters

const struct xarray *xa
XArray.

Context

Any context.

Return

`true` if the array contains only NULL pointers.

bool **xa_marked**(const struct *xarray* *xa, xa_mark_t mark)
Inquire whether any entry in this array has a mark set

Parameters

const struct xarray *xa
Array

xa_mark_t mark
Mark value

Context

Any context.

Return

`true` if any entry has this mark set.

xa_for_each_range

`xa_for_each_range (xa, index, entry, start, last)`

Iterate over a portion of an XArray.

Parameters

xa
XArray.

index
Index of **entry**.

entry
Entry retrieved from array.

start
First index to retrieve from array.

last
Last index to retrieve from array.

Description

During the iteration, **entry** will have the value of the entry stored in **xa** at **index**. You may modify **index** during the iteration if you want to skip or reprocess indices. It is safe to modify the array during the iteration. At the end of the iteration, **entry** will be set to NULL and **index** will have a value less than or equal to max.

xa_for_each_range() is O(n.log(n)) while *xas_for_each()* is O(n). You have to handle your own locking with *xas_for_each()*, and if you have to unlock after each iteration, it will also end up being O(n.log(n)). *xa_for_each_range()* will spin if it hits a retry entry; if you intend to see retry entries, you should use the *xas_for_each()* iterator instead. The *xas_for_each()* iterator will expand into more inline code than *xa_for_each_range()*.

Context

Any context. Takes and releases the RCU lock.

xa_for_each_start

`xa_for_each_start (xa, index, entry, start)`

Iterate over a portion of an XArray.

Parameters

xa
XArray.

index
Index of **entry**.

entry
Entry retrieved from array.

start
First index to retrieve from array.

Description

During the iteration, **entry** will have the value of the entry stored in **xa** at **index**. You may modify **index** during the iteration if you want to skip or reprocess indices. It is safe to modify the array during the iteration. At the end of the iteration, **entry** will be set to NULL and **index** will have a value less than or equal to max.

xa_for_each_start() is O(n.log(n)) while *xas_for_each()* is O(n). You have to handle your own locking with *xas_for_each()*, and if you have to unlock after each iteration, it will also end up being O(n.log(n)). *xa_for_each_start()* will spin if it hits a retry entry; if you intend to see retry entries, you should use the *xas_for_each()* iterator instead. The *xas_for_each()* iterator will expand into more inline code than *xa_for_each_start()*.

Context

Any context. Takes and releases the RCU lock.

xa_for_each

`xa_for_each (xa, index, entry)`

Iterate over present entries in an XArray.

Parameters

xa
XArray.

index
Index of **entry**.

entry
Entry retrieved from array.

Description

During the iteration, **entry** will have the value of the entry stored in **xa** at **index**. You may modify **index** during the iteration if you want to skip or reprocess indices. It is safe to modify the array during the iteration. At the end of the iteration, **entry** will be set to NULL and **index** will have a value less than or equal to max.

xa_for_each() is O(n.log(n)) while *xas_for_each()* is O(n). You have to handle your own locking with *xas_for_each()*, and if you have to unlock after each iteration, it will also end up being O(n.log(n)). *xa_for_each()* will spin if it hits a retry entry; if you intend to see retry entries, you should use the *xas_for_each()*

iterator instead. The *xas_for_each()* iterator will expand into more inline code than *xa_for_each()*.

Context

Any context. Takes and releases the RCU lock.

xa_for_each_marked

`xa_for_each_marked (xa, index, entry, filter)`

Iterate over marked entries in an XArray.

Parameters

xa
XArray.

index
Index of **entry**.

entry
Entry retrieved from array.

filter
Selection criterion.

Description

During the iteration, **entry** will have the value of the entry stored in **xa** at **index**. The iteration will skip all entries in the array which do not match **filter**. You may modify **index** during the iteration if you want to skip or reprocess indices. It is safe to modify the array during the iteration. At the end of the iteration, **entry** will be set to NULL and **index** will have a value less than or equal to max.

xa_for_each_marked() is O(n.log(n)) while *xas_for_each_marked()* is O(n). You have to handle your own locking with *xas_for_each()*, and if you have to unlock after each iteration, it will also end up being O(n.log(n)). *xa_for_each_marked()* will spin if it hits a retry entry; if you intend to see retry entries, you should use the *xas_for_each_marked()* iterator instead. The *xas_for_each_marked()* iterator will expand into more inline code than *xa_for_each_marked()*.

Context

Any context. Takes and releases the RCU lock.

void ***xa_store_bh**(struct *xarray* *xa, unsigned long index, void *entry, gfp_t gfp)

Store this entry in the XArray.

Parameters

struct xarray *xa
XArray.

unsigned long index
Index into array.

void *entry
New entry.

gfp_t gfp
Memory allocation flags.

Description

This function is like calling *xa_store()* except it disables softirqs while holding the array lock.

Context

Any context. Takes and releases the xa_lock while disabling softirqs.

Return

The old entry at this index or *xa_err()* if an error happened.

void ***xa_store_irq**(struct *xarray* *xa, unsigned long index, void *entry, gfp_t gfp)

Store this entry in the XArray.

Parameters

struct xarray *xa
XArray.

unsigned long index
Index into array.

void *entry
New entry.

gfp_t gfp
Memory allocation flags.

Description

This function is like calling *xa_store()* except it disables interrupts while holding the array lock.

Context

Process context. Takes and releases the xa_lock while disabling interrupts.

Return

The old entry at this index or *xa_err()* if an error happened.

void ***xa_erase_bh**(struct *xarray* *xa, unsigned long index)

Erase this entry from the XArray.

Parameters

struct xarray *xa
XArray.

unsigned long index
Index of entry.

Description

After this function returns, loading from **index** will return `NULL`. If the index is part of a multi-index entry, all indices will be erased and none of the entries will be part of a multi-index entry.

Context

Any context. Takes and releases the xa_lock while disabling softirqs.

Return

The entry which used to be at this index.

void *`xa_erase_irq`(struct *xarray* *xa, unsigned long index)

Erase this entry from the XArray.

Parameters

struct xarray *xa
XArray.

unsigned long index
Index of entry.

Description

After this function returns, loading from **index** will return `NULL`. If the index is part of a multi-index entry, all indices will be erased and none of the entries will be part of a multi-index entry.

Context

Process context. Takes and releases the xa_lock while disabling interrupts.

Return

The entry which used to be at this index.

void *`xa_cmpxchg`(struct *xarray* *xa, unsigned long index, void *old, void *entry, gfp_t gfp)

Conditionally replace an entry in the XArray.

Parameters

struct xarray *xa
XArray.

unsigned long index
Index into array.

void *old
Old value to test against.

void *entry
New value to place in array.

gfp_t gfp
Memory allocation flags.

Description

If the entry at **index** is the same as **old**, replace it with **entry**. If the return value is equal to **old**, then the exchange was successful.

Context

Any context. Takes and releases the xa_lock. May sleep if the **gfp** flags permit.

Return

The old value at this index or *xa_err()* if an error happened.

void ***xa_cmpxchg_bh**(struct *xarray* *xa, unsigned long index, void *old, void *entry, gfp_t gfp)

Conditionally replace an entry in the XArray.

Parameters

struct xarray *xa
XArray.

unsigned long index
Index into array.

void *old
Old value to test against.

void *entry
New value to place in array.

gfp_t gfp
Memory allocation flags.

Description

This function is like calling *xa_cmpxchg()* except it disables softirqs while holding the array lock.

Context

Any context. Takes and releases the xa_lock while disabling softirqs. May sleep if the **gfp** flags permit.

Return

The old value at this index or *xa_err()* if an error happened.

void ***xa_cmpxchg_irq**(struct *xarray* *xa, unsigned long index, void *old, void *entry, gfp_t gfp)

Conditionally replace an entry in the XArray.

Parameters

struct xarray *xa
XArray.

unsigned long index
Index into array.

void *old
Old value to test against.

void *entry
New value to place in array.

gfp_t gfp
Memory allocation flags.

Description

This function is like calling *xa_cmpxchg()* except it disables interrupts while holding the array lock.

Context

Process context. Takes and releases the xa_lock while disabling interrupts. May sleep if the **gfp** flags permit.

Return

The old value at this index or *xa_err()* if an error happened.

int **xa_insert**(struct *xarray* *xa, unsigned long index, void *entry, gfp_t gfp)

Store this entry in the XArray unless another entry is already present.

Parameters

struct xarray *xa
XArray.

unsigned long index
Index into array.

void *entry
New entry.

gfp_t gfp
Memory allocation flags.

Description

Inserting a NULL entry will store a reserved entry (like *xa_reserve()*) if no entry is present. Inserting will fail if a reserved entry is present, even though loading from this index will return NULL.

Context

Any context. Takes and releases the xa_lock. May sleep if the **gfp** flags permit.

Return

0 if the store succeeded. -EBUSY if another entry was present. -ENOMEM if memory could not be allocated.

int **xa_insert_bh**(struct *xarray* *xa, unsigned long index, void *entry, gfp_t gfp)

Store this entry in the XArray unless another entry is already present.

Parameters

struct xarray *xa
XArray.

unsigned long index
Index into array.

void *entry
New entry.

gfp_t gfp
Memory allocation flags.

Description

Inserting a NULL entry will store a reserved entry (like *xa_reserve()*) if no entry is present. Inserting will fail if a reserved entry is present, even though loading from this index will return NULL.

Context

Any context. Takes and releases the xa_lock while disabling softirqs. May sleep if the **gfp** flags permit.

Return

0 if the store succeeded. -EBUSY if another entry was present. -ENOMEM if memory could not be allocated.

int **xa_insert_irq**(struct *xarray* *xa, unsigned long index, void *entry, gfp_t gfp)

Store this entry in the XArray unless another entry is already present.

Parameters

struct xarray *xa
XArray.

unsigned long index
Index into array.

void *entry
New entry.

gfp_t gfp
Memory allocation flags.

Description

Inserting a NULL entry will store a reserved entry (like *xa_reserve()*) if no entry is present. Inserting will fail if a reserved entry is present, even though loading from this index will return NULL.

Context

Process context. Takes and releases the xa_lock while disabling interrupts. May sleep if the **gfp** flags permit.

Return

0 if the store succeeded. -EBUSY if another entry was present. -ENOMEM if memory could not be allocated.

int **xa_alloc**(struct *xarray* *xa, u32 *id, void *entry, struct *xa_limit* limit, gfp_t gfp)

Find somewhere to store this entry in the XArray.

Parameters

struct xarray *xa
XArray.

u32 *id
Pointer to ID.

void *entry
: New entry.

struct xa_limit limit
: Range of ID to allocate.

gfp_t gfp
: Memory allocation flags.

Description

Finds an empty entry in **xa** between **limit.min** and **limit.max**, stores the index into the **id** pointer, then stores the entry at that index. A concurrent lookup will not see an uninitialised **id**.

Context

Any context. Takes and releases the xa_lock. May sleep if the **gfp** flags permit.

Return

0 on success, -ENOMEM if memory could not be allocated or -EBUSY if there are no free entries in **limit**.

int **xa_alloc_bh**(struct *xarray* *xa, u32 *id, void *entry, struct *xa_limit* limit, gfp_t gfp)

Find somewhere to store this entry in the XArray.

Parameters

struct xarray *xa
: XArray.

u32 *id
: Pointer to ID.

void *entry
: New entry.

struct xa_limit limit
: Range of ID to allocate.

gfp_t gfp
: Memory allocation flags.

Description

Finds an empty entry in **xa** between **limit.min** and **limit.max**, stores the index into the **id** pointer, then stores the entry at that index. A concurrent lookup will not see an uninitialised **id**.

Context

Any context. Takes and releases the xa_lock while disabling softirqs. May sleep if the **gfp** flags permit.

Return

0 on success, -ENOMEM if memory could not be allocated or -EBUSY if there are no free entries in **limit**.

int **xa_alloc_irq**(struct *xarray* *xa, u32 *id, void *entry, struct *xa_limit* limit, gfp_t gfp)

Find somewhere to store this entry in the XArray.

Parameters

struct xarray *xa
XArray.

u32 *id
Pointer to ID.

void *entry
New entry.

struct xa_limit limit
Range of ID to allocate.

gfp_t gfp
Memory allocation flags.

Description

Finds an empty entry in **xa** between **limit.min** and **limit.max**, stores the index into the **id** pointer, then stores the entry at that index. A concurrent lookup will not see an uninitialised **id**.

Context

Process context. Takes and releases the xa_lock while disabling interrupts. May sleep if the **gfp** flags permit.

Return

0 on success, -ENOMEM if memory could not be allocated or -EBUSY if there are no free entries in **limit**.

int **xa_alloc_cyclic**(struct *xarray* *xa, u32 *id, void *entry, struct *xa_limit* limit, u32 *next, gfp_t gfp)

Find somewhere to store this entry in the XArray.

Parameters

struct xarray *xa
XArray.

u32 *id
Pointer to ID.

void *entry
New entry.

struct xa_limit limit
Range of allocated ID.

u32 *next
Pointer to next ID to allocate.

gfp_t gfp
Memory allocation flags.

Description

Finds an empty entry in **xa** between **limit.min** and **limit.max**, stores the index into the **id** pointer, then stores the entry at that index. A concurrent lookup will not see an uninitialised **id**. The search for an empty entry will start at **next** and will wrap around if necessary.

Context

Any context. Takes and releases the xa_lock. May sleep if the **gfp** flags permit.

Return

0 if the allocation succeeded without wrapping. 1 if the allocation succeeded after wrapping, -ENOMEM if memory could not be allocated or -EBUSY if there are no free entries in **limit**.

int **xa_alloc_cyclic_bh**(struct *xarray* *xa, u32 *id, void *entry, struct *xa_limit* limit, u32 *next, gfp_t gfp)

Find somewhere to store this entry in the XArray.

Parameters

struct xarray *xa
XArray.

u32 *id
Pointer to ID.

void *entry
New entry.

struct xa_limit limit
Range of allocated ID.

u32 *next
Pointer to next ID to allocate.

gfp_t gfp
Memory allocation flags.

Description

Finds an empty entry in **xa** between **limit.min** and **limit.max**, stores the index into the **id** pointer, then stores the entry at that index. A concurrent lookup will not see an uninitialised **id**. The search for an empty entry will start at **next** and will wrap around if necessary.

Context

Any context. Takes and releases the xa_lock while disabling softirqs. May sleep if the **gfp** flags permit.

Return

0 if the allocation succeeded without wrapping. 1 if the allocation succeeded after wrapping, -ENOMEM if memory could not be allocated or -EBUSY if there are no free entries in **limit**.

int **xa_alloc_cyclic_irq**(struct *xarray* *xa, u32 *id, void *entry, struct *xa_limit* limit, u32 *next, gfp_t gfp)

Find somewhere to store this entry in the XArray.

Parameters

struct xarray *xa
XArray.

u32 *id
Pointer to ID.

void *entry
New entry.

struct xa_limit limit
Range of allocated ID.

u32 *next
Pointer to next ID to allocate.

gfp_t gfp
Memory allocation flags.

Description

Finds an empty entry in **xa** between **limit.min** and **limit.max**, stores the index into the **id** pointer, then stores the entry at that index. A concurrent lookup will not see an uninitialised **id**. The search for an empty entry will start at **next** and will wrap around if necessary.

Context

Process context. Takes and releases the xa_lock while disabling interrupts. May sleep if the **gfp** flags permit.

Return

0 if the allocation succeeded without wrapping. 1 if the allocation succeeded after wrapping, -ENOMEM if memory could not be allocated or -EBUSY if there are no free entries in **limit**.

int **xa_reserve**(struct *xarray* *xa, unsigned long index, gfp_t gfp)

Reserve this index in the XArray.

Parameters

struct xarray *xa
XArray.

unsigned long index
Index into array.

gfp_t gfp
Memory allocation flags.

Description

Ensures there is somewhere to store an entry at **index** in the array. If there is already something stored at **index**, this function does nothing. If there was nothing there, the entry is marked as reserved. Loading from a reserved entry returns a `NULL` pointer.

If you do not use the entry that you have reserved, call *xa_release()* or *xa_erase()* to free any unnecessary memory.

Context

Any context. Takes and releases the xa_lock. May sleep if the **gfp** flags permit.

Return

0 if the reservation succeeded or -ENOMEM if it failed.

int **xa_reserve_bh**(struct *xarray* *xa, unsigned long index, gfp_t gfp)

Reserve this index in the XArray.

Parameters

struct xarray *xa
XArray.

unsigned long index
Index into array.

gfp_t gfp
Memory allocation flags.

Description

A softirq-disabling version of *xa_reserve()*.

Context

Any context. Takes and releases the xa_lock while disabling softirqs.

Return

0 if the reservation succeeded or -ENOMEM if it failed.

int **xa_reserve_irq**(struct *xarray* *xa, unsigned long index, gfp_t gfp)

Reserve this index in the XArray.

Parameters

struct xarray *xa
XArray.

unsigned long index
Index into array.

gfp_t gfp
Memory allocation flags.

Description

An interrupt-disabling version of *xa_reserve()*.

Context

Process context. Takes and releases the xa_lock while disabling interrupts.

Return

0 if the reservation succeeded or -ENOMEM if it failed.

void **xa_release**(struct *xarray* *xa, unsigned long index)

Release a reserved entry.

Parameters

struct xarray *xa
XArray.

unsigned long index
Index of entry.

Description

After calling *xa_reserve()*, you can call this function to release the reservation. If the entry at **index** has been stored to, this function will do nothing.

bool **xa_is_sibling**(const void *entry)

Is the entry a sibling entry?

Parameters

const void *entry
Entry retrieved from the XArray

Return

`true` if the entry is a sibling entry.

bool **xa_is_retry**(const void *entry)

Is the entry a retry entry?

Parameters

const void *entry
Entry retrieved from the XArray

Return

`true` if the entry is a retry entry.

bool **xa_is_advanced**(const void *entry)

Is the entry only permitted for the advanced API?

Parameters

const void *entry
Entry to be stored in the XArray.

Return

`true` if the entry cannot be stored by the normal API.

xa_update_node_t

Typedef: A callback function from the XArray.

Syntax

```
void xa_update_node_t (struct xa_node *node)
```

Parameters

struct xa_node *node
The node which is being processed

Description

This function is called every time the XArray updates the count of present and value entries in a node. It allows advanced users to maintain the private_list in the node.

Context

The xa_lock is held and interrupts may be disabled. Implementations should not drop the xa_lock, nor re-enable interrupts.

XA_STATE

`XA_STATE (name, array, index)`

Declare an XArray operation state.

Parameters

name
Name of this operation state (usually xas).

array
Array to operate on.

index
Initial index of interest.

Description

Declare and initialise an xa_state on the stack.

XA_STATE_ORDER

`XA_STATE_ORDER (name, array, index, order)`

Declare an XArray operation state.

Parameters

name
Name of this operation state (usually xas).

array
Array to operate on.

index
Initial index of interest.

order
Order of entry.

Description

Declare and initialise an xa_state on the stack. This variant of *XA_STATE()* allows you to specify the 'order' of the element you want to operate on.`

int **xas_error**(const struct xa_state *xas)
Return an errno stored in the xa_state.

Parameters

const struct xa_state *xas
XArray operation state.

Return

0 if no error has been noted. A negative errno if one has.

void **xas_set_err**(struct xa_state *xas, long err)
Note an error in the xa_state.

Parameters

struct xa_state *xas
XArray operation state.

long err
Negative error number.

Description

Only call this function with a negative **err**; zero or positive errors will probably not behave the way you think they should. If you want to clear the error from an xa_state, use *xas_reset()*.

bool **xas_invalid**(const struct xa_state *xas)
Is the xas in a retry or error state?

Parameters

const struct xa_state *xas
XArray operation state.

Return

`true` if the xas cannot be used for operations.

bool **xas_valid**(const struct xa_state *xas)
Is the xas a valid cursor into the array?

Parameters

const struct xa_state *xas
XArray operation state.

Return

`true` if the xas can be used for operations.

bool **xas_is_node**(const struct xa_state *xas)
Does the xas point to a node?

Parameters

const struct xa_state *xas
XArray operation state.

Return

`true` if the xas currently references a node.

void **xas_reset**(struct xa_state *xas)

Reset an XArray operation state.

Parameters

struct xa_state *xas
XArray operation state.

Description

Resets the error or walk state of the **xas** so future walks of the array will start from the root. Use this if you have dropped the xarray lock and want to reuse the xa_state.

Context

Any context.

bool **xas_retry**(struct xa_state *xas, const void *entry)

Retry the operation if appropriate.

Parameters

struct xa_state *xas
XArray operation state.

const void *entry
Entry from xarray.

Description

The advanced functions may sometimes return an internal entry, such as a retry entry or a zero entry. This function sets up the **xas** to restart the walk from the head of the array if needed.

Context

Any context.

Return

true if the operation needs to be retried.

void ***xas_reload**(struct xa_state *xas)

Refetch an entry from the xarray.

Parameters

struct xa_state *xas
XArray operation state.

Description

Use this function to check that a previously loaded entry still has the same value. This is useful for the lockless pagecache lookup where we walk the array with only the RCU lock to protect us, lock the page, then check that the page hasn't moved since we looked it up.

The caller guarantees that **xas** is still valid. If it may be in an error or restart state, call *xas_load()* instead.

Return

The entry at this location in the xarray.

void **xas_set**(struct xa_state *xas, unsigned long index)

Set up XArray operation state for a different index.

Parameters

struct xa_state *xas
XArray operation state.

unsigned long index
New index into the XArray.

Description

Move the operation state to refer to a different index. This will have the effect of starting a walk from the top; see *xas_next()* to move to an adjacent index.

void **xas_set_order**(struct xa_state *xas, unsigned long index, unsigned int order)

Set up XArray operation state for a multislot entry.

Parameters

struct xa_state *xas
XArray operation state.

unsigned long index
Target of the operation.

unsigned int order
Entry occupies 2^**order** indices.

void **xas_set_update**(struct xa_state *xas, *xa_update_node_t* update)

Set up XArray operation state for a callback.

Parameters

struct xa_state *xas
XArray operation state.

xa_update_node_t update
Function to call when updating a node.

Description

The XArray can notify a caller after it has updated an xa_node. This is advanced functionality and is only needed by the page cache.

void ***xas_next_entry**(struct xa_state *xas, unsigned long max)

Advance iterator to next present entry.

Parameters

struct xa_state *xas
XArray operation state.

unsigned long max
Highest index to return.

Description

xas_next_entry() is an inline function to optimise xarray traversal for speed. It is equivalent to calling *xas_find()*, and will call *xas_find()* for all the hard cases.

Return

The next present entry after the one currently referred to by **xas**.

void ***xas_next_marked**(struct xa_state *xas, unsigned long max, xa_mark_t mark)

Advance iterator to next marked entry.

Parameters

struct xa_state *xas
XArray operation state.

unsigned long max
Highest index to return.

xa_mark_t mark
Mark to search for.

Description

xas_next_marked() is an inline function to optimise xarray traversal for speed. It is equivalent to calling *xas_find_marked()*, and will call *xas_find_marked()* for all the hard cases.

Return

The next marked entry after the one currently referred to by **xas**.

xas_for_each

`xas_for_each (xas, entry, max)`

Iterate over a range of an XArray.

Parameters

xas
XArray operation state.

entry
Entry retrieved from the array.

max
Maximum index to retrieve from array.

Description

The loop body will be executed for each entry present in the xarray between the current xas position and **max**. **entry** will be set to the entry retrieved from the xarray. It is safe to delete entries from the array in the loop body. You should hold either the RCU lock or the xa_lock while iterating. If you need to drop the lock, call *xas_pause()* first.

xas_for_each_marked

`xas_for_each_marked (xas, entry, max, mark)`

Iterate over a range of an XArray.

Parameters

xas
XArray operation state.

entry
Entry retrieved from the array.

max
Maximum index to retrieve from array.

mark
Mark to search for.

Description

The loop body will be executed for each marked entry in the xarray between the current xas position and **max**. **entry** will be set to the entry retrieved from the xarray. It is safe to delete entries from the array in the loop body. You should hold either the RCU lock or the xa_lock while iterating. If you need to drop the lock, call *xas_pause()* first.

xas_for_each_conflict

`xas_for_each_conflict (xas, entry)`

Iterate over a range of an XArray.

Parameters

xas
XArray operation state.

entry
Entry retrieved from the array.

Description

The loop body will be executed for each entry in the XArray that lies within the range specified by **xas**. If the loop terminates normally, **entry** will be `NULL`. The user may break out of the loop, which will leave **entry** set to the conflicting entry. The caller may also call xa_set_err() to exit the loop while setting an error to record the reason.

void ***xas_prev**(struct xa_state *xas)

Move iterator to previous index.

Parameters

struct xa_state *xas
XArray operation state.

Description

If the **xas** was in an error state, it will remain in an error state and this function will return `NULL`. If the **xas** has never been walked, it will have the effect of calling *xas_load()*. Otherwise one will be subtracted from the index and the state will be walked to the correct location in the array for the next operation.

If the iterator was referencing index 0, this function wraps around to ULONG_MAX.

Return

The entry at the new index. This may be NULL or an internal entry.

void ***xas_next**(struct xa_state *xas)

Move state to next index.

Parameters

struct xa_state *xas
XArray operation state.

Description

If the **xas** was in an error state, it will remain in an error state and this function will return NULL. If the **xas** has never been walked, it will have the effect of calling *xas_load()*. Otherwise one will be added to the index and the state will be walked to the correct location in the array for the next operation.

If the iterator was referencing index ULONG_MAX, this function wraps around to 0.

Return

The entry at the new index. This may be NULL or an internal entry.

void ***xas_load**(struct xa_state *xas)

Load an entry from the XArray (advanced).

Parameters

struct xa_state *xas
XArray operation state.

Description

Usually walks the **xas** to the appropriate state to load the entry stored at xa_index. However, it will do nothing and return NULL if **xas** is in an error state. *xas_load()* will never expand the tree.

If the xa_state is set up to operate on a multi-index entry, *xas_load()* may return NULL or an internal entry, even if there are entries present within the range specified by **xas**.

Context

Any context. The caller should hold the xa_lock or the RCU lock.

Return

Usually an entry in the XArray, but see description for exceptions.

bool **xas_nomem**(struct xa_state *xas, gfp_t gfp)

Allocate memory if needed.

Parameters

struct xa_state *xas
XArray operation state.

gfp_t gfp
Memory allocation flags.

Description

If we need to add new nodes to the XArray, we try to allocate memory with GFP_NOWAIT while holding the lock, which will usually succeed. If it fails, **xas** is flagged as needing memory to continue. The caller should drop the lock and call *xas_nomem()*. If *xas_nomem()* succeeds, the caller should retry the operation.

Forward progress is guaranteed as one node is allocated here and stored in the xa_state where it will be found by xas_alloc(). More nodes will likely be found in the slab allocator, but we do not tie them up here.

Return

true if memory was needed, and was successfully allocated.

void **xas_free_nodes**(struct xa_state *xas, struct xa_node *top)

Free this node and all nodes that it references

Parameters

struct xa_state *xas
Array operation state.

struct xa_node *top
Node to free

Description

This node has been removed from the tree. We must now free it and all of its subnodes. There may be RCU walkers with references into the tree, so we must replace all entries with retry markers.

void **xas_create_range**(struct xa_state *xas)

Ensure that stores to this range will succeed

Parameters

struct xa_state *xas
XArray operation state.

Description

Creates all of the slots in the range covered by **xas**. Sets **xas** to create single-index entries and positions it at the beginning of the range. This is for the benefit of users which have not yet been converted to use multi-index entries.

void ***xas_store**(struct xa_state *xas, void *entry)

Store this entry in the XArray.

Parameters

struct xa_state *xas
XArray operation state.

void *entry
New entry.

Description

If **xas** is operating on a multi-index entry, the entry returned by this function is essentially meaningless (it may be an internal entry or it may be `NULL`, even if there are non-NULL entries at some of the indices covered by the range). This is not a problem for any current users, and can be changed if needed.

Return

The old entry at this index.

bool **xas_get_mark**(const struct xa_state *xas, xa_mark_t mark)

Returns the state of this mark.

Parameters

const struct xa_state *xas
XArray operation state.

xa_mark_t mark
Mark number.

Return

true if the mark is set, false if the mark is clear or **xas** is in an error state.

void **xas_set_mark**(const struct xa_state *xas, xa_mark_t mark)

Sets the mark on this entry and its parents.

Parameters

const struct xa_state *xas
XArray operation state.

xa_mark_t mark
Mark number.

Description

Sets the specified mark on this entry, and walks up the tree setting it on all the ancestor entries. Does nothing if **xas** has not been walked to an entry, or is in an error state.

void **xas_clear_mark**(const struct xa_state *xas, xa_mark_t mark)

Clears the mark on this entry and its parents.

Parameters

const struct xa_state *xas
XArray operation state.

xa_mark_t mark
Mark number.

Description

Clears the specified mark on this entry, and walks back to the head attempting to clear it on all the ancestor entries. Does nothing if **xas** has not been walked to an entry, or is in an error state.

void **xas_init_marks**(const struct xa_state *xas)

Initialise all marks for the entry

Parameters

const struct xa_state *xas
Array operations state.

Description

Initialise all marks for the entry specified by **xas**. If we're tracking free entries with a mark, we need to set it on all entries. All other marks are cleared.

This implementation is not as efficient as it could be; we may walk up the tree multiple times.

void **xas_split_alloc**(struct xa_state *xas, void *entry, unsigned int order, gfp_t gfp)
Allocate memory for splitting an entry.

Parameters

struct xa_state *xas
XArray operation state.

void *entry
New entry which will be stored in the array.

unsigned int order
New entry order.

gfp_t gfp
Memory allocation flags.

Description

This function should be called before calling *xas_split()*. If necessary, it will allocate new nodes (and fill them with **entry**) to prepare for the upcoming split of an entry of **order** size into entries of the order stored in the **xas**.

Context

May sleep if **gfp** flags permit.

void **xas_split**(struct xa_state *xas, void *entry, unsigned int order)
Split a multi-index entry into smaller entries.

Parameters

struct xa_state *xas
XArray operation state.

void *entry
New entry to store in the array.

unsigned int order
New entry order.

Description

The value in the entry is copied to all the replacement entries.

Context

Any context. The caller should hold the xa_lock.

void **xas_pause**(struct xa_state *xas)

Pause a walk to drop a lock.

Parameters

struct xa_state *xas
XArray operation state.

Description

Some users need to pause a walk and drop the lock they're holding in order to yield to a higher priority thread or carry out an operation on an entry. Those users should call this function before they drop the lock. It resets the **xas** to be suitable for the next iteration of the loop after the user has reacquired the lock. If most entries found during a walk require you to call *xas_pause()*, the *xa_for_each()* iterator may be more appropriate.

Note that *xas_pause()* only works for forward iteration. If a user needs to pause a reverse iteration, we will need a xas_pause_rev().

void ***xas_find**(struct xa_state *xas, unsigned long max)

Find the next present entry in the XArray.

Parameters

struct xa_state *xas
XArray operation state.

unsigned long max
Highest index to return.

Description

If the **xas** has not yet been walked to an entry, return the entry which has an index >= xas.xa_index. If it has been walked, the entry currently being pointed at has been processed, and so we move to the next entry.

If no entry is found and the array is smaller than **max**, the iterator is set to the smallest index not yet in the array. This allows **xas** to be immediately passed to *xas_store()*.

Return

The entry, if found, otherwise `NULL`.

void ***xas_find_marked**(struct xa_state *xas, unsigned long max, xa_mark_t mark)

Find the next marked entry in the XArray.

Parameters

struct xa_state *xas
XArray operation state.

unsigned long max
Highest index to return.

xa_mark_t mark
Mark number to search for.

Description

If the **xas** has not yet been walked to an entry, return the marked entry which has an index >= xas.xa_index. If it has been walked, the entry currently being pointed at has been processed, and so we return the first marked entry with an index > xas.xa_index.

If no marked entry is found and the array is smaller than **max**, **xas** is set to the bounds state and xas->xa_index is set to the smallest index not yet in the array. This allows **xas** to be immediately passed to *xas_store()*.

If no entry is found before **max** is reached, **xas** is set to the restart state.

Return

The entry, if found, otherwise `NULL`.

void ***xas_find_conflict**(struct xa_state *xas)

Find the next present entry in a range.

Parameters

struct xa_state *xas
XArray operation state.

Description

The **xas** describes both a range and a position within that range.

Context

Any context. Expects xa_lock to be held.

Return

The next entry in the range covered by **xas** or `NULL`.

void ***xa_load**(struct *xarray* *xa, unsigned long index)

Load an entry from an XArray.

Parameters

struct xarray *xa
XArray.

unsigned long index
index into array.

Context

Any context. Takes and releases the RCU lock.

Return

The entry at **index** in **xa**.

void ***__xa_erase**(struct *xarray* *xa, unsigned long index)

Erase this entry from the XArray while locked.

Parameters

struct xarray *xa
XArray.

unsigned long index
Index into array.

Description

After this function returns, loading from **index** will return NULL. If the index is part of a multi-index entry, all indices will be erased and none of the entries will be part of a multi-index entry.

Context

Any context. Expects xa_lock to be held on entry.

Return

The entry which used to be at this index.

void ***xa_erase**(struct *xarray* *xa, unsigned long index)
Erase this entry from the XArray.

Parameters

struct xarray *xa
XArray.

unsigned long index
Index of entry.

Description

After this function returns, loading from **index** will return NULL. If the index is part of a multi-index entry, all indices will be erased and none of the entries will be part of a multi-index entry.

Context

Any context. Takes and releases the xa_lock.

Return

The entry which used to be at this index.

void ***__xa_store**(struct *xarray* *xa, unsigned long index, void *entry, gfp_t gfp)
Store this entry in the XArray.

Parameters

struct xarray *xa
XArray.

unsigned long index
Index into array.

void *entry
New entry.

gfp_t gfp
Memory allocation flags.

Description

You must already be holding the xa_lock when calling this function. It will drop the lock if needed to allocate memory, and then reacquire it afterwards.

Context

Any context. Expects xa_lock to be held on entry. May release and reacquire xa_lock if **gfp** flags permit.

Return

The old entry at this index or *xa_err()* if an error happened.

void ***xa_store**(struct *xarray* *xa, unsigned long index, void *entry, gfp_t gfp)

Store this entry in the XArray.

Parameters

struct xarray *xa
XArray.

unsigned long index
Index into array.

void *entry
New entry.

gfp_t gfp
Memory allocation flags.

Description

After this function returns, loads from this index will return **entry**. Storing into an existing multi-index entry updates the entry of every index. The marks associated with **index** are unaffected unless **entry** is NULL.

Context

Any context. Takes and releases the xa_lock. May sleep if the **gfp** flags permit.

Return

The old entry at this index on success, xa_err(-EINVAL) if **entry** cannot be stored in an XArray, or xa_err(-ENOMEM) if memory allocation failed.

void ***__xa_cmpxchg**(struct *xarray* *xa, unsigned long index, void *old, void *entry, gfp_t gfp)

Store this entry in the XArray.

Parameters

struct xarray *xa
XArray.

unsigned long index
Index into array.

void *old
Old value to test against.

void *entry
New entry.

gfp_t gfp
Memory allocation flags.

Description

You must already be holding the xa_lock when calling this function. It will drop the lock if needed to allocate memory, and then reacquire it afterwards.

Context

Any context. Expects xa_lock to be held on entry. May release and reacquire xa_lock if **gfp** flags permit.

Return

The old entry at this index or *xa_err()* if an error happened.

int **__xa_insert**(struct *xarray* *xa, unsigned long index, void *entry, gfp_t gfp)

Store this entry in the XArray if no entry is present.

Parameters

struct xarray *xa
XArray.

unsigned long index
Index into array.

void *entry
New entry.

gfp_t gfp
Memory allocation flags.

Description

Inserting a NULL entry will store a reserved entry (like *xa_reserve()*) if no entry is present. Inserting will fail if a reserved entry is present, even though loading from this index will return NULL.

Context

Any context. Expects xa_lock to be held on entry. May release and reacquire xa_lock if **gfp** flags permit.

Return

0 if the store succeeded. -EBUSY if another entry was present. -ENOMEM if memory could not be allocated.

void ***xa_store_range**(struct *xarray* *xa, unsigned long first, unsigned long last, void *entry, gfp_t gfp)

Store this entry at a range of indices in the XArray.

Parameters

struct xarray *xa
XArray.

unsigned long first
First index to affect.

unsigned long last
Last index to affect.

void *entry
New entry.

gfp_t gfp
Memory allocation flags.

Description

After this function returns, loads from any index between **first** and **last**, inclusive will return **entry**. Storing into an existing multi-index entry updates the entry of every index. The marks associated with **index** are unaffected unless **entry** is `NULL`.

Context

Process context. Takes and releases the xa_lock. May sleep if the **gfp** flags permit.

Return

`NULL` on success, xa_err(-EINVAL) if **entry** cannot be stored in an XArray, or xa_err(-ENOMEM) if memory allocation failed.

int **xa_get_order**(struct *xarray* *xa, unsigned long index)
Get the order of an entry.

Parameters

struct xarray *xa
XArray.

unsigned long index
Index of the entry.

Return

A number between 0 and 63 indicating the order of the entry.

int **__xa_alloc**(struct *xarray* *xa, u32 *id, void *entry, struct *xa_limit* limit, gfp_t gfp)
Find somewhere to store this entry in the XArray.

Parameters

struct xarray *xa
XArray.

u32 *id
Pointer to ID.

void *entry
New entry.

struct xa_limit limit
Range for allocated ID.

gfp_t gfp
Memory allocation flags.

Description

Finds an empty entry in **xa** between **limit.min** and **limit.max**, stores the index into the **id** pointer, then stores the entry at that index. A concurrent lookup will not see an uninitialised **id**.

Context

Any context. Expects xa_lock to be held on entry. May release and reacquire xa_lock if **gfp** flags permit.

Return

0 on success, -ENOMEM if memory could not be allocated or -EBUSY if there are no free entries in **limit**.

int **__xa_alloc_cyclic**(struct *xarray* *xa, u32 *id, void *entry, struct *xa_limit* limit, u32 *next, gfp_t gfp)

Find somewhere to store this entry in the XArray.

Parameters

struct xarray *xa
XArray.

u32 *id
Pointer to ID.

void *entry
New entry.

struct xa_limit limit
Range of allocated ID.

u32 *next
Pointer to next ID to allocate.

gfp_t gfp
Memory allocation flags.

Description

Finds an empty entry in **xa** between **limit.min** and **limit.max**, stores the index into the **id** pointer, then stores the entry at that index. A concurrent lookup will not see an uninitialised **id**. The search for an empty entry will start at **next** and will wrap around if necessary.

Context

Any context. Expects xa_lock to be held on entry. May release and reacquire xa_lock if **gfp** flags permit.

Return

0 if the allocation succeeded without wrapping. 1 if the allocation succeeded after wrapping, -ENOMEM if memory could not be allocated or -EBUSY if there are no free entries in **limit**.

void **__xa_set_mark**(struct *xarray* *xa, unsigned long index, xa_mark_t mark)

Set this mark on this entry while locked.

Parameters

struct xarray *xa
XArray.

unsigned long index
Index of entry.

xa_mark_t mark
Mark number.

Description

Attempting to set a mark on a NULL entry does not succeed.

Context

Any context. Expects xa_lock to be held on entry.

void **__xa_clear_mark**(struct *xarray* *xa, unsigned long index, xa_mark_t mark)
Clear this mark on this entry while locked.

Parameters

struct xarray *xa
XArray.

unsigned long index
Index of entry.

xa_mark_t mark
Mark number.

Context

Any context. Expects xa_lock to be held on entry.

bool **xa_get_mark**(struct *xarray* *xa, unsigned long index, xa_mark_t mark)
Inquire whether this mark is set on this entry.

Parameters

struct xarray *xa
XArray.

unsigned long index
Index of entry.

xa_mark_t mark
Mark number.

Description

This function uses the RCU read lock, so the result may be out of date by the time it returns. If you need the result to be stable, use a lock.

Context

Any context. Takes and releases the RCU lock.

Return

True if the entry at **index** has this mark set, false if it doesn't.

void **xa_set_mark**(struct *xarray* *xa, unsigned long index, xa_mark_t mark)
Set this mark on this entry.

Parameters

struct xarray *xa
XArray.

unsigned long index
Index of entry.

xa_mark_t mark
Mark number.

Description

Attempting to set a mark on a NULL entry does not succeed.

Context

Process context. Takes and releases the xa_lock.

void **xa_clear_mark**(struct *xarray* *xa, unsigned long index, xa_mark_t mark)
Clear this mark on this entry.

Parameters

struct xarray *xa
XArray.

unsigned long index
Index of entry.

xa_mark_t mark
Mark number.

Description

Clearing a mark always succeeds.

Context

Process context. Takes and releases the xa_lock.

void ***xa_find**(struct *xarray* *xa, unsigned long *indexp, unsigned long max, xa_mark_t filter)
Search the XArray for an entry.

Parameters

struct xarray *xa
XArray.

unsigned long *indexp
Pointer to an index.

unsigned long max
Maximum index to search to.

xa_mark_t filter
Selection criterion.

Description

Finds the entry in **xa** which matches the **filter**, and has the lowest index that is at least **indexp** and no more than **max**. If an entry is found, **indexp** is updated to be the index of the entry. This function is protected by the RCU read lock, so it may not find entries which are being simultaneously added. It will not return an XA_RETRY_ENTRY; if you need to see retry entries, use *xas_find()*.

Context

Any context. Takes and releases the RCU lock.

Return

The entry, if found, otherwise NULL.

void ***xa_find_after**(struct *xarray* *xa, unsigned long *indexp, unsigned long max, xa_mark_t filter)

Search the XArray for a present entry.

Parameters

struct xarray *xa
XArray.

unsigned long *indexp
Pointer to an index.

unsigned long max
Maximum index to search to.

xa_mark_t filter
Selection criterion.

Description

Finds the entry in **xa** which matches the **filter** and has the lowest index that is above **indexp** and no more than **max**. If an entry is found, **indexp** is updated to be the index of the entry. This function is protected by the RCU read lock, so it may miss entries which are being simultaneously added. It will not return an XA_RETRY_ENTRY; if you need to see retry entries, use *xas_find()*.

Context

Any context. Takes and releases the RCU lock.

Return

The pointer, if found, otherwise NULL.

unsigned int **xa_extract**(struct *xarray* *xa, void **dst, unsigned long start, unsigned long max, unsigned int n, xa_mark_t filter)

Copy selected entries from the XArray into a normal array.

Parameters

struct xarray *xa
The source XArray to copy from.

void **dst
The buffer to copy entries into.

unsigned long start
The first index in the XArray eligible to be selected.

unsigned long max
The last index in the XArray eligible to be selected.

unsigned int n
The maximum number of entries to copy.

xa_mark_t filter
Selection criterion.

Description

Copies up to **n** entries that match **filter** from the XArray. The copied entries will have indices between **start** and **max**, inclusive.

The **filter** may be an XArray mark value, in which case entries which are marked with that mark will be copied. It may also be `XA_PRESENT`, in which case all entries which are not `NULL` will be copied.

The entries returned may not represent a snapshot of the XArray at a moment in time. For example, if another thread stores to index 5, then index 10, calling *xa_extract()* may return the old contents of index 5 and the new contents of index 10. Indices not modified while this function is running will not be skipped.

If you need stronger guarantees, holding the xa_lock across calls to this function will prevent concurrent modification.

Context

Any context. Takes and releases the RCU lock.

Return

The number of entries copied.

void **xa_delete_node**(struct xa_node *node, *xa_update_node_t* update)
Private interface for workingset code.

Parameters

struct xa_node *node
Node to be removed from the tree.

xa_update_node_t update
Function to call to update ancestor nodes.

Context

xa_lock must be held on entry and will not be released.

void **xa_destroy**(struct *xarray* *xa)
Free all internal data structures.

Parameters

struct xarray *xa
XArray.

Description

After calling this function, the XArray is empty and has freed all memory allocated for its internal data structures. You are responsible for freeing the objects referenced by the XArray.

Context

Any context. Takes and releases the xa_lock, interrupt-safe.

2.5 ID Allocation

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2.5.1 Overview

A common problem to solve is allocating identifiers (IDs); generally small numbers which identify a thing. Examples include file descriptors, process IDs, packet identifiers in networking protocols, SCSI tags and device instance numbers. The IDR and the IDA provide a reasonable solution to the problem to avoid everybody inventing their own. The IDR provides the ability to map an ID to a pointer, while the IDA provides only ID allocation, and as a result is much more memory-efficient.

2.5.2 IDR usage

Start by initialising an IDR, either with *DEFINE_IDR()* for statically allocated IDRs or *idr_init()* for dynamically allocated IDRs.

You can call *idr_alloc()* to allocate an unused ID. Look up the pointer you associated with the ID by calling *idr_find()* and free the ID by calling *idr_remove()*.

If you need to change the pointer associated with an ID, you can call *idr_replace()*. One common reason to do this is to reserve an ID by passing a `NULL` pointer to the allocation function; initialise the object with the reserved ID and finally insert the initialised object into the IDR.

Some users need to allocate IDs larger than `INT_MAX`. So far all of these users have been content with a `UINT_MAX` limit, and they use *idr_alloc_u32()*. If you need IDs that will not fit in a u32, we will work with you to address your needs.

If you need to allocate IDs sequentially, you can use *idr_alloc_cyclic()*. The IDR becomes less efficient when dealing with larger IDs, so using this function comes at a slight cost.

To perform an action on all pointers used by the IDR, you can either use the callback-based *idr_for_each()* or the iterator-style *idr_for_each_entry()*. You may need to use *idr_for_each_entry_continue()* to continue an iteration. You can also use *idr_get_next()* if the iterator doesn't fit your needs.

When you have finished using an IDR, you can call idr_destroy() to release the memory used by the IDR. This will not free the objects pointed to from the IDR; if you want to do that, use one of the iterators to do it.

You can use *idr_is_empty()* to find out whether there are any IDs currently allocated.

If you need to take a lock while allocating a new ID from the IDR, you may need to pass a restrictive set of GFP flags, which can lead to the IDR being unable to allocate memory. To work around this, you can call idr_preload() before taking the lock, and then *idr_preload_end()* after the allocation.

idr synchronization (stolen from radix-tree.h)

idr_find() is able to be called locklessly, using RCU. The caller must ensure calls to this function are made within *rcu_read_lock()* regions. Other readers (lock-free or otherwise) and modifications may be running concurrently.

It is still required that the caller manage the synchronization and lifetimes of the items. So if RCU lock-free lookups are used, typically this would mean that the items have their own locks, or are amenable to lock-free access; and that the items are freed by RCU (or only freed after having been deleted from the idr tree *and* a *synchronize_rcu()* grace period).

2.5.3 IDA usage

The IDA is an ID allocator which does not provide the ability to associate an ID with a pointer. As such, it only needs to store one bit per ID, and so is more space efficient than an IDR. To use an IDA, define it using DEFINE_IDA() (or embed a `struct ida` in a data structure, then initialise it using ida_init()). To allocate a new ID, call *ida_alloc()*, *ida_alloc_min()*, *ida_alloc_max()* or *ida_alloc_range()*. To free an ID, call *ida_free()*.

ida_destroy() can be used to dispose of an IDA without needing to free the individual IDs in it. You can use ida_is_empty() to find out whether the IDA has any IDs currently allocated.

The IDA handles its own locking. It is safe to call any of the IDA functions without synchronisation in your code.

IDs are currently limited to the range [0-INT_MAX]. If this is an awkward limitation, it should be quite straightforward to raise the maximum.

2.5.4 Functions and structures

IDR_INIT

`IDR_INIT (name)`

Initialise an IDR.

Parameters

name
Name of IDR.

Description

A freshly-initialised IDR contains no IDs.

DEFINE_IDR

`DEFINE_IDR (name)`

Define a statically-allocated IDR.

Parameters

name
: Name of IDR.

Description

An IDR defined using this macro is ready for use with no additional initialisation required. It contains no IDs.

unsigned int **idr_get_cursor**(const struct *idr* *idr)
: Return the current position of the cyclic allocator

Parameters

const struct idr *idr
: idr handle

Description

The value returned is the value that will be next returned from *idr_alloc_cyclic()* if it is free (otherwise the search will start from this position).

void **idr_set_cursor**(struct *idr* *idr, unsigned int val)
: Set the current position of the cyclic allocator

Parameters

struct idr *idr
: idr handle

unsigned int val
: new position

Description

The next call to *idr_alloc_cyclic()* will return **val** if it is free (otherwise the search will start from this position).

void **idr_init_base**(struct *idr* *idr, int base)
: Initialise an IDR.

Parameters

struct idr *idr
: IDR handle.

int base
: The base value for the IDR.

Description

This variation of *idr_init()* creates an IDR which will allocate IDs starting at `base`.

void **idr_init**(struct *idr* *idr)
: Initialise an IDR.

Parameters

struct idr *idr
IDR handle.

Description

Initialise a dynamically allocated IDR. To initialise a statically allocated IDR, use *DEFINE_IDR()*.

bool **idr_is_empty**(const struct *idr* *idr)
Are there any IDs allocated?

Parameters

const struct idr *idr
IDR handle.

Return

`true` if any IDs have been allocated from this IDR.

void **idr_preload_end**(void)
end preload section started with idr_preload()

Parameters

void
no arguments

Description

Each idr_preload() should be matched with an invocation of this function. See idr_preload() for details.

idr_for_each_entry

`idr_for_each_entry (idr, entry, id)`

Iterate over an IDR's elements of a given type.

Parameters

idr
IDR handle.

entry
The type * to use as cursor

id
Entry ID.

Description

entry and **id** do not need to be initialized before the loop, and after normal termination **entry** is left with the value NULL. This is convenient for a "not found" value.

idr_for_each_entry_ul

`idr_for_each_entry_ul (idr, entry, tmp, id)`

Iterate over an IDR's elements of a given type.

Parameters

idr
IDR handle.

entry
The type * to use as cursor.

tmp
A temporary placeholder for ID.

id
Entry ID.

Description

entry and **id** do not need to be initialized before the loop, and after normal termination **entry** is left with the value NULL. This is convenient for a "not found" value.

idr_for_each_entry_continue

`idr_for_each_entry_continue (idr, entry, id)`

Continue iteration over an IDR's elements of a given type

Parameters

idr
IDR handle.

entry
The type * to use as a cursor.

id
Entry ID.

Description

Continue to iterate over entries, continuing after the current position.

idr_for_each_entry_continue_ul

`idr_for_each_entry_continue_ul (idr, entry, tmp, id)`

Continue iteration over an IDR's elements of a given type

Parameters

idr
IDR handle.

entry
The type * to use as a cursor.

tmp
A temporary placeholder for ID.

id
Entry ID.

Description

Continue to iterate over entries, continuing after the current position. After normal termination **entry** is left with the value NULL. This is convenient for a "not found" value.

int **ida_alloc**(struct *ida* *ida, gfp_t gfp)

Allocate an unused ID.

Parameters

struct ida *ida
IDA handle.

gfp_t gfp
Memory allocation flags.

Description

Allocate an ID between 0 and `INT_MAX`, inclusive.

Context

Any context. It is safe to call this function without locking in your code.

Return

The allocated ID, or `-ENOMEM` if memory could not be allocated, or `-ENOSPC` if there are no free IDs.

int **ida_alloc_min**(struct *ida* *ida, unsigned int min, gfp_t gfp)

Allocate an unused ID.

Parameters

struct ida *ida
IDA handle.

unsigned int min
Lowest ID to allocate.

gfp_t gfp
Memory allocation flags.

Description

Allocate an ID between **min** and `INT_MAX`, inclusive.

Context

Any context. It is safe to call this function without locking in your code.

Return

The allocated ID, or `-ENOMEM` if memory could not be allocated, or `-ENOSPC` if there are no free IDs.

int **ida_alloc_max**(struct *ida* *ida, unsigned int max, gfp_t gfp)

Allocate an unused ID.

Parameters

struct ida *ida
IDA handle.

unsigned int max
Highest ID to allocate.

gfp_t gfp
Memory allocation flags.

Description

Allocate an ID between 0 and **max**, inclusive.

Context

Any context. It is safe to call this function without locking in your code.

Return

The allocated ID, or `-ENOMEM` if memory could not be allocated, or `-ENOSPC` if there are no free IDs.

int **idr_alloc_u32**(struct *idr* *idr, void *ptr, u32 *nextid, unsigned long max, gfp_t gfp)

Allocate an ID.

Parameters

struct idr *idr
IDR handle.

void *ptr
Pointer to be associated with the new ID.

u32 *nextid
Pointer to an ID.

unsigned long max
The maximum ID to allocate (inclusive).

gfp_t gfp
Memory allocation flags.

Description

Allocates an unused ID in the range specified by **nextid** and **max**. Note that **max** is inclusive whereas the **end** parameter to *idr_alloc()* is exclusive. The new ID is assigned to **nextid** before the pointer is inserted into the IDR, so if **nextid** points into the object pointed to by **ptr**, a concurrent lookup will not find an uninitialised ID.

The caller should provide their own locking to ensure that two concurrent modifications to the IDR are not possible. Read-only accesses to the IDR may be done under the RCU read lock or may exclude simultaneous writers.

Return

0 if an ID was allocated, -ENOMEM if memory allocation failed, or -ENOSPC if no free IDs could be found. If an error occurred, **nextid** is unchanged.

int **idr_alloc**(struct *idr* *idr, void *ptr, int start, int end, gfp_t gfp)

Allocate an ID.

Parameters

struct idr *idr
IDR handle.

void *ptr
Pointer to be associated with the new ID.

int start
The minimum ID (inclusive).

int end
The maximum ID (exclusive).

gfp_t gfp
Memory allocation flags.

Description

Allocates an unused ID in the range specified by **start** and **end**. If **end** is <= 0, it is treated as one larger than `INT_MAX`. This allows callers to use **start** + N as **end** as long as N is within integer range.

The caller should provide their own locking to ensure that two concurrent modifications to the IDR are not possible. Read-only accesses to the IDR may be done under the RCU read lock or may exclude simultaneous writers.

Return

The newly allocated ID, -ENOMEM if memory allocation failed, or -ENOSPC if no free IDs could be found.

int **idr_alloc_cyclic**(struct *idr* *idr, void *ptr, int start, int end, gfp_t gfp)
Allocate an ID cyclically.

Parameters

struct idr *idr
IDR handle.

void *ptr
Pointer to be associated with the new ID.

int start
The minimum ID (inclusive).

int end
The maximum ID (exclusive).

gfp_t gfp
Memory allocation flags.

Description

Allocates an unused ID in the range specified by **start** and **end**. If **end** is <= 0, it is treated as one larger than `INT_MAX`. This allows callers to use **start** + N as **end** as long as N is within integer range. The search for an unused ID will start at the last ID allocated and will wrap around to **start** if no free IDs are found before reaching **end**.

The caller should provide their own locking to ensure that two concurrent modifications to the IDR are not possible. Read-only accesses to the IDR may be done under the RCU read lock or may exclude simultaneous writers.

Return

The newly allocated ID, -ENOMEM if memory allocation failed, or -ENOSPC if no free IDs could be found.

void *`idr_remove`(struct *idr* *idr, unsigned long id)

Remove an ID from the IDR.

Parameters

`struct idr *idr`
IDR handle.

`unsigned long id`
Pointer ID.

Description

Removes this ID from the IDR. If the ID was not previously in the IDR, this function returns `NULL`.

Since this function modifies the IDR, the caller should provide their own locking to ensure that concurrent modification of the same IDR is not possible.

Return

The pointer formerly associated with this ID.

void *`idr_find`(const struct *idr* *idr, unsigned long id)

Return pointer for given ID.

Parameters

`const struct idr *idr`
IDR handle.

`unsigned long id`
Pointer ID.

Description

Looks up the pointer associated with this ID. A `NULL` pointer may indicate that **id** is not allocated or that the `NULL` pointer was associated with this ID.

This function can be called under *`rcu_read_lock()`*, given that the leaf pointers lifetimes are correctly managed.

Return

The pointer associated with this ID.

int `idr_for_each`(const struct *idr* *idr, int (*fn)(int id, void *p, void *data), void *data)

Iterate through all stored pointers.

Parameters

`const struct idr *idr`
IDR handle.

`int (*fn)(int id, void *p, void *data)`
Function to be called for each pointer.

void *data
Data passed to callback function.

Description

The callback function will be called for each entry in **idr**, passing the ID, the entry and **data**.

If **fn** returns anything other than `0`, the iteration stops and that value is returned from this function.

idr_for_each() can be called concurrently with *idr_alloc()* and *idr_remove()* if protected by RCU. Newly added entries may not be seen and deleted entries may be seen, but adding and removing entries will not cause other entries to be skipped, nor spurious ones to be seen.

void ***idr_get_next_ul**(struct *idr* *idr, unsigned long *nextid)
Find next populated entry.

Parameters

struct idr *idr
IDR handle.

unsigned long *nextid
Pointer to an ID.

Description

Returns the next populated entry in the tree with an ID greater than or equal to the value pointed to by **nextid**. On exit, **nextid** is updated to the ID of the found value. To use in a loop, the value pointed to by nextid must be incremented by the user.

void ***idr_get_next**(struct *idr* *idr, int *nextid)
Find next populated entry.

Parameters

struct idr *idr
IDR handle.

int *nextid
Pointer to an ID.

Description

Returns the next populated entry in the tree with an ID greater than or equal to the value pointed to by **nextid**. On exit, **nextid** is updated to the ID of the found value. To use in a loop, the value pointed to by nextid must be incremented by the user.

void ***idr_replace**(struct *idr* *idr, void *ptr, unsigned long id)
replace pointer for given ID.

Parameters

struct idr *idr
IDR handle.

void *ptr
New pointer to associate with the ID.

unsigned long id
ID to change.

Description

Replace the pointer registered with an ID and return the old value. This function can be called under the RCU read lock concurrently with *idr_alloc()* and *idr_remove()* (as long as the ID being removed is not the one being replaced!).

Return

the old value on success. -ENOENT indicates that **id** was not found. -EINVAL indicates that **ptr** was not valid.

int **ida_alloc_range**(struct *ida* *ida, unsigned int min, unsigned int max, gfp_t gfp)

Allocate an unused ID.

Parameters

struct ida *ida
IDA handle.

unsigned int min
Lowest ID to allocate.

unsigned int max
Highest ID to allocate.

gfp_t gfp
Memory allocation flags.

Description

Allocate an ID between **min** and **max**, inclusive. The allocated ID will not exceed INT_MAX, even if **max** is larger.

Context

Any context. It is safe to call this function without locking in your code.

Return

The allocated ID, or -ENOMEM if memory could not be allocated, or -ENOSPC if there are no free IDs.

void **ida_free**(struct *ida* *ida, unsigned int id)

Release an allocated ID.

Parameters

struct ida *ida
IDA handle.

unsigned int id
Previously allocated ID.

Context

Any context. It is safe to call this function without locking in your code.

void **ida_destroy**(struct *ida* *ida)

Free all IDs.

Parameters

struct ida *ida
IDA handle.

Description

Calling this function frees all IDs and releases all resources used by an IDA. When this call returns, the IDA is empty and can be reused or freed. If the IDA is already empty, there is no need to call this function.

Context

Any context. It is safe to call this function without locking in your code.

2.6 Circular Buffers

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Linux provides a number of features that can be used to implement circular buffering. There are two sets of such features:

(1) Convenience functions for determining information about power-of-2 sized buffers.

(2) Memory barriers for when the producer and the consumer of objects in the buffer don't want to share a lock.

To use these facilities, as discussed below, there needs to be just one producer and just one consumer. It is possible to handle multiple producers by serialising them, and to handle multiple consumers by serialising them.

2.6.1 What is a circular buffer?

First of all, what is a circular buffer? A circular buffer is a buffer of fixed, finite size into which there are two indices:

(1) A 'head' index - the point at which the producer inserts items into the buffer.

(2) A 'tail' index - the point at which the consumer finds the next item in the buffer.

Typically when the tail pointer is equal to the head pointer, the buffer is empty; and the buffer is full when the head pointer is one less than the tail pointer.

The head index is incremented when items are added, and the tail index when items are removed. The tail index should never jump the head index, and both indices should be wrapped to 0 when they reach the end of the buffer, thus allowing an infinite amount of data to flow through the buffer.

Typically, items will all be of the same unit size, but this isn't strictly required to use the techniques below. The indices can be increased by more than 1 if multiple items or variable-sized items are to be included in the buffer, provided that neither index overtakes the other. The implementer must be careful, however, as a region more than one unit in size may wrap the end of the buffer and be broken into two segments.

2.6.2 Measuring power-of-2 buffers

Calculation of the occupancy or the remaining capacity of an arbitrarily sized circular buffer would normally be a slow operation, requiring the use of a modulus (divide) instruction. However, if the buffer is of a power-of-2 size, then a much quicker bitwise-AND instruction can be used instead.

Linux provides a set of macros for handling power-of-2 circular buffers. These can be made use of by:

```
#include <linux/circ_buf.h>
```

The macros are:

(1) Measure the remaining capacity of a buffer:

```
CIRC_SPACE(head_index, tail_index, buffer_size);
```

This returns the amount of space left in the buffer[1] into which items can be inserted.

(2) Measure the maximum consecutive immediate space in a buffer:

```
CIRC_SPACE_TO_END(head_index, tail_index, buffer_size);
```

This returns the amount of consecutive space left in the buffer[1] into which items can be immediately inserted without having to wrap back to the beginning of the buffer.

(3) Measure the occupancy of a buffer:

```
CIRC_CNT(head_index, tail_index, buffer_size);
```

This returns the number of items currently occupying a buffer[2].

(4) Measure the non-wrapping occupancy of a buffer:

```
CIRC_CNT_TO_END(head_index, tail_index, buffer_size);
```

This returns the number of consecutive items[2] that can be extracted from the buffer without having to wrap back to the beginning of the buffer.

Each of these macros will nominally return a value between 0 and buffer_size-1, however:

(1) CIRC_SPACE*() are intended to be used in the producer. To the producer they will return a lower bound as the producer controls the head index, but the consumer may still be depleting the buffer on another CPU and moving the tail index.

    To the consumer it will show an upper bound as the producer may be busy depleting the space.

(2) CIRC_CNT*() are intended to be used in the consumer. To the consumer they will return a lower bound as the consumer controls the tail index, but the producer may still be filling the buffer on another CPU and moving the head index.

    To the producer it will show an upper bound as the consumer may be busy emptying the buffer.

(3) To a third party, the order in which the writes to the indices by the producer and consumer become visible cannot be guaranteed as they are independent and may be made on different CPUs - so the result in such a situation will merely be a guess, and may even be negative.

2.6.3 Using memory barriers with circular buffers

By using memory barriers in conjunction with circular buffers, you can avoid the need to:

(1) use a single lock to govern access to both ends of the buffer, thus allowing the buffer to be filled and emptied at the same time; and

(2) use atomic counter operations.

There are two sides to this: the producer that fills the buffer, and the consumer that empties it. Only one thing should be filling a buffer at any one time, and only one thing should be emptying a buffer at any one time, but the two sides can operate simultaneously.

The producer

The producer will look something like this:

```
spin_lock(&producer_lock);

unsigned long head = buffer->head;
/* The spin_unlock() and next spin_lock() provide needed ordering.␣
↪*/
unsigned long tail = READ_ONCE(buffer->tail);

if (CIRC_SPACE(head, tail, buffer->size) >= 1) {
        /* insert one item into the buffer */
        struct item *item = buffer[head];

        produce_item(item);
```

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```
        smp_store_release(buffer->head,
                          (head + 1) & (buffer->size - 1));

        /* wake_up() will make sure that the head is committed␣
↪before
         * waking anyone up */
        wake_up(consumer);
}

spin_unlock(&producer_lock);
```

This will instruct the CPU that the contents of the new item must be written before the head index makes it available to the consumer and then instructs the CPU that the revised head index must be written before the consumer is woken.

Note that wake_up() does not guarantee any sort of barrier unless something is actually awakened. We therefore cannot rely on it for ordering. However, there is always one element of the array left empty. Therefore, the producer must produce two elements before it could possibly corrupt the element currently being read by the consumer. Therefore, the unlock-lock pair between consecutive invocations of the consumer provides the necessary ordering between the read of the index indicating that the consumer has vacated a given element and the write by the producer to that same element.

The Consumer

The consumer will look something like this:

```
spin_lock(&consumer_lock);

/* Read index before reading contents at that index. */
unsigned long head = smp_load_acquire(buffer->head);
unsigned long tail = buffer->tail;

if (CIRC_CNT(head, tail, buffer->size) >= 1) {

        /* extract one item from the buffer */
        struct item *item = buffer[tail];

        consume_item(item);

        /* Finish reading descriptor before incrementing tail. */
        smp_store_release(buffer->tail,
                          (tail + 1) & (buffer->size - 1));
}

spin_unlock(&consumer_lock);
```

This will instruct the CPU to make sure the index is up to date before reading the new item, and then it shall make sure the CPU has finished reading the item before it writes the new tail pointer, which will erase the item.

Note the use of READ_ONCE() and smp_load_acquire() to read the opposition index. This prevents the compiler from discarding and reloading its cached value. This isn't strictly needed if you can be sure that the opposition index will _only_ be used the once. The smp_load_acquire() additionally forces the CPU to order against subsequent memory references. Similarly, smp_store_release() is used in both algorithms to write the thread's index. This documents the fact that we are writing to something that can be read concurrently, prevents the compiler from tearing the store, and enforces ordering against previous accesses.

2.6.4 Further reading

See also Documentation/memory-barriers.txt for a description of Linux's memory barrier facilities.

2.7 Red-black Trees (rbtree) in Linux

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2.7.1 What are red-black trees, and what are they for?

Red-black trees are a type of self-balancing binary search tree, used for storing sortable key/value data pairs. This differs from radix trees (which are used to efficiently store sparse arrays and thus use long integer indexes to insert/access/delete nodes) and hash tables (which are not kept sorted to be easily traversed in order, and must be tuned for a specific size and hash function where rbtrees scale gracefully storing arbitrary keys).

Red-black trees are similar to AVL trees, but provide faster real-time bounded worst case performance for insertion and deletion (at most two rotations and three rotations, respectively, to balance the tree), with slightly slower (but still O(log n)) lookup time.

To quote Linux Weekly News:

> There are a number of red-black trees in use in the kernel. The deadline and CFQ I/O schedulers employ rbtrees to track requests; the packet CD/DVD driver does the same. The high-resolution timer code uses an rbtree to organize outstanding timer requests. The ext3 filesystem tracks directory entries in a red-black tree. Virtual memory areas (VMAs) are tracked with red-black trees, as are epoll file descriptors, cryptographic keys, and network packets in the "hierarchical token bucket" scheduler.

This document covers use of the Linux rbtree implementation. For more information on the nature and implementation of Red Black Trees, see:

Linux Weekly News article on red-black trees
https://lwn.net/Articles/184495/

Wikipedia entry on red-black trees
https://en.wikipedia.org/wiki/Red-black_tree

2.7.2 Linux implementation of red-black trees

Linux' s rbtree implementation lives in the file "lib/rbtree.c". To use it, "#include <linux/rbtree.h>".

The Linux rbtree implementation is optimized for speed, and thus has one less layer of indirection (and better cache locality) than more traditional tree implementations. Instead of using pointers to separate rb_node and data structures, each instance of struct rb_node is embedded in the data structure it organizes. And instead of using a comparison callback function pointer, users are expected to write their own tree search and insert functions which call the provided rbtree functions. Locking is also left up to the user of the rbtree code.

2.7.3 Creating a new rbtree

Data nodes in an rbtree tree are structures containing a struct rb_node member:

```
struct mytype {
      struct rb_node node;
      char *keystring;
};
```

When dealing with a pointer to the embedded struct rb_node, the containing data structure may be accessed with the standard container_of() macro. In addition, individual members may be accessed directly via rb_entry(node, type, member).

At the root of each rbtree is an rb_root structure, which is initialized to be empty via:

> struct rb_root mytree = RB_ROOT;

2.7.4 Searching for a value in an rbtree

Writing a search function for your tree is fairly straightforward: start at the root, compare each value, and follow the left or right branch as necessary.

Example:

```
struct mytype *my_search(struct rb_root *root, char *string)
{
      struct rb_node *node = root->rb_node;

      while (node) {
              struct mytype *data = container_of(node, struct␣
↪mytype, node);
```

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```
                int result;

                result = strcmp(string, data->keystring);

                if (result < 0)
                        node = node->rb_left;
                else if (result > 0)
                        node = node->rb_right;
                else
                        return data;
        }
        return NULL;
}
```

2.7.5 Inserting data into an rbtree

Inserting data in the tree involves first searching for the place to insert the new node, then inserting the node and rebalancing (“recoloring”) the tree.

The search for insertion differs from the previous search by finding the location of the pointer on which to graft the new node. The new node also needs a link to its parent node for rebalancing purposes.

Example:

```
int my_insert(struct rb_root *root, struct mytype *data)
{
        struct rb_node **new = &(root->rb_node), *parent = NULL;

        /* Figure out where to put new node */
        while (*new) {
                struct mytype *this = container_of(*new, struct␣
↪mytype, node);
                int result = strcmp(data->keystring, this->keystring);

                parent = *new;
                if (result < 0)
                        new = &((*new)->rb_left);
                else if (result > 0)
                        new = &((*new)->rb_right);
                else
                        return FALSE;
        }

        /* Add new node and rebalance tree. */
        rb_link_node(&data->node, parent, new);
        rb_insert_color(&data->node, root);

        return TRUE;
}
```

2.7.6 Removing or replacing existing data in an rbtree

To remove an existing node from a tree, call:

```
void rb_erase(struct rb_node *victim, struct rb_root *tree);
```

Example:

```
struct mytype *data = mysearch(&mytree, "walrus");

if (data) {
      rb_erase(&data->node, &mytree);
      myfree(data);
}
```

To replace an existing node in a tree with a new one with the same key, call:

```
void rb_replace_node(struct rb_node *old, struct rb_node *new,
                      struct rb_root *tree);
```

Replacing a node this way does not re-sort the tree: If the new node doesn't have the same key as the old node, the rbtree will probably become corrupted.

2.7.7 Iterating through the elements stored in an rbtree (in sort order)

Four functions are provided for iterating through an rbtree's contents in sorted order. These work on arbitrary trees, and should not need to be modified or wrapped (except for locking purposes):

```
struct rb_node *rb_first(struct rb_root *tree);
struct rb_node *rb_last(struct rb_root *tree);
struct rb_node *rb_next(struct rb_node *node);
struct rb_node *rb_prev(struct rb_node *node);
```

To start iterating, call rb_first() or rb_last() with a pointer to the root of the tree, which will return a pointer to the node structure contained in the first or last element in the tree. To continue, fetch the next or previous node by calling rb_next() or rb_prev() on the current node. This will return NULL when there are no more nodes left.

The iterator functions return a pointer to the embedded struct rb_node, from which the containing data structure may be accessed with the container_of() macro, and individual members may be accessed directly via rb_entry(node, type, member).

Example:

```
struct rb_node *node;
for (node = rb_first(&mytree); node; node = rb_next(node))
      printk("key=%s\n", rb_entry(node, struct mytype, node)->
↪keystring);
```

2.7.8 Cached rbtrees

Computing the leftmost (smallest) node is quite a common task for binary search trees, such as for traversals or users relying on a the particular order for their own logic. To this end, users can use 'struct rb_root_cached' to optimize O(logN) rb_first() calls to a simple pointer fetch avoiding potentially expensive tree iterations. This is done at negligible runtime overhead for maintanence; albeit larger memory footprint.

Similar to the rb_root structure, cached rbtrees are initialized to be empty via:

```
struct rb_root_cached mytree = RB_ROOT_CACHED;
```

Cached rbtree is simply a regular rb_root with an extra pointer to cache the leftmost node. This allows rb_root_cached to exist wherever rb_root does, which permits augmented trees to be supported as well as only a few extra interfaces:

```
struct rb_node *rb_first_cached(struct rb_root_cached *tree);
void rb_insert_color_cached(struct rb_node *, struct rb_root_cached␣
↪*, bool);
void rb_erase_cached(struct rb_node *node, struct rb_root_cached *);
```

Both insert and erase calls have their respective counterpart of augmented trees:

```
void rb_insert_augmented_cached(struct rb_node *node, struct rb_
↪root_cached *,
                                bool, struct rb_augment_callbacks␣
↪*);
void rb_erase_augmented_cached(struct rb_node *, struct rb_root_
↪cached *,
                               struct rb_augment_callbacks *);
```

2.7.9 Support for Augmented rbtrees

Augmented rbtree is an rbtree with "some" additional data stored in each node, where the additional data for node N must be a function of the contents of all nodes in the subtree rooted at N. This data can be used to augment some new functionality to rbtree. Augmented rbtree is an optional feature built on top of basic rbtree infrastructure. An rbtree user who wants this feature will have to call the augmentation functions with the user provided augmentation callback when inserting and erasing nodes.

C files implementing augmented rbtree manipulation must include <linux/rbtree_augmented.h> instead of <linux/rbtree.h>. Note that linux/rbtree_augmented.h exposes some rbtree implementations details you are not expected to rely on; please stick to the documented APIs there and do not include <linux/rbtree_augmented.h> from header files either so as to minimize chances of your users accidentally relying on such implementation details.

On insertion, the user must update the augmented information on the path leading to the inserted node, then call rb_link_node() as usual and rb_augment_inserted() instead of the usual rb_insert_color() call. If rb_augment_inserted() rebalances the rbtree, it will callback into a user provided function to update the augmented information on the affected subtrees.

When erasing a node, the user must call rb_erase_augmented() instead of rb_erase(). rb_erase_augmented() calls back into user provided functions to updated the augmented information on affected subtrees.

In both cases, the callbacks are provided through struct rb_augment_callbacks. 3 callbacks must be defined:

- A propagation callback, which updates the augmented value for a given node and its ancestors, up to a given stop point (or NULL to update all the way to the root).
- A copy callback, which copies the augmented value for a given subtree to a newly assigned subtree root.
- A tree rotation callback, which copies the augmented value for a given subtree to a newly assigned subtree root AND recomputes the augmented information for the former subtree root.

The compiled code for rb_erase_augmented() may inline the propagation and copy callbacks, which results in a large function, so each augmented rbtree user should have a single rb_erase_augmented() call site in order to limit compiled code size.

Sample usage

Interval tree is an example of augmented rb tree. Reference - "Introduction to Algorithms" by Cormen, Leiserson, Rivest and Stein. More details about interval trees:

Classical rbtree has a single key and it cannot be directly used to store interval ranges like [lo:hi] and do a quick lookup for any overlap with a new lo:hi or to find whether there is an exact match for a new lo:hi.

However, rbtree can be augmented to store such interval ranges in a structured way making it possible to do efficient lookup and exact match.

This "extra information" stored in each node is the maximum hi (max_hi) value among all the nodes that are its descendants. This information can be maintained at each node just be looking at the node and its immediate children. And this will be used in O(log n) lookup for lowest match (lowest start address among all possible matches) with something like:

```
struct interval_tree_node *
interval_tree_first_match(struct rb_root *root,
                          unsigned long start, unsigned long last)
{
      struct interval_tree_node *node;

      if (!root->rb_node)
              return NULL;
      node = rb_entry(root->rb_node, struct interval_tree_node, rb);

      while (true) {
```

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```
                if (node->rb.rb_left) {
                        struct interval_tree_node *left =
                                rb_entry(node->rb.rb_left,
                                         struct interval_tree_node,␣
↪rb);
                        if (left->__subtree_last >= start) {
                                /*
                                 * Some nodes in left subtree satisfy␣
↪Cond2.
                                 * Iterate to find the leftmost such␣
↪node N.
                                 * If it also satisfies Cond1, that's␣
↪the match
                                 * we are looking for. Otherwise,␣
↪there is no
                                 * matching interval as nodes to the␣
↪right of N
                                 * can't satisfy Cond1 either.
                                 */
                                node = left;
                                continue;
                        }
                }
                if (node->start <= last) {              /* Cond1 */
                        if (node->last >= start)        /* Cond2 */
                                return node;    /* node is leftmost␣
↪match */
                        if (node->rb.rb_right) {
                                node = rb_entry(node->rb.rb_right,
                                        struct interval_tree_node,␣
↪rb);
                                if (node->__subtree_last >= start)
                                        continue;
                        }
                }
                return NULL;    /* No match */
        }
}
```

Insertion/removal are defined using the following augmented callbacks:

```
static inline unsigned long
compute_subtree_last(struct interval_tree_node *node)
{
        unsigned long max = node->last, subtree_last;
        if (node->rb.rb_left) {
                subtree_last = rb_entry(node->rb.rb_left,
                        struct interval_tree_node, rb)->__subtree_
↪last;
```

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```
                if (max < subtree_last)
                        max = subtree_last;
        }
        if (node->rb.rb_right) {
                subtree_last = rb_entry(node->rb.rb_right,
                        struct interval_tree_node, rb)->__subtree_
↪last;
                if (max < subtree_last)
                        max = subtree_last;
        }
        return max;
}

static void augment_propagate(struct rb_node *rb, struct rb_node␣
↪*stop)
{
        while (rb != stop) {
                struct interval_tree_node *node =
                        rb_entry(rb, struct interval_tree_node, rb);
                unsigned long subtree_last = compute_subtree_
↪last(node);
                if (node->__subtree_last == subtree_last)
                        break;
                node->__subtree_last = subtree_last;
                rb = rb_parent(&node->rb);
        }
}

static void augment_copy(struct rb_node *rb_old, struct rb_node *rb_
↪new)
{
        struct interval_tree_node *old =
                rb_entry(rb_old, struct interval_tree_node, rb);
        struct interval_tree_node *new =
                rb_entry(rb_new, struct interval_tree_node, rb);

        new->__subtree_last = old->__subtree_last;
}

static void augment_rotate(struct rb_node *rb_old, struct rb_node␣
↪*rb_new)
{
        struct interval_tree_node *old =
                rb_entry(rb_old, struct interval_tree_node, rb);
        struct interval_tree_node *new =
                rb_entry(rb_new, struct interval_tree_node, rb);

        new->__subtree_last = old->__subtree_last;
        old->__subtree_last = compute_subtree_last(old);
```

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```
}

static const struct rb_augment_callbacks augment_callbacks = {
      augment_propagate, augment_copy, augment_rotate
};

void interval_tree_insert(struct interval_tree_node *node,
                          struct rb_root *root)
{
      struct rb_node **link = &root->rb_node, *rb_parent = NULL;
      unsigned long start = node->start, last = node->last;
      struct interval_tree_node *parent;

      while (*link) {
              rb_parent = *link;
              parent = rb_entry(rb_parent, struct interval_tree_
↪node, rb);
              if (parent->__subtree_last < last)
                      parent->__subtree_last = last;
              if (start < parent->start)
                      link = &parent->rb.rb_left;
              else
                      link = &parent->rb.rb_right;
      }

      node->__subtree_last = last;
      rb_link_node(&node->rb, rb_parent, link);
      rb_insert_augmented(&node->rb, root, &augment_callbacks);
}

void interval_tree_remove(struct interval_tree_node *node,
                          struct rb_root *root)
{
      rb_erase_augmented(&node->rb, root, &augment_callbacks);
}
```

2.8 Generic radix trees/sparse arrays

Very simple and minimalistic, supporting arbitrary size entries up to PAGE_SIZE.

A genradix is defined with the type it will store, like so:

static GENRADIX(struct foo) foo_genradix;

The main operations are:

- genradix_init(radix) - initialize an empty genradix
- genradix_free(radix) - free all memory owned by the genradix and reinitialize it

- genradix_ptr(radix, idx) - gets a pointer to the entry at idx, returning NULL if that entry does not exist
- genradix_ptr_alloc(radix, idx, gfp) - gets a pointer to an entry, allocating it if necessary
- genradix_for_each(radix, iter, p) - iterate over each entry in a genradix

The radix tree allocates one page of entries at a time, so entries may exist that were never explicitly allocated - they will be initialized to all zeroes.

Internally, a genradix is just a radix tree of pages, and indexing works in terms of byte offsets. The wrappers in this header file use sizeof on the type the radix contains to calculate a byte offset from the index - see __idx_to_offset.

2.8.1 generic radix tree functions

genradix_init

`genradix_init (_radix)`

initialize a genradix

Parameters

_radix
genradix to initialize

Description

Does not fail

genradix_free

`genradix_free (_radix)`

Parameters

_radix
the genradix to free

Description

After freeing, **_radix** will be reinitialized and empty

genradix_ptr

`genradix_ptr (_radix, _idx)`

get a pointer to a genradix entry

Parameters

_radix
genradix to access

_idx
index to fetch

Description

Returns a pointer to entry at **_idx**, or NULL if that entry does not exist.

genradix_ptr_alloc

`genradix_ptr_alloc (_radix, _idx, _gfp)`

get a pointer to a genradix entry, allocating it if necessary

Parameters

_radix
genradix to access

_idx
index to fetch

_gfp
gfp mask

Description

Returns a pointer to entry at **_idx**, or NULL on allocation failure

genradix_iter_init

`genradix_iter_init (_radix, _idx)`

initialize a genradix_iter

Parameters

_radix
genradix that will be iterated over

_idx
index to start iterating from

genradix_iter_peek

`genradix_iter_peek (_iter, _radix)`

get first entry at or above iterator's current position

Parameters

_iter
a genradix_iter

_radix
genradix being iterated over

Description

If no more entries exist at or above **_iter**'s current position, returns NULL

genradix_for_each

`genradix_for_each (_radix, _iter, _p)`

iterate over entry in a genradix

Parameters

_radix
genradix to iterate over

_iter
: a genradix_iter to track current position

_p
: pointer to genradix entry type

Description

On every iteration, **_p** will point to the current entry, and **_iter.pos** will be the current entry's index.

genradix_prealloc

`genradix_prealloc (_radix, _nr, _gfp)`

preallocate entries in a generic radix tree

Parameters

_radix
: genradix to preallocate

_nr
: number of entries to preallocate

_gfp
: gfp mask

Description

Returns 0 on success, -ENOMEM on failure

2.9 Generic bitfield packing and unpacking functions

2.9.1 Problem statement

When working with hardware, one has to choose between several approaches of interfacing with it. One can memory-map a pointer to a carefully crafted struct over the hardware device's memory region, and access its fields as struct members (potentially declared as bitfields). But writing code this way would make it less portable, due to potential endianness mismatches between the CPU and the hardware device. Additionally, one has to pay close attention when translating register definitions from the hardware documentation into bit field indices for the structs. Also, some hardware (typically networking equipment) tends to group its register fields in ways that violate any reasonable word boundaries (sometimes even 64 bit ones). This creates the inconvenience of having to define "high" and "low" portions of register fields within the struct. A more robust alternative to struct field definitions would be to extract the required fields by shifting the appropriate number of bits. But this would still not protect from endianness mismatches, except if all memory accesses were performed byte-by-byte. Also the code can easily get cluttered, and the high-level idea might get lost among the many bit shifts required. Many drivers take the bit-shifting approach and then attempt to reduce the clutter with tailored macros, but more often than not these macros take shortcuts that still prevent the code from being truly portable.

2.9.2 The solution

This API deals with 2 basic operations:

- Packing a CPU-usable number into a memory buffer (with hardware constraints/quirks)
- Unpacking a memory buffer (which has hardware constraints/quirks) into a CPU-usable number.

The API offers an abstraction over said hardware constraints and quirks, over CPU endianness and therefore between possible mismatches between the two.

The basic unit of these API functions is the u64. From the CPU's perspective, bit 63 always means bit offset 7 of byte 7, albeit only logically. The question is: where do we lay this bit out in memory?

The following examples cover the memory layout of a packed u64 field. The byte offsets in the packed buffer are always implicitly 0, 1, …7. What the examples show is where the logical bytes and bits sit.

1. Normally (no quirks), we would do it like this:

```
63 62 61 60 59 58 57 56 55 54 53 52 51 50 49 48 47 46 45 44 43 42␣
↪41 40 39 38 37 36 35 34 33 32
7                       6                       5                ␣
↪      4
31 30 29 28 27 26 25 24 23 22 21 20 19 18 17 16 15 14 13 12 11 10 ␣
↪9  8  7  6  5  4  3  2  1  0
3                       2                       1                ␣
↪      0
```

That is, the MSByte (7) of the CPU-usable u64 sits at memory offset 0, and the LSByte (0) of the u64 sits at memory offset 7. This corresponds to what most folks would regard to as "big endian", where bit i corresponds to the number 2^i. This is also referred to in the code comments as "logical" notation.

2. If QUIRK_MSB_ON_THE_RIGHT is set, we do it like this:

```
56 57 58 59 60 61 62 63 48 49 50 51 52 53 54 55 40 41 42 43 44 45␣
↪46 47 32 33 34 35 36 37 38 39
7                       6                        5               ␣
↪      4
24 25 26 27 28 29 30 31 16 17 18 19 20 21 22 23  8  9 10 11 12 13␣
↪14 15  0  1  2  3  4  5  6  7
3                       2                        1               ␣
↪      0
```

That is, QUIRK_MSB_ON_THE_RIGHT does not affect byte positioning, but inverts bit offsets inside a byte.

3. If QUIRK_LITTLE_ENDIAN is set, we do it like this:

```
39 38 37 36 35 34 33 32 47 46 45 44 43 42 41 40 55 54 53 52 51 50␣
↪49 48 63 62 61 60 59 58 57 56
```

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```
4                       5                       6                       ␣
↪     7
7  6  5  4  3  2  1  0  15 14 13 12 11 10  9  8 23 22 21 20 19 18␣
↪17 16 31 30 29 28 27 26 25 24
0                       1                       2                       ␣
↪     3
```

Therefore, QUIRK_LITTLE_ENDIAN means that inside the memory region, every byte from each 4-byte word is placed at its mirrored position compared to the boundary of that word.

4. If QUIRK_MSB_ON_THE_RIGHT and QUIRK_LITTLE_ENDIAN are both set, we do it like this:

```
32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53␣
↪54 55 56 57 58 59 60 61 62 63
4                       5                       6                       ␣
↪     7
0  1  2  3  4  5  6  7  8   9 10 11 12 13 14 15 16 17 18 19 20 21␣
↪22 23 24 25 26 27 28 29 30 31
0                       1                       2                       ␣
↪     3
```

5. If just QUIRK_LSW32_IS_FIRST is set, we do it like this:

```
31 30 29 28 27 26 25 24 23 22 21 20 19 18 17 16 15 14 13 12 11 10 ␣
↪9  8  7  6  5  4  3  2  1  0
3                       2                       1                       ␣
↪      0
63 62 61 60 59 58 57 56 55 54 53 52 51 50 49 48 47 46 45 44 43 42␣
↪41 40 39 38 37 36 35 34 33 32
7                       6                       5                       ␣
↪      4
```

In this case the 8 byte memory region is interpreted as follows: first 4 bytes correspond to the least significant 4-byte word, next 4 bytes to the more significant 4-byte word.

6. If QUIRK_LSW32_IS_FIRST and QUIRK_MSB_ON_THE_RIGHT are set, we do it like this:

```
24 25 26 27 28 29 30 31 16 17 18 19 20 21 22 23  8  9 10 11 12 13␣
↪14 15  0  1  2  3  4  5  6  7
3                       2                        1                      ␣
↪      0
56 57 58 59 60 61 62 63 48 49 50 51 52 53 54 55 40 41 42 43 44 45␣
↪46 47 32 33 34 35 36 37 38 39
7                       6                        5                      ␣
↪      4
```

7. If QUIRK_LSW32_IS_FIRST and QUIRK_LITTLE_ENDIAN are set, it looks like this:

```
7  6  5  4  3  2  1  0  15 14 13 12 11 10  9  8 23 22 21 20 19 18␣
↪17 16 31 30 29 28 27 26 25 24
0                       1                       2                      ␣
↪     3
39 38 37 36 35 34 33 32 47 46 45 44 43 42 41 40 55 54 53 52 51 50␣
↪49 48 63 62 61 60 59 58 57 56
4                       5                       6                      ␣
↪     7
```

8. If QUIRK_LSW32_IS_FIRST, QUIRK_LITTLE_ENDIAN and QUIRK_MSB_ON_THE_RIGHT are set, it looks like this:

```
0  1  2  3  4  5  6  7  8   9 10 11 12 13 14 15 16 17 18 19 20 21␣
↪22 23 24 25 26 27 28 29 30 31
0                       1                       2                      ␣
↪     3
32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53␣
↪54 55 56 57 58 59 60 61 62 63
4                       5                       6                      ␣
↪     7
```

We always think of our offsets as if there were no quirk, and we translate them afterwards, before accessing the memory region.

2.9.3 Intended use

Drivers that opt to use this API first need to identify which of the above 3 quirk combinations (for a total of 8) match what the hardware documentation describes. Then they should wrap the packing() function, creating a new xxx_packing() that calls it using the proper QUIRK_* one-hot bits set.

The packing() function returns an int-encoded error code, which protects the programmer against incorrect API use. The errors are not expected to occur durring runtime, therefore it is reasonable for xxx_packing() to return void and simply swallow those errors. Optionally it can dump stack or print the error description.

2.10 How to access I/O mapped memory from within device drivers

Author
Linus

Warning: The virt_to_bus() and bus_to_virt() functions have been superseded by the functionality provided by the PCI DMA interface (see *Dynamic DMA mapping Guide*). They continue to be documented below for historical purposes, but new code must not use them. –davidm 00/12/12

```
[ This is a mail message in response to a query on IO mapping, thus␣
↪the
  strange format for a "document" ]
```

The AHA-1542 is a bus-master device, and your patch makes the driver give the controller the physical address of the buffers, which is correct on x86 (because all bus master devices see the physical memory mappings directly).

However, on many setups, there are actually **three** different ways of looking at memory addresses, and in this case we actually want the third, the so-called "bus address".

Essentially, the three ways of addressing memory are (this is "real memory", that is, normal RAM–see later about other details):

- CPU untranslated. This is the "physical" address. Physical address 0 is what the CPU sees when it drives zeroes on the memory bus.
- CPU translated address. This is the "virtual" address, and is completely internal to the CPU itself with the CPU doing the appropriate translations into "CPU untranslated".
- bus address. This is the address of memory as seen by OTHER devices, not the CPU. Now, in theory there could be many different bus addresses, with each device seeing memory in some device-specific way, but happily most hardware designers aren't actually actively trying to make things any more complex than necessary, so you can assume that all external hardware sees the memory the same way.

Now, on normal PCs the bus address is exactly the same as the physical address, and things are very simple indeed. However, they are that simple because the memory and the devices share the same address space, and that is not generally necessarily true on other PCI/ISA setups.

Now, just as an example, on the PReP (PowerPC Reference Platform), the CPU sees a memory map something like this (this is from memory):

```
0-2 GB          "real memory"
2 GB-3 GB       "system IO" (inb/out and similar accesses on x86)
3 GB-4 GB       "IO memory" (shared memory over the IO bus)
```

Now, that looks simple enough. However, when you look at the same thing from the viewpoint of the devices, you have the reverse, and the physical memory address 0 actually shows up as address 2 GB for any IO master.

So when the CPU wants any bus master to write to physical memory 0, it has to give the master address 0x80000000 as the memory address.

So, for example, depending on how the kernel is actually mapped on the PPC, you can end up with a setup like this:

```
physical address:      0
virtual address:       0xC0000000
bus address:           0x80000000
```

where all the addresses actually point to the same thing. It's just seen through different translations..

Similarly, on the Alpha, the normal translation is:

```
physical address:       0
virtual address:        0xfffffc0000000000
bus address:            0x40000000
```

(but there are also Alphas where the physical address and the bus address are the same).

Anyway, the way to look up all these translations, you do:

```
#include <asm/io.h>

phys_addr = virt_to_phys(virt_addr);
virt_addr = phys_to_virt(phys_addr);
 bus_addr = virt_to_bus(virt_addr);
virt_addr = bus_to_virt(bus_addr);
```

Now, when do you need these?

You want the **virtual** address when you are actually going to access that pointer from the kernel. So you can have something like this:

```
/*
 * this is the hardware "mailbox" we use to communicate with
 * the controller. The controller sees this directly.
 */
struct mailbox {
        __u32 status;
        __u32 bufstart;
        __u32 buflen;
        ..
} mbox;

        unsigned char * retbuffer;

        /* get the address from the controller */
        retbuffer = bus_to_virt(mbox.bufstart);
        switch (retbuffer[0]) {
                case STATUS_OK:
                        ...
```

on the other hand, you want the bus address when you have a buffer that you want to give to the controller:

```
/* ask the controller to read the sense status into "sense_buffer"␣
↪*/
mbox.bufstart = virt_to_bus(&sense_buffer);
mbox.buflen = sizeof(sense_buffer);
```

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```
mbox.status = 0;
notify_controller(&mbox);
```

And you generally **never** want to use the physical address, because you can't use that from the CPU (the CPU only uses translated virtual addresses), and you can't use it from the bus master.

So why do we care about the physical address at all? We do need the physical address in some cases, it's just not very often in normal code. The physical address is needed if you use memory mappings, for example, because the "*remap_pfn_range()*" mm function wants the physical address of the memory to be remapped as measured in units of pages, a.k.a. the pfn (the memory management layer doesn't know about devices outside the CPU, so it shouldn't need to know about "bus addresses" etc).

Note: The above is only one part of the whole equation. The above only talks about "real memory", that is, CPU memory (RAM).

There is a completely different type of memory too, and that's the "shared memory" on the PCI or ISA bus. That's generally not RAM (although in the case of a video graphics card it can be normal DRAM that is just used for a frame buffer), but can be things like a packet buffer in a network card etc.

This memory is called "PCI memory" or "shared memory" or "IO memory" or whatever, and there is only one way to access it: the readb/writeb and related functions. You should never take the address of such memory, because there is really nothing you can do with such an address: it's not conceptually in the same memory space as "real memory" at all, so you cannot just dereference a pointer. (Sadly, on x86 it **is** in the same memory space, so on x86 it actually works to just deference a pointer, but it's not portable).

For such memory, you can do things like:

- reading:

  ```
  /*
   * read first 32 bits from ISA memory at 0xC0000, aka
   * C000:0000 in DOS terms
   */
  unsigned int signature = isa_readl(0xC0000);
  ```

- remapping and writing:

  ```
  /*
   * remap framebuffer PCI memory area at 0xFC000000,
   * size 1MB, so that we can access it: We can directly
   * access only the 640k-1MB area, so anything else
   * has to be remapped.
   */
  void __iomem *baseptr = ioremap(0xFC000000, 1024*1024);
  ```

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```
/* write a 'A' to the offset 10 of the area */
writeb('A',baseptr+10);

/* unmap when we unload the driver */
iounmap(baseptr);
```

- copying and clearing:

```
/* get the 6-byte Ethernet address at ISA address E000:0040 */
memcpy_fromio(kernel_buffer, 0xE0040, 6);
/* write a packet to the driver */
memcpy_toio(0xE1000, skb->data, skb->len);
/* clear the frame buffer */
memset_io(0xA0000, 0, 0x10000);
```

OK, that just about covers the basics of accessing IO portably. Questions? Comments? You may think that all the above is overly complex, but one day you might find yourself with a 500 MHz Alpha in front of you, and then you'll be happy that your driver works ;)

Note that kernel versions 2.0.x (and earlier) mistakenly called the ioremap() function "vremap()". ioremap() is the proper name, but I didn't think straight when I wrote it originally. People who have to support both can do something like:

```
/* support old naming silliness */
#if LINUX_VERSION_CODE < 0x020100
#define ioremap vremap
#define iounmap vfree
#endif
```

at the top of their source files, and then they can use the right names even on 2.0.x systems.

And the above sounds worse than it really is. Most real drivers really don't do all that complex things (or rather: the complexity is not so much in the actual IO accesses as in error handling and timeouts etc). It's generally not hard to fix drivers, and in many cases the code actually looks better afterwards:

```
unsigned long signature = *(unsigned int *) 0xC0000;
        vs
unsigned long signature = readl(0xC0000);
```

I think the second version actually is more readable, no?

2.11 this_cpu operations

Author
Christoph Lameter, August 4th, 2014

Author
Pranith Kumar, Aug 2nd, 2014

this_cpu operations are a way of optimizing access to per cpu variables associated with the *currently* executing processor. This is done through the use of segment registers (or a dedicated register where the cpu permanently stored the beginning of the per cpu area for a specific processor).

this_cpu operations add a per cpu variable offset to the processor specific per cpu base and encode that operation in the instruction operating on the per cpu variable.

This means that there are no atomicity issues between the calculation of the offset and the operation on the data. Therefore it is not necessary to disable preemption or interrupts to ensure that the processor is not changed between the calculation of the address and the operation on the data.

Read-modify-write operations are of particular interest. Frequently processors have special lower latency instructions that can operate without the typical synchronization overhead, but still provide some sort of relaxed atomicity guarantees. The x86, for example, can execute RMW (Read Modify Write) instructions like inc/dec/cmpxchg without the lock prefix and the associated latency penalty.

Access to the variable without the lock prefix is not synchronized but synchronization is not necessary since we are dealing with per cpu data specific to the currently executing processor. Only the current processor should be accessing that variable and therefore there are no concurrency issues with other processors in the system.

Please note that accesses by remote processors to a per cpu area are exceptional situations and may impact performance and/or correctness (remote write operations) of local RMW operations via this_cpu_*.

The main use of the this_cpu operations has been to optimize counter operations.

The following this_cpu() operations with implied preemption protection are defined. These operations can be used without worrying about preemption and interrupts:

```
this_cpu_read(pcp)
this_cpu_write(pcp, val)
this_cpu_add(pcp, val)
this_cpu_and(pcp, val)
this_cpu_or(pcp, val)
this_cpu_add_return(pcp, val)
this_cpu_xchg(pcp, nval)
this_cpu_cmpxchg(pcp, oval, nval)
this_cpu_cmpxchg_double(pcp1, pcp2, oval1, oval2, nval1, nval2)
this_cpu_sub(pcp, val)
this_cpu_inc(pcp)
```

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```
this_cpu_dec(pcp)
this_cpu_sub_return(pcp, val)
this_cpu_inc_return(pcp)
this_cpu_dec_return(pcp)
```

2.11.1 Inner working of this_cpu operations

On x86 the fs: or the gs: segment registers contain the base of the per cpu area. It is then possible to simply use the segment override to relocate a per cpu relative address to the proper per cpu area for the processor. So the relocation to the per cpu base is encoded in the instruction via a segment register prefix.

For example:

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

z = this_cpu_read(x);
```

results in a single instruction:

```
mov ax, gs:[x]
```

instead of a sequence of calculation of the address and then a fetch from that address which occurs with the per cpu operations. Before this_cpu_ops such sequence also required preempt disable/enable to prevent the kernel from moving the thread to a different processor while the calculation is performed.

Consider the following this_cpu operation:

```
this_cpu_inc(x)
```

The above results in the following single instruction (no lock prefix!):

```
inc gs:[x]
```

instead of the following operations required if there is no segment register:

```
int *y;
int cpu;

cpu = get_cpu();
y = per_cpu_ptr(&x, cpu);
(*y)++;
put_cpu();
```

Note that these operations can only be used on per cpu data that is reserved for a specific processor. Without disabling preemption in the surrounding code this_cpu_inc() will only guarantee that one of the per cpu counters is correctly incremented. However, there is no guarantee that the OS will not move the process directly before or after the this_cpu instruction is executed. In general this means that the value of the individual counters for each processor are meaningless. The sum of all the per cpu counters is the only value that is of interest.

Per cpu variables are used for performance reasons. Bouncing cache lines can be avoided if multiple processors concurrently go through the same code paths. Since each processor has its own per cpu variables no concurrent cache line updates take place. The price that has to be paid for this optimization is the need to add up the per cpu counters when the value of a counter is needed.

2.11.2 Special operations

```
y = this_cpu_ptr(&x)
```

Takes the offset of a per cpu variable (&x !) and returns the address of the per cpu variable that belongs to the currently executing processor. this_cpu_ptr avoids multiple steps that the common get_cpu/put_cpu sequence requires. No processor number is available. Instead, the offset of the local per cpu area is simply added to the per cpu offset.

Note that this operation is usually used in a code segment when preemption has been disabled. The pointer is then used to access local per cpu data in a critical section. When preemption is re-enabled this pointer is usually no longer useful since it may no longer point to per cpu data of the current processor.

2.11.3 Per cpu variables and offsets

Per cpu variables have *offsets* to the beginning of the per cpu area. They do not have addresses although they look like that in the code. Offsets cannot be directly dereferenced. The offset must be added to a base pointer of a per cpu area of a processor in order to form a valid address.

Therefore the use of x or &x outside of the context of per cpu operations is invalid and will generally be treated like a NULL pointer dereference.

```
DEFINE_PER_CPU(int, x);
```

In the context of per cpu operations the above implies that x is a per cpu variable. Most this_cpu operations take a cpu variable.

```
int __percpu *p = &x;
```

&x and hence p is the *offset* of a per cpu variable. this_cpu_ptr() takes the offset of a per cpu variable which makes this look a bit strange.

2.11.4 Operations on a field of a per cpu structure

Let's say we have a percpu structure:

```
struct s {
        int n,m;
};

DEFINE_PER_CPU(struct s, p);
```

Operations on these fields are straightforward:

```
this_cpu_inc(p.m)

z = this_cpu_cmpxchg(p.m, 0, 1);
```

If we have an offset to struct s:

```
struct s __percpu *ps = &p;

this_cpu_dec(ps->m);

z = this_cpu_inc_return(ps->n);
```

The calculation of the pointer may require the use of this_cpu_ptr() if we do not make use of this_cpu ops later to manipulate fields:

```
struct s *pp;

pp = this_cpu_ptr(&p);

pp->m--;

z = pp->n++;
```

2.11.5 Variants of this_cpu ops

this_cpu ops are interrupt safe. Some architectures do not support these per cpu local operations. In that case the operation must be replaced by code that disables interrupts, then does the operations that are guaranteed to be atomic and then re-enable interrupts. Doing so is expensive. If there are other reasons why the scheduler cannot change the processor we are executing on then there is no reason to disable interrupts. For that purpose the following __this_cpu operations are provided.

These operations have no guarantee against concurrent interrupts or preemption. If a per cpu variable is not used in an interrupt context and the scheduler cannot preempt, then they are safe. If any interrupts still occur while an operation is in progress and if the interrupt too modifies the variable, then RMW actions can not be guaranteed to be safe:

```
__this_cpu_read(pcp)
__this_cpu_write(pcp, val)
__this_cpu_add(pcp, val)
__this_cpu_and(pcp, val)
__this_cpu_or(pcp, val)
__this_cpu_add_return(pcp, val)
__this_cpu_xchg(pcp, nval)
__this_cpu_cmpxchg(pcp, oval, nval)
__this_cpu_cmpxchg_double(pcp1, pcp2, oval1, oval2, nval1, nval2)
__this_cpu_sub(pcp, val)
__this_cpu_inc(pcp)
__this_cpu_dec(pcp)
__this_cpu_sub_return(pcp, val)
__this_cpu_inc_return(pcp)
__this_cpu_dec_return(pcp)
```

Will increment x and will not fall-back to code that disables interrupts on platforms that cannot accomplish atomicity through address relocation and a Read-Modify-Write operation in the same instruction.

2.11.6 &this_cpu_ptr(pp)->n vs this_cpu_ptr(&pp->n)

The first operation takes the offset and forms an address and then adds the offset of the n field. This may result in two add instructions emitted by the compiler.

The second one first adds the two offsets and then does the relocation. IMHO the second form looks cleaner and has an easier time with (). The second form also is consistent with the way this_cpu_read() and friends are used.

2.11.7 Remote access to per cpu data

Per cpu data structures are designed to be used by one cpu exclusively. If you use the variables as intended, this_cpu_ops() are guaranteed to be "atomic" as no other CPU has access to these data structures.

There are special cases where you might need to access per cpu data structures remotely. It is usually safe to do a remote read access and that is frequently done to summarize counters. Remote write access something which could be problematic because this_cpu ops do not have lock semantics. A remote write may interfere with a this_cpu RMW operation.

Remote write accesses to percpu data structures are highly discouraged unless absolutely necessary. Please consider using an IPI to wake up the remote CPU and perform the update to its per cpu area.

To access per-cpu data structure remotely, typically the per_cpu_ptr() function is used:

```
DEFINE_PER_CPU(struct data, datap);

struct data *p = per_cpu_ptr(&datap, cpu);
```

This makes it explicit that we are getting ready to access a percpu area remotely.

You can also do the following to convert the datap offset to an address:

```
struct data *p = this_cpu_ptr(&datap);
```

but, passing of pointers calculated via this_cpu_ptr to other cpus is unusual and should be avoided.

Remote access are typically only for reading the status of another cpus per cpu data. Write accesses can cause unique problems due to the relaxed synchronization requirements for this_cpu operations.

One example that illustrates some concerns with write operations is the following scenario that occurs because two per cpu variables share a cache-line but the relaxed synchronization is applied to only one process updating the cache-line.

Consider the following example:

```
struct test {
        atomic_t a;
        int b;
};

DEFINE_PER_CPU(struct test, onecacheline);
```

There is some concern about what would happen if the field 'a' is updated remotely from one processor and the local processor would use this_cpu ops to update field b. Care should be taken that such simultaneous accesses to data within the same cache line are avoided. Also costly synchronization may be necessary. IPIs are generally recommended in such scenarios instead of a remote write to the per cpu area of another processor.

Even in cases where the remote writes are rare, please bear in mind that a remote write will evict the cache line from the processor that most likely will access it. If the processor wakes up and finds a missing local cache line of a per cpu area, its performance and hence the wake up times will be affected.

2.12 ktime accessors

Device drivers can read the current time using *ktime_get()* and the many related functions declared in linux/timekeeping.h. As a rule of thumb, using an accessor with a shorter name is preferred over one with a longer name if both are equally fit for a particular use case.

2.12.1 Basic ktime_t based interfaces

The recommended simplest form returns an opaque ktime_t, with variants that return time for different clock references:

ktime_t **ktime_get**(void)

CLOCK_MONOTONIC

Useful for reliable timestamps and measuring short time intervals accurately. Starts at system boot time but stops during suspend.

ktime_t **ktime_get_boottime**(void)

CLOCK_BOOTTIME

Like *ktime_get()*, but does not stop when suspended. This can be used e.g. for key expiration times that need to be synchronized with other machines across a suspend operation.

ktime_t **ktime_get_real**(void)

CLOCK_REALTIME

Returns the time in relative to the UNIX epoch starting in 1970 using the Coordinated Universal Time (UTC), same as gettimeofday() user space. This is used for all timestamps that need to persist across a reboot, like inode times, but should be avoided for internal uses, since it can jump backwards due to a leap second update, NTP adjustment settimeofday() operation from user space.

ktime_t **ktime_get_clocktai**(void)

CLOCK_TAI

Like *ktime_get_real()*, but uses the International Atomic Time (TAI) reference instead of UTC to avoid jumping on leap second updates. This is rarely useful in the kernel.

ktime_t **ktime_get_raw**(void)

CLOCK_MONOTONIC_RAW

Like *ktime_get()*, but runs at the same rate as the hardware clocksource without (NTP) adjustments for clock drift. This is also rarely needed in the kernel.

2.12.2 nanosecond, timespec64, and second output

For all of the above, there are variants that return the time in a different format depending on what is required by the user:

u64 **ktime_get_ns**(void)

u64 **ktime_get_boottime_ns**(void)

u64 **ktime_get_real_ns**(void)

u64 **ktime_get_clocktai_ns**(void)

u64 **ktime_get_raw_ns**(void)

Same as the plain ktime_get functions, but returning a u64 number of nanoseconds in the respective time reference, which may be more convenient for some callers.

void **ktime_get_ts64**(struct timespec64*)

void **ktime_get_boottime_ts64**(struct timespec64*)

void **ktime_get_real_ts64**(struct timespec64*)

void **ktime_get_clocktai_ts64**(struct timespec64*)

void **ktime_get_raw_ts64**(struct timespec64*)

Same above, but returns the time in a 'struct timespec64', split into seconds and nanoseconds. This can avoid an extra division when printing the time, or when passing it into an external interface that expects a 'timespec' or 'timeval' structure.

time64_t **ktime_get_seconds**(void)

time64_t **ktime_get_boottime_seconds**(void)

time64_t **ktime_get_real_seconds**(void)

time64_t **ktime_get_clocktai_seconds**(void)

time64_t **ktime_get_raw_seconds**(void)

Return a coarse-grained version of the time as a scalar time64_t. This avoids accessing the clock hardware and rounds down the seconds to the full seconds of the last timer tick using the respective reference.

2.12.3 Coarse and fast_ns access

Some additional variants exist for more specialized cases:

ktime_t **ktime_get_coarse**(void)

ktime_t **ktime_get_coarse_boottime**(void)

ktime_t **ktime_get_coarse_real**(void)

ktime_t **ktime_get_coarse_clocktai**(void)

u64 **ktime_get_coarse_ns**(void)

u64 **ktime_get_coarse_boottime_ns**(void)

u64 **ktime_get_coarse_real_ns**(void)

u64 **ktime_get_coarse_clocktai_ns**(void)

void **ktime_get_coarse_ts64**(struct timespec64*)

void **ktime_get_coarse_boottime_ts64**(struct timespec64*) void **ktime_get_coarse_real_ts64**(struct timespec64*)

void **ktime_get_coarse_clocktai_ts64**(struct timespec64*)

These are quicker than the non-coarse versions, but less accurate, corresponding to CLOCK_MONOTONIC_COARSE and CLOCK_REALTIME_COARSE in user space, along with the equivalent boottime/tai/raw timebase not available in user space.

The time returned here corresponds to the last timer tick, which may be as much as 10ms in the past (for CONFIG_HZ=100), same as reading the 'jiffies' variable. These are only useful when called in a fast path and one still expects better than second accuracy, but can't easily use 'jiffies', e.g. for inode timestamps. Skipping the hardware clock access saves around 100 CPU cycles on most modern machines with a reliable cycle counter, but up to several microseconds on older hardware with an external clocksource.

u64 **ktime_get_mono_fast_ns**(void)

u64 **ktime_get_raw_fast_ns**(void)

u64 **ktime_get_boot_fast_ns**(void)

u64 **ktime_get_real_fast_ns**(void)

These variants are safe to call from any context, including from a non-maskable interrupt (NMI) during a timekeeper update, and while we are entering suspend with the clocksource powered down. This is useful in some tracing or debugging code as well as machine check reporting, but most drivers should never call them, since the time is allowed to jump under certain conditions.

2.12.4 Deprecated time interfaces

Older kernels used some other interfaces that are now being phased out but may appear in third-party drivers being ported here. In particular, all interfaces returning a 'struct timeval' or 'struct timespec' have been replaced because the tv_sec member overflows in year 2038 on 32-bit architectures. These are the recommended replacements:

void **ktime_get_ts**(struct timespec*)

Use *ktime_get()* or *ktime_get_ts64()* instead.

void **do_gettimeofday**(struct timeval*)

void **getnstimeofday**(struct timespec*)

void **getnstimeofday64**(struct timespec64*)

void **ktime_get_real_ts**(struct timespec*)

ktime_get_real_ts64() is a direct replacement, but consider using monotonic time (*ktime_get_ts64()*) and/or a ktime_t based interface (*ktime_get()*/*ktime_get_real()*).

struct timespec **current_kernel_time**(void)

struct timespec64 **current_kernel_time64**(void)

struct timespec **get_monotonic_coarse**(void) struct timespec64 **get_monotonic_coarse64**(void)

These are replaced by *ktime_get_coarse_real_ts64()* and *ktime_get_coarse_ts64()*. However, A lot of code that wants coarse-grained times can use the simple 'jiffies' instead, while some drivers may actually want the higher resolution accessors these days.

struct timespec **getrawmonotonic**(void)

struct timespec64 **getrawmonotonic64**(void)

struct timespec **timekeeping_clocktai**(void)

struct timespec64 **timekeeping_clocktai64**(void)

struct timespec **get_monotonic_boottime**(void)

struct timespec64 **get_monotonic_boottime64**(void)

These are replaced by *ktime_get_raw()*/*ktime_get_raw_ts64()*, *ktime_get_clocktai()*/*ktime_get_clocktai_ts64()* as well as *ktime_get_boottime()*/*ktime_get_boottime_ts64()*. However, if the particular choice of clock source is not important for the user, consider converting to *ktime_get()*/*ktime_get_ts64()* instead for consistency.

2.13 The errseq_t datatype

An errseq_t is a way of recording errors in one place, and allowing any number of "subscribers" to tell whether it has changed since a previous point where it was sampled.

The initial use case for this is tracking errors for file synchronization syscalls (fsync, fdatasync, msync and sync_file_range), but it may be usable in other situations.

It's implemented as an unsigned 32-bit value. The low order bits are designated to hold an error code (between 1 and MAX_ERRNO). The upper bits are used as a counter. This is done with atomics instead of locking so that these functions can be called from any context.

Note that there is a risk of collisions if new errors are being recorded frequently, since we have so few bits to use as a counter.

To mitigate this, the bit between the error value and counter is used as a flag to tell whether the value has been sampled since a new value was recorded. That allows us to avoid bumping the counter if no one has sampled it since the last time an error was recorded.

Thus we end up with a value that looks something like this:

31..13	12	11..0
counter	SF	errno

The general idea is for "watchers" to sample an errseq_t value and keep it as a running cursor. That value can later be used to tell whether any new errors have occurred since that sampling was done, and atomically record the state at the time that it was checked. This allows us to record errors in one place, and then have a number of "watchers" that can tell whether the value has changed since they last checked it.

A new errseq_t should always be zeroed out. An errseq_t value of all zeroes is the special (but common) case where there has never been an error. An all zero value thus serves as the "epoch" if one wishes to know whether there has ever been an error set since it was first initialized.

2.13.1 API usage

Let me tell you a story about a worker drone. Now, he's a good worker overall, but the company is a little…management heavy. He has to report to 77 supervisors today, and tomorrow the "big boss" is coming in from out of town and he's sure to test the poor fellow too.

They're all handing him work to do – so much he can't keep track of who handed him what, but that's not really a big problem. The supervisors just want to know when he's finished all of the work they've handed him so far and whether he made any mistakes since they last asked.

He might have made the mistake on work they didn't actually hand him, but he can't keep track of things at that level of detail, all he can remember is the most recent mistake that he made.

Here's our worker_drone representation:

```
struct worker_drone {
        errseq_t        wd_err; /* for recording errors */
};
```

Every day, the worker_drone starts out with a blank slate:

```
struct worker_drone wd;

wd.wd_err = (errseq_t)0;
```

The supervisors come in and get an initial read for the day. They don't care about anything that happened before their watch begins:

```
struct supervisor {
        errseq_t        s_wd_err; /* private "cursor" for wd_err */
        spinlock_t      s_wd_err_lock; /* protects s_wd_err */
}

struct supervisor       su;

su.s_wd_err = errseq_sample(&wd.wd_err);
spin_lock_init(&su.s_wd_err_lock);
```

Now they start handing him tasks to do. Every few minutes they ask him to finish up all of the work they've handed him so far. Then they ask him whether he made any mistakes on any of it:

```
spin_lock(&su.su_wd_err_lock);
err = errseq_check_and_advance(&wd.wd_err, &su.s_wd_err);
spin_unlock(&su.su_wd_err_lock);
```

Up to this point, that just keeps returning 0.

Now, the owners of this company are quite miserly and have given him substandard equipment with which to do his job. Occasionally it glitches and he makes a mistake. He sighs a heavy sigh, and marks it down:

```
errseq_set(&wd.wd_err, -EIO);
```

…and then gets back to work. The supervisors eventually poll again and they each get the error when they next check. Subsequent calls will return 0, until another error is recorded, at which point it's reported to each of them once.

Note that the supervisors can't tell how many mistakes he made, only whether one was made since they last checked, and the latest value recorded.

Occasionally the big boss comes in for a spot check and asks the worker to do a one-off job for him. He's not really watching the worker full-time like the supervisors, but he does need to know whether a mistake occurred while his job was processing.

He can just sample the current errseq_t in the worker, and then use that to tell whether an error has occurred later:

```
errseq_t since = errseq_sample(&wd.wd_err);
/* submit some work and wait for it to complete */
err = errseq_check(&wd.wd_err, since);
```

Since he's just going to discard "since" after that point, he doesn't need to advance it here. He also doesn't need any locking since it's not usable by anyone else.

2.13.2 Serializing errseq_t cursor updates

Note that the errseq_t API does not protect the errseq_t cursor during a check_and_advance_operation. Only the canonical error code is handled atomically. In a situation where more than one task might be using the same errseq_t cursor at the same time, it's important to serialize updates to that cursor.

If that's not done, then it's possible for the cursor to go backward in which case the same error could be reported more than once.

Because of this, it's often advantageous to first do an errseq_check to see if anything has changed, and only later do an errseq_check_and_advance after taking the lock. e.g.:

```
if (errseq_check(&wd.wd_err, READ_ONCE(su.s_wd_err)) {
        /* su.s_wd_err is protected by s_wd_err_lock */
        spin_lock(&su.s_wd_err_lock);
        err = errseq_check_and_advance(&wd.wd_err, &su.s_wd_err);
```

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```
        spin_unlock(&su.s_wd_err_lock);
}
```

That avoids the spinlock in the common case where nothing has changed since the last time it was checked.

2.13.3 Functions

errseq_t **errseq_set**(errseq_t *eseq, int err)

set a errseq_t for later reporting

Parameters

errseq_t *eseq
errseq_t field that should be set

int err
error to set (must be between -1 and -MAX_ERRNO)

Description

This function sets the error in **eseq**, and increments the sequence counter if the last sequence was sampled at some point in the past.

Any error set will always overwrite an existing error.

Return

The previous value, primarily for debugging purposes. The return value should not be used as a previously sampled value in later calls as it will not have the SEEN flag set.

errseq_t **errseq_sample**(errseq_t *eseq)

Grab current errseq_t value.

Parameters

errseq_t *eseq
Pointer to errseq_t to be sampled.

Description

This function allows callers to initialise their errseq_t variable. If the error has been "seen", new callers will not see an old error. If there is an unseen error in **eseq**, the caller of this function will see it the next time it checks for an error.

Context

Any context.

Return

The current errseq value.

int **errseq_check**(errseq_t *eseq, errseq_t since)

Has an error occurred since a particular sample point?

Parameters

errseq_t *eseq
Pointer to errseq_t value to be checked.

errseq_t since
Previously-sampled errseq_t from which to check.

Description

Grab the value that eseq points to, and see if it has changed **since** the given value was sampled. The **since** value is not advanced, so there is no need to mark the value as seen.

Return

The latest error set in the errseq_t or 0 if it hasn't changed.

int **errseq_check_and_advance**(errseq_t *eseq, errseq_t *since)
Check an errseq_t and advance to current value.

Parameters

errseq_t *eseq
Pointer to value being checked and reported.

errseq_t *since
Pointer to previously-sampled errseq_t to check against and advance.

Description

Grab the eseq value, and see whether it matches the value that **since** points to. If it does, then just return 0.

If it doesn't, then the value has changed. Set the "seen" flag, and try to swap it into place as the new eseq value. Then, set that value as the new "since" value, and return whatever the error portion is set to.

Note that no locking is provided here for concurrent updates to the "since" value. The caller must provide that if necessary. Because of this, callers may want to do a lockless errseq_check before taking the lock and calling this.

Return

Negative errno if one has been stored, or 0 if no new error has occurred.

CHAPTER

THREE

CONCURRENCY PRIMITIVES

How Linux keeps everything from happening at the same time. See /locking/index for more related documentation.

3.1 Semantics and Behavior of Atomic and Bitmask Operations

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This document is intended to serve as a guide to Linux port maintainers on how to implement atomic counter, bitops, and spinlock interfaces properly.

3.1.1 Atomic Type And Operations

The atomic_t type should be defined as a signed integer and the atomic_long_t type as a signed long integer. Also, they should be made opaque such that any kind of cast to a normal C integer type will fail. Something like the following should suffice:

```
typedef struct { int counter; } atomic_t;
typedef struct { long counter; } atomic_long_t;
```

Historically, counter has been declared volatile. This is now discouraged. See Documentation/process/volatile-considered-harmful.rst for the complete rationale.

local_t is very similar to atomic_t. If the counter is per CPU and only updated by one CPU, local_t is probably more appropriate. Please see Semantics and Behavior of Local Atomic Operations for the semantics of local_t.

The first operations to implement for atomic_t' s are the initializers and plain writes.

```
#define ATOMIC_INIT(i)          { (i) }
#define atomic_set(v, i)        ((v)->counter = (i))
```

The first macro is used in definitions, such as:

```
static atomic_t my_counter = ATOMIC_INIT(1);
```

The initializer is atomic in that the return values of the atomic operations are guaranteed to be correct reflecting the initialized value if the initializer is used before runtime. If the initializer is used at runtime, a proper implicit or explicit read memory barrier is needed before reading the value with atomic_read from another thread.

As with all of the `atomic_` interfaces, replace the leading `atomic_` with `atomic_long_` to operate on atomic_long_t.

The second interface can be used at runtime, as in:

```
struct foo { atomic_t counter; };
...

struct foo *k;

k = kmalloc(sizeof(*k), GFP_KERNEL);
if (!k)
        return -ENOMEM;
atomic_set(&k->counter, 0);
```

The setting is atomic in that the return values of the atomic operations by all threads are guaranteed to be correct reflecting either the value that has been set with this operation or set with another operation. A proper implicit or explicit memory barrier is needed before the value set with the operation is guaranteed to be readable with atomic_read from another thread.

Next, we have:

```
#define atomic_read(v)  ((v)->counter)
```

which simply reads the counter value currently visible to the calling thread. The read is atomic in that the return value is guaranteed to be one of the values initialized or modified with the interface operations if a proper implicit or explicit memory barrier is used after possible runtime initialization by any other thread and the value is modified only with the interface operations. atomic_read does not guarantee that the runtime initialization by any other thread is visible yet, so the user of the interface must take care of that with a proper implicit or explicit memory barrier.

Warning: `atomic_read()` and `atomic_set()` DO NOT IMPLY BARRIERS!

Some architectures may choose to use the volatile keyword, barriers, or inline assembly to guarantee some degree of immediacy for atomic_read() and atomic_set(). This is not uniformly guaranteed, and may change in the future, so all users of atomic_t should treat atomic_read() and atomic_set() as simple C statements that may be reordered or optimized away entirely by the compiler or processor, and explicitly invoke the appropriate compiler and/or memory barrier for each use case. Failure to do so will result in code that may suddenly break when used with different architectures or compiler optimizations,

> or even changes in unrelated code which changes how the compiler optimizes the section accessing atomic_t variables.

Properly aligned pointers, longs, ints, and chars (and unsigned equivalents) may be atomically loaded from and stored to in the same sense as described for atomic_read() and atomic_set(). The READ_ONCE() and WRITE_ONCE() macros should be used to prevent the compiler from using optimizations that might otherwise optimize accesses out of existence on the one hand, or that might create unsolicited accesses on the other.

For example consider the following code:

```
while (a > 0)
        do_something();
```

If the compiler can prove that do_something() does not store to the variable a, then the compiler is within its rights transforming this to the following:

```
if (a > 0)
        for (;;)
                do_something();
```

If you don't want the compiler to do this (and you probably don't), then you should use something like the following:

```
while (READ_ONCE(a) > 0)
        do_something();
```

Alternatively, you could place a barrier() call in the loop.

For another example, consider the following code:

```
tmp_a = a;
do_something_with(tmp_a);
do_something_else_with(tmp_a);
```

If the compiler can prove that do_something_with() does not store to the variable a, then the compiler is within its rights to manufacture an additional load as follows:

```
tmp_a = a;
do_something_with(tmp_a);
tmp_a = a;
do_something_else_with(tmp_a);
```

This could fatally confuse your code if it expected the same value to be passed to do_something_with() and do_something_else_with().

The compiler would be likely to manufacture this additional load if do_something_with() was an inline function that made very heavy use of registers: reloading from variable a could save a flush to the stack and later reload. To prevent the compiler from attacking your code in this manner, write the following:

```
tmp_a = READ_ONCE(a);
do_something_with(tmp_a);
do_something_else_with(tmp_a);
```

For a final example, consider the following code, assuming that the variable a is set at boot time before the second CPU is brought online and never changed later, so that memory barriers are not needed:

```
if (a)
        b = 9;
else
        b = 42;
```

The compiler is within its rights to manufacture an additional store by transforming the above code into the following:

```
b = 42;
if (a)
        b = 9;
```

This could come as a fatal surprise to other code running concurrently that expected b to never have the value 42 if a was zero. To prevent the compiler from doing this, write something like:

```
if (a)
        WRITE_ONCE(b, 9);
else
        WRITE_ONCE(b, 42);
```

Don't even -think- about doing this without proper use of memory barriers, locks, or atomic operations if variable a can change at runtime!

> **Warning:** `READ_ONCE()` OR `WRITE_ONCE()` DO NOT IMPLY A BARRIER!

Now, we move onto the atomic operation interfaces typically implemented with the help of assembly code.

```
void atomic_add(int i, atomic_t *v);
void atomic_sub(int i, atomic_t *v);
void atomic_inc(atomic_t *v);
void atomic_dec(atomic_t *v);
```

These four routines add and subtract integral values to/from the given atomic_t value. The first two routines pass explicit integers by which to make the adjustment, whereas the latter two use an implicit adjustment value of "1".

One very important aspect of these two routines is that they DO NOT require any explicit memory barriers. They need only perform the atomic_t counter update in an SMP safe manner.

Next, we have:

```
int atomic_inc_return(atomic_t *v);
int atomic_dec_return(atomic_t *v);
```

These routines add 1 and subtract 1, respectively, from the given atomic_t and return the new counter value after the operation is performed.

Unlike the above routines, it is required that these primitives include explicit memory barriers that are performed before and after the operation. It must be done such that all memory operations before and after the atomic operation calls are strongly ordered with respect to the atomic operation itself.

For example, it should behave as if a smp_mb() call existed both before and after the atomic operation.

If the atomic instructions used in an implementation provide explicit memory barrier semantics which satisfy the above requirements, that is fine as well.

Let's move on:

```
int atomic_add_return(int i, atomic_t *v);
int atomic_sub_return(int i, atomic_t *v);
```

These behave just like atomic_{inc,dec}_return() except that an explicit counter adjustment is given instead of the implicit "1". This means that like atomic_{inc,dec}_return(), the memory barrier semantics are required.

Next:

```
int atomic_inc_and_test(atomic_t *v);
int atomic_dec_and_test(atomic_t *v);
```

These two routines increment and decrement by 1, respectively, the given atomic counter. They return a boolean indicating whether the resulting counter value was zero or not.

Again, these primitives provide explicit memory barrier semantics around the atomic operation:

```
int atomic_sub_and_test(int i, atomic_t *v);
```

This is identical to atomic_dec_and_test() except that an explicit decrement is given instead of the implicit "1". This primitive must provide explicit memory barrier semantics around the operation:

```
int atomic_add_negative(int i, atomic_t *v);
```

The given increment is added to the given atomic counter value. A boolean is return which indicates whether the resulting counter value is negative. This primitive must provide explicit memory barrier semantics around the operation.

Then:

```
int atomic_xchg(atomic_t *v, int new);
```

This performs an atomic exchange operation on the atomic variable v, setting the given new value. It returns the old value that the atomic variable v had just before the operation.

atomic_xchg must provide explicit memory barriers around the operation.

```
int atomic_cmpxchg(atomic_t *v, int old, int new);
```

This performs an atomic compare exchange operation on the atomic value v, with the given old and new values. Like all atomic_xxx operations, atomic_cmpxchg will only satisfy its atomicity semantics as long as all other accesses of *v are performed through atomic_xxx operations.

atomic_cmpxchg must provide explicit memory barriers around the operation, although if the comparison fails then no memory ordering guarantees are required.

The semantics for atomic_cmpxchg are the same as those defined for 'cas' below.

Finally:

```
int atomic_add_unless(atomic_t *v, int a, int u);
```

If the atomic value v is not equal to u, this function adds a to v, and returns non zero. If v is equal to u then it returns zero. This is done as an atomic operation.

atomic_add_unless must provide explicit memory barriers around the operation unless it fails (returns 0).

atomic_inc_not_zero, equivalent to atomic_add_unless(v, 1, 0)

If a caller requires memory barrier semantics around an atomic_t operation which does not return a value, a set of interfaces are defined which accomplish this:

```
void smp_mb__before_atomic(void);
void smp_mb__after_atomic(void);
```

Preceding a non-value-returning read-modify-write atomic operation with smp_mb__before_atomic() and following it with smp_mb__after_atomic() provides the same full ordering that is provided by value-returning read-modify-write atomic operations.

For example, smp_mb__before_atomic() can be used like so:

```
obj->dead = 1;
smp_mb__before_atomic();
atomic_dec(&obj->ref_count);
```

It makes sure that all memory operations preceding the atomic_dec() call are strongly ordered with respect to the atomic counter operation. In the above example, it guarantees that the assignment of "1" to obj->dead will be globally visible to other cpus before the atomic counter decrement.

Without the explicit smp_mb__before_atomic() call, the implementation could legally allow the atomic counter update visible to other cpus before the "obj->dead = 1;" assignment.

A missing memory barrier in the cases where they are required by the atomic_t implementation above can have disastrous results. Here is an example, which follows a pattern occurring frequently in the Linux kernel. It is the use of atomic counters to implement reference counting, and it works such that once the counter falls to zero it can be guaranteed that no other entity can be accessing the object:

```
static void obj_list_add(struct obj *obj, struct list_head *head)
{
        obj->active = 1;
        list_add(&obj->list, head);
}

static void obj_list_del(struct obj *obj)
{
        list_del(&obj->list);
        obj->active = 0;
}

static void obj_destroy(struct obj *obj)
{
        BUG_ON(obj->active);
        kfree(obj);
}

struct obj *obj_list_peek(struct list_head *head)
{
        if (!list_empty(head)) {
                struct obj *obj;

                obj = list_entry(head->next, struct obj, list);
                atomic_inc(&obj->refcnt);
                return obj;
        }
        return NULL;
}

void obj_poke(void)
{
        struct obj *obj;

        spin_lock(&global_list_lock);
        obj = obj_list_peek(&global_list);
        spin_unlock(&global_list_lock);

        if (obj) {
                obj->ops->poke(obj);
                if (atomic_dec_and_test(&obj->refcnt))
                        obj_destroy(obj);
        }
}
```

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```
void obj_timeout(struct obj *obj)
{
        spin_lock(&global_list_lock);
        obj_list_del(obj);
        spin_unlock(&global_list_lock);

        if (atomic_dec_and_test(&obj->refcnt))
                obj_destroy(obj);
}
```

Note: This is a simplification of the ARP queue management in the generic neighbour discover code of the networking. Olaf Kirch found a bug wrt. memory barriers in kfree_skb() that exposed the atomic_t memory barrier requirements quite clearly.

Given the above scheme, it must be the case that the obj->active update done by the obj list deletion be visible to other processors before the atomic counter decrement is performed.

Otherwise, the counter could fall to zero, yet obj->active would still be set, thus triggering the assertion in obj_destroy(). The error sequence looks like this:

```
cpu 0                           cpu 1
obj_poke()                      obj_timeout()
obj = obj_list_peek();
... gains ref to obj, refcnt=2
                                obj_list_del(obj);
                                obj->active = 0 ...
                                ... visibility delayed ...
                                atomic_dec_and_test()
                                ... refcnt drops to 1 ...
atomic_dec_and_test()
... refcount drops to 0 ...
obj_destroy()
BUG() triggers since obj->active
still seen as one
                                obj->active update visibility occurs
```

With the memory barrier semantics required of the atomic_t operations which return values, the above sequence of memory visibility can never happen. Specifically, in the above case the atomic_dec_and_test() counter decrement would not become globally visible until the obj->active update does.

As a historical note, 32-bit Sparc used to only allow usage of 24-bits of its atomic_t type. This was because it used 8 bits as a spinlock for SMP safety. Sparc32 lacked a "compare and swap" type instruction. However, 32-bit Sparc has since been moved over to a "hash table of spinlocks" scheme, that allows the full 32-bit counter to be realized. Essentially, an array of spinlocks are indexed into based upon the address of the atomic_t being operated on, and that lock protects the atomic operation. Parisc uses the same scheme.

Another note is that the atomic_t operations returning values are extremely slow on an old 386.

3.1.2 Atomic Bitmask

We will now cover the atomic bitmask operations. You will find that their SMP and memory barrier semantics are similar in shape and scope to the atomic_t ops above.

Native atomic bit operations are defined to operate on objects aligned to the size of an "unsigned long" C data type, and are least of that size. The endianness of the bits within each "unsigned long" are the native endianness of the cpu.

```
void set_bit(unsigned long nr, volatile unsigned long *addr);
void clear_bit(unsigned long nr, volatile unsigned long *addr);
void change_bit(unsigned long nr, volatile unsigned long *addr);
```

These routines set, clear, and change, respectively, the bit number indicated by "nr" on the bit mask pointed to by "ADDR".

They must execute atomically, yet there are no implicit memory barrier semantics required of these interfaces.

```
int test_and_set_bit(unsigned long nr, volatile unsigned long␣
↪*addr);
int test_and_clear_bit(unsigned long nr, volatile unsigned long␣
↪*addr);
int test_and_change_bit(unsigned long nr, volatile unsigned long␣
↪*addr);
```

Like the above, except that these routines return a boolean which indicates whether the changed bit was set _BEFORE_ the atomic bit operation.

Warning: It is incredibly important that the value be a boolean, ie. "0" or "1". Do not try to be fancy and save a few instructions by declaring the above to return "long" and just returning something like "old_val & mask" because that will not work.

For one thing, this return value gets truncated to int in many code paths using these interfaces, so on 64-bit if the bit is set in the upper 32-bits then testers will never see that.

One great example of where this problem crops up are the thread_info flag operations. Routines such as test_and_set_ti_thread_flag() chop the return value into an int. There are other places where things like this occur as well.

These routines, like the atomic_t counter operations returning values, must provide explicit memory barrier semantics around their execution. All memory operations before the atomic bit operation call must be made visible globally before the atomic bit operation is made visible. Likewise, the atomic bit operation must be visible globally before any subsequent memory operation is made visible. For example:

```
obj->dead = 1;
if (test_and_set_bit(0, &obj->flags))
        /* ... */;
obj->killed = 1;
```

The implementation of *test_and_set_bit()* must guarantee that "obj->dead = 1;" is visible to cpus before the atomic memory operation done by *test_and_set_bit()* becomes visible. Likewise, the atomic memory operation done by *test_and_set_bit()* must become visible before "obj->killed = 1;" is visible.

Finally there is the basic operation:

```
int test_bit(unsigned long nr, __const__ volatile unsigned long␣
↪*addr);
```

Which returns a boolean indicating if bit "nr" is set in the bitmask pointed to by "addr".

If explicit memory barriers are required around {set,clear}_bit() (which do not return a value, and thus does not need to provide memory barrier semantics), two interfaces are provided:

```
void smp_mb__before_atomic(void);
void smp_mb__after_atomic(void);
```

They are used as follows, and are akin to their atomic_t operation brothers:

```
/* All memory operations before this call will
 * be globally visible before the clear_bit().
 */
smp_mb__before_atomic();
clear_bit( ... );

/* The clear_bit() will be visible before all
 * subsequent memory operations.
 */
 smp_mb__after_atomic();
```

There are two special bitops with lock barrier semantics (acquire/release, same as spinlocks). These operate in the same way as their non-_lock/unlock postfixed variants, except that they are to provide acquire/release semantics, respectively. This means they can be used for bit_spin_trylock and bit_spin_unlock type operations without specifying any more barriers.

```
int test_and_set_bit_lock(unsigned long nr, unsigned long *addr);
void clear_bit_unlock(unsigned long nr, unsigned long *addr);
void __clear_bit_unlock(unsigned long nr, unsigned long *addr);
```

The __clear_bit_unlock version is non-atomic, however it still implements unlock barrier semantics. This can be useful if the lock itself is protecting the other bits in the word.

Finally, there are non-atomic versions of the bitmask operations provided. They are used in contexts where some other higher-level SMP locking scheme is being used to protect the bitmask, and thus less expensive non-atomic operations may be used in the implementation. They have names similar to the above bitmask operation interfaces, except that two underscores are prefixed to the interface name.

```
void __set_bit(unsigned long nr, volatile unsigned long *addr);
void __clear_bit(unsigned long nr, volatile unsigned long *addr);
void __change_bit(unsigned long nr, volatile unsigned long *addr);
int __test_and_set_bit(unsigned long nr, volatile unsigned long␣
↪*addr);
int __test_and_clear_bit(unsigned long nr, volatile unsigned long␣
↪*addr);
int __test_and_change_bit(unsigned long nr, volatile unsigned long␣
↪*addr);
```

These non-atomic variants also do not require any special memory barrier semantics.

The routines xchg() and cmpxchg() must provide the same exact memory-barrier semantics as the atomic and bit operations returning values.

Note: If someone wants to use xchg(), cmpxchg() and their variants, linux/atomic.h should be included rather than asm/cmpxchg.h, unless the code is in arch/* and can take care of itself.

Spinlocks and rwlocks have memory barrier expectations as well. The rule to follow is simple:

1) When acquiring a lock, the implementation must make it globally visible before any subsequent memory operation.

2) When releasing a lock, the implementation must make it such that all previous memory operations are globally visible before the lock release.

Which finally brings us to _atomic_dec_and_lock(). There is an architecture-neutral version implemented in lib/dec_and_lock.c, but most platforms will wish to optimize this in assembler.

```
int _atomic_dec_and_lock(atomic_t *atomic, spinlock_t *lock);
```

Atomically decrement the given counter, and if will drop to zero atomically acquire the given spinlock and perform the decrement of the counter to zero. If it does not drop to zero, do nothing with the spinlock.

It is actually pretty simple to get the memory barrier correct. Simply satisfy the spinlock grab requirements, which is make sure the spinlock operation is globally visible before any subsequent memory operation.

We can demonstrate this operation more clearly if we define an abstract atomic operation:

```
long cas(long *mem, long old, long new);
```

"cas" stands for "compare and swap". It atomically:

1) Compares "old" with the value currently at "mem".
2) If they are equal, "new" is written to "mem".
3) Regardless, the current value at "mem" is returned.

As an example usage, here is what an atomic counter update might look like:

```
void example_atomic_inc(long *counter)
{
        long old, new, ret;

        while (1) {
                old = *counter;
                new = old + 1;

                ret = cas(counter, old, new);
                if (ret == old)
                        break;
        }
}
```

Let's use cas() in order to build a pseudo-C atomic_dec_and_lock():

```
int _atomic_dec_and_lock(atomic_t *atomic, spinlock_t *lock)
{
        long old, new, ret;
        int went_to_zero;

        went_to_zero = 0;
        while (1) {
                old = atomic_read(atomic);
                new = old - 1;
                if (new == 0) {
                        went_to_zero = 1;
                        spin_lock(lock);
                }
                ret = cas(atomic, old, new);
                if (ret == old)
                        break;
                if (went_to_zero) {
                        spin_unlock(lock);
                        went_to_zero = 0;
                }
        }

        return went_to_zero;
}
```

Now, as far as memory barriers go, as long as spin_lock() strictly orders all subsequent memory operations (including the cas()) with respect to itself, things will be fine.

Said another way, _atomic_dec_and_lock() must guarantee that a counter dropping to zero is never made visible before the spinlock being acquired.

Note: Note that this also means that for the case where the counter is not dropping to zero, there are no memory ordering requirements.

3.2 refcount_t API compared to atomic_t

3.2.1 Introduction

The goal of refcount_t API is to provide a minimal API for implementing an object's reference counters. While a generic architecture-independent implementation from lib/refcount.c uses atomic operations underneath, there are a number of differences between some of the `refcount_*()` and `atomic_*()` functions with regards to the memory ordering guarantees. This document outlines the differences and provides respective examples in order to help maintainers validate their code against the change in these memory ordering guarantees.

The terms used through this document try to follow the formal LKMM defined in tools/memory-model/Documentation/explanation.txt.

memory-barriers.txt and atomic_t.txt provide more background to the memory ordering in general and for atomic operations specifically.

3.2.2 Relevant types of memory ordering

Note: The following section only covers some of the memory ordering types that are relevant for the atomics and reference counters and used through this document. For a much broader picture please consult memory-barriers.txt document.

In the absence of any memory ordering guarantees (i.e. fully unordered) atomics & refcounters only provide atomicity and program order (po) relation (on the same CPU). It guarantees that each `atomic_*()` and `refcount_*()` operation is atomic and instructions are executed in program order on a single CPU. This is implemented using READ_ONCE()/WRITE_ONCE() and compare-and-swap primitives.

A strong (full) memory ordering guarantees that all prior loads and stores (all po-earlier instructions) on the same CPU are completed before any po-later instruction is executed on the same CPU. It also guarantees that all po-earlier stores on the same CPU and all propagated stores from other CPUs must propagate to all other CPUs before any po-later instruction is executed on the original CPU (A-cumulative property). This is implemented using smp_mb().

A RELEASE memory ordering guarantees that all prior loads and stores (all po-earlier instructions) on the same CPU are completed before the operation. It also guarantees that all po-earlier stores on the same CPU and all propagated stores from other CPUs must propagate to all other CPUs before the release operation (A-cumulative property). This is implemented using smp_store_release().

An ACQUIRE memory ordering guarantees that all post loads and stores (all po-later instructions) on the same CPU are completed after the acquire operation. It also guarantees that all po-later stores on the same CPU must propagate to all other CPUs after the acquire operation executes. This is implemented using smp_acquire__after_ctrl_dep().

A control dependency (on success) for refcounters guarantees that if a reference for an object was successfully obtained (reference counter increment or addition happened, function returned true), then further stores are ordered against this operation. Control dependency on stores are not implemented using any explicit barriers, but rely on CPU not to speculate on stores. This is only a single CPU relation and provides no guarantees for other CPUs.

3.2.3 Comparison of functions

case 1) - non- "Read/Modify/Write" (RMW) ops

Function changes:

- atomic_set() –> refcount_set()
- atomic_read() –> refcount_read()

Memory ordering guarantee changes:

- none (both fully unordered)

case 2) - increment-based ops that return no value

Function changes:

- atomic_inc() –> refcount_inc()
- atomic_add() –> refcount_add()

Memory ordering guarantee changes:

- none (both fully unordered)

case 3) - decrement-based RMW ops that return no value

Function changes:

- atomic_dec() –> refcount_dec()

Memory ordering guarantee changes:

- fully unordered –> RELEASE ordering

case 4) - increment-based RMW ops that return a value

Function changes:

- atomic_inc_not_zero() –> refcount_inc_not_zero()
- no atomic counterpart –> refcount_add_not_zero()

Memory ordering guarantees changes:

- fully ordered –> control dependency on success for stores

Note: We really assume here that necessary ordering is provided as a result of obtaining pointer to the object!

case 5) - generic dec/sub decrement-based RMW ops that return a value

Function changes:

- atomic_dec_and_test() –> refcount_dec_and_test()
- atomic_sub_and_test() –> refcount_sub_and_test()

Memory ordering guarantees changes:

- fully ordered –> RELEASE ordering + ACQUIRE ordering on success

case 6) other decrement-based RMW ops that return a value

Function changes:

- no atomic counterpart -> refcount_dec_if_one()
- `atomic_add_unless(&var, -1, 1)` -> `refcount_dec_not_one(&var)`

Memory ordering guarantees changes:

- fully ordered -> RELEASE ordering + control dependency

Note: atomic_add_unless() only provides full order on success.

---

case 7) - lock-based RMW

Function changes:

- atomic_dec_and_lock() -> refcount_dec_and_lock()
- atomic_dec_and_mutex_lock() -> refcount_dec_and_mutex_lock()

Memory ordering guarantees changes:

- fully ordered -> RELEASE ordering + control dependency + hold spin_lock() on success

3.3 IRQs

3.3.1 What is an IRQ?

An IRQ is an interrupt request from a device. Currently they can come in over a pin, or over a packet. Several devices may be connected to the same pin thus sharing an IRQ.

An IRQ number is a kernel identifier used to talk about a hardware interrupt source. Typically this is an index into the global irq_desc array, but except for what linux/interrupt.h implements the details are architecture specific.

An IRQ number is an enumeration of the possible interrupt sources on a machine. Typically what is enumerated is the number of input pins on all of the interrupt controller in the system. In the case of ISA what is enumerated are the 16 input pins on the two i8259 interrupt controllers.

Architectures can assign additional meaning to the IRQ numbers, and are encouraged to in the case where there is any manual configuration of the hardware involved. The ISA IRQs are a classic example of assigning this kind of additional meaning.

3.3.2 SMP IRQ affinity

ChangeLog:

- Started by Ingo Molnar <mingo@redhat.com>
- Update by Max Krasnyansky <maxk@qualcomm.com>

/proc/irq/IRQ#/smp_affinity and /proc/irq/IRQ#/smp_affinity_list specify which target CPUs are permitted for a given IRQ source. It's a bitmask (smp_affinity) or cpu list (smp_affinity_list) of allowed CPUs. It's not allowed to turn off all CPUs, and if an IRQ controller does not support IRQ affinity then the value will not change from the default of all cpus.

/proc/irq/default_smp_affinity specifies default affinity mask that applies to all non-active IRQs. Once IRQ is allocated/activated its affinity bitmask will be set to the default mask. It can then be changed as described above. Default mask is 0xffffffff.

Here is an example of restricting IRQ44 (eth1) to CPU0-3 then restricting it to CPU4-7 (this is an 8-CPU SMP box):

```
[root@moon 44]# cd /proc/irq/44
[root@moon 44]# cat smp_affinity
ffffffff

[root@moon 44]# echo 0f > smp_affinity
[root@moon 44]# cat smp_affinity
0000000f
[root@moon 44]# ping -f h
PING hell (195.4.7.3): 56 data bytes
...
--- hell ping statistics ---
6029 packets transmitted, 6027 packets received, 0% packet loss
round-trip min/avg/max = 0.1/0.1/0.4 ms
[root@moon 44]# cat /proc/interrupts | grep 'CPU\|44:'
        CPU0       CPU1       CPU2       CPU3      CPU4       CPU5 ␣
↪       CPU6       CPU7
44:       1068       1785       1785       1783         0          ␣
↪0          0          0    IO-APIC-level  eth1
```

As can be seen from the line above IRQ44 was delivered only to the first four processors (0-3). Now lets restrict that IRQ to CPU(4-7).

```
[root@moon 44]# echo f0 > smp_affinity
[root@moon 44]# cat smp_affinity
000000f0
[root@moon 44]# ping -f h
PING hell (195.4.7.3): 56 data bytes
..
--- hell ping statistics ---
2779 packets transmitted, 2777 packets received, 0% packet loss
round-trip min/avg/max = 0.1/0.5/585.4 ms
[root@moon 44]# cat /proc/interrupts |  'CPU\|44:'
```

(continues on next page)

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```
        CPU0       CPU1       CPU2       CPU3      CPU4       CPU5 ␣
↪       CPU6       CPU7
44:       1068       1785       1785       1783       1784         ␣
↪1069       1070       1069   IO-APIC-level  eth1
```

This time around IRQ44 was delivered only to the last four processors. i.e counters for the CPU0-3 did not change.

Here is an example of limiting that same irq (44) to cpus 1024 to 1031:

```
[root@moon 44]# echo 1024-1031 > smp_affinity_list
[root@moon 44]# cat smp_affinity_list
1024-1031
```

Note that to do this with a bitmask would require 32 bitmasks of zero to follow the pertinent one.

3.3.3 The irq_domain interrupt number mapping library

The current design of the Linux kernel uses a single large number space where each separate IRQ source is assigned a different number. This is simple when there is only one interrupt controller, but in systems with multiple interrupt controllers the kernel must ensure that each one gets assigned non-overlapping allocations of Linux IRQ numbers.

The number of interrupt controllers registered as unique irqchips show a rising tendency: for example subdrivers of different kinds such as GPIO controllers avoid reimplementing identical callback mechanisms as the IRQ core system by modelling their interrupt handlers as irqchips, i.e. in effect cascading interrupt controllers.

Here the interrupt number loose all kind of correspondence to hardware interrupt numbers: whereas in the past, IRQ numbers could be chosen so they matched the hardware IRQ line into the root interrupt controller (i.e. the component actually fireing the interrupt line to the CPU) nowadays this number is just a number.

For this reason we need a mechanism to separate controller-local interrupt numbers, called hardware irq's, from Linux IRQ numbers.

The irq_alloc_desc*() and irq_free_desc*() APIs provide allocation of irq numbers, but they don't provide any support for reverse mapping of the controller-local IRQ (hwirq) number into the Linux IRQ number space.

The irq_domain library adds mapping between hwirq and IRQ numbers on top of the irq_alloc_desc*() API. An irq_domain to manage mapping is preferred over interrupt controller drivers open coding their own reverse mapping scheme.

irq_domain also implements translation from an abstract irq_fwspec structure to hwirq numbers (Device Tree and ACPI GSI so far), and can be easily extended to support other IRQ topology data sources.

irq_domain usage

An interrupt controller driver creates and registers an irq_domain by calling one of the irq_domain_add_*() functions (each mapping method has a different allocator function, more on that later). The function will return a pointer to the irq_domain on success. The caller must provide the allocator function with an irq_domain_ops structure.

In most cases, the irq_domain will begin empty without any mappings between hwirq and IRQ numbers. Mappings are added to the irq_domain by calling irq_create_mapping() which accepts the irq_domain and a hwirq number as arguments. If a mapping for the hwirq doesn't already exist then it will allocate a new Linux irq_desc, associate it with the hwirq, and call the .map() callback so the driver can perform any required hardware setup.

When an interrupt is received, irq_find_mapping() function should be used to find the Linux IRQ number from the hwirq number.

The irq_create_mapping() function must be called *atleast once* before any call to irq_find_mapping(), lest the descriptor will not be allocated.

If the driver has the Linux IRQ number or the irq_data pointer, and needs to know the associated hwirq number (such as in the irq_chip callbacks) then it can be directly obtained from irq_data->hwirq.

Types of irq_domain mappings

There are several mechanisms available for reverse mapping from hwirq to Linux irq, and each mechanism uses a different allocation function. Which reverse map type should be used depends on the use case. Each of the reverse map types are described below:

Linear

```
irq_domain_add_linear()
irq_domain_create_linear()
```

The linear reverse map maintains a fixed size table indexed by the hwirq number. When a hwirq is mapped, an irq_desc is allocated for the hwirq, and the IRQ number is stored in the table.

The Linear map is a good choice when the maximum number of hwirqs is fixed and a relatively small number (~ < 256). The advantages of this map are fixed time lookup for IRQ numbers, and irq_descs are only allocated for in-use IRQs. The disadvantage is that the table must be as large as the largest possible hwirq number.

irq_domain_add_linear() and irq_domain_create_linear() are functionally equivalent, except for the first argument is different - the former accepts an Open Firmware specific 'struct device_node', while the latter accepts a more general abstraction 'struct fwnode_handle'.

The majority of drivers should use the linear map.

Tree

```
irq_domain_add_tree()
irq_domain_create_tree()
```

The irq_domain maintains a radix tree map from hwirq numbers to Linux IRQs. When an hwirq is mapped, an irq_desc is allocated and the hwirq is used as the lookup key for the radix tree.

The tree map is a good choice if the hwirq number can be very large since it doesn't need to allocate a table as large as the largest hwirq number. The disadvantage is that hwirq to IRQ number lookup is dependent on how many entries are in the table.

irq_domain_add_tree() and irq_domain_create_tree() are functionally equivalent, except for the first argument is different - the former accepts an Open Firmware specific 'struct device_node', while the latter accepts a more general abstraction 'struct fwnode_handle'.

Very few drivers should need this mapping.

No Map

```
irq_domain_add_nomap()
```

The No Map mapping is to be used when the hwirq number is programmable in the hardware. In this case it is best to program the Linux IRQ number into the hardware itself so that no mapping is required. Calling irq_create_direct_mapping() will allocate a Linux IRQ number and call the .map() callback so that driver can program the Linux IRQ number into the hardware.

Most drivers cannot use this mapping.

Legacy

```
irq_domain_add_simple()
irq_domain_add_legacy()
irq_domain_add_legacy_isa()
```

The Legacy mapping is a special case for drivers that already have a range of irq_descs allocated for the hwirqs. It is used when the driver cannot be immediately converted to use the linear mapping. For example, many embedded system board support files use a set of #defines for IRQ numbers that are passed to struct device registrations. In that case the Linux IRQ numbers cannot be dynamically assigned and the legacy mapping should be used.

The legacy map assumes a contiguous range of IRQ numbers has already been allocated for the controller and that the IRQ number can be calculated by adding a fixed offset to the hwirq number, and visa-versa. The disadvantage is that it requires the interrupt controller to manage IRQ allocations and it requires an irq_desc to be allocated for every hwirq, even if it is unused.

The legacy map should only be used if fixed IRQ mappings must be supported. For example, ISA controllers would use the legacy map for mapping Linux IRQs 0-15 so that existing ISA drivers get the correct IRQ numbers.

Most users of legacy mappings should use irq_domain_add_simple() which will use a legacy domain only if an IRQ range is supplied by the system and will otherwise use a linear domain mapping. The semantics of this call are such that if an IRQ range is specified then descriptors will be allocated on-the-fly for it, and if no range is specified it will fall through to irq_domain_add_linear() which means *no* irq descriptors will be allocated.

A typical use case for simple domains is where an irqchip provider is supporting both dynamic and static IRQ assignments.

In order to avoid ending up in a situation where a linear domain is used and no descriptor gets allocated it is very important to make sure that the driver using the simple domain call irq_create_mapping() before any irq_find_mapping() since the latter will actually work for the static IRQ assignment case.

Hierarchy IRQ domain

On some architectures, there may be multiple interrupt controllers involved in delivering an interrupt from the device to the target CPU. Let's look at a typical interrupt delivering path on x86 platforms:

```
Device --> IOAPIC -> Interrupt remapping Controller -> Local APIC ->
↪ CPU
```

There are three interrupt controllers involved:

1) IOAPIC controller
2) Interrupt remapping controller
3) Local APIC controller

To support such a hardware topology and make software architecture match hardware architecture, an irq_domain data structure is built for each interrupt controller and those irq_domains are organized into hierarchy. When building irq_domain hierarchy, the irq_domain near to the device is child and the irq_domain near to CPU is parent. So a hierarchy structure as below will be built for the example above:

```
CPU Vector irq_domain (root irq_domain to manage CPU vectors)
        ^
        |
Interrupt Remapping irq_domain (manage irq_remapping entries)
        ^
        |
IOAPIC irq_domain (manage IOAPIC delivery entries/pins)
```

There are four major interfaces to use hierarchy irq_domain:

1) irq_domain_alloc_irqs(): allocate IRQ descriptors and interrupt controller related resources to deliver these interrupts.

2) irq_domain_free_irqs(): free IRQ descriptors and interrupt controller related resources associated with these interrupts.
3) irq_domain_activate_irq(): activate interrupt controller hardware to deliver the interrupt.
4) irq_domain_deactivate_irq(): deactivate interrupt controller hardware to stop delivering the interrupt.

Following changes are needed to support hierarchy irq_domain:

1) a new field 'parent' is added to struct irq_domain; it's used to maintain irq_domain hierarchy information.
2) a new field 'parent_data' is added to *struct irq_data*; it's used to build hierarchy irq_data to match hierarchy irq_domains. The irq_data is used to store irq_domain pointer and hardware irq number.
3) new callbacks are added to struct irq_domain_ops to support hierarchy irq_domain operations.

With support of hierarchy irq_domain and hierarchy irq_data ready, an irq_domain structure is built for each interrupt controller, and an irq_data structure is allocated for each irq_domain associated with an IRQ. Now we could go one step further to support stacked(hierarchy) irq_chip. That is, an irq_chip is associated with each irq_data along the hierarchy. A child irq_chip may implement a required action by itself or by cooperating with its parent irq_chip.

With stacked irq_chip, interrupt controller driver only needs to deal with the hardware managed by itself and may ask for services from its parent irq_chip when needed. So we could achieve a much cleaner software architecture.

For an interrupt controller driver to support hierarchy irq_domain, it needs to:

1) Implement irq_domain_ops.alloc and irq_domain_ops.free
2) Optionally implement irq_domain_ops.activate and irq_domain_ops.deactivate.
3) Optionally implement an irq_chip to manage the interrupt controller hardware.
4) No need to implement irq_domain_ops.map and irq_domain_ops.unmap, they are unused with hierarchy irq_domain.

Hierarchy irq_domain is in no way x86 specific, and is heavily used to support other architectures, such as ARM, ARM64 etc.

Debugging

Most of the internals of the IRQ subsystem are exposed in debugfs by turning CONFIG_GENERIC_IRQ_DEBUGFS on.

3.3.4 IRQ-flags state tracing

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The "irq-flags tracing" feature "traces" hardirq and softirq state, in that it gives interested subsystems an opportunity to be notified of every hardirqs-off/hardirqs-on, softirqs-off/softirqs-on event that happens in the kernel.

CONFIG_TRACE_IRQFLAGS_SUPPORT is needed for CONFIG_PROVE_SPIN_LOCKING and CONFIG_PROVE_RW_LOCKING to be offered by the generic lock debugging code. Otherwise only CONFIG_PROVE_MUTEX_LOCKING and CONFIG_PROVE_RWSEM_LOCKING will be offered on an architecture - these are locking APIs that are not used in IRQ context. (the one exception for rwsems is worked around)

Architecture support for this is certainly not in the "trivial" category, because lots of lowlevel assembly code deal with irq-flags state changes. But an architecture can be irq-flags-tracing enabled in a rather straightforward and risk-free manner.

Architectures that want to support this need to do a couple of code-organizational changes first:

- add and enable TRACE_IRQFLAGS_SUPPORT in their arch level Kconfig file

and then a couple of functional changes are needed as well to implement irq-flags-tracing support:

- in lowlevel entry code add (build-conditional) calls to the trace_hardirqs_off()/trace_hardirqs_on() functions. The lock validator closely guards whether the 'real' irq-flags matches the 'virtual' irq-flags state, and complains loudly (and turns itself off) if the two do not match. Usually most of the time for arch support for irq-flags-tracing is spent in this state: look at the lockdep complaint, try to figure out the assembly code we did not cover yet, fix and repeat. Once the system has booted up and works without a lockdep complaint in the irq-flags-tracing functions arch support is complete.
- if the architecture has non-maskable interrupts then those need to be excluded from the irq-tracing [and lock validation] mechanism via lockdep_off()/lockdep_on().

In general there is no risk from having an incomplete irq-flags-tracing implementation in an architecture: lockdep will detect that and will turn itself off. I.e. the lock validator will still be reliable. There should be no crashes due to irq-tracing bugs. (except if the assembly changes break other code by modifying conditions or registers that shouldn't be)

3.4 Semantics and Behavior of Local Atomic Operations

Author
Mathieu Desnoyers

This document explains the purpose of the local atomic operations, how to implement them for any given architecture and shows how they can be used properly. It also stresses on the precautions that must be taken when reading those local variables across CPUs when the order of memory writes matters.

Note: Note that `local_t` based operations are not recommended for general kernel use. Please use the `this_cpu` operations instead unless there is really a special purpose. Most uses of `local_t` in the kernel have been replaced by `this_cpu` operations. `this_cpu` operations combine the relocation with the `local_t` like semantics in a single instruction and yield more compact and faster executing code.

3.4.1 Purpose of local atomic operations

Local atomic operations are meant to provide fast and highly reentrant per CPU counters. They minimize the performance cost of standard atomic operations by removing the LOCK prefix and memory barriers normally required to synchronize across CPUs.

Having fast per CPU atomic counters is interesting in many cases: it does not require disabling interrupts to protect from interrupt handlers and it permits coherent counters in NMI handlers. It is especially useful for tracing purposes and for various performance monitoring counters.

Local atomic operations only guarantee variable modification atomicity wrt the CPU which owns the data. Therefore, care must taken to make sure that only one CPU writes to the `local_t` data. This is done by using per cpu data and making sure that we modify it from within a preemption safe context. It is however permitted to read `local_t` data from any CPU: it will then appear to be written out of order wrt other memory writes by the owner CPU.

3.4.2 Implementation for a given architecture

It can be done by slightly modifying the standard atomic operations: only their UP variant must be kept. It typically means removing LOCK prefix (on i386 and x86_64) and any SMP synchronization barrier. If the architecture does not have a different behavior between SMP and UP, including `asm-generic/local.h` in your architecture's `local.h` is sufficient.

The `local_t` type is defined as an opaque `signed long` by embedding an `atomic_long_t` inside a structure. This is made so a cast from this type to a `long` fails. The definition looks like:

```
typedef struct { atomic_long_t a; } local_t;
```

3.4.3 Rules to follow when using local atomic operations

- Variables touched by local ops must be per cpu variables.
- *Only* the CPU owner of these variables must write to them.
- This CPU can use local ops from any context (process, irq, softirq, nmi, …) to update its `local_t` variables.
- Preemption (or interrupts) must be disabled when using local ops in process context to make sure the process won't be migrated to a different CPU between getting the per-cpu variable and doing the actual local op.
- When using local ops in interrupt context, no special care must be taken on a mainline kernel, since they will run on the local CPU with preemption already disabled. I suggest, however, to explicitly disable preemption anyway to make sure it will still work correctly on -rt kernels.
- Reading the local cpu variable will provide the current copy of the variable.
- Reads of these variables can be done from any CPU, because updates to "`long`", aligned, variables are always atomic. Since no memory synchronization is done by the writer CPU, an outdated copy of the variable can be read when reading some *other* cpu's variables.

3.4.4 How to use local atomic operations

```
#include <linux/percpu.h>
#include <asm/local.h>

static DEFINE_PER_CPU(local_t, counters) = LOCAL_INIT(0);
```

3.4.5 Counting

Counting is done on all the bits of a signed long.

In preemptible context, use `get_cpu_var()` and `put_cpu_var()` around local atomic operations: it makes sure that preemption is disabled around write access to the per cpu variable. For instance:

```
local_inc(&get_cpu_var(counters));
put_cpu_var(counters);
```

If you are already in a preemption-safe context, you can use `this_cpu_ptr()` instead:

```
local_inc(this_cpu_ptr(&counters));
```

3.4.6 Reading the counters

Those local counters can be read from foreign CPUs to sum the count. Note that the data seen by local_read across CPUs must be considered to be out of order relatively to other memory writes happening on the CPU that owns the data:

```
long sum = 0;
for_each_online_cpu(cpu)
        sum += local_read(&per_cpu(counters, cpu));
```

If you want to use a remote local_read to synchronize access to a resource between CPUs, explicit `smp_wmb()` and `smp_rmb()` memory barriers must be used respectively on the writer and the reader CPUs. It would be the case if you use the `local_t` variable as a counter of bytes written in a buffer: there should be a `smp_wmb()` between the buffer write and the counter increment and also a `smp_rmb()` between the counter read and the buffer read.

Here is a sample module which implements a basic per cpu counter using `local.h`:

```
/* test-local.c
 *
 * Sample module for local.h usage.
 */


#include <asm/local.h>
#include <linux/module.h>
#include <linux/timer.h>

static DEFINE_PER_CPU(local_t, counters) = LOCAL_INIT(0);

static struct timer_list test_timer;

/* IPI called on each CPU. */
static void test_each(void *info)
{
        /* Increment the counter from a non preemptible context */
        printk("Increment on cpu %d\n", smp_processor_id());
        local_inc(this_cpu_ptr(&counters));

        /* This is what incrementing the variable would look like␣
↪within a
         * preemptible context (it disables preemption) :
         *
         * local_inc(&get_cpu_var(counters));
         * put_cpu_var(counters);
         */
}

static void do_test_timer(unsigned long data)
{
```

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```
        int cpu;

        /* Increment the counters */
        on_each_cpu(test_each, NULL, 1);
        /* Read all the counters */
        printk("Counters read from CPU %d\n", smp_processor_id());
        for_each_online_cpu(cpu) {
                printk("Read : CPU %d, count %ld\n", cpu,
                        local_read(&per_cpu(counters, cpu)));
        }
        mod_timer(&test_timer, jiffies + 1000);
}

static int __init test_init(void)
{
        /* initialize the timer that will increment the counter */
        timer_setup(&test_timer, do_test_timer, 0);
        mod_timer(&test_timer, jiffies + 1);

        return 0;
}

static void __exit test_exit(void)
{
        del_timer_sync(&test_timer);
}

module_init(test_init);
module_exit(test_exit);

MODULE_LICENSE("GPL");
MODULE_AUTHOR("Mathieu Desnoyers");
MODULE_DESCRIPTION("Local Atomic Ops");
```

3.5 The padata parallel execution mechanism

Date
May 2020

Padata is a mechanism by which the kernel can farm jobs out to be done in parallel on multiple CPUs while optionally retaining their ordering.

It was originally developed for IPsec, which needs to perform encryption and decryption on large numbers of packets without reordering those packets. This is currently the sole consumer of padata's serialized job support.

Padata also supports multithreaded jobs, splitting up the job evenly while load balancing and coordinating between threads.

3.5.1 Running Serialized Jobs

Initializing

The first step in using padata to run serialized jobs is to set up a padata_instance structure for overall control of how jobs are to be run:

```
#include <linux/padata.h>

struct padata_instance *padata_alloc(const char *name);
```

'name' simply identifies the instance.

Then, complete padata initialization by allocating a padata_shell:

```
struct padata_shell *padata_alloc_shell(struct padata_instance␣
↪*pinst);
```

A padata_shell is used to submit a job to padata and allows a series of such jobs to be serialized independently. A padata_instance may have one or more padata_shells associated with it, each allowing a separate series of jobs.

Modifying cpumasks

The CPUs used to run jobs can be changed in two ways, programatically with *padata_set_cpumask()* or via sysfs. The former is defined:

```
int padata_set_cpumask(struct padata_instance *pinst, int cpumask_
↪type,
                       cpumask_var_t cpumask);
```

Here cpumask_type is one of PADATA_CPU_PARALLEL or PADATA_CPU_SERIAL, where a parallel cpumask describes which processors will be used to execute jobs submitted to this instance in parallel and a serial cpumask defines which processors are allowed to be used as the serialization callback processor. cpumask specifies the new cpumask to use.

There may be sysfs files for an instance's cpumasks. For example, pcrypt's live in /sys/kernel/pcrypt/<instance-name>. Within an instance's directory there are two files, parallel_cpumask and serial_cpumask, and either cpumask may be changed by echoing a bitmask into the file, for example:

```
echo f > /sys/kernel/pcrypt/pencrypt/parallel_cpumask
```

Reading one of these files shows the user-supplied cpumask, which may be different from the 'usable' cpumask.

Padata maintains two pairs of cpumasks internally, the user-supplied cpumasks and the 'usable' cpumasks. (Each pair consists of a parallel and a serial cpumask.) The user-supplied cpumasks default to all possible CPUs on instance allocation and may be changed as above. The usable cpumasks are always a subset of the user-supplied cpumasks and contain only the online CPUs in the user-supplied masks; these are the cpumasks padata actually uses. So it is legal to supply a cpumask to padata that contains offline CPUs. Once an offline CPU in the user-supplied cpumask comes online, padata is going to use it.

Changing the CPU masks are expensive operations, so it should not be done with great frequency.

Running A Job

Actually submitting work to the padata instance requires the creation of a padata_priv structure, which represents one job:

```
struct padata_priv {
    /* Other stuff here... */
    void                    (*parallel)(struct padata_priv *padata);
    void                    (*serial)(struct padata_priv *padata);
};
```

This structure will almost certainly be embedded within some larger structure specific to the work to be done. Most of its fields are private to padata, but the structure should be zeroed at initialisation time, and the parallel() and serial() functions should be provided. Those functions will be called in the process of getting the work done as we will see momentarily.

The submission of the job is done with:

```
int padata_do_parallel(struct padata_shell *ps,
                       struct padata_priv *padata, int *cb_cpu);
```

The ps and padata structures must be set up as described above; cb_cpu points to the preferred CPU to be used for the final callback when the job is done; it must be in the current instance's CPU mask (if not the cb_cpu pointer is updated to point to the CPU actually chosen). The return value from *padata_do_parallel()* is zero on success, indicating that the job is in progress. -EBUSY means that somebody, somewhere else is messing with the instance's CPU mask, while -EINVAL is a complaint about cb_cpu not being in the serial cpumask, no online CPUs in the parallel or serial cpumasks, or a stopped instance.

Each job submitted to *padata_do_parallel()* will, in turn, be passed to exactly one call to the above-mentioned parallel() function, on one CPU, so true parallelism is achieved by submitting multiple jobs. parallel() runs with software interrupts disabled and thus cannot sleep. The parallel() function gets the padata_priv structure pointer as its lone parameter; information about the actual work to be done is probably obtained by using container_of() to find the enclosing structure.

Note that parallel() has no return value; the padata subsystem assumes that parallel() will take responsibility for the job from this point. The job need not be completed during this call, but, if parallel() leaves work outstanding, it should be prepared to be called again with a new job before the previous one completes.

Serializing Jobs

When a job does complete, parallel() (or whatever function actually finishes the work) should inform padata of the fact with a call to:

```
void padata_do_serial(struct padata_priv *padata);
```

At some point in the future, *padata_do_serial()* will trigger a call to the serial() function in the padata_priv structure. That call will happen on the CPU requested in the initial call to *padata_do_parallel()*; it, too, is run with local software interrupts disabled. Note that this call may be deferred for a while since the padata code takes pains to ensure that jobs are completed in the order in which they were submitted.

Destroying

Cleaning up a padata instance predictably involves calling the two free functions that correspond to the allocation in reverse:

```
void padata_free_shell(struct padata_shell *ps);
void padata_free(struct padata_instance *pinst);
```

It is the user's responsibility to ensure all outstanding jobs are complete before any of the above are called.

3.5.2 Running Multithreaded Jobs

A multithreaded job has a main thread and zero or more helper threads, with the main thread participating in the job and then waiting until all helpers have finished. padata splits the job into units called chunks, where a chunk is a piece of the job that one thread completes in one call to the thread function.

A user has to do three things to run a multithreaded job. First, describe the job by defining a padata_mt_job structure, which is explained in the Interface section. This includes a pointer to the thread function, which padata will call each time it assigns a job chunk to a thread. Then, define the thread function, which accepts three arguments, `start`, `end`, and `arg`, where the first two delimit the range that the thread operates on and the last is a pointer to the job's shared state, if any. Prepare the shared state, which is typically allocated on the main thread's stack. Last, call *padata_do_multithreaded()*, which will return once the job is finished.

3.5.3 Interface

struct **padata_priv**

Represents one job

Definition

```
struct padata_priv {
  struct list_head        list;
  struct parallel_data    *pd;
  int cb_cpu;
  unsigned int            seq_nr;
  int info;
  void (*parallel)(struct padata_priv *padata);
  void (*serial)(struct padata_priv *padata);
};
```

Members

list
List entry, to attach to the padata lists.

pd
Pointer to the internal control structure.

cb_cpu
Callback cpu for serializatioon.

seq_nr
Sequence number of the parallelized data object.

info
Used to pass information from the parallel to the serial function.

parallel
Parallel execution function.

serial
Serial complete function.

struct **padata_list**
one per work type per CPU

Definition

```
struct padata_list {
  struct list_head        list;
  spinlock_t lock;
};
```

Members

list
List head.

lock
List lock.

struct **padata_serial_queue**
The percpu padata serial queue

Definition

```
struct padata_serial_queue {
  struct padata_list    serial;
  struct work_struct    work;
  struct parallel_data *pd;
};
```

Members

serial
List to wait for serialization after reordering.

work
work struct for serialization.

pd
Backpointer to the internal control structure.

struct **padata_cpumask**

The cpumasks for the parallel/serial workers

Definition

```
struct padata_cpumask {
  cpumask_var_t pcpu;
  cpumask_var_t cbcpu;
};
```

Members

pcpu
cpumask for the parallel workers.

cbcpu
cpumask for the serial (callback) workers.

struct **parallel_data**

Internal control structure, covers everything that depends on the cpumask in use.

Definition

```
struct parallel_data {
  struct padata_shell             *ps;
  struct padata_list              __percpu *reorder_list;
  struct padata_serial_queue      __percpu *squeue;
  refcount_t refcnt;
  unsigned int                    seq_nr;
  unsigned int                    processed;
  int cpu;
  struct padata_cpumask           cpumask;
  struct work_struct              reorder_work;
  spinlock_t lock;
};
```

Members

ps
padata_shell object.

reorder_list
percpu reorder lists

squeue
percpu padata queues used for serialuzation.

refcnt
Number of objects holding a reference on this parallel_data.

seq_nr
Sequence number of the parallelized data object.

processed
Number of already processed objects.

cpu
Next CPU to be processed.

cpumask
The cpumasks in use for parallel and serial workers.

reorder_work
work struct for reordering.

lock
Reorder lock.

struct **padata_shell**

Wrapper around *struct parallel_data*, its purpose is to allow the underlying control structure to be replaced on the fly using RCU.

Definition

```
struct padata_shell {
  struct padata_instance         *pinst;
  struct parallel_data __rcu     *pd;
  struct parallel_data           *opd;
  struct list_head               list;
};
```

Members

pinst
padat instance.

pd
Actual parallel_data structure which may be substituted on the fly.

opd
Pointer to old pd to be freed by padata_replace.

list
List entry in padata_instance list.

struct **padata_mt_job**

represents one multithreaded job

Definition

```
struct padata_mt_job {
  void (*thread_fn)(unsigned long start, unsigned long end, void␣
↪*arg);
  void *fn_arg;
  unsigned long           start;
  unsigned long           size;
  unsigned long           align;
  unsigned long           min_chunk;
  int max_threads;
};
```

Members

thread_fn
Called for each chunk of work that a padata thread does.

fn_arg
The thread function argument.

start
The start of the job (units are job-specific).

size
size of this node's work (units are job-specific).

align
Ranges passed to the thread function fall on this boundary, with the possible exceptions of the beginning and end of the job.

min_chunk
The minimum chunk size in job-specific units. This allows the client to communicate the minimum amount of work that's appropriate for one worker thread to do at once.

max_threads
Max threads to use for the job, actual number may be less depending on task size and minimum chunk size.

struct **padata_instance**

The overall control structure.

Definition

```
struct padata_instance {
  struct hlist_node               cpu_online_node;
  struct hlist_node               cpu_dead_node;
  struct workqueue_struct         *parallel_wq;
  struct workqueue_struct         *serial_wq;
  struct list_head                pslist;
  struct padata_cpumask           cpumask;
  struct kobject                   kobj;
  struct mutex                     lock;
  u8 flags;
```

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```
#define PADATA_INIT     1;
#define PADATA_RESET    2;
#define PADATA_INVALID  4;
};
```

Members

cpu_online_node
Linkage for CPU online callback.

cpu_dead_node
Linkage for CPU offline callback.

parallel_wq
The workqueue used for parallel work.

serial_wq
The workqueue used for serial work.

pslist
List of padata_shell objects attached to this instance.

cpumask
User supplied cpumasks for parallel and serial works.

kobj
padata instance kernel object.

lock
padata instance lock.

flags
padata flags.

int **padata_do_parallel**(struct *padata_shell* *ps, struct *padata_priv* *padata, int *cb_cpu)

padata parallelization function

Parameters

struct padata_shell *ps
padatashell

struct padata_priv *padata
object to be parallelized

int *cb_cpu
pointer to the CPU that the serialization callback function should run on. If it's not in the serial cpumask of **pinst** (i.e. cpumask.cbcpu), this function selects a fallback CPU and if none found, returns -EINVAL.

Description

The parallelization callback function will run with BHs off.

Note

Every object which is parallelized by padata_do_parallel must be seen by padata_do_serial.

Return

0 on success or else negative error code.

void **padata_do_serial**(struct *padata_priv* *padata)

padata serialization function

Parameters

struct padata_priv *padata
object to be serialized.

Description

padata_do_serial must be called for every parallelized object. The serialization callback function will run with BHs off.

void **padata_do_multithreaded**(struct *padata_mt_job* *job)

run a multithreaded job

Parameters

struct padata_mt_job *job
Description of the job.

Description

See the definition of `struct padata_mt_job` for more details.

int **padata_set_cpumask**(struct *padata_instance* *pinst, int cpumask_type, cpumask_var_t cpumask)

Sets specified by **cpumask_type** cpumask to the value equivalent to **cpumask**.

Parameters

struct padata_instance *pinst
padata instance

int cpumask_type
PADATA_CPU_SERIAL or PADATA_CPU_PARALLEL corresponding to parallel and serial cpumasks respectively.

cpumask_var_t cpumask
the cpumask to use

Return

0 on success or negative error code

struct *padata_instance* ***padata_alloc**(const char *name)

allocate and initialize a padata instance

Parameters

const char *name
used to identify the instance

Return

new instance on success, NULL on error

void **padata_free**(struct *padata_instance* *pinst)

free a padata instance

Parameters

struct padata_instance *pinst
padata instance to free

struct *padata_shell* ***padata_alloc_shell**(struct *padata_instance* *pinst)

Allocate and initialize padata shell.

Parameters

struct padata_instance *pinst
Parent padata_instance object.

Return

new shell on success, NULL on error

void **padata_free_shell**(struct *padata_shell* *ps)

free a padata shell

Parameters

struct padata_shell *ps
padata shell to free

3.6 RCU concepts

3.6.1 Using RCU to Protect Read-Mostly Arrays

Although RCU is more commonly used to protect linked lists, it can also be used to protect arrays. Three situations are as follows:

1. *Hash Tables*
2. *Static Arrays*
3. *Resizable Arrays*

Each of these three situations involves an RCU-protected pointer to an array that is separately indexed. It might be tempting to consider use of RCU to instead protect the index into an array, however, this use case is **not** supported. The problem with RCU-protected indexes into arrays is that compilers can play way too many optimization games with integers, which means that the rules governing handling of these indexes are far more trouble than they are worth. If RCU-protected indexes into arrays prove to be particularly valuable (which they have not thus far), explicit cooperation from the compiler will be required to permit them to be safely used.

That aside, each of the three RCU-protected pointer situations are described in the following sections.

Situation 1: Hash Tables

Hash tables are often implemented as an array, where each array entry has a linked-list hash chain. Each hash chain can be protected by RCU as described in the listRCU.txt document. This approach also applies to other array-of-list situations, such as radix trees.

Situation 2: Static Arrays

Static arrays, where the data (rather than a pointer to the data) is located in each array element, and where the array is never resized, have not been used with RCU. Rik van Riel recommends using seqlock in this situation, which would also have minimal read-side overhead as long as updates are rare.

Quick Quiz:
Why is it so important that updates be rare when using seqlock?

Answer to Quick Quiz

Situation 3: Resizable Arrays

Use of RCU for resizable arrays is demonstrated by the grow_ary() function formerly used by the System V IPC code. The array is used to map from semaphore, message-queue, and shared-memory IDs to the data structure that represents the corresponding IPC construct. The grow_ary() function does not acquire any locks; instead its caller must hold the ids->sem semaphore.

The grow_ary() function, shown below, does some limit checks, allocates a new ipc_id_ary, copies the old to the new portion of the new, initializes the remainder of the new, updates the ids->entries pointer to point to the new array, and invokes ipc_rcu_putref() to free up the old array. Note that *rcu_assign_pointer()* is used to update the ids->entries pointer, which includes any memory barriers required on whatever architecture you are running on:

```
static int grow_ary(struct ipc_ids* ids, int newsize)
{
        struct ipc_id_ary* new;
        struct ipc_id_ary* old;
        int i;
        int size = ids->entries->size;

        if(newsize > IPCMNI)
                newsize = IPCMNI;
        if(newsize <= size)
                return newsize;

        new = ipc_rcu_alloc(sizeof(struct kern_ipc_perm *)*newsize +
                            sizeof(struct ipc_id_ary));
        if(new == NULL)
                return size;
        new->size = newsize;
```

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```
        memcpy(new->p, ids->entries->p,
               sizeof(struct kern_ipc_perm *)*size +
               sizeof(struct ipc_id_ary));
        for(i=size;i<newsize;i++) {
                new->p[i] = NULL;
        }
        old = ids->entries;

        /*
         * Use rcu_assign_pointer() to make sure the memcpyed
         * contents of the new array are visible before the new
         * array becomes visible.
         */
        rcu_assign_pointer(ids->entries, new);

        ipc_rcu_putref(old);
        return newsize;
}
```

The ipc_rcu_putref() function decrements the array's reference count and then, if the reference count has dropped to zero, uses `call_rcu()` to free the array after a grace period has elapsed.

The array is traversed by the ipc_lock() function. This function indexes into the array under the protection of `rcu_read_lock()`, using `rcu_dereference()` to pick up the pointer to the array so that it may later safely be dereferenced – memory barriers are required on the Alpha CPU. Since the size of the array is stored with the array itself, there can be no array-size mismatches, so a simple check suffices. The pointer to the structure corresponding to the desired IPC object is placed in "out", with NULL indicating a non-existent entry. After acquiring "out->lock", the "out->deleted" flag indicates whether the IPC object is in the process of being deleted, and, if not, the pointer is returned:

```
struct kern_ipc_perm* ipc_lock(struct ipc_ids* ids, int id)
{
        struct kern_ipc_perm* out;
        int lid = id % SEQ_MULTIPLIER;
        struct ipc_id_ary* entries;

        rcu_read_lock();
        entries = rcu_dereference(ids->entries);
        if(lid >= entries->size) {
                rcu_read_unlock();
                return NULL;
        }
        out = entries->p[lid];
        if(out == NULL) {
                rcu_read_unlock();
                return NULL;
        }
```

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```
        spin_lock(&out->lock);

        /* ipc_rmid() may have already freed the ID while ipc_lock
         * was spinning: here verify that the structure is still␣
↪valid
         */
        if (out->deleted) {
                spin_unlock(&out->lock);
                rcu_read_unlock();
                return NULL;
        }
        return out;
}
```

Answer to Quick Quiz:

Why is it so important that updates be rare when using seqlock?

The reason that it is important that updates be rare when using seqlock is that frequent updates can livelock readers. One way to avoid this problem is to assign a seqlock for each array entry rather than to the entire array.

3.6.2 Review Checklist for RCU Patches

This document contains a checklist for producing and reviewing patches that make use of RCU. Violating any of the rules listed below will result in the same sorts of problems that leaving out a locking primitive would cause. This list is based on experiences reviewing such patches over a rather long period of time, but improvements are always welcome!

0. Is RCU being applied to a read-mostly situation? If the data structure is updated more than about 10% of the time, then you should strongly consider some other approach, unless detailed performance measurements show that RCU is nonetheless the right tool for the job. Yes, RCU does reduce read-side overhead by increasing write-side overhead, which is exactly why normal uses of RCU will do much more reading than updating.

   Another exception is where performance is not an issue, and RCU provides a simpler implementation. An example of this situation is the dynamic NMI code in the Linux 2.6 kernel, at least on architectures where NMIs are rare.

   Yet another exception is where the low real-time latency of RCU's read-side primitives is critically important.

   One final exception is where RCU readers are used to prevent the ABA problem (https://en.wikipedia.org/wiki/ABA_problem) for lockless updates. This does result in the mildly counter-intuitive situation where *rcu_read_lock()* and *rcu_read_unlock()* are used to protect updates, however, this approach provides the same potential simplifications that garbage collectors do.

1. Does the update code have proper mutual exclusion?

   RCU does allow -readers- to run (almost) naked, but -writers- must still use some sort of mutual exclusion, such as:

   a. locking,

   b. atomic operations, or

   c. restricting updates to a single task.

   If you choose #b, be prepared to describe how you have handled memory barriers on weakly ordered machines (pretty much all of them – even x86 allows later loads to be reordered to precede earlier stores), and be prepared to explain why this added complexity is worthwhile. If you choose #c, be prepared to explain how this single task does not become a major bottleneck on big multiprocessor machines (for example, if the task is updating information relating to itself that other tasks can read, there by definition can be no bottleneck). Note that the definition of "large" has changed significantly: Eight CPUs was "large" in the year 2000, but a hundred CPUs was unremarkable in 2017.

2. Do the RCU read-side critical sections make proper use of `rcu_read_lock()` and friends? These primitives are needed to prevent grace periods from ending prematurely, which could result in data being unceremoniously freed out from under your read-side code, which can greatly increase the actuarial risk of your kernel.

   As a rough rule of thumb, any dereference of an RCU-protected pointer must be covered by `rcu_read_lock()`, `rcu_read_lock_bh()`, `rcu_read_lock_sched()`, or by the appropriate update-side lock. Disabling of preemption can serve as `rcu_read_lock_sched()`, but is less readable and prevents lockdep from detecting locking issues.

   Letting RCU-protected pointers "leak" out of an RCU read-side critical section is every bid as bad as letting them leak out from under a lock. Unless, of course, you have arranged some other means of protection, such as a lock or a reference count -before- letting them out of the RCU read-side critical section.

3. Does the update code tolerate concurrent accesses?

   The whole point of RCU is to permit readers to run without any locks or atomic operations. This means that readers will be running while updates are in progress. There are a number of ways to handle this concurrency, depending on the situation:

   a. Use the RCU variants of the list and hlist update primitives to add, remove, and replace elements on an RCU-protected list. Alternatively, use the other RCU-protected data structures that have been added to the Linux kernel.

      This is almost always the best approach.

   b. Proceed as in (a) above, but also maintain per-element locks (that are acquired by both readers and writers) that guard per-element state. Of course, fields that the readers refrain from accessing can be guarded by some other lock acquired only by updaters, if desired.

      This works quite well, also.

   c. Make updates appear atomic to readers. For example, pointer updates to properly aligned fields will appear atomic, as will individual atomic primitives. Sequences of operations performed under a lock will -not- appear to be atomic to RCU readers, nor will sequences of multiple atomic primitives.

This can work, but is starting to get a bit tricky.

d. Carefully order the updates and the reads so that readers see valid data at all phases of the update. This is often more difficult than it sounds, especially given modern CPUs' tendency to reorder memory references. One must usually liberally sprinkle memory barriers (smp_wmb(), smp_rmb(), smp_mb()) through the code, making it difficult to understand and to test.

It is usually better to group the changing data into a separate structure, so that the change may be made to appear atomic by updating a pointer to reference a new structure containing updated values.

4. Weakly ordered CPUs pose special challenges. Almost all CPUs are weakly ordered – even x86 CPUs allow later loads to be reordered to precede earlier stores. RCU code must take all of the following measures to prevent memory-corruption problems:

   a. Readers must maintain proper ordering of their memory accesses. The *rcu_dereference()* primitive ensures that the CPU picks up the pointer before it picks up the data that the pointer points to. This really is necessary on Alpha CPUs. If you don't believe me, see:

      http://www.openvms.compaq.com/wizard/wiz_2637.html

   The *rcu_dereference()* primitive is also an excellent documentation aid, letting the person reading the code know exactly which pointers are protected by RCU. Please note that compilers can also reorder code, and they are becoming increasingly aggressive about doing just that. The *rcu_dereference()* primitive therefore also prevents destructive compiler optimizations. However, with a bit of devious creativity, it is possible to mishandle the return value from *rcu_dereference()*. Please see rcu_dereference.txt in this directory for more information.

   The *rcu_dereference()* primitive is used by the various "_rcu()" list-traversal primitives, such as the *list_for_each_entry_rcu()*. Note that it is perfectly legal (if redundant) for update-side code to use *rcu_dereference()* and the "_rcu()" list-traversal primitives. This is particularly useful in code that is common to readers and updaters. However, lockdep will complain if you access *rcu_dereference()* outside of an RCU read-side critical section. See lockdep.txt to learn what to do about this.

   Of course, neither *rcu_dereference()* nor the "_rcu()"list-traversal primitives can substitute for a good concurrency design coordinating among multiple updaters.

   b. If the list macros are being used, the *list_add_tail_rcu()* and *list_add_rcu()* primitives must be used in order to prevent weakly ordered machines from misordering structure initialization and pointer planting. Similarly, if the hlist macros are being used, the *hlist_add_head_rcu()* primitive is required.

c. If the list macros are being used, the `list_del_rcu()` primitive must be used to keep `list_del()`'s pointer poisoning from inflicting toxic effects on concurrent readers. Similarly, if the hlist macros are being used, the `hlist_del_rcu()` primitive is required.

   The `list_replace_rcu()` and `hlist_replace_rcu()` primitives may be used to replace an old structure with a new one in their respective types of RCU-protected lists.

d. Rules similar to (4b) and (4c) apply to the "hlist_nulls" type of RCU-protected linked lists.

e. Updates must ensure that initialization of a given structure happens before pointers to that structure are publicized. Use the `rcu_assign_pointer()` primitive when publicizing a pointer to a structure that can be traversed by an RCU read-side critical section.

5. If `call_rcu()` or `call_srcu()` is used, the callback function will be called from softirq context. In particular, it cannot block.

6. Since `synchronize_rcu()` can block, it cannot be called from any sort of irq context. The same rule applies for `synchronize_srcu()`, `synchronize_rcu_expedited()`, and `synchronize_srcu_expedited()`.

   The expedited forms of these primitives have the same semantics as the non-expedited forms, but expediting is both expensive and (with the exception of `synchronize_srcu_expedited()`) unfriendly to real-time workloads. Use of the expedited primitives should be restricted to rare configuration-change operations that would not normally be undertaken while a real-time workload is running. However, real-time workloads can use rcupdate.rcu_normal kernel boot parameter to completely disable expedited grace periods, though this might have performance implications.

   In particular, if you find yourself invoking one of the expedited primitives repeatedly in a loop, please do everyone a favor: Restructure your code so that it batches the updates, allowing a single non-expedited primitive to cover the entire batch. This will very likely be faster than the loop containing the expedited primitive, and will be much much easier on the rest of the system, especially to real-time workloads running on the rest of the system.

7. As of v4.20, a given kernel implements only one RCU flavor, which is RCU-sched for PREEMPT=n and RCU-preempt for PREEMPT=y. If the updater uses `call_rcu()` or `synchronize_rcu()`, then the corresponding readers my use `rcu_read_lock()` and `rcu_read_unlock()`, `rcu_read_lock_bh()` and `rcu_read_unlock_bh()`, or any pair of primitives that disables and re-enables preemption, for example, `rcu_read_lock_sched()` and `rcu_read_unlock_sched()`. If the updater uses `synchronize_srcu()` or `call_srcu()`, then the corresponding readers must use `srcu_read_lock()` and `srcu_read_unlock()`, and with the same srcu_struct. The rules for the expedited primitives are the same as for their non-expedited counterparts. Mixing things up will result in confusion and broken kernels, and has even resulted in an exploitable security issue.

   One exception to this rule: `rcu_read_lock()` and `rcu_read_unlock()` may be substituted for `rcu_read_lock_bh()` and `rcu_read_unlock_bh()` in cases where local bottom halves are already known to be disabled, for example, in irq or softirq context. Commenting such cases is a must, of course! And the jury is still out on whether the increased speed is worth it.

8. Although `synchronize_rcu()` is slower than is `call_rcu()`, it usually results in simpler code. So, unless update performance is critically important, the updaters cannot block, or the latency of `synchronize_rcu()` is visible from userspace, `synchronize_rcu()` should be used in preference to `call_rcu()`. Furthermore, `kfree_rcu()` usually results in even simpler code than does `synchronize_rcu()` without `synchronize_rcu()`'s multi-millisecond latency. So please take advantage of `kfree_rcu()`'s "fire and forget" memory-freeing capabilities where it applies.

   An especially important property of the `synchronize_rcu()` primitive is that it automatically self-limits: if grace periods are delayed for whatever reason, then the `synchronize_rcu()` primitive will correspondingly delay updates. In contrast, code using `call_rcu()` should explicitly limit update rate in cases where grace periods are delayed, as failing to do so can result in excessive realtime latencies or even OOM conditions.

   Ways of gaining this self-limiting property when using `call_rcu()` include:

   a. Keeping a count of the number of data-structure elements used by the RCU-protected data structure, including those waiting for a grace period to elapse. Enforce a limit on this number, stalling updates as needed to allow previously deferred frees to complete. Alternatively, limit only the number awaiting deferred free rather than the total number of elements.

      One way to stall the updates is to acquire the update-side mutex. (Don't try this with a spinlock – other CPUs spinning on the lock could prevent the grace period from ever ending.) Another way to stall the updates is for the updates to use a wrapper function around the memory allocator, so that this wrapper function simulates OOM when there is too much memory awaiting an RCU grace period. There are of course many other variations on this theme.

   b. Limiting update rate. For example, if updates occur only once per hour, then no explicit rate limiting is required, unless your system is already badly broken. Older versions of the dcache subsystem take this approach, guarding updates with a global lock, limiting their rate.

   c. Trusted update – if updates can only be done manually by superuser or some other trusted user, then it might not be necessary to automatically limit them. The theory here is that superuser already has lots of ways to crash the machine.

   d. Periodically invoke `synchronize_rcu()`, permitting a limited number of updates per grace period.

   The same cautions apply to `call_srcu()` and `kfree_rcu()`.

   Note that although these primitives do take action to avoid memory exhaustion when any given CPU has too many callbacks, a determined user could still exhaust memory. This is especially the case if a system with a large number of CPUs has been configured to offload all of its RCU callbacks onto a single CPU, or if the system has relatively little free memory.

9. All RCU list-traversal primitives, which include `rcu_dereference()`, `list_for_each_entry_rcu()`, and list_for_each_safe_rcu(), must be either within an RCU read-side critical section or must be protected by appropriate update-side locks. RCU read-side critical sections are delimited by `rcu_read_lock()` and `rcu_read_unlock()`, or by similar primitives such as `rcu_read_lock_bh()` and `rcu_read_unlock_bh()`, in which case the matching `rcu_dereference()` primitive must be used in order to keep lockdep happy, in this case, `rcu_dereference_bh()`.

   The reason that it is permissible to use RCU list-traversal primitives when the update-side lock is held is that doing so can be quite helpful in reducing code bloat when common code is shared between readers and updaters. Additional primitives are provided for this case, as discussed in lockdep.txt.

10. Conversely, if you are in an RCU read-side critical section, and you don't hold the appropriate update-side lock, you -must- use the "_rcu()" variants of the list macros. Failing to do so will break Alpha, cause aggressive compilers to generate bad code, and confuse people trying to read your code.

11. Any lock acquired by an RCU callback must be acquired elsewhere with softirq disabled, e.g., via spin_lock_irqsave(), spin_lock_bh(), etc. Failing to disable softirq on a given acquisition of that lock will result in deadlock as soon as the RCU softirq handler happens to run your RCU callback while interrupting that acquisition's critical section.

12. RCU callbacks can be and are executed in parallel. In many cases, the callback code simply wrappers around `kfree()`, so that this is not an issue (or, more accurately, to the extent that it is an issue, the memory-allocator locking handles it). However, if the callbacks do manipulate a shared data structure, they must use whatever locking or other synchronization is required to safely access and/or modify that data structure.

    Do not assume that RCU callbacks will be executed on the same CPU that executed the corresponding `call_rcu()` or `call_srcu()`. For example, if a given CPU goes offline while having an RCU callback pending, then that RCU callback will execute on some surviving CPU. (If this was not the case, a self-spawning RCU callback would prevent the victim CPU from ever going offline.) Furthermore, CPUs designated by rcu_nocbs= might well -always- have their RCU callbacks executed on some other CPUs, in fact, for some real-time workloads, this is the whole point of using the rcu_nocbs= kernel boot parameter.

13. Unlike other forms of RCU, it -is- permissible to block in an SRCU read-side critical section (demarked by `srcu_read_lock()` and `srcu_read_unlock()`), hence the "SRCU": "sleepable RCU". Please note that if you don't need to sleep in read-side critical sections, you should be using RCU rather than SRCU, because RCU is almost always faster and easier to use than is SRCU.

    Also unlike other forms of RCU, explicit initialization and cleanup is required either at build time via DEFINE_SRCU() or DEFINE_STATIC_SRCU() or at runtime via `init_srcu_struct()` and `cleanup_srcu_struct()`. These last two are passed a "struct srcu_struct" that defines the scope of a given SRCU domain. Once initialized, the srcu_struct is passed to `srcu_read_lock()`, `srcu_read_unlock()` `synchronize_srcu()`, `synchronize_srcu_expedited()`, and `call_srcu()`. A given `synchronize_srcu()` waits only for SRCU read-side critical sections governed by `srcu_read_lock()` and `srcu_read_unlock()` calls that have been passed the same srcu_struct. This property is what makes sleeping read-side critical sections tolerable – a given subsystem delays only its own updates, not those of other subsystems using SRCU. Therefore, SRCU is less prone to OOM the system than RCU would be if RCU's read-side critical sections were permitted to sleep.

The ability to sleep in read-side critical sections does not come for free. First, corresponding `srcu_read_lock()` and `srcu_read_unlock()` calls must be passed the same srcu_struct. Second, grace-period-detection overhead is amortized only over those updates sharing a given srcu_struct, rather than being globally amortized as they are for other forms of RCU. Therefore, SRCU should be used in preference to rw_semaphore only in extremely read-intensive situations, or in situations requiring SRCU's read-side deadlock immunity or low read-side realtime latency. You should also consider percpu_rw_semaphore when you need lightweight readers.

SRCU's expedited primitive (`synchronize_srcu_expedited()`) never sends IPIs to other CPUs, so it is easier on real-time workloads than is `synchronize_rcu_expedited()`.

Note that `rcu_assign_pointer()` relates to SRCU just as it does to other forms of RCU, but instead of `rcu_dereference()` you should use `srcu_dereference()` in order to avoid lockdep splats.

14. The whole point of `call_rcu()`, `synchronize_rcu()`, and friends is to wait until all pre-existing readers have finished before carrying out some otherwise-destructive operation. It is therefore critically important to -first- remove any path that readers can follow that could be affected by the destructive operation, and -only- -then- invoke `call_rcu()`, `synchronize_rcu()`, or friends.

    Because these primitives only wait for pre-existing readers, it is the caller's responsibility to guarantee that any subsequent readers will execute safely.

15. The various RCU read-side primitives do -not- necessarily contain memory barriers. You should therefore plan for the CPU and the compiler to freely reorder code into and out of RCU read-side critical sections. It is the responsibility of the RCU update-side primitives to deal with this.

    For SRCU readers, you can use `smp_mb__after_srcu_read_unlock()` immediately after an `srcu_read_unlock()` to get a full barrier.

16. Use CONFIG_PROVE_LOCKING, CONFIG_DEBUG_OBJECTS_RCU_HEAD, and the __rcu sparse checks to validate your RCU code. These can help find problems as follows:

    CONFIG_PROVE_LOCKING:
    check that accesses to RCU-protected data structures are carried out under the proper RCU read-side critical section, while holding the right combination of locks, or whatever other conditions are appropriate.

    CONFIG_DEBUG_OBJECTS_RCU_HEAD:
    check that you don't pass the same object to `call_rcu()` (or friends) before an RCU grace period has elapsed since the last time that you passed that same object to `call_rcu()` (or friends).

__rcu sparse checks:
tag the pointer to the RCU-protected data structure with __rcu, and sparse will warn you if you access that pointer without the services of one of the variants of *rcu_dereference()*.

These debugging aids can help you find problems that are otherwise extremely difficult to spot.

17. If you register a callback using *call_rcu()* or *call_srcu()*, and pass in a function defined within a loadable module, then it in necessary to wait for all pending callbacks to be invoked after the last invocation and before unloading that module. Note that it is absolutely -not- sufficient to wait for a grace period! The current (say) *synchronize_rcu()* implementation is -not- guaranteed to wait for callbacks registered on other CPUs. Or even on the current CPU if that CPU recently went offline and came back online.

    You instead need to use one of the barrier functions:

    - *call_rcu()* -> *rcu_barrier()*
    - *call_srcu()* -> *srcu_barrier()*

    However, these barrier functions are absolutely -not- guaranteed to wait for a grace period. In fact, if there are no *call_rcu()* callbacks waiting anywhere in the system, *rcu_barrier()* is within its rights to return immediately.

    So if you need to wait for both an RCU grace period and for all pre-existing *call_rcu()* callbacks, you will need to execute both *rcu_barrier()* and *synchronize_rcu()*, if necessary, using something like workqueues to to execute them concurrently.

    See rcubarrier.txt for more information.

3.6.3 RCU and lockdep checking

All flavors of RCU have lockdep checking available, so that lockdep is aware of when each task enters and leaves any flavor of RCU read-side critical section. Each flavor of RCU is tracked separately (but note that this is not the case in 2.6.32 and earlier). This allows lockdep's tracking to include RCU state, which can sometimes help when debugging deadlocks and the like.

In addition, RCU provides the following primitives that check lockdep's state:

```
rcu_read_lock_held() for normal RCU.
rcu_read_lock_bh_held() for RCU-bh.
rcu_read_lock_sched_held() for RCU-sched.
srcu_read_lock_held() for SRCU.
```

These functions are conservative, and will therefore return 1 if they aren't certain (for example, if CONFIG_DEBUG_LOCK_ALLOC is not set). This prevents things like WARN_ON(!*rcu_read_lock_held()*) from giving false positives when lockdep is disabled.

In addition, a separate kernel config parameter CONFIG_PROVE_RCU enables checking of *rcu_dereference()* primitives:

rcu_dereference(p):
Check for RCU read-side critical section.

rcu_dereference_bh(p):
Check for RCU-bh read-side critical section.

rcu_dereference_sched(p):
Check for RCU-sched read-side critical section.

srcu_dereference(p, sp):
Check for SRCU read-side critical section.

rcu_dereference_check(p, c):
Use explicit check expression "c"along with *rcu_read_lock_held()*. This is useful in code that is invoked by both RCU readers and updaters.

rcu_dereference_bh_check(p, c):
Use explicit check expression "c" along with *rcu_read_lock_bh_held()*. This is useful in code that is invoked by both RCU-bh readers and updaters.

rcu_dereference_sched_check(p, c):
Use explicit check expression "c" along with rcu_read_lock_sched_held(). This is useful in code that is invoked by both RCU-sched readers and updaters.

srcu_dereference_check(p, c):
Use explicit check expression "c" along with *srcu_read_lock_held()*. This is useful in code that is invoked by both SRCU readers and updaters.

rcu_dereference_raw(p):
Don't check. (Use sparingly, if at all.)

rcu_dereference_protected(p, c):
Use explicit check expression "c", and omit all barriers and compiler constraints. This is useful when the data structure cannot change, for example, in code that is invoked only by updaters.

rcu_access_pointer(p):
Return the value of the pointer and omit all barriers, but retain the compiler constraints that prevent duplicating or coalescsing. This is useful when when testing the value of the pointer itself, for example, against NULL.

The *rcu_dereference_check()* check expression can be any boolean expression, but would normally include a lockdep expression. However, any boolean expression can be used. For a moderately ornate example, consider the following:

```
file = rcu_dereference_check(fdt->fd[fd],
                             lockdep_is_held(&files->file_lock) ||
                             atomic_read(&files->count) == 1);
```

This expression picks up the pointer "fdt->fd[fd]" in an RCU-safe manner, and, if CONFIG_PROVE_RCU is configured, verifies that this expression is used in:

1. An RCU read-side critical section (implicit), or
2. with files->file_lock held, or
3. on an unshared files_struct.

In case (1), the pointer is picked up in an RCU-safe manner for vanilla RCU read-side critical sections, in case (2) the ->file_lock prevents any change from taking place, and finally, in case (3) the current task is the only task accessing the file_struct, again preventing any change from taking place. If the above statement was invoked only from updater code, it could instead be written as follows:

```
file = rcu_dereference_protected(fdt->fd[fd],
                                 lockdep_is_held(&files->file_lock)␣
↪||
                                 atomic_read(&files->count) == 1);
```

This would verify cases #2 and #3 above, and furthermore lockdep would complain if this was used in an RCU read-side critical section unless one of these two cases held. Because *rcu_dereference_protected()* omits all barriers and compiler constraints, it generates better code than do the other flavors of *rcu_dereference()*. On the other hand, it is illegal to use *rcu_dereference_protected()* if either the RCU-protected pointer or the RCU-protected data that it points to can change concurrently.

Like *rcu_dereference()*, when lockdep is enabled, RCU list and hlist traversal primitives check for being called from within an RCU read-side critical section. However, a lockdep expression can be passed to them as a additional optional argument. With this lockdep expression, these traversal primitives will complain only if the lockdep expression is false and they are called from outside any RCU read-side critical section.

For example, the workqueue *for_each_pwq()* macro is intended to be used either within an RCU read-side critical section or with wq->mutex held. It is thus implemented as follows:

```
#define for_each_pwq(pwq, wq)
        list_for_each_entry_rcu((pwq), &(wq)->pwqs, pwqs_node,
                                lock_is_held(&(wq->mutex).dep_map))
```

3.6.4 Lockdep-RCU Splat

Lockdep-RCU was added to the Linux kernel in early 2010 (http://lwn.net/Articles/371986/). This facility checks for some common misuses of the RCU API, most notably using one of the *rcu_dereference()* family to access an RCU-protected pointer without the proper protection. When such misuse is detected, an lockdep-RCU splat is emitted.

The usual cause of a lockdep-RCU slat is someone accessing an RCU-protected data structure without either (1) being in the right kind of RCU read-side critical section or (2) holding the right update-side lock. This problem can therefore be serious: it might result in random memory overwriting or worse. There can of course be false positives, this being the real world and all that.

So let's look at an example RCU lockdep splat from 3.0-rc5, one that has long since been fixed:

```
=============================
WARNING: suspicious RCU usage
-----------------------------
block/cfq-iosched.c:2776 suspicious rcu_dereference_protected()␣
↪usage!
```

other info that might help us debug this:

```
rcu_scheduler_active = 1, debug_locks = 0
3 locks held by scsi_scan_6/1552:
#0:  (&shost->scan_mutex){+.+.}, at: [<ffffffff8145efca>]
scsi_scan_host_selected+0x5a/0x150
#1:  (&eq->sysfs_lock){+.+.}, at: [<ffffffff812a5032>]
elevator_exit+0x22/0x60
#2:  (&(&q->__queue_lock)->rlock){-.-.}, at: [<ffffffff812b6233>]
cfq_exit_queue+0x43/0x190

stack backtrace:
Pid: 1552, comm: scsi_scan_6 Not tainted 3.0.0-rc5 #17
Call Trace:
[<ffffffff810abb9b>] lockdep_rcu_dereference+0xbb/0xc0
[<ffffffff812b6139>] __cfq_exit_single_io_context+0xe9/0x120
[<ffffffff812b626c>] cfq_exit_queue+0x7c/0x190
[<ffffffff812a5046>] elevator_exit+0x36/0x60
[<ffffffff812a802a>] blk_cleanup_queue+0x4a/0x60
[<ffffffff8145cc09>] scsi_free_queue+0x9/0x10
[<ffffffff81460944>] __scsi_remove_device+0x84/0xd0
[<ffffffff8145dca3>] scsi_probe_and_add_lun+0x353/0xb10
[<ffffffff817da069>] ? error_exit+0x29/0xb0
[<ffffffff817d98ed>] ? _raw_spin_unlock_irqrestore+0x3d/0x80
[<ffffffff8145e722>] __scsi_scan_target+0x112/0x680
[<ffffffff812c690d>] ? trace_hardirqs_off_thunk+0x3a/0x3c
[<ffffffff817da069>] ? error_exit+0x29/0xb0
[<ffffffff812bcc60>] ? kobject_del+0x40/0x40
[<ffffffff8145ed16>] scsi_scan_channel+0x86/0xb0
[<ffffffff8145f0b0>] scsi_scan_host_selected+0x140/0x150
[<ffffffff8145f149>] do_scsi_scan_host+0x89/0x90
[<ffffffff8145f170>] do_scan_async+0x20/0x160
[<ffffffff8145f150>] ? do_scsi_scan_host+0x90/0x90
[<ffffffff810975b6>] kthread+0xa6/0xb0
[<ffffffff817db154>] kernel_thread_helper+0x4/0x10
[<ffffffff81066430>] ? finish_task_switch+0x80/0x110
[<ffffffff817d9c04>] ? retint_restore_args+0xe/0xe
[<ffffffff81097510>] ? __kthread_init_worker+0x70/0x70
[<ffffffff817db150>] ? gs_change+0xb/0xb
```

Line 2776 of block/cfq-iosched.c in v3.0-rc5 is as follows:

```
if (rcu_dereference(ioc->ioc_data) == cic) {
```

This form says that it must be in a plain vanilla RCU read-side critical section, but the "other info" list above shows that this is not the case. Instead, we hold three locks, one of which might be RCU related. And maybe that lock really does protect this reference. If so, the fix is to inform RCU, perhaps by changing __cfq_exit_single_io_context() to take the struct request_queue "q" from cfq_exit_queue() as an argument, which would permit us to invoke rcu_dereference_protected as follows:

```
if (rcu_dereference_protected(ioc->ioc_data,
                              lockdep_is_held(&q->queue_lock)) ==␣
↪cic) {
```

With this change, there would be no lockdep-RCU splat emitted if this code was invoked either from within an RCU read-side critical section or with the ->queue_lock held. In particular, this would have suppressed the above lockdep-RCU splat because ->queue_lock is held (see #2 in the list above).

On the other hand, perhaps we really do need an RCU read-side critical section. In this case, the critical section must span the use of the return value from *rcu_dereference()*, or at least until there is some reference count incremented or some such. One way to handle this is to add *rcu_read_lock()* and *rcu_read_unlock()* as follows:

```
rcu_read_lock();
if (rcu_dereference(ioc->ioc_data) == cic) {
        spin_lock(&ioc->lock);
        rcu_assign_pointer(ioc->ioc_data, NULL);
        spin_unlock(&ioc->lock);
}
rcu_read_unlock();
```

With this change, the *rcu_dereference()* is always within an RCU read-side critical section, which again would have suppressed the above lockdep-RCU splat.

But in this particular case, we don't actually dereference the pointer returned from *rcu_dereference()*. Instead, that pointer is just compared to the cic pointer, which means that the *rcu_dereference()* can be replaced by *rcu_access_pointer()* as follows:

```
if (rcu_access_pointer(ioc->ioc_data) == cic) {
```

Because it is legal to invoke *rcu_access_pointer()* without protection, this change would also suppress the above lockdep-RCU splat.

3.6.5 RCU and Unloadable Modules

[Originally published in LWN Jan. 14, 2007: http://lwn.net/Articles/217484/]

RCU (read-copy update) is a synchronization mechanism that can be thought of as a replacement for read-writer locking (among other things), but with very low-overhead readers that are immune to deadlock, priority inversion, and unbounded latency. RCU read-side critical sections are delimited by *rcu_read_lock()* and *rcu_read_unlock()*, which, in non-CONFIG_PREEMPT kernels, generate no code whatsoever.

This means that RCU writers are unaware of the presence of concurrent readers, so that RCU updates to shared data must be undertaken quite carefully, leaving an old version of the data structure in place until all pre-existing readers have finished. These old versions are needed because such readers might hold a reference to them. RCU updates can therefore be rather expensive, and RCU is thus best suited for read-mostly situations.

How can an RCU writer possibly determine when all readers are finished, given that readers might well leave absolutely no trace of their presence? There is a *synchronize_rcu()* primitive that blocks until all pre-existing readers have completed. An updater wishing to delete an element p from a linked list might do the following, while holding an appropriate lock, of course:

```
list_del_rcu(p);
synchronize_rcu();
kfree(p);
```

But the above code cannot be used in IRQ context – the *call_rcu()* primitive must be used instead. This primitive takes a pointer to an rcu_head struct placed within the RCU-protected data structure and another pointer to a function that may be invoked later to free that structure. Code to delete an element p from the linked list from IRQ context might then be as follows:

```
list_del_rcu(p);
call_rcu(&p->rcu, p_callback);
```

Since *call_rcu()* never blocks, this code can safely be used from within IRQ context. The function p_callback() might be defined as follows:

```
static void p_callback(struct rcu_head *rp)
{
        struct pstruct *p = container_of(rp, struct pstruct, rcu);

        kfree(p);
}
```

Unloading Modules That Use call_rcu()

But what if p_callback is defined in an unloadable module?

If we unload the module while some RCU callbacks are pending, the CPUs executing these callbacks are going to be severely disappointed when they are later invoked, as fancifully depicted at http://lwn.net/images/ns/kernel/rcu-drop.jpg.

We could try placing a *synchronize_rcu()* in the module-exit code path, but this is not sufficient. Although *synchronize_rcu()* does wait for a grace period to elapse, it does not wait for the callbacks to complete.

One might be tempted to try several back-to-back *synchronize_rcu()* calls, but this is still not guaranteed to work. If there is a very heavy RCU-callback load, then some of the callbacks might be deferred in order to allow other processing to proceed. Such deferral is required in realtime kernels in order to avoid excessive scheduling latencies.

rcu_barrier()

We instead need the *rcu_barrier()* primitive. Rather than waiting for a grace period to elapse, *rcu_barrier()* waits for all outstanding RCU callbacks to complete. Please note that *rcu_barrier()* does **not** imply *synchronize_rcu()*, in particular, if there are no RCU callbacks queued anywhere, *rcu_barrier()* is within its rights to return immediately, without waiting for a grace period to elapse.

Pseudo-code using *rcu_barrier()* is as follows:

1. Prevent any new RCU callbacks from being posted.
2. Execute *rcu_barrier()*.
3. Allow the module to be unloaded.

There is also an *srcu_barrier()* function for SRCU, and you of course must match the flavor of *rcu_barrier()* with that of *call_rcu()*. If your module uses multiple flavors of *call_rcu()*, then it must also use multiple flavors of *rcu_barrier()* when unloading that module. For example, if it uses *call_rcu()*, *call_srcu()* on srcu_struct_1, and *call_srcu()* on srcu_struct_2, then the following three lines of code will be required when unloading:

```
rcu_barrier();
srcu_barrier(&srcu_struct_1);
srcu_barrier(&srcu_struct_2);
```

The rcutorture module makes use of *rcu_barrier()* in its exit function as follows:

```
static void
rcu_torture_cleanup(void)
{
  int i;

  fullstop = 1;
  if (shuffler_task != NULL) {
```

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```
    VERBOSE_PRINTK_STRING("Stopping rcu_torture_shuffle task");
    kthread_stop(shuffler_task);
  }
  shuffler_task = NULL;

  if (writer_task != NULL) {
    VERBOSE_PRINTK_STRING("Stopping rcu_torture_writer task");
    kthread_stop(writer_task);
  }
  writer_task = NULL;

  if (reader_tasks != NULL) {
    for (i = 0; i < nrealreaders; i++) {
      if (reader_tasks[i] != NULL) {
        VERBOSE_PRINTK_STRING(
          "Stopping rcu_torture_reader task");
        kthread_stop(reader_tasks[i]);
      }
      reader_tasks[i] = NULL;
    }
    kfree(reader_tasks);
    reader_tasks = NULL;
  }
  rcu_torture_current = NULL;

  if (fakewriter_tasks != NULL) {
    for (i = 0; i < nfakewriters; i++) {
      if (fakewriter_tasks[i] != NULL) {
        VERBOSE_PRINTK_STRING(
          "Stopping rcu_torture_fakewriter task");
        kthread_stop(fakewriter_tasks[i]);
      }
      fakewriter_tasks[i] = NULL;
    }
    kfree(fakewriter_tasks);
    fakewriter_tasks = NULL;
  }

  if (stats_task != NULL) {
    VERBOSE_PRINTK_STRING("Stopping rcu_torture_stats task");
    kthread_stop(stats_task);
  }
  stats_task = NULL;

  /* Wait for all RCU callbacks to fire. */
  rcu_barrier();

  rcu_torture_stats_print(); /* -After- the stats thread is stopped! */
```

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```
56
57   if (cur_ops->cleanup != NULL)
58     cur_ops->cleanup();
59   if (atomic_read(&n_rcu_torture_error))
60     rcu_torture_print_module_parms("End of test: FAILURE");
61   else
62     rcu_torture_print_module_parms("End of test: SUCCESS");
63 }
```

Line 6 sets a global variable that prevents any RCU callbacks from re-posting themselves. This will not be necessary in most cases, since RCU callbacks rarely include calls to *call_rcu()*. However, the rcutorture module is an exception to this rule, and therefore needs to set this global variable.

Lines 7-50 stop all the kernel tasks associated with the rcutorture module. Therefore, once execution reaches line 53, no more rcutorture RCU callbacks will be posted. The *rcu_barrier()* call on line 53 waits for any pre-existing callbacks to complete.

Then lines 55-62 print status and do operation-specific cleanup, and then return, permitting the module-unload operation to be completed.

Quick Quiz #1:
Is there any other situation where *rcu_barrier()* might be required?

Answer to Quick Quiz #1

Your module might have additional complications. For example, if your module invokes *call_rcu()* from timers, you will need to first cancel all the timers, and only then invoke *rcu_barrier()* to wait for any remaining RCU callbacks to complete.

Of course, if you module uses *call_rcu()*, you will need to invoke *rcu_barrier()* before unloading. Similarly, if your module uses *call_srcu()*, you will need to invoke *srcu_barrier()* before unloading, and on the same srcu_struct structure. If your module uses *call_rcu()* **and** *call_srcu()*, then you will need to invoke *rcu_barrier()* **and** *srcu_barrier()*.

Implementing rcu_barrier()

Dipankar Sarma’s implementation of *rcu_barrier()* makes use of the fact that RCU callbacks are never reordered once queued on one of the per-CPU queues. His implementation queues an RCU callback on each of the per-CPU callback queues, and then waits until they have all started executing, at which point, all earlier RCU callbacks are guaranteed to have completed.

The original code for *rcu_barrier()* was as follows:

```
void rcu_barrier(void)
{
  BUG_ON(in_interrupt());
  /* Take cpucontrol mutex to protect against CPU hotplug */
  mutex_lock(&rcu_barrier_mutex);
```

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```
6    init_completion(&rcu_barrier_completion);
7    atomic_set(&rcu_barrier_cpu_count, 0);
8    on_each_cpu(rcu_barrier_func, NULL, 0, 1);
9    wait_for_completion(&rcu_barrier_completion);
10   mutex_unlock(&rcu_barrier_mutex);
11 }
```

Line 3 verifies that the caller is in process context, and lines 5 and 10 use rcu_barrier_mutex to ensure that only one *rcu_barrier()* is using the global completion and counters at a time, which are initialized on lines 6 and 7. Line 8 causes each CPU to invoke rcu_barrier_func(), which is shown below. Note that the final "1" in on_each_cpu()'s argument list ensures that all the calls to rcu_barrier_func() will have completed before on_each_cpu() returns. Line 9 then waits for the completion.

This code was rewritten in 2008 and several times thereafter, but this still gives the general idea.

The rcu_barrier_func() runs on each CPU, where it invokes *call_rcu()* to post an RCU callback, as follows:

```
1  static void rcu_barrier_func(void *notused)
2  {
3    int cpu = smp_processor_id();
4    struct rcu_data *rdp = &per_cpu(rcu_data, cpu);
5    struct rcu_head *head;
6
7    head = &rdp->barrier;
8    atomic_inc(&rcu_barrier_cpu_count);
9    call_rcu(head, rcu_barrier_callback);
10 }
```

Lines 3 and 4 locate RCU's internal per-CPU rcu_data structure, which contains the struct rcu_head that needed for the later call to *call_rcu()*. Line 7 picks up a pointer to this struct rcu_head, and line 8 increments a global counter. This counter will later be decremented by the callback. Line 9 then registers the rcu_barrier_callback() on the current CPU's queue.

The rcu_barrier_callback() function simply atomically decrements the rcu_barrier_cpu_count variable and finalizes the completion when it reaches zero, as follows:

```
static void rcu_barrier_callback(struct rcu_head *notused)
{
  if (atomic_dec_and_test(&rcu_barrier_cpu_count))
    complete(&rcu_barrier_completion);
}
```

Quick Quiz #2:

What happens if CPU 0's rcu_barrier_func() executes immediately (thus incrementing rcu_barrier_cpu_count to the value one), but the other CPU's rcu_barrier_func() invocations are delayed for a full grace period? Couldn't this result in *rcu_barrier()* returning prematurely?

Answer to Quick Quiz #2

The current *rcu_barrier()* implementation is more complex, due to the need to avoid disturbing idle CPUs (especially on battery-powered systems) and the need to minimally disturb non-idle CPUs in real-time systems. However, the code above illustrates the concepts.

rcu_barrier() Summary

The *rcu_barrier()* primitive has seen relatively little use, since most code using RCU is in the core kernel rather than in modules. However, if you are using RCU from an unloadable module, you need to use *rcu_barrier()* so that your module may be safely unloaded.

Answers to Quick Quizzes

Quick Quiz #1:
Is there any other situation where *rcu_barrier()* might be required?

Answer: Interestingly enough, rcu_barrier() was not originally
implemented for module unloading. Nikita Danilov was using RCU in a filesystem, which resulted in a similar situation at filesystem-unmount time. Dipankar Sarma coded up *rcu_barrier()* in response, so that Nikita could invoke it during the filesystem-unmount process.

Much later, yours truly hit the RCU module-unload problem when implementing rcutorture, and found that *rcu_barrier()* solves this problem as well.

Back to Quick Quiz #1

Quick Quiz #2:
What happens if CPU 0's rcu_barrier_func() executes immediately (thus incrementing rcu_barrier_cpu_count to the value one), but the other CPU's rcu_barrier_func() invocations are delayed for a full grace period? Couldn't this result in *rcu_barrier()* returning prematurely?

Answer: This cannot happen. The reason is that on_each_cpu() has its last
argument, the wait flag, set to "1". This flag is passed through to smp_call_function() and further to smp_call_function_on_cpu(), causing this latter to spin until the cross-CPU invocation of rcu_barrier_func() has completed. This by itself would prevent a grace period from completing on non-CONFIG_PREEMPT kernels, since each CPU must undergo a context switch (or other quiescent state) before the grace period can complete. However, this is of no use in CONFIG_PREEMPT kernels.

Therefore, on_each_cpu() disables preemption across its call to smp_call_function() and also across the local call to rcu_barrier_func(). This prevents the local CPU from context switching, again preventing grace periods from completing. This means that all CPUs have executed rcu_barrier_func() before the first rcu_barrier_callback() can possibly execute, in turn preventing rcu_barrier_cpu_count from prematurely reaching zero.

Currently, -rt implementations of RCU keep but a single global queue for RCU callbacks, and thus do not suffer from this problem. However, when the -rt RCU eventually does have per-CPU callback queues, things will have to change. One simple change is to add an `rcu_read_lock()` before line 8 of `rcu_barrier()` and an `rcu_read_unlock()` after line 8 of this same function. If you can think of a better change, please let me know!

Back to Quick Quiz #2

3.6.6 PROPER CARE AND FEEDING OF RETURN VALUES FROM rcu_dereference()

Most of the time, you can use values from `rcu_dereference()` or one of the similar primitives without worries. Dereferencing (prefix "*"), field selection ("->"), assignment ("="), address-of ("&"), addition and subtraction of constants, and casts all work quite naturally and safely.

It is nevertheless possible to get into trouble with other operations. Follow these rules to keep your RCU code working properly:

- You must use one of the `rcu_dereference()` family of primitives to load an RCU-protected pointer, otherwise CONFIG_PROVE_RCU will complain. Worse yet, your code can see random memory-corruption bugs due to games that compilers and DEC Alpha can play. Without one of the `rcu_dereference()` primitives, compilers can reload the value, and won't your code have fun with two different values for a single pointer! Without `rcu_dereference()`, DEC Alpha can load a pointer, dereference that pointer, and return data preceding initialization that preceded the store of the pointer.

  In addition, the volatile cast in `rcu_dereference()` prevents the compiler from deducing the resulting pointer value. Please see the section entitled "EXAMPLE WHERE THE COMPILER KNOWS TOO MUCH" for an example where the compiler can in fact deduce the exact value of the pointer, and thus cause misordering.

- You are only permitted to use rcu_dereference on pointer values. The compiler simply knows too much about integral values to trust it to carry dependencies through integer operations. There are a very few exceptions, namely that you can temporarily cast the pointer to uintptr_t in order to:

  - Set bits and clear bits down in the must-be-zero low-order bits of that pointer. This clearly means that the pointer must have alignment constraints, for example, this does -not- work in general for char* pointers.
  - XOR bits to translate pointers, as is done in some classic buddy-allocator algorithms.

  It is important to cast the value back to pointer before doing much of anything else with it.

- Avoid cancellation when using the "+" and "-" infix arithmetic operators. For example, for a given variable "x", avoid "(x-(uintptr_t)x)" for char* pointers. The compiler is within its rights to substitute zero for this sort of expression, so that subsequent accesses no longer depend on the `rcu_dereference()`, again possibly resulting in bugs due to misordering.

Of course, if "p" is a pointer from rcu_dereference(), and "a" and "b" are integers that happen to be equal, the expression "p+a-b" is safe because its value still necessarily depends on the rcu_dereference(), thus maintaining proper ordering.

- If you are using RCU to protect JITed functions, so that the "()" function-invocation operator is applied to a value obtained (directly or indirectly) from rcu_dereference(), you may need to interact directly with the hardware to flush instruction caches. This issue arises on some systems when a newly JITed function is using the same memory that was used by an earlier JITed function.
- Do not use the results from relational operators ("==" , "!=" , ">" , ">=" , "<" , or "<=") when dereferencing. For example, the following (quite strange) code is buggy:

```
int *p;
int *q;

...

p = rcu_dereference(gp)
q = &global_q;
q += p > &oom_p;
r1 = *q;  /* BUGGY!!! */
```

  As before, the reason this is buggy is that relational operators are often compiled using branches. And as before, although weak-memory machines such as ARM or PowerPC do order stores after such branches, but can speculate loads, which can again result in misordering bugs.

- Be very careful about comparing pointers obtained from rcu_dereference() against non-NULL values. As Linus Torvalds explained, if the two pointers are equal, the compiler could substitute the pointer you are comparing against for the pointer obtained from rcu_dereference(). For example:

```
p = rcu_dereference(gp);
if (p == &default_struct)
        do_default(p->a);
```

  Because the compiler now knows that the value of "p" is exactly the address of the variable "default_struct" , it is free to transform this code into the following:

```
p = rcu_dereference(gp);
if (p == &default_struct)
        do_default(default_struct.a);
```

  On ARM and Power hardware, the load from "default_struct.a" can now be speculated, such that it might happen before the rcu_dereference(). This could result in bugs due to misordering.

  However, comparisons are OK in the following cases:

- The comparison was against the NULL pointer. If the compiler knows that the pointer is NULL, you had better not be dereferencing it anyway. If the comparison is non-equal, the compiler is none the wiser. Therefore, it is safe to compare pointers from *rcu_dereference()* against NULL pointers.
- The pointer is never dereferenced after being compared. Since there are no subsequent dereferences, the compiler cannot use anything it learned from the comparison to reorder the non-existent subsequent dereferences. This sort of comparison occurs frequently when scanning RCU-protected circular linked lists.

  Note that if checks for being within an RCU read-side critical section are not required and the pointer is never dereferenced, *rcu_access_pointer()* should be used in place of *rcu_dereference()*.
- The comparison is against a pointer that references memory that was initialized "a long time ago." The reason this is safe is that even if misordering occurs, the misordering will not affect the accesses that follow the comparison. So exactly how long ago is "a long time ago"? Here are some possibilities:
  * Compile time.
  * Boot time.
  * Module-init time for module code.
  * Prior to kthread creation for kthread code.
  * During some prior acquisition of the lock that we now hold.
  * Before mod_timer() time for a timer handler.

  There are many other possibilities involving the Linux kernel's wide array of primitives that cause code to be invoked at a later time.
- The pointer being compared against also came from *rcu_dereference()*. In this case, both pointers depend on one *rcu_dereference()* or another, so you get proper ordering either way.

  That said, this situation can make certain RCU usage bugs more likely to happen. Which can be a good thing, at least if they happen during testing. An example of such an RCU usage bug is shown in the section titled "EXAMPLE OF AMPLIFIED RCU-USAGE BUG".
- All of the accesses following the comparison are stores, so that a control dependency preserves the needed ordering. That said, it is easy to get control dependencies wrong. Please see the "CONTROL DEPENDENCIES" section of Documentation/memory-barriers.txt for more details.
- The pointers are not equal -and- the compiler does not have enough information to deduce the value of the pointer. Note that the volatile cast in *rcu_dereference()* will normally prevent the compiler from knowing too much.

  However, please note that if the compiler knows that the pointer takes on only one of two values, a not-equal comparison will provide exactly the information that the compiler needs to deduce the value of the pointer.

- Disable any value-speculation optimizations that your compiler might provide, especially if you are making use of feedback-based optimizations that take data collected from prior runs. Such value-speculation optimizations reorder operations by design.

  There is one exception to this rule: Value-speculation optimizations that leverage the branch-prediction hardware are safe on strongly ordered systems (such as x86), but not on weakly ordered systems (such as ARM or Power). Choose your compiler command-line options wisely!

EXAMPLE OF AMPLIFIED RCU-USAGE BUG

Because updaters can run concurrently with RCU readers, RCU readers can see stale and/or inconsistent values. If RCU readers need fresh or consistent values, which they sometimes do, they need to take proper precautions. To see this, consider the following code fragment:

```
struct foo {
        int a;
        int b;
        int c;
};
struct foo *gp1;
struct foo *gp2;

void updater(void)
{
        struct foo *p;

        p = kmalloc(...);
        if (p == NULL)
                deal_with_it();
        p->a = 42;  /* Each field in its own cache line. */
        p->b = 43;
        p->c = 44;
        rcu_assign_pointer(gp1, p);
        p->b = 143;
        p->c = 144;
        rcu_assign_pointer(gp2, p);
}

void reader(void)
{
        struct foo *p;
        struct foo *q;
        int r1, r2;

        p = rcu_dereference(gp2);
        if (p == NULL)
                return;
        r1 = p->b;  /* Guaranteed to get 143. */
```

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```
        q = rcu_dereference(gp1);  /* Guaranteed non-NULL. */
        if (p == q) {
                /* The compiler decides that q->c is same as p->c.␣
↪*/
                r2 = p->c; /* Could get 44 on weakly order system.␣
↪*/
        }
        do_something_with(r1, r2);
}
```

You might be surprised that the outcome (r1 == 143 && r2 == 44) is possible, but you should not be. After all, the updater might have been invoked a second time between the time reader() loaded into "r1" and the time that it loaded into "r2". The fact that this same result can occur due to some reordering from the compiler and CPUs is beside the point.

But suppose that the reader needs a consistent view?

Then one approach is to use locking, for example, as follows:

```
struct foo {
        int a;
        int b;
        int c;
        spinlock_t lock;
};
struct foo *gp1;
struct foo *gp2;

void updater(void)
{
        struct foo *p;

        p = kmalloc(...);
        if (p == NULL)
                deal_with_it();
        spin_lock(&p->lock);
        p->a = 42;  /* Each field in its own cache line. */
        p->b = 43;
        p->c = 44;
        spin_unlock(&p->lock);
        rcu_assign_pointer(gp1, p);
        spin_lock(&p->lock);
        p->b = 143;
        p->c = 144;
        spin_unlock(&p->lock);
        rcu_assign_pointer(gp2, p);
}

void reader(void)
```

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```
{
        struct foo *p;
        struct foo *q;
        int r1, r2;

        p = rcu_dereference(gp2);
        if (p == NULL)
                return;
        spin_lock(&p->lock);
        r1 = p->b;  /* Guaranteed to get 143. */
        q = rcu_dereference(gp1);  /* Guaranteed non-NULL. */
        if (p == q) {
                /* The compiler decides that q->c is same as p->c.␣
↪*/
                r2 = p->c; /* Locking guarantees r2 == 144. */
        }
        spin_unlock(&p->lock);
        do_something_with(r1, r2);
}
```

As always, use the right tool for the job!

EXAMPLE WHERE THE COMPILER KNOWS TOO MUCH

If a pointer obtained from *rcu_dereference()* compares not-equal to some other pointer, the compiler normally has no clue what the value of the first pointer might be. This lack of knowledge prevents the compiler from carrying out optimizations that otherwise might destroy the ordering guarantees that RCU depends on. And the volatile cast in *rcu_dereference()* should prevent the compiler from guessing the value.

But without *rcu_dereference()*, the compiler knows more than you might expect. Consider the following code fragment:

```
struct foo {
        int a;
        int b;
};
static struct foo variable1;
static struct foo variable2;
static struct foo *gp = &variable1;

void updater(void)
{
        initialize_foo(&variable2);
        rcu_assign_pointer(gp, &variable2);
        /*
         * The above is the only store to gp in this translation␣
↪unit,
```

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```
         * and the address of gp is not exported in any way.
         */
}

int reader(void)
{
        struct foo *p;

        p = gp;
        barrier();
        if (p == &variable1)
                return p->a; /* Must be variable1.a. */
        else
                return p->b; /* Must be variable2.b. */
}
```

Because the compiler can see all stores to "gp", it knows that the only possible values of "gp" are "variable1" on the one hand and "variable2" on the other. The comparison in reader() therefore tells the compiler the exact value of "p" even in the not-equals case. This allows the compiler to make the return values independent of the load from "gp", in turn destroying the ordering between this load and the loads of the return values. This can result in "p->b" returning pre-initialization garbage values.

In short, *rcu_dereference()* is -not- optional when you are going to dereference the resulting pointer.

WHICH MEMBER OF THE rcu_dereference() FAMILY SHOULD YOU USE?

First, please avoid using rcu_dereference_raw() and also please avoid using *rcu_dereference_check()* and *rcu_dereference_protected()* with a second argument with a constant value of 1 (or true, for that matter). With that caution out of the way, here is some guidance for which member of the *rcu_dereference()* to use in various situations:

1. If the access needs to be within an RCU read-side critical section, use *rcu_dereference()*. With the new consolidated RCU flavors, an RCU read-side critical section is entered using *rcu_read_lock()*, anything that disables bottom halves, anything that disables interrupts, or anything that disables preemption.
2. If the access might be within an RCU read-side critical section on the one hand, or protected by (say) my_lock on the other, use *rcu_dereference_check()*, for example:

   ```
   p1 = rcu_dereference_check(p->rcu_protected_pointer,
                              lockdep_is_held(&my_lock));
   ```

3. If the access might be within an RCU read-side critical section on the one hand, or protected by either my_lock or your_lock on the other, again use *rcu_dereference_check()*, for example:

```
p1 = rcu_dereference_check(p->rcu_protected_pointer,
                           lockdep_is_held(&my_lock) ||
                           lockdep_is_held(&your_lock));
```

4. If the access is on the update side, so that it is always protected by my_lock, use *rcu_dereference_protected()*:

```
p1 = rcu_dereference_protected(p->rcu_protected_pointer,
                               lockdep_is_held(&my_lock));
```

   This can be extended to handle multiple locks as in #3 above, and both can be extended to check other conditions as well.

5. If the protection is supplied by the caller, and is thus unknown to this code, that is the rare case when rcu_dereference_raw() is appropriate. In addition, rcu_dereference_raw() might be appropriate when the lockdep expression would be excessively complex, except that a better approach in that case might be to take a long hard look at your synchronization design. Still, there are data-locking cases where any one of a very large number of locks or reference counters suffices to protect the pointer, so rcu_dereference_raw() does have its place.

   However, its place is probably quite a bit smaller than one might expect given the number of uses in the current kernel. Ditto for its synonym, rcu_dereference_check(···, 1), and its close relative, rcu_dereference_protected(···, 1).

SPARSE CHECKING OF RCU-PROTECTED POINTERS

The sparse static-analysis tool checks for direct access to RCU-protected pointers, which can result in "interesting" bugs due to compiler optimizations involving invented loads and perhaps also load tearing. For example, suppose someone mistakenly does something like this:

```
p = q->rcu_protected_pointer;
do_something_with(p->a);
do_something_else_with(p->b);
```

If register pressure is high, the compiler might optimize "p" out of existence, transforming the code to something like this:

```
do_something_with(q->rcu_protected_pointer->a);
do_something_else_with(q->rcu_protected_pointer->b);
```

This could fatally disappoint your code if q->rcu_protected_pointer changed in the meantime. Nor is this a theoretical problem: Exactly this sort of bug cost Paul E. McKenney (and several of his innocent colleagues) a three-day weekend back in the early 1990s.

Load tearing could of course result in dereferencing a mashup of a pair of pointers, which also might fatally disappoint your code.

These problems could have been avoided simply by making the code instead read as follows:

```
p = rcu_dereference(q->rcu_protected_pointer);
do_something_with(p->a);
do_something_else_with(p->b);
```

Unfortunately, these sorts of bugs can be extremely hard to spot during review. This is where the sparse tool comes into play, along with the "__rcu" marker. If you mark a pointer declaration, whether in a structure or as a formal parameter, with "__rcu", which tells sparse to complain if this pointer is accessed directly. It will also cause sparse to complain if a pointer not marked with "__rcu" is accessed using *rcu_dereference()* and friends. For example, ->rcu_protected_pointer might be declared as follows:

```
struct foo __rcu *rcu_protected_pointer;
```

Use of "__rcu" is opt-in. If you choose not to use it, then you should ignore the sparse warnings.

3.6.7 What is RCU? – "Read, Copy, Update"

Please note that the "What is RCU?" LWN series is an excellent place to start learning about RCU:

1. What is RCU, Fundamentally? http://lwn.net/Articles/262464/
2. What is RCU? Part 2: Usage http://lwn.net/Articles/263130/
3. RCU part 3: the RCU API http://lwn.net/Articles/264090/
4. The RCU API, 2010 Edition http://lwn.net/Articles/418853/
   2010 Big API Table http://lwn.net/Articles/419086/
5. The RCU API, 2014 Edition http://lwn.net/Articles/609904/
   2014 Big API Table http://lwn.net/Articles/609973/

What is RCU?

RCU is a synchronization mechanism that was added to the Linux kernel during the 2.5 development effort that is optimized for read-mostly situations. Although RCU is actually quite simple once you understand it, getting there can sometimes be a challenge. Part of the problem is that most of the past descriptions of RCU have been written with the mistaken assumption that there is "one true way" to describe RCU. Instead, the experience has been that different people must take different paths to arrive at an understanding of RCU. This document provides several different paths, as follows:

1. RCU OVERVIEW

2. WHAT IS RCU'S CORE API?

3. WHAT ARE SOME EXAMPLE USES OF CORE RCU API?

4. WHAT IF MY UPDATING THREAD CANNOT BLOCK?

People who prefer starting with a conceptual overview should focus on Section 1, though most readers will profit by reading this section at some point. People who prefer to start with an API that they can then experiment with should focus on Section 2. People who prefer to start with example uses should focus on Sections 3 and 4. People who need to understand the RCU implementation should focus on Section 5, then dive into the kernel source code. People who reason best by analogy should focus on Section 6. Section 7 serves as an index to the docbook API documentation, and Section 8 is the traditional answer key.

So, start with the section that makes the most sense to you and your preferred method of learning. If you need to know everything about everything, feel free to read the whole thing – but if you are really that type of person, you have perused the source code and will therefore never need this document anyway. ;-)

1. RCU OVERVIEW

The basic idea behind RCU is to split updates into "removal" and "reclamation" phases. The removal phase removes references to data items within a data structure (possibly by replacing them with references to new versions of these data items), and can run concurrently with readers. The reason that it is safe to run the removal phase concurrently with readers is the semantics of modern CPUs guarantee that readers will see either the old or the new version of the data structure rather than a partially updated reference. The reclamation phase does the work of reclaiming (e.g., freeing) the data items removed from the data structure during the removal phase. Because reclaiming data items can disrupt any readers concurrently referencing those data items, the reclamation phase must not start until readers no longer hold references to those data items.

Splitting the update into removal and reclamation phases permits the updater to perform the removal phase immediately, and to defer the reclamation phase until all readers active during the removal phase have completed, either by blocking until they finish or by registering a callback that is invoked after they finish. Only readers that are active during the removal phase need be considered, because any reader starting after the removal phase will be unable to gain a reference to the removed data items, and therefore cannot be disrupted by the reclamation phase.

So the typical RCU update sequence goes something like the following:

a. Remove pointers to a data structure, so that subsequent readers cannot gain a reference to it.

b. Wait for all previous readers to complete their RCU read-side critical sections.

c. At this point, there cannot be any readers who hold references to the data structure, so it now may safely be reclaimed (e.g., `kfree()`d).

Step (b) above is the key idea underlying RCU's deferred destruction. The ability to wait until all readers are done allows RCU readers to use much lighter-weight synchronization, in some cases, absolutely no synchronization at all. In contrast, in more conventional lock-based schemes, readers must use heavy-weight synchronization in order to prevent an updater from deleting the data structure out from under them. This is because lock-based updaters typically update data items in place, and must therefore exclude readers. In contrast, RCU-based updaters typically take advantage of the fact that writes to single aligned pointers are atomic on modern CPUs, allowing atomic insertion, removal, and replacement of data items in a linked structure without disrupting readers. Concurrent RCU readers can then continue accessing the old versions, and can dispense with the atomic operations, memory barriers, and communications cache misses that are so expensive on present-day SMP computer systems, even in absence of lock contention.

In the three-step procedure shown above, the updater is performing both the removal and the reclamation step, but it is often helpful for an entirely different thread to do the reclamation, as is in fact the case in the Linux kernel's directory-entry cache (dcache). Even if the same thread performs both the update step (step (a) above) and the reclamation step (step (c) above), it is often helpful to think of them separately. For example, RCU readers and updaters need not communicate at all, but RCU provides implicit low-overhead communication between readers and reclaimers, namely, in step (b) above.

So how the heck can a reclaimer tell when a reader is done, given that readers are not doing any sort of synchronization operations??? Read on to learn about how RCU's API makes this easy.

2. WHAT IS RCU'S CORE API?

The core RCU API is quite small:

a. *rcu_read_lock()*
b. *rcu_read_unlock()*
c. *synchronize_rcu()* / *call_rcu()*
d. *rcu_assign_pointer()*
e. *rcu_dereference()*

There are many other members of the RCU API, but the rest can be expressed in terms of these five, though most implementations instead express *synchronize_rcu()* in terms of the *call_rcu()* callback API.

The five core RCU APIs are described below, the other 18 will be enumerated later. See the kernel docbook documentation for more info, or look directly at the function header comments.

rcu_read_lock()

void rcu_read_lock(void);

Used by a reader to inform the reclaimer that the reader is entering an RCU read-side critical section. It is illegal to block while in an RCU read-side critical section, though kernels built with CONFIG_PREEMPT_RCU can preempt RCU read-side critical sections. Any RCU-protected data structure accessed during an RCU read-side critical section is guaranteed to remain unreclaimed for the full duration of that critical section. Reference counts may be used in conjunction with RCU to maintain longer-term references to data structures.

rcu_read_unlock()

void rcu_read_unlock(void);

Used by a reader to inform the reclaimer that the reader is exiting an RCU read-side critical section. Note that RCU read-side critical sections may be nested and/or overlapping.

synchronize_rcu()

void synchronize_rcu(void);

Marks the end of updater code and the beginning of reclaimer code. It does this by blocking until all pre-existing RCU read-side critical sections on all CPUs have completed. Note that *synchronize_rcu()* will **not** necessarily wait for any subsequent RCU read-side critical sections to complete. For example, consider the following sequence of events:

```
        CPU 0                  CPU 1                 CPU 2
    ----------------- ------------------------- ------------
↪---
1.  rcu_read_lock()
2.                   enters synchronize_rcu()
3.                                                 rcu_read_
↪lock()
4.  rcu_read_unlock()
5.                    exits synchronize_rcu()
6.                                                rcu_read_
↪unlock()
```

To reiterate, *synchronize_rcu()* waits only for ongoing RCU read-side critical sections to complete, not necessarily for any that begin after *synchronize_rcu()* is invoked.

Of course, *synchronize_rcu()* does not necessarily return **immediately** after the last pre-existing RCU read-side critical section completes. For one thing, there might well be scheduling delays. For another thing, many RCU implementations process requests in batches in order to improve efficiencies, which can further delay *synchronize_rcu()*.

Since *synchronize_rcu()* is the API that must figure out when readers are done, its implementation is key to RCU. For RCU to be useful in all but the most read-intensive situations, *synchronize_rcu()*'s overhead must also be quite small.

The *call_rcu()* API is a callback form of *synchronize_rcu()*, and is described in more detail in a later section. Instead of blocking, it registers a function and argument which are invoked after all ongoing RCU read-side critical sections have completed. This callback variant is particularly useful in situations where it is illegal to block or where update-side performance is critically important.

However, the *call_rcu()* API should not be used lightly, as use of the *synchronize_rcu()* API generally results in simpler code. In addition, the *synchronize_rcu()* API has the nice property of automatically limiting update rate should grace periods be delayed. This property results in system resilience in face of denial-of-service attacks. Code using *call_rcu()* should limit update rate in order to gain this same sort of resilience. See checklist.txt for some approaches to limiting the update rate.

rcu_assign_pointer()

void rcu_assign_pointer(p, typeof(p) v);

Yes, *rcu_assign_pointer()* **is** implemented as a macro, though it would be cool to be able to declare a function in this manner. (Compiler experts will no doubt disagree.)

The updater uses this function to assign a new value to an RCU-protected pointer, in order to safely communicate the change in value from the updater to the reader. This macro does not evaluate to an rvalue, but it does execute any memory-barrier instructions required for a given CPU architecture.

Perhaps just as important, it serves to document (1) which pointers are protected by RCU and (2) the point at which a given structure becomes accessible to other CPUs. That said, *rcu_assign_pointer()* is most frequently used indirectly, via the _rcu list-manipulation primitives such as *list_add_rcu()*.

rcu_dereference()

typeof(p) rcu_dereference(p);

Like *rcu_assign_pointer()*, *rcu_dereference()* must be implemented as a macro.

The reader uses *rcu_dereference()* to fetch an RCU-protected pointer, which returns a value that may then be safely dereferenced. Note that *rcu_dereference()* does not actually dereference the pointer, instead, it protects the pointer for later dereferencing. It also executes any needed memory-barrier instructions for a given CPU architecture. Currently, only Alpha needs memory barriers within *rcu_dereference()* – on other CPUs, it compiles to nothing, not even a compiler directive.

Common coding practice uses *rcu_dereference()* to copy an RCU-protected pointer to a local variable, then dereferences this local variable, for example as follows:

```
p = rcu_dereference(head.next);
return p->data;
```

However, in this case, one could just as easily combine these into one statement:

```
return rcu_dereference(head.next)->data;
```

If you are going to be fetching multiple fields from the RCU-protected structure, using the local variable is of course preferred. Repeated *rcu_dereference()* calls look ugly, do not guarantee that the same pointer will be returned if an update happened while in the critical section, and incur unnecessary overhead on Alpha CPUs.

Note that the value returned by *rcu_dereference()* is valid only within the enclosing RCU read-side critical section[1]. For example, the following is **not** legal:

```
rcu_read_lock();
p = rcu_dereference(head.next);
rcu_read_unlock();
x = p->address; /* BUG!!! */
rcu_read_lock();
y = p->data;    /* BUG!!! */
rcu_read_unlock();
```

[1] The variant *rcu_dereference_protected()* can be used outside of an RCU read-side critical section as long as the usage is protected by locks acquired by the update-side code. This variant avoids the lockdep warning that would happen when using (for example) *rcu_dereference()* without *rcu_read_lock()* protection. Using *rcu_dereference_protected()* also has the advantage of permitting compiler optimizations that *rcu_dereference()* must prohibit. The *rcu_dereference_protected()* variant takes a lockdep expression to indicate which locks must be acquired by the caller. If the indicated protection is not provided, a lockdep splat is emitted. See *A Tour Through RCU's Requirements* and the API's code comments for more details and example usage.

> Holding a reference from one RCU read-side critical section to another is just as illegal as holding a reference from one lock-based critical section to another! Similarly, using a reference outside of the critical section in which it was acquired is just as illegal as doing so with normal locking.
>
> As with *rcu_assign_pointer()*, an important function of *rcu_dereference()* is to document which pointers are protected by RCU, in particular, flagging a pointer that is subject to changing at any time, including immediately after the *rcu_dereference()*. And, again like *rcu_assign_pointer()*, *rcu_dereference()* is typically used indirectly, via the _rcu list-manipulation primitives, such as *list_for_each_entry_rcu()*[2].

The following diagram shows how each API communicates among the reader, updater, and reclaimer.

```
rcu_assign_pointer()
                        +--------+
+---------------------->| reader |---------+
|                       +--------+         |
|                           |              |
|                           |              | Protect:
|                           |              | rcu_read_lock()
|                           |              | rcu_read_unlock()
|        rcu_dereference()  |              |
+---------+                 |              |
| updater |<----------------+              |
+---------+                                V
|                                    +-----------+
+----------------------------------->| reclaimer |
                                     +-----------+
  Defer:
  synchronize_rcu() & call_rcu()
```

The RCU infrastructure observes the time sequence of *rcu_read_lock()*, *rcu_read_unlock()*, *synchronize_rcu()*, and *call_rcu()* invocations in order to determine when (1) *synchronize_rcu()* invocations may return to their callers and (2) *call_rcu()* callbacks may be invoked. Efficient implementations of the RCU infrastructure make heavy use of batching in order to amortize their overhead over many uses of the corresponding APIs.

There are at least three flavors of RCU usage in the Linux kernel. The diagram above shows the most common one. On the updater side, the *rcu_assign_pointer()*, *synchronize_rcu()* and *call_rcu()* primitives used are the same for all three flavors. However for protection (on the reader side), the primitives used vary depending on the flavor:

a. *rcu_read_lock()* / *rcu_read_unlock()* *rcu_dereference()*

[2] If the *list_for_each_entry_rcu()* instance might be used by update-side code as well as by RCU readers, then an additional lockdep expression can be added to its list of arguments. For example, given an additional "lock_is_held(&mylock)" argument, the RCU lockdep code would complain only if this instance was invoked outside of an RCU read-side critical section and without the protection of mylock.

b. *rcu_read_lock_bh()* / *rcu_read_unlock_bh()* local_bh_disable() / local_bh_enable() *rcu_dereference_bh()*

c. *rcu_read_lock_sched()* / *rcu_read_unlock_sched()* preempt_disable() / preempt_enable() local_irq_save() / local_irq_restore() hardirq enter / hardirq exit NMI enter / NMI exit *rcu_dereference_sched()*

These three flavors are used as follows:

a. RCU applied to normal data structures.

b. RCU applied to networking data structures that may be subjected to remote denial-of-service attacks.

c. RCU applied to scheduler and interrupt/NMI-handler tasks.

Again, most uses will be of (a). The (b) and (c) cases are important for specialized uses, but are relatively uncommon.

3. WHAT ARE SOME EXAMPLE USES OF CORE RCU API?

This section shows a simple use of the core RCU API to protect a global pointer to a dynamically allocated structure. More-typical uses of RCU may be found in *listRCU.rst*, *arrayRCU.rst*, and *NMI-RCU.rst*.

```
struct foo {
        int a;
        char b;
        long c;
};
DEFINE_SPINLOCK(foo_mutex);

struct foo __rcu *gbl_foo;

/*
 * Create a new struct foo that is the same as the one currently
 * pointed to by gbl_foo, except that field "a" is replaced
 * with "new_a".  Points gbl_foo to the new structure, and
 * frees up the old structure after a grace period.
 *
 * Uses rcu_assign_pointer() to ensure that concurrent readers
 * see the initialized version of the new structure.
 *
 * Uses synchronize_rcu() to ensure that any readers that might
 * have references to the old structure complete before freeing
 * the old structure.
 */
void foo_update_a(int new_a)
{
        struct foo *new_fp;
        struct foo *old_fp;

        new_fp = kmalloc(sizeof(*new_fp), GFP_KERNEL);
```

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```
        spin_lock(&foo_mutex);
        old_fp = rcu_dereference_protected(gbl_foo, lockdep_is_
↪held(&foo_mutex));
        *new_fp = *old_fp;
        new_fp->a = new_a;
        rcu_assign_pointer(gbl_foo, new_fp);
        spin_unlock(&foo_mutex);
        synchronize_rcu();
        kfree(old_fp);
}

/*
 * Return the value of field "a" of the current gbl_foo
 * structure.  Use rcu_read_lock() and rcu_read_unlock()
 * to ensure that the structure does not get deleted out
 * from under us, and use rcu_dereference() to ensure that
 * we see the initialized version of the structure (important
 * for DEC Alpha and for people reading the code).
 */
int foo_get_a(void)
{
        int retval;

        rcu_read_lock();
        retval = rcu_dereference(gbl_foo)->a;
        rcu_read_unlock();
        return retval;
}
```

So, to sum up:

- Use *rcu_read_lock()* and *rcu_read_unlock()* to guard RCU read-side critical sections.
- Within an RCU read-side critical section, use *rcu_dereference()* to dereference RCU-protected pointers.
- Use some solid scheme (such as locks or semaphores) to keep concurrent updates from interfering with each other.
- Use *rcu_assign_pointer()* to update an RCU-protected pointer. This primitive protects concurrent readers from the updater, **not** concurrent updates from each other! You therefore still need to use locking (or something similar) to keep concurrent *rcu_assign_pointer()* primitives from interfering with each other.
- Use *synchronize_rcu()* **after** removing a data element from an RCU-protected data structure, but **before** reclaiming/freeing the data element, in order to wait for the completion of all RCU read-side critical sections that might be referencing that data item.

See checklist.txt for additional rules to follow when using RCU. And again, more-typical uses of RCU may be found in *listRCU.rst*, *arrayRCU.rst*, and *NMI-RCU.rst*.

4. WHAT IF MY UPDATING THREAD CANNOT BLOCK?

In the example above, foo_update_a() blocks until a grace period elapses. This is quite simple, but in some cases one cannot afford to wait so long – there might be other high-priority work to be done.

In such cases, one uses *call_rcu()* rather than *synchronize_rcu()*. The *call_rcu()* API is as follows:

```
void call_rcu(struct rcu_head * head,
              void (*func)(struct rcu_head *head));
```

This function invokes func(head) after a grace period has elapsed. This invocation might happen from either softirq or process context, so the function is not permitted to block. The foo struct needs to have an rcu_head structure added, perhaps as follows:

```
struct foo {
        int a;
        char b;
        long c;
        struct rcu_head rcu;
};
```

The foo_update_a() function might then be written as follows:

```
/*
 * Create a new struct foo that is the same as the one currently
 * pointed to by gbl_foo, except that field "a" is replaced
 * with "new_a".  Points gbl_foo to the new structure, and
 * frees up the old structure after a grace period.
 *
 * Uses rcu_assign_pointer() to ensure that concurrent readers
 * see the initialized version of the new structure.
 *
 * Uses call_rcu() to ensure that any readers that might have
 * references to the old structure complete before freeing the
 * old structure.
 */
void foo_update_a(int new_a)
{
        struct foo *new_fp;
        struct foo *old_fp;

        new_fp = kmalloc(sizeof(*new_fp), GFP_KERNEL);
        spin_lock(&foo_mutex);
        old_fp = rcu_dereference_protected(gbl_foo, lockdep_is_
→held(&foo_mutex));
        *new_fp = *old_fp;
        new_fp->a = new_a;
        rcu_assign_pointer(gbl_foo, new_fp);
        spin_unlock(&foo_mutex);
```

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```
        call_rcu(&old_fp->rcu, foo_reclaim);
}
```

The foo_reclaim() function might appear as follows:

```
void foo_reclaim(struct rcu_head *rp)
{
        struct foo *fp = container_of(rp, struct foo, rcu);

        foo_cleanup(fp->a);

        kfree(fp);
}
```

The container_of() primitive is a macro that, given a pointer into a struct, the type of the struct, and the pointed-to field within the struct, returns a pointer to the beginning of the struct.

The use of *call_rcu()* permits the caller of foo_update_a() to immediately regain control, without needing to worry further about the old version of the newly updated element. It also clearly shows the RCU distinction between updater, namely foo_update_a(), and reclaimer, namely foo_reclaim().

The summary of advice is the same as for the previous section, except that we are now using *call_rcu()* rather than *synchronize_rcu()*:

- Use *call_rcu()* **after** removing a data element from an RCU-protected data structure in order to register a callback function that will be invoked after the completion of all RCU read-side critical sections that might be referencing that data item.

If the callback for *call_rcu()* is not doing anything more than calling *kfree()* on the structure, you can use *kfree_rcu()* instead of *call_rcu()* to avoid having to write your own callback:

```
kfree_rcu(old_fp, rcu);
```

Again, see checklist.txt for additional rules governing the use of RCU.

5. WHAT ARE SOME SIMPLE IMPLEMENTATIONS OF RCU?

One of the nice things about RCU is that it has extremely simple "toy" implementations that are a good first step towards understanding the production-quality implementations in the Linux kernel. This section presents two such "toy" implementations of RCU, one that is implemented in terms of familiar locking primitives, and another that more closely resembles "classic" RCU. Both are way too simple for real-world use, lacking both functionality and performance. However, they are useful in getting a feel for how RCU works. See kernel/rcu/update.c for a production-quality implementation, and see:

> http://www.rdrop.com/users/paulmck/RCU

for papers describing the Linux kernel RCU implementation. The OLS'01 and OLS'02 papers are a good introduction, and the dissertation provides more details on the current implementation as of early 2004.

5A. "TOY" IMPLEMENTATION #1: LOCKING

This section presents a "toy" RCU implementation that is based on familiar locking primitives. Its overhead makes it a non-starter for real-life use, as does its lack of scalability. It is also unsuitable for realtime use, since it allows scheduling latency to "bleed" from one read-side critical section to another. It also assumes recursive reader-writer locks: If you try this with non-recursive locks, and you allow nested *rcu_read_lock()* calls, you can deadlock.

However, it is probably the easiest implementation to relate to, so is a good starting point.

It is extremely simple:

```
static DEFINE_RWLOCK(rcu_gp_mutex);

void rcu_read_lock(void)
{
        read_lock(&rcu_gp_mutex);
}

void rcu_read_unlock(void)
{
        read_unlock(&rcu_gp_mutex);
}

void synchronize_rcu(void)
{
        write_lock(&rcu_gp_mutex);
        smp_mb__after_spinlock();
        write_unlock(&rcu_gp_mutex);
}
```

[You can ignore *rcu_assign_pointer()* and *rcu_dereference()* without missing much. But here are simplified versions anyway. And whatever you do, don't forget about them when submitting patches making use of RCU!]:

```
#define rcu_assign_pointer(p, v) \
({ \
        smp_store_release(&(p), (v)); \
})

#define rcu_dereference(p) \
({ \
        typeof(p) _________p1 = READ_ONCE(p); \
        (_________p1); \
})
```

The *rcu_read_lock()* and *rcu_read_unlock()* primitive read-acquire and release a global reader-writer lock. The *synchronize_rcu()* primitive write-acquires this same lock, then releases it. This means that once *synchronize_rcu()* exits, all RCU read-side critical sections that were in progress before *synchronize_rcu()* was called are guaranteed to have completed - there is no way that *synchronize_rcu()* would have been able to write-acquire the lock otherwise. The smp_mb__after_spinlock() promotes *synchronize_rcu()* to a full memory barrier in compliance with the "Memory-Barrier Guarantees" listed in:

> *A Tour Through RCU's Requirements*

It is possible to nest *rcu_read_lock()*, since reader-writer locks may be recursively acquired. Note also that *rcu_read_lock()* is immune from deadlock (an important property of RCU). The reason for this is that the only thing that can block *rcu_read_lock()* is a *synchronize_rcu()*. But *synchronize_rcu()* does not acquire any locks while holding rcu_gp_mutex, so there can be no deadlock cycle.

Quick Quiz #1:
> Why is this argument naive? How could a deadlock occur when using this algorithm in a real-world Linux kernel? How could this deadlock be avoided?

Answers to Quick Quiz

5B. "TOY" EXAMPLE #2: CLASSIC RCU

This section presents a "toy" RCU implementation that is based on "classic RCU" . It is also short on performance (but only for updates) and on features such as hotplug CPU and the ability to run in CONFIG_PREEMPT kernels. The definitions of *rcu_dereference()* and *rcu_assign_pointer()* are the same as those shown in the preceding section, so they are omitted.

```
void rcu_read_lock(void) { }

void rcu_read_unlock(void) { }

void synchronize_rcu(void)
{
        int cpu;

        for_each_possible_cpu(cpu)
                run_on(cpu);
}
```

Note that *rcu_read_lock()* and *rcu_read_unlock()* do absolutely nothing. This is the great strength of classic RCU in a non-preemptive kernel: read-side overhead is precisely zero, at least on non-Alpha CPUs. And there is absolutely no way that *rcu_read_lock()* can possibly participate in a deadlock cycle!

The implementation of *synchronize_rcu()* simply schedules itself on each CPU in turn. The run_on() primitive can be implemented straightforwardly in terms of the sched_setaffinity() primitive. Of course, a somewhat less "toy" implementation would restore the affinity upon completion rather than just leaving all tasks running on the last CPU, but when I said "toy", I meant **toy**!

So how the heck is this supposed to work???

Remember that it is illegal to block while in an RCU read-side critical section. Therefore, if a given CPU executes a context switch, we know that it must have completed all preceding RCU read-side critical sections. Once **all** CPUs have executed a context switch, then **all** preceding RCU read-side critical sections will have completed.

So, suppose that we remove a data item from its structure and then invoke *synchronize_rcu()*. Once *synchronize_rcu()* returns, we are guaranteed that there are no RCU read-side critical sections holding a reference to that data item, so we can safely reclaim it.

Quick Quiz #2:
Give an example where Classic RCU's read-side overhead is **negative**.

Answers to Quick Quiz

Quick Quiz #3:
If it is illegal to block in an RCU read-side critical section, what the heck do you do in PREEMPT_RT, where normal spinlocks can block???

Answers to Quick Quiz

6. ANALOGY WITH READER-WRITER LOCKING

Although RCU can be used in many different ways, a very common use of RCU is analogous to reader-writer locking. The following unified diff shows how closely related RCU and reader-writer locking can be.

```
@@ -5,5 +5,5 @@ struct el {
        int data;
        /* Other data fields */
 };
-rwlock_t listmutex;
+spinlock_t listmutex;
 struct el head;

@@ -13,15 +14,15 @@
        struct list_head *lp;
        struct el *p;

-       read_lock(&listmutex);
-       list_for_each_entry(p, head, lp) {
+       rcu_read_lock();
+       list_for_each_entry_rcu(p, head, lp) {
                if (p->key == key) {
                        *result = p->data;
-                       read_unlock(&listmutex);
+                       rcu_read_unlock();
                        return 1;
                }
```

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```
        }
-       read_unlock(&listmutex);
+       rcu_read_unlock();
        return 0;
 }

@@ -29,15 +30,16 @@
 {
        struct el *p;

-       write_lock(&listmutex);
+       spin_lock(&listmutex);
        list_for_each_entry(p, head, lp) {
                if (p->key == key) {
-                       list_del(&p->list);
-                       write_unlock(&listmutex);
+                       list_del_rcu(&p->list);
+                       spin_unlock(&listmutex);
+                       synchronize_rcu();
                        kfree(p);
                        return 1;
                }
        }
-       write_unlock(&listmutex);
+       spin_unlock(&listmutex);
        return 0;
 }
```

Or, for those who prefer a side-by-side listing:

```
1 struct el {                          1 struct el {
2   struct list_head list;             2   struct list_head list;
3   long key;                          3   long key;
4   spinlock_t mutex;                  4   spinlock_t mutex;
5   int data;                          5   int data;
6   /* Other data fields */            6   /* Other data fields */
7 };                                   7 };
8 rwlock_t listmutex;                  8 spinlock_t listmutex;
9 struct el head;                      9 struct el head;
```

```
 1 int search(long key, int *result)    1 int search(long key, int␣
↪*result)
 2 {                                    2 {
 3   struct list_head *lp;              3   struct list_head *lp;
 4   struct el *p;                      4   struct el *p;
 5                                      5
 6   read_lock(&listmutex);             6   rcu_read_lock();
 7   list_for_each_entry(p, head, lp) { 7   list_for_each_entry_
↪rcu(p, head, lp) {
```

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```
    if (p->key == key) {
      *result = p->data;
      read_unlock(&listmutex);
      return 1;
    }
  }
  read_unlock(&listmutex);
  return 0;
}
```

```
    if (p->key == key) {
      *result = p->data;
      rcu_read_unlock();
      return 1;
    }
  }
  rcu_read_unlock();
  return 0;
}
```

```
int delete(long key)
{
  struct el *p;

  write_lock(&listmutex);
  list_for_each_entry(p, head, lp) {
    if (p->key == key) {
      list_del(&p->list);
      write_unlock(&listmutex);
      kfree(p);
      return 1;
    }
  }
  write_unlock(&listmutex);
  return 0;
}
```

```
int delete(long key)
{
  struct el *p;

  spin_lock(&listmutex);
  list_for_each_entry(p,
    if (p->key == key) {
      list_del_rcu(&p->
      spin_unlock(&
      synchronize_rcu();
      kfree(p);
      return 1;
    }
  }
  spin_unlock(&listmutex);
  return 0;
}
```

Either way, the differences are quite small. Read-side locking moves to *rcu_read_lock()* and rcu_read_unlock, update-side locking moves from a reader-writer lock to a simple spinlock, and a *synchronize_rcu()* precedes the *kfree()*.

However, there is one potential catch: the read-side and update-side critical sections can now run concurrently. In many cases, this will not be a problem, but it is necessary to check carefully regardless. For example, if multiple independent list updates must be seen as a single atomic update, converting to RCU will require special care.

Also, the presence of *synchronize_rcu()* means that the RCU version of delete() can now block. If this is a problem, there is a callback-based mechanism that never blocks, namely *call_rcu()* or *kfree_rcu()*, that can be used in place of *synchronize_rcu()*.

7. FULL LIST OF RCU APIs

The RCU APIs are documented in docbook-format header comments in the Linux-kernel source code, but it helps to have a full list of the APIs, since there does not appear to be a way to categorize them in docbook. Here is the list, by category.

RCU list traversal:

```
list_entry_rcu
list_entry_lockless
list_first_entry_rcu
list_next_rcu
list_for_each_entry_rcu
list_for_each_entry_continue_rcu
list_for_each_entry_from_rcu
list_first_or_null_rcu
list_next_or_null_rcu
hlist_first_rcu
hlist_next_rcu
hlist_pprev_rcu
hlist_for_each_entry_rcu
hlist_for_each_entry_rcu_bh
hlist_for_each_entry_from_rcu
hlist_for_each_entry_continue_rcu
hlist_for_each_entry_continue_rcu_bh
hlist_nulls_first_rcu
hlist_nulls_for_each_entry_rcu
hlist_bl_first_rcu
hlist_bl_for_each_entry_rcu
```

RCU pointer/list update:

```
rcu_assign_pointer
list_add_rcu
list_add_tail_rcu
list_del_rcu
list_replace_rcu
hlist_add_behind_rcu
hlist_add_before_rcu
hlist_add_head_rcu
hlist_add_tail_rcu
hlist_del_rcu
hlist_del_init_rcu
hlist_replace_rcu
list_splice_init_rcu
list_splice_tail_init_rcu
hlist_nulls_del_init_rcu
hlist_nulls_del_rcu
hlist_nulls_add_head_rcu
hlist_bl_add_head_rcu
hlist_bl_del_init_rcu
```

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```
hlist_bl_del_rcu
hlist_bl_set_first_rcu
```

RCU:

```
Critical sections       Grace period            Barrier

rcu_read_lock           synchronize_net         rcu_barrier
rcu_read_unlock         synchronize_rcu
rcu_dereference         synchronize_rcu_expedited
rcu_read_lock_held      call_rcu
rcu_dereference_check   kfree_rcu
rcu_dereference_protected
```

bh:

```
Critical sections       Grace period            Barrier

rcu_read_lock_bh        call_rcu                rcu_barrier
rcu_read_unlock_bh      synchronize_rcu
[local_bh_disable]      synchronize_rcu_expedited
[and friends]
rcu_dereference_bh
rcu_dereference_bh_check
rcu_dereference_bh_protected
rcu_read_lock_bh_held
```

sched:

```
Critical sections       Grace period            Barrier

rcu_read_lock_sched     call_rcu                rcu_barrier
rcu_read_unlock_sched   synchronize_rcu
[preempt_disable]       synchronize_rcu_expedited
[and friends]
rcu_read_lock_sched_notrace
rcu_read_unlock_sched_notrace
rcu_dereference_sched
rcu_dereference_sched_check
rcu_dereference_sched_protected
rcu_read_lock_sched_held
```

SRCU:

```
Critical sections       Grace period            Barrier

srcu_read_lock          call_srcu               srcu_barrier
srcu_read_unlock        synchronize_srcu
srcu_dereference        synchronize_srcu_expedited
srcu_dereference_check
srcu_read_lock_held
```

SRCU: Initialization/cleanup:

```
DEFINE_SRCU
DEFINE_STATIC_SRCU
init_srcu_struct
cleanup_srcu_struct
```

All: lockdep-checked RCU-protected pointer access:

```
rcu_access_pointer
rcu_dereference_raw
RCU_LOCKDEP_WARN
rcu_sleep_check
RCU_NONIDLE
```

See the comment headers in the source code (or the docbook generated from them) for more information.

However, given that there are no fewer than four families of RCU APIs in the Linux kernel, how do you choose which one to use? The following list can be helpful:

a. Will readers need to block? If so, you need SRCU.

b. What about the -rt patchset? If readers would need to block in an non-rt kernel, you need SRCU. If readers would block in a -rt kernel, but not in a non-rt kernel, SRCU is not necessary. (The -rt patchset turns spinlocks into sleeplocks, hence this distinction.)

c. Do you need to treat NMI handlers, hardirq handlers, and code segments with preemption disabled (whether via preempt_disable(), local_irq_save(), local_bh_disable(), or some other mechanism) as if they were explicit RCU readers? If so, RCU-sched is the only choice that will work for you.

d. Do you need RCU grace periods to complete even in the face of softirq monopolization of one or more of the CPUs? For example, is your code subject to network-based denial-of-service attacks? If so, you should disable softirq across your readers, for example, by using `rcu_read_lock_bh()`.

e. Is your workload too update-intensive for normal use of RCU, but inappropriate for other synchronization mechanisms? If so, consider SLAB_TYPESAFE_BY_RCU (which was originally named SLAB_DESTROY_BY_RCU). But please be careful!

f. Do you need read-side critical sections that are respected even though they are in the middle of the idle loop, during user-mode execution, or on an offlined CPU? If so, SRCU is the only choice that will work for you.

g. Otherwise, use RCU.

Of course, this all assumes that you have determined that RCU is in fact the right tool for your job.

8. ANSWERS TO QUICK QUIZZES

Quick Quiz #1:
Why is this argument naive? How could a deadlock occur when using this algorithm in a real-world Linux kernel? [Referring to the lock-based "toy" RCU algorithm.]

Answer:
Consider the following sequence of events:

1. CPU 0 acquires some unrelated lock, call it "problematic_lock", disabling irq via spin_lock_irqsave().
2. CPU 1 enters *synchronize_rcu()*, write-acquiring rcu_gp_mutex.
3. CPU 0 enters *rcu_read_lock()*, but must wait because CPU 1 holds rcu_gp_mutex.
4. CPU 1 is interrupted, and the irq handler attempts to acquire problematic_lock.

The system is now deadlocked.

One way to avoid this deadlock is to use an approach like that of CONFIG_PREEMPT_RT, where all normal spinlocks become blocking locks, and all irq handlers execute in the context of special tasks. In this case, in step 4 above, the irq handler would block, allowing CPU 1 to release rcu_gp_mutex, avoiding the deadlock.

Even in the absence of deadlock, this RCU implementation allows latency to "bleed" from readers to other readers through *synchronize_rcu()*. To see this, consider task A in an RCU read-side critical section (thus read-holding rcu_gp_mutex), task B blocked attempting to write-acquire rcu_gp_mutex, and task C blocked in *rcu_read_lock()* attempting to read_acquire rcu_gp_mutex. Task A's RCU read-side latency is holding up task C, albeit indirectly via task B.

Realtime RCU implementations therefore use a counter-based approach where tasks in RCU read-side critical sections cannot be blocked by tasks executing *synchronize_rcu()*.

Back to Quick Quiz #1

Quick Quiz #2:
Give an example where Classic RCU's read-side overhead is **negative**.

Answer:
Imagine a single-CPU system with a non-CONFIG_PREEMPT kernel where a routing table is used by process-context code, but can be updated by irq-context code (for example, by an "ICMP REDIRECT" packet). The usual way of handling this would be to have the process-context code disable interrupts while searching the routing table. Use of RCU allows such interrupt-disabling to be dispensed with. Thus, without RCU, you pay the cost of disabling interrupts, and with RCU you don't.

One can argue that the overhead of RCU in this case is negative with respect to the single-CPU interrupt-disabling approach. Others might argue that the overhead of RCU is merely zero, and that replacing the positive overhead of the interrupt-disabling scheme with the zero-overhead RCU scheme does not constitute negative overhead.

In real life, of course, things are more complex. But even the theoretical possibility of negative overhead for a synchronization primitive is a bit unexpected. ;-)

Back to Quick Quiz #2

Quick Quiz #3:
If it is illegal to block in an RCU read-side critical section, what the heck do you do in PREEMPT_RT, where normal spinlocks can block???

Answer:
Just as PREEMPT_RT permits preemption of spinlock critical sections, it permits preemption of RCU read-side critical sections. It also permits spinlocks blocking while in RCU read-side critical sections.

Why the apparent inconsistency? Because it is possible to use priority boosting to keep the RCU grace periods short if need be (for example, if running short of memory). In contrast, if blocking waiting for (say) network reception, there is no way to know what should be boosted. Especially given that the process we need to boost might well be a human being who just went out for a pizza or something. And although a computer-operated cattle prod might arouse serious interest, it might also provoke serious objections. Besides, how does the computer know what pizza parlor the human being went to???

Back to Quick Quiz #3

ACKNOWLEDGEMENTS

My thanks to the people who helped make this human-readable, including Jon Walpole, Josh Triplett, Serge Hallyn, Suzanne Wood, and Alan Stern.

For more information, see http://www.rdrop.com/users/paulmck/RCU.

3.6.8 RCU Concepts

The basic idea behind RCU (read-copy update) is to split destructive operations into two parts, one that prevents anyone from seeing the data item being destroyed, and one that actually carries out the destruction. A "grace period" must elapse between the two parts, and this grace period must be long enough that any readers accessing the item being deleted have since dropped their references. For example, an RCU-protected deletion from a linked list would first remove the item from the list, wait for a grace period to elapse, then free the element. See the Using RCU to Protect Read-Mostly Linked Lists for more information on using RCU with linked lists.

Frequently Asked Questions

- Why would anyone want to use RCU?

  The advantage of RCU's two-part approach is that RCU readers need not acquire any locks, perform any atomic instructions, write to shared memory, or (on CPUs other than Alpha) execute any memory barriers. The fact that these operations are quite expensive on modern CPUs is what gives RCU its performance advantages in read-mostly situations. The fact that RCU readers need not acquire locks can also greatly simplify deadlock-avoidance code.

- How can the updater tell when a grace period has completed if the RCU readers give no indication when they are done?

  Just as with spinlocks, RCU readers are not permitted to block, switch to user-mode execution, or enter the idle loop. Therefore, as soon as a CPU is seen passing through any of these three states, we know that that CPU has exited any previous RCU read-side critical sections. So, if we remove an item from a linked list, and then wait until all CPUs have switched context, executed in user mode, or executed in the idle loop, we can safely free up that item.

  Preemptible variants of RCU (CONFIG_PREEMPT_RCU) get the same effect, but require that the readers manipulate CPU-local counters. These counters allow limited types of blocking within RCU read-side critical sections. SRCU also uses CPU-local counters, and permits general blocking within RCU read-side critical sections. These variants of RCU detect grace periods by sampling these counters.

- If I am running on a uniprocessor kernel, which can only do one thing at a time, why should I wait for a grace period?

  See RCU on Uniprocessor Systems for more information.

- How can I see where RCU is currently used in the Linux kernel?

  Search for "rcu_read_lock", "rcu_read_unlock", "call_rcu", "rcu_read_lock_bh", "rcu_read_unlock_bh", "srcu_read_lock", "srcu_read_unlock", "synchronize_rcu", "synchronize_net", "synchronize_srcu", and the other RCU primitives. Or grab one of the cscope databases from:

  (http://www.rdrop.com/users/paulmck/RCU/linuxusage/rculocktab.html).

- What guidelines should I follow when writing code that uses RCU?

  See the checklist.txt file in this directory.

- Why the name "RCU"?

  "RCU" stands for "read-copy update". Using RCU to Protect Read-Mostly Linked Lists has more information on where this name came from, search for "read-copy update" to find it.

- I hear that RCU is patented? What is with that?

  Yes, it is. There are several known patents related to RCU, search for the string "Patent" in Documentation/RCU/RTFP.txt to find them. Of these, one was allowed to lapse by the assignee, and the others have been contributed to the Linux kernel under GPL. There are now also LGPL implementations of user-level RCU available (https://liburcu.org/).

- I hear that RCU needs work in order to support realtime kernels?

  Realtime-friendly RCU can be enabled via the CONFIG_PREEMPT_RCU kernel configuration parameter.

- Where can I find more information on RCU?

  See the Documentation/RCU/RTFP.txt file. Or point your browser at (http://www.rdrop.com/users/paulmck/RCU/).

3.6.9 Using RCU hlist_nulls to protect list and objects

This section describes how to use hlist_nulls to protect read-mostly linked lists and objects using SLAB_TYPESAFE_BY_RCU allocations.

Please read the basics in *Using RCU to Protect Read-Mostly Linked Lists*

Using 'nulls'

Using special makers (called 'nulls') is a convenient way to solve following problem :

A typical RCU linked list managing objects which are allocated with SLAB_TYPESAFE_BY_RCU kmem_cache can use following algos :

1) Lookup algo

```
rcu_read_lock()
begin:
obj = lockless_lookup(key);
if (obj) {
  if (!try_get_ref(obj)) // might fail for free objects
    goto begin;
  /*
  * Because a writer could delete object, and a writer could
  * reuse these object before the RCU grace period, we
  * must check key after getting the reference on object
  */
  if (obj->key != key) { // not the object we expected
    put_ref(obj);
    goto begin;
  }
}
rcu_read_unlock();
```

Beware that lockless_lookup(key) cannot use traditional *hlist_for_each_entry_rcu()* but a version with an additional memory barrier (smp_rmb())

```
lockless_lookup(key)
{
  struct hlist_node *node, *next;
  for (pos = rcu_dereference((head)->first);
      pos && ({ next = pos->next; smp_rmb(); prefetch(next); 1; }) &
↪&
      ({ tpos = hlist_entry(pos, typeof(*tpos), member); 1; });
      pos = rcu_dereference(next))
    if (obj->key == key)
      return obj;
  return NULL;
}
```

And note the traditional *hlist_for_each_entry_rcu()* misses this smp_rmb():

```
struct hlist_node *node;
for (pos = rcu_dereference((head)->first);
      pos && ({ prefetch(pos->next); 1; }) &&
      ({ tpos = hlist_entry(pos, typeof(*tpos), member); 1; });
      pos = rcu_dereference(pos->next))
 if (obj->key == key)
   return obj;
return NULL;
```

Quoting Corey Minyard:

```
"If the object is moved from one list to another list in-between the
time the hash is calculated and the next field is accessed, and the
object has moved to the end of a new list, the traversal will not
complete properly on the list it should have, since the object will
be on the end of the new list and there's not a way to tell it's on␣
↪a
new list and restart the list traversal. I think that this can be
solved by pre-fetching the "next" field (with proper barriers)␣
↪before
checking the key."
```

2) Insert algo

We need to make sure a reader cannot read the new 'obj->obj_next' value and previous value of 'obj->key'. Or else, an item could be deleted from a chain, and inserted into another chain. If new chain was empty before the move, 'next' pointer is NULL, and lockless reader can not detect it missed following items in original chain.

```
/*
* Please note that new inserts are done at the head of list,
* not in the middle or end.
*/
```

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```
obj = kmem_cache_alloc(...);
lock_chain(); // typically a spin_lock()
obj->key = key;
/*
* we need to make sure obj->key is updated before obj->next
* or obj->refcnt
*/
smp_wmb();
atomic_set(&obj->refcnt, 1);
hlist_add_head_rcu(&obj->obj_node, list);
unlock_chain(); // typically a spin_unlock()
```

3) Remove algo

Nothing special here, we can use a standard RCU hlist deletion. But thanks to SLAB_TYPESAFE_BY_RCU, beware a deleted object can be reused very very fast (before the end of RCU grace period)

```
if (put_last_reference_on(obj) {
  lock_chain(); // typically a spin_lock()
  hlist_del_init_rcu(&obj->obj_node);
  unlock_chain(); // typically a spin_unlock()
  kmem_cache_free(cachep, obj);
}
```

Avoiding extra smp_rmb()

With hlist_nulls we can avoid extra smp_rmb() in lockless_lookup() and extra smp_wmb() in insert function.

For example, if we choose to store the slot number as the 'nulls' end-of-list marker for each slot of the hash table, we can detect a race (some writer did a delete and/or a move of an object to another chain) checking the final 'nulls' value if the lookup met the end of chain. If final 'nulls' value is not the slot number, then we must restart the lookup at the beginning. If the object was moved to the same chain, then the reader doesn't care : It might eventually scan the list again without harm.

1) lookup algo

```
head = &table[slot];
rcu_read_lock();
begin:
hlist_nulls_for_each_entry_rcu(obj, node, head, member) {
  if (obj->key == key) {
    if (!try_get_ref(obj)) // might fail for free objects
```

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```
      goto begin;
    if (obj->key != key) { // not the object we expected
      put_ref(obj);
      goto begin;
    }
  goto out;
}
/*
* if the nulls value we got at the end of this lookup is
* not the expected one, we must restart lookup.
* We probably met an item that was moved to another chain.
*/
if (get_nulls_value(node) != slot)
goto begin;
obj = NULL;

out:
rcu_read_unlock();
```

2) Insert function

```
/*
* Please note that new inserts are done at the head of list,
* not in the middle or end.
*/
obj = kmem_cache_alloc(cachep);
lock_chain(); // typically a spin_lock()
obj->key = key;
/*
* changes to obj->key must be visible before refcnt one
*/
smp_wmb();
atomic_set(&obj->refcnt, 1);
/*
* insert obj in RCU way (readers might be traversing chain)
*/
hlist_nulls_add_head_rcu(&obj->obj_node, list);
unlock_chain(); // typically a spin_unlock()
```

3.6.10 Reference-count design for elements of lists/arrays protected by RCU

Please note that the percpu-ref feature is likely your first stop if you need to combine reference counts and RCU. Please see include/linux/percpu-refcount.h for more information. However, in those unusual cases where percpu-ref would consume too much memory, please read on.

Reference counting on elements of lists which are protected by traditional reader/writer spinlocks or semaphores are straightforward:

CODE LISTING A:

```
1.                                          2.
add()                                       search_and_reference()
{                                           {
    alloc_object                                read_lock(&list_lock);
    ...                                         search_for_element
    atomic_set(&el->rc, 1);                     atomic_inc(&el->rc);
    write_lock(&list_lock);                      ...
    add_element                                 read_unlock(&list_lock);
    ...                                         ...
    write_unlock(&list_lock);              }
}

3.                                          4.
release_referenced()                        delete()
{                                           {
    ...                                         write_lock(&list_lock);
    if(atomic_dec_and_test(&el->rc))            ...
        kfree(el);
    ...                                         remove_element
}                                               write_unlock(&list_
↪lock);
                                                ...
                                                if (atomic_dec_and_
↪test(&el->rc))
                                                    kfree(el);
                                                ...
                                            }
```

If this list/array is made lock free using RCU as in changing the write_lock() in add() and delete() to spin_lock() and changing read_lock() in search_and_reference() to *rcu_read_lock()*, the atomic_inc() in search_and_reference() could potentially hold reference to an element which has already been deleted from the list/array. Use atomic_inc_not_zero() in this scenario as follows:

CODE LISTING B:

```
1.                                          2.
add()                                       search_and_reference()
```

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```
{                                         {
    alloc_object                              rcu_read_lock();
    ...                                       search_for_element
    atomic_set(&el->rc, 1);                   if (!atomic_inc_not_
↪zero(&el->rc)) {
    spin_lock(&list_lock);                        rcu_read_unlock();
                                                  return FAIL;
    add_element                               }
    ...                                       ...
    spin_unlock(&list_lock);                  rcu_read_unlock();
}                                         }
3.                                        4.
release_referenced()                      delete()
{                                         {
    ...                                       spin_lock(&list_lock);
    if (atomic_dec_and_test(&el->rc))         ...
        call_rcu(&el->head, el_free);         remove_element
    ...                                       spin_unlock(&list_lock);
}                                             ...
                                              if (atomic_dec_and_
↪test(&el->rc))
                                                  call_rcu(&el->head,␣
↪el_free);
                                              ...
                                          }
```

Sometimes, a reference to the element needs to be obtained in the update (write) stream. In such cases, atomic_inc_not_zero() might be overkill, since we hold the update-side spinlock. One might instead use atomic_inc() in such cases.

It is not always convenient to deal with "FAIL" in the search_and_reference() code path. In such cases, the atomic_dec_and_test() may be moved from delete() to el_free() as follows:

CODE LISTING C:

```
1.                                        2.
add()                                     search_and_reference()
{                                         {
    alloc_object                              rcu_read_lock();
    ...                                       search_for_element
    atomic_set(&el->rc, 1);                   atomic_inc(&el->rc);
    spin_lock(&list_lock);                    ...

    add_element                               rcu_read_unlock();
    ...                                   }
    spin_unlock(&list_lock);              4.
}                                         delete()
3.                                        {
release_referenced()                          spin_lock(&list_lock);
```

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```
{                                                   ...
    ...                                             remove_element
    if (atomic_dec_and_test(&el->rc))               spin_unlock(&list_lock);
        kfree(el);                                  ...
    ...                                             call_rcu(&el->head, el_
↪free);
}                                                   ...
5.                                              }
void el_free(struct rcu_head *rhp)
{
    release_referenced();
}
```

The key point is that the initial reference added by add() is not removed until after a grace period has elapsed following removal. This means that search_and_reference() cannot find this element, which means that the value of el->rc cannot increase. Thus, once it reaches zero, there are no readers that can or ever will be able to reference the element. The element can therefore safely be freed. This in turn guarantees that if any reader finds the element, that reader may safely acquire a reference without checking the value of the reference counter.

A clear advantage of the RCU-based pattern in listing C over the one in listing B is that any call to search_and_reference() that locates a given object will succeed in obtaining a reference to that object, even given a concurrent invocation of delete() for that same object. Similarly, a clear advantage of both listings B and C over listing A is that a call to delete() is not delayed even if there are an arbitrarily large number of calls to search_and_reference() searching for the same object that delete() was invoked on. Instead, all that is delayed is the eventual invocation of *kfree()*, which is usually not a problem on modern computer systems, even the small ones.

In cases where delete() can sleep, *synchronize_rcu()* can be called from delete(), so that el_free() can be subsumed into delete as follows:

```
4.
delete()
{
    spin_lock(&list_lock);
    ...
    remove_element
    spin_unlock(&list_lock);
    ...
    synchronize_rcu();
    if (atomic_dec_and_test(&el->rc))
        kfree(el);
    ...
}
```

As additional examples in the kernel, the pattern in listing C is used by reference counting of struct pid, while the pattern in listing B is used by struct posix_acl.

3.6.11 RCU Torture Test Operation

CONFIG_RCU_TORTURE_TEST

The CONFIG_RCU_TORTURE_TEST config option is available for all RCU implementations. It creates an rcutorture kernel module that can be loaded to run a torture test. The test periodically outputs status messages via *printk()*, which can be examined via the dmesg command (perhaps grepping for "torture"). The test is started when the module is loaded, and stops when the module is unloaded.

Module parameters are prefixed by "rcutorture." in Documentation/admin-guide/kernel-parameters.txt.

Output

The statistics output is as follows:

```
rcu-torture:--- Start of test: nreaders=16 nfakewriters=4 stat_
↪interval=30 verbose=0 test_no_idle_hz=1 shuffle_interval=3␣
↪stutter=5 irqreader=1 fqs_duration=0 fqs_holdoff=0 fqs_stutter=3␣
↪test_boost=1/0 test_boost_interval=7 test_boost_duration=4
rcu-torture: rtc:           (null) ver: 155441 tfle: 0 rta: 155441␣
↪rtaf: 8884 rtf: 155440 rtmbe: 0 rtbe: 0 rtbke: 0 rtbre: 0 rtbf: 0␣
↪rtb: 0 nt: 3055767
rcu-torture: Reader Pipe:  727860534 34213 0 0 0 0 0 0 0 0 0
rcu-torture: Reader Batch:  727877838 17003 0 0 0 0 0 0 0 0 0
rcu-torture: Free-Block Circulation:  155440 155440 155440 155440␣
↪155440 155440 155440 155440 155440 155440 0
rcu-torture:--- End of test: SUCCESS: nreaders=16 nfakewriters=4␣
↪stat_interval=30 verbose=0 test_no_idle_hz=1 shuffle_interval=3␣
↪stutter=5 irqreader=1 fqs_duration=0 fqs_holdoff=0 fqs_stutter=3␣
↪test_boost=1/0 test_boost_interval=7 test_boost_duration=4
```

The command "dmesg | grep torture:"will extract this information on most systems. On more esoteric configurations, it may be necessary to use other commands to access the output of the *printk()*s used by the RCU torture test. The *printk()*s use KERN_ALERT, so they should be evident. ;-)

The first and last lines show the rcutorture module parameters, and the last line shows either "SUCCESS" or "FAILURE", based on rcutorture's automatic determination as to whether RCU operated correctly.

The entries are as follows:

- "rtc": The hexadecimal address of the structure currently visible to readers.
- "ver": The number of times since boot that the RCU writer task has changed the structure visible to readers.
- "tfle": If non-zero, indicates that the "torture freelist" containing structures to be placed into the "rtc" area is empty. This condition is important, since it can fool you into thinking that RCU is working when it is not. :-/
- "rta": Number of structures allocated from the torture freelist.

- "rtaf": Number of allocations from the torture freelist that have failed due to the list being empty. It is not unusual for this to be non-zero, but it is bad for it to be a large fraction of the value indicated by "rta".
- "rtf": Number of frees into the torture freelist.
- "rtmbe": A non-zero value indicates that rcutorture believes that *rcu_assign_pointer()* and *rcu_dereference()* are not working correctly. This value should be zero.
- "rtbe": A non-zero value indicates that one of the *rcu_barrier()* family of functions is not working correctly.
- "rtbke": rcutorture was unable to create the real-time kthreads used to force RCU priority inversion. This value should be zero.
- "rtbre": Although rcutorture successfully created the kthreads used to force RCU priority inversion, it was unable to set them to the real-time priority level of 1. This value should be zero.
- "rtbf": The number of times that RCU priority boosting failed to resolve RCU priority inversion.
- "rtb": The number of times that rcutorture attempted to force an RCU priority inversion condition. If you are testing RCU priority boosting via the "test_boost" module parameter, this value should be non-zero.
- "nt": The number of times rcutorture ran RCU read-side code from within a timer handler. This value should be non-zero only if you specified the "irqreader" module parameter.
- "Reader Pipe": Histogram of "ages" of structures seen by readers. If any entries past the first two are non-zero, RCU is broken. And rcutorture prints the error flag string "!!!"to make sure you notice. The age of a newly allocated structure is zero, it becomes one when removed from reader visibility, and is incremented once per grace period subsequently – and is freed after passing through (RCU_TORTURE_PIPE_LEN-2) grace periods.

  The output displayed above was taken from a correctly working RCU. If you want to see what it looks like when broken, break it yourself. ;-)
- "Reader Batch": Another histogram of "ages" of structures seen by readers, but in terms of counter flips (or batches) rather than in terms of grace periods. The legal number of non-zero entries is again two. The reason for this separate view is that it is sometimes easier to get the third entry to show up in the "Reader Batch" list than in the "Reader Pipe" list.
- "Free-Block Circulation": Shows the number of torture structures that have reached a given point in the pipeline. The first element should closely correspond to the number of structures allocated, the second to the number that have been removed from reader view, and all but the last remaining to the corresponding number of passes through a grace period. The last entry should be zero, as it is only incremented if a torture structure's counter somehow gets incremented farther than it should.

Different implementations of RCU can provide implementation-specific additional information. For example, Tree SRCU provides the following additional line:

```
srcud-torture: Tree SRCU per-CPU(idx=0): 0(35,-21) 1(-4,24) 2(1,1)␣
↪3(-26,20) 4(28,-47) 5(-9,4) 6(-10,14) 7(-14,11) T(1,6)
```

This line shows the per-CPU counter state, in this case for Tree SRCU using a dynamically allocated srcu_struct (hence "srcud-" rather than "srcu-"). The numbers in parentheses are the values of the "old" and "current" counters for the corresponding CPU. The "idx" value maps the "old" and "current" values to the underlying array, and is useful for debugging. The final "T" entry contains the totals of the counters.

Usage on Specific Kernel Builds

It is sometimes desirable to torture RCU on a specific kernel build, for example, when preparing to put that kernel build into production. In that case, the kernel should be built with CONFIG_RCU_TORTURE_TEST=m so that the test can be started using modprobe and terminated using rmmod.

For example, the following script may be used to torture RCU:

```
#!/bin/sh

modprobe rcutorture
sleep 3600
rmmod rcutorture
dmesg | grep torture:
```

The output can be manually inspected for the error flag of "!!!". One could of course create a more elaborate script that automatically checked for such errors. The "rmmod" command forces a "SUCCESS", "FAILURE", or "RCU_HOTPLUG" indication to be `printk()`ed. The first two are self-explanatory, while the last indicates that while there were no RCU failures, CPU-hotplug problems were detected.

Usage on Mainline Kernels

When using rcutorture to test changes to RCU itself, it is often necessary to build a number of kernels in order to test that change across a broad range of combinations of the relevant Kconfig options and of the relevant kernel boot parameters. In this situation, use of modprobe and rmmod can be quite time-consuming and error-prone.

Therefore, the tools/testing/selftests/rcutorture/bin/kvm.sh script is available for mainline testing for x86, arm64, and powerpc. By default, it will run the series of tests specified by tools/testing/selftests/rcutorture/configs/rcu/CFLIST, with each test running for 30 minutes within a guest OS using a minimal userspace supplied by an automatically generated initrd. After the tests are complete, the resulting build products and console output are analyzed for errors and the results of the runs are summarized.

On larger systems, rcutorture testing can be accelerated by passing the –cpus argument to kvm.sh. For example, on a 64-CPU system, "–cpus 43" would use up to 43 CPUs to run tests concurrently, which as of v5.4 would complete all the scenarios in two batches, reducing the time to complete from about eight hours to about one hour (not counting the time to build the sixteen kernels). The "–dryrun sched" argument will not run tests, but rather tell you how the tests would be scheduled into batches. This can be useful when working out how many CPUs to specify in the –cpus argument.

Not all changes require that all scenarios be run. For example, a change to Tree SRCU might run only the SRCU-N and SRCU-P scenarios using the –configs argument to kvm.sh as follows: "–configs 'SRCU-N SRCU-P' ". Large systems can run multiple copies of of the full set of scenarios, for example, a system with 448 hardware threads can run five instances of the full set concurrently. To make this happen:

```
kvm.sh --cpus 448 --configs '5*CFLIST'
```

Alternatively, such a system can run 56 concurrent instances of a single eight-CPU scenario:

```
kvm.sh --cpus 448 --configs '56*TREE04'
```

Or 28 concurrent instances of each of two eight-CPU scenarios:

```
kvm.sh --cpus 448 --configs '28*TREE03 28*TREE04'
```

Of course, each concurrent instance will use memory, which can be limited using the –memory argument, which defaults to 512M. Small values for memory may require disabling the callback-flooding tests using the –bootargs parameter discussed below.

Sometimes additional debugging is useful, and in such cases the –kconfig parameter to kvm.sh may be used, for example, `--kconfig 'CONFIG_KASAN=y'`.

Kernel boot arguments can also be supplied, for example, to control rcutorture's module parameters. For example, to test a change to RCU's CPU stall-warning code, use "–bootargs 'rcutorture.stall_cpu=30' ". This will of course result in the scripting reporting a failure, namely the resuling RCU CPU stall warning. As noted above, reducing memory may require disabling rcutorture's callback-flooding tests:

```
kvm.sh --cpus 448 --configs '56*TREE04' --memory 128M \
        --bootargs 'rcutorture.fwd_progress=0'
```

Sometimes all that is needed is a full set of kernel builds. This is what the –buildonly argument does.

Finally, the –trust-make argument allows each kernel build to reuse what it can from the previous kernel build.

There are additional more arcane arguments that are documented in the source code of the kvm.sh script.

If a run contains failures, the number of buildtime and runtime failures is listed at the end of the kvm.sh output, which you really should redirect to a file. The build products and console output of each run is kept in tools/testing/selftests/rcutorture/res in timestamped directories. A given directory can be supplied to kvm-find-errors.sh in order to have it cycle you through summaries of errors and full error logs. For example:

```
tools/testing/selftests/rcutorture/bin/kvm-find-errors.sh \
        tools/testing/selftests/rcutorture/res/2020.01.20-15.54.23
```

However, it is often more convenient to access the files directly. Files pertaining to all scenarios in a run reside in the top-level directory (2020.01.20-15.54.23 in the example above), while per-scenario files reside in a subdirectory named after the scenario (for example, "TREE04"). If a given scenario ran more than once (as in "–configs '56*TREE04'" above), the directories corresponding to the second and subsequent runs of that scenario include a sequence number, for example, "TREE04.2", "TREE04.3", and so on.

The most frequently used file in the top-level directory is testid.txt. If the test ran in a git repository, then this file contains the commit that was tested and any uncommitted changes in diff format.

The most frequently used files in each per-scenario-run directory are:

.config:
: This file contains the Kconfig options.

Make.out:
: This contains build output for a specific scenario.

console.log:
: This contains the console output for a specific scenario. This file may be examined once the kernel has booted, but it might not exist if the build failed.

vmlinux:
: This contains the kernel, which can be useful with tools like objdump and gdb.

A number of additional files are available, but are less frequently used. Many are intended for debugging of rcutorture itself or of its scripting.

As of v5.4, a successful run with the default set of scenarios produces the following summary at the end of the run on a 12-CPU system:

```
SRCU-N ------- 804233 GPs (148.932/s) [srcu: g10008272 f0x0 ]
SRCU-P ------- 202320 GPs (37.4667/s) [srcud: g1809476 f0x0 ]
SRCU-t ------- 1122086 GPs (207.794/s) [srcu: g0 f0x0 ]
SRCU-u ------- 1111285 GPs (205.794/s) [srcud: g1 f0x0 ]
TASKS01 ------- 19666 GPs (3.64185/s) [tasks: g0 f0x0 ]
TASKS02 ------- 20541 GPs (3.80389/s) [tasks: g0 f0x0 ]
TASKS03 ------- 19416 GPs (3.59556/s) [tasks: g0 f0x0 ]
TINY01 ------- 836134 GPs (154.84/s) [rcu: g0 f0x0 ] n_max_cbs:␣
↪34198
TINY02 ------- 850371 GPs (157.476/s) [rcu: g0 f0x0 ] n_max_cbs:␣
↪2631
TREE01 ------- 162625 GPs (30.1157/s) [rcu: g1124169 f0x0 ]
TREE02 ------- 333003 GPs (61.6672/s) [rcu: g2647753 f0x0 ] n_max_
↪cbs: 35844
```

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```
TREE03 ------- 306623 GPs (56.782/s) [rcu: g2975325 f0x0 ] n_max_
↪cbs: 1496497
CPU count limited from 16 to 12
TREE04 ------- 246149 GPs (45.5831/s) [rcu: g1695737 f0x0 ] n_max_
↪cbs: 434961
TREE05 ------- 314603 GPs (58.2598/s) [rcu: g2257741 f0x2 ] n_max_
↪cbs: 193997
TREE07 ------- 167347 GPs (30.9902/s) [rcu: g1079021 f0x0 ] n_max_
↪cbs: 478732
CPU count limited from 16 to 12
TREE09 ------- 752238 GPs (139.303/s) [rcu: g13075057 f0x0 ] n_max_
↪cbs: 99011
```

3.6.12 Using RCU's CPU Stall Detector

This document first discusses what sorts of issues RCU's CPU stall detector can locate, and then discusses kernel parameters and Kconfig options that can be used to fine-tune the detector's operation. Finally, this document explains the stall detector's "splat" format.

What Causes RCU CPU Stall Warnings?

So your kernel printed an RCU CPU stall warning. The next question is "What caused it?" The following problems can result in RCU CPU stall warnings:

- A CPU looping in an RCU read-side critical section.
- A CPU looping with interrupts disabled.
- A CPU looping with preemption disabled.
- A CPU looping with bottom halves disabled.
- For !CONFIG_PREEMPT kernels, a CPU looping anywhere in the kernel without invoking schedule(). If the looping in the kernel is really expected and desirable behavior, you might need to add some calls to cond_resched().
- Booting Linux using a console connection that is too slow to keep up with the boot-time console-message rate. For example, a 115Kbaud serial console can be -way- too slow to keep up with boot-time message rates, and will frequently result in RCU CPU stall warning messages. Especially if you have added debug *printk()*s.
- Anything that prevents RCU's grace-period kthreads from running. This can result in the "All QSes seen" console-log message. This message will include information on when the kthread last ran and how often it should be expected to run. It can also result in the `rcu_.*kthread starved for` console-log message, which will include additional debugging information.
- A CPU-bound real-time task in a CONFIG_PREEMPT kernel, which might happen to preempt a low-priority task in the middle of an RCU read-side critical section. This is especially damaging if that low-priority task is not permitted

to run on any other CPU, in which case the next RCU grace period can never complete, which will eventually cause the system to run out of memory and hang. While the system is in the process of running itself out of memory, you might see stall-warning messages.

- A CPU-bound real-time task in a CONFIG_PREEMPT_RT kernel that is running at a higher priority than the RCU softirq threads. This will prevent RCU callbacks from ever being invoked, and in a CONFIG_PREEMPT_RCU kernel will further prevent RCU grace periods from ever completing. Either way, the system will eventually run out of memory and hang. In the CONFIG_PREEMPT_RCU case, you might see stall-warning messages.

  You can use the rcutree.kthread_prio kernel boot parameter to increase the scheduling priority of RCU's kthreads, which can help avoid this problem. However, please note that doing this can increase your system's context-switch rate and thus degrade performance.

- A periodic interrupt whose handler takes longer than the time interval between successive pairs of interrupts. This can prevent RCU's kthreads and softirq handlers from running. Note that certain high-overhead debugging options, for example the function_graph tracer, can result in interrupt handler taking considerably longer than normal, which can in turn result in RCU CPU stall warnings.
- Testing a workload on a fast system, tuning the stall-warning timeout down to just barely avoid RCU CPU stall warnings, and then running the same workload with the same stall-warning timeout on a slow system. Note that thermal throttling and on-demand governors can cause a single system to be sometimes fast and sometimes slow!
- A hardware or software issue shuts off the scheduler-clock interrupt on a CPU that is not in dyntick-idle mode. This problem really has happened, and seems to be most likely to result in RCU CPU stall warnings for CONFIG_NO_HZ_COMMON=n kernels.
- A hardware or software issue that prevents time-based wakeups from occurring. These issues can range from misconfigured or buggy timer hardware through bugs in the interrupt or exception path (whether hardware, firmware, or software) through bugs in Linux's timer subsystem through bugs in the scheduler, and, yes, even including bugs in RCU itself.
- A bug in the RCU implementation.
- A hardware failure. This is quite unlikely, but has occurred at least once in real life. A CPU failed in a running system, becoming unresponsive, but not causing an immediate crash. This resulted in a series of RCU CPU stall warnings, eventually leading the realization that the CPU had failed.

The RCU, RCU-sched, and RCU-tasks implementations have CPU stall warning. Note that SRCU does -not- have CPU stall warnings. Please note that RCU only detects CPU stalls when there is a grace period in progress. No grace period, no CPU stall warnings.

To diagnose the cause of the stall, inspect the stack traces. The offending function will usually be near the top of the stack. If you have a series of stall warnings from a single extended stall, comparing the stack traces can often help determine where the stall is occurring, which will usually be in the function nearest the top of that portion of the stack which remains the same from trace to trace. If you can reliably trigger the stall, ftrace can be quite helpful.

RCU bugs can often be debugged with the help of CONFIG_RCU_TRACE and with RCU's event tracing. For information on RCU's event tracing, see include/trace/events/rcu.h.

Fine-Tuning the RCU CPU Stall Detector

The rcuupdate.rcu_cpu_stall_suppress module parameter disables RCU's CPU stall detector, which detects conditions that unduly delay RCU grace periods. This module parameter enables CPU stall detection by default, but may be overridden via boot-time parameter or at runtime via sysfs. The stall detector's idea of what constitutes "unduly delayed" is controlled by a set of kernel configuration variables and cpp macros:

CONFIG_RCU_CPU_STALL_TIMEOUT

This kernel configuration parameter defines the period of time that RCU will wait from the beginning of a grace period until it issues an RCU CPU stall warning. This time period is normally 21 seconds.

This configuration parameter may be changed at runtime via the /sys/module/rcupdate/parameters/rcu_cpu_stall_timeout, however this parameter is checked only at the beginning of a cycle. So if you are 10 seconds into a 40-second stall, setting this sysfs parameter to (say) five will shorten the timeout for the -next- stall, or the following warning for the current stall (assuming the stall lasts long enough). It will not affect the timing of the next warning for the current stall.

Stall-warning messages may be enabled and disabled completely via /sys/module/rcupdate/parameters/rcu_cpu_stall_suppress.

RCU_STALL_DELAY_DELTA

Although the lockdep facility is extremely useful, it does add some overhead. Therefore, under CONFIG_PROVE_RCU, the RCU_STALL_DELAY_DELTA macro allows five extra seconds before giving an RCU CPU stall warning message. (This is a cpp macro, not a kernel configuration parameter.)

RCU_STALL_RAT_DELAY

The CPU stall detector tries to make the offending CPU print its own warnings, as this often gives better-quality stack traces. However, if the offending CPU does not detect its own stall in the number of jiffies specified by RCU_STALL_RAT_DELAY, then some other CPU will complain. This delay is normally set to two jiffies. (This is a cpp macro, not a kernel configuration parameter.)

rcupdate.rcu_task_stall_timeout

This boot/sysfs parameter controls the RCU-tasks stall warning interval. A value of zero or less suppresses RCU-tasks stall warnings. A positive value sets the stall-warning interval in seconds. An RCU-tasks stall warning starts with the line:

INFO: rcu_tasks detected stalls on tasks:

And continues with the output of sched_show_task() for each task stalling the current RCU-tasks grace period.

Interpreting RCU's CPU Stall-Detector "Splats"

For non-RCU-tasks flavors of RCU, when a CPU detects that it is stalling, it will print a message similar to the following:

```
INFO: rcu_sched detected stalls on CPUs/tasks:
2-...: (3 GPs behind) idle=06c/0/0 softirq=1453/1455 fqs=0
16-...: (0 ticks this GP) idle=81c/0/0 softirq=764/764 fqs=0
(detected by 32, t=2603 jiffies, g=7075, q=625)
```

This message indicates that CPU 32 detected that CPUs 2 and 16 were both causing stalls, and that the stall was affecting RCU-sched. This message will normally be followed by stack dumps for each CPU. Please note that PREEMPT_RCU builds can be stalled by tasks as well as by CPUs, and that the tasks will be indicated by PID, for example, "P3421". It is even possible for an rcu_state stall to be caused by both CPUs -and- tasks, in which case the offending CPUs and tasks will all be called out in the list.

CPU 2's "(3 GPs behind)" indicates that this CPU has not interacted with the RCU core for the past three grace periods. In contrast, CPU 16's "(0 ticks this GP)" indicates that this CPU has not taken any scheduling-clock interrupts during the current stalled grace period.

The "idle=" portion of the message prints the dyntick-idle state. The hex number before the first "/" is the low-order 12 bits of the dynticks counter, which will have an even-numbered value if the CPU is in dyntick-idle mode and an odd-numbered value otherwise. The hex number between the two "/"s is the value of the nesting, which will be a small non-negative number if in the idle loop (as shown above) and a very large positive number otherwise.

The "softirq=" portion of the message tracks the number of RCU softirq handlers that the stalled CPU has executed. The number before the "/" is the number that had executed since boot at the time that this CPU last noted the beginning of a grace period, which might be the current (stalled) grace period, or it might be some earlier grace period (for example, if the CPU might have been in dyntick-idle mode for an extended time period. The number after the "/" is the number that have executed since boot until the current time. If this latter number stays constant across repeated stall-warning messages, it is possible that RCU's softirq handlers are no longer able to execute on this CPU. This can happen if the stalled CPU is spinning with interrupts are disabled, or, in -rt kernels, if a high-priority process is starving RCU's softirq handler.

The "fqs=" shows the number of force-quiescent-state idle/offline detection passes that the grace-period kthread has made across this CPU since the last time that this CPU noted the beginning of a grace period.

The "detected by" line indicates which CPU detected the stall (in this case, CPU 32), how many jiffies have elapsed since the start of the grace period (in this case 2603), the grace-period sequence number (7075), and an estimate of the total number of RCU callbacks queued across all CPUs (625 in this case).

In kernels with CONFIG_RCU_FAST_NO_HZ, more information is printed for each CPU:

```
0: (64628 ticks this GP) idle=dd5/3fffffffffffffff/0 softirq=82/543␣
↪last_accelerate: a345/d342 dyntick_enabled: 1
```

The "last_accelerate:" prints the low-order 16 bits (in hex) of the jiffies counter when this CPU last invoked rcu_try_advance_all_cbs() from rcu_needs_cpu() or last invoked rcu_accelerate_cbs() from rcu_prepare_for_idle(). "dyntick_enabled: 1" indicates that dyntick-idle processing is enabled.

If the grace period ends just as the stall warning starts printing, there will be a spurious stall-warning message, which will include the following:

```
INFO: Stall ended before state dump start
```

This is rare, but does happen from time to time in real life. It is also possible for a zero-jiffy stall to be flagged in this case, depending on how the stall warning and the grace-period initialization happen to interact. Please note that it is not possible to entirely eliminate this sort of false positive without resorting to things like stop_machine(), which is overkill for this sort of problem.

If all CPUs and tasks have passed through quiescent states, but the grace period has nevertheless failed to end, the stall-warning splat will include something like the following:

```
All QSes seen, last rcu_preempt kthread activity 23807 (4297905177-
↪4297881370), jiffies_till_next_fqs=3, root ->qsmask 0x0
```

The "23807" indicates that it has been more than 23 thousand jiffies since the grace-period kthread ran. The "jiffies_till_next_fqs" indicates how frequently that kthread should run, giving the number of jiffies between force-quiescent-state scans, in this case three, which is way less than 23807. Finally, the root rcu_node structure's ->qsmask field is printed, which will normally be zero.

If the relevant grace-period kthread has been unable to run prior to the stall warning, as was the case in the "All QSes seen" line above, the following additional line is printed:

```
kthread starved for 23807 jiffies! g7075 f0x0 RCU_GP_WAIT_FQS(3) ->
↪state=0x1 ->cpu=5
```

Starving the grace-period kthreads of CPU time can of course result in RCU CPU stall warnings even when all CPUs and tasks have passed through the required quiescent states. The "g" number shows the current grace-period sequence number, the "f" precedes the ->gp_flags command to the grace-period kthread, the "RCU_GP_WAIT_FQS" indicates that the kthread is waiting for a short timeout, the "state" precedes value of the task_struct ->state field, and the "cpu" indicates that the grace-period kthread last ran on CPU 5.

Multiple Warnings From One Stall

If a stall lasts long enough, multiple stall-warning messages will be printed for it. The second and subsequent messages are printed at longer intervals, so that the time between (say) the first and second message will be about three times the interval between the beginning of the stall and the first message.

Stall Warnings for Expedited Grace Periods

If an expedited grace period detects a stall, it will place a message like the following in dmesg:

```
INFO: rcu_sched detected expedited stalls on CPUs/tasks: { 7-... }␣
↪21119 jiffies s: 73 root: 0x2/.
```

This indicates that CPU 7 has failed to respond to a reschedule IPI. The three periods (".") following the CPU number indicate that the CPU is online (otherwise the first period would instead have been "O"), that the CPU was online at the beginning of the expedited grace period (otherwise the second period would have instead been "o"), and that the CPU has been online at least once since boot (otherwise, the third period would instead have been "N"). The number before the "jiffies" indicates that the expedited grace period has been going on for 21,119 jiffies. The number following the "s:" indicates that the expedited grace-period sequence counter is 73. The fact that this last value is odd indicates that an expedited grace period is in flight. The number following "root:" is a bitmask that indicates which children of the root rcu_node structure correspond to CPUs and/or tasks that are blocking the current expedited grace period. If the tree had more than one level, additional hex numbers would be printed for the states of the other rcu_node structures in the tree.

As with normal grace periods, PREEMPT_RCU builds can be stalled by tasks as well as by CPUs, and that the tasks will be indicated by PID, for example, "P3421" .

It is entirely possible to see stall warnings from normal and from expedited grace periods at about the same time during the same run.

3.6.13 Using RCU to Protect Read-Mostly Linked Lists

One of the best applications of RCU is to protect read-mostly linked lists (`struct list_head` in list.h). One big advantage of this approach is that all of the required memory barriers are included for you in the list macros. This document describes several applications of RCU, with the best fits first.

Example 1: Read-mostly list: Deferred Destruction

A widely used usecase for RCU lists in the kernel is lockless iteration over all processes in the system. `task_struct::tasks` represents the list node that links all the processes. The list can be traversed in parallel to any list additions or removals.

The traversal of the list is done using `for_each_process()` which is defined by the 2 macros:

```
#define next_task(p) \
        list_entry_rcu((p)->tasks.next, struct task_struct, tasks)

#define for_each_process(p) \
        for (p = &init_task ; (p = next_task(p)) != &init_task ; )
```

The code traversing the list of all processes typically looks like:

```
rcu_read_lock();
for_each_process(p) {
        /* Do something with p */
}
rcu_read_unlock();
```

The simplified code for removing a process from a task list is:

```
void release_task(struct task_struct *p)
{
        write_lock(&tasklist_lock);
        list_del_rcu(&p->tasks);
        write_unlock(&tasklist_lock);
        call_rcu(&p->rcu, delayed_put_task_struct);
}
```

When a process exits, `release_task()` calls `list_del_rcu(&p->tasks)` under `tasklist_lock` writer lock protection, to remove the task from the list of all tasks. The `tasklist_lock` prevents concurrent list additions/removals from corrupting the list. Readers using `for_each_process()` are not protected with the `tasklist_lock`. To prevent readers from noticing changes in the list pointers, the `task_struct` object is freed only after one or more grace periods elapse (with the help of *`call_rcu()`*). This deferring of destruction ensures that any readers traversing the list will see valid `p->tasks.next` pointers and deletion/freeing can happen in parallel with traversal of the list. This pattern is also called an **existence lock**, since RCU pins the object in memory until all existing readers finish.

Example 2: Read-Side Action Taken Outside of Lock: No In-Place Updates

The best applications are cases where, if reader-writer locking were used, the read-side lock would be dropped before taking any action based on the results of the search. The most celebrated example is the routing table. Because the routing table is tracking the state of equipment outside of the computer, it will at times contain stale data. Therefore, once the route has been computed, there is no need to hold the routing table static during transmission of the packet. After all, you can hold the routing table static all you want, but that won't keep the external Internet from changing, and it is the state of the external Internet that really matters. In addition, routing entries are typically added or deleted, rather than being modified in place.

A straightforward example of this use of RCU may be found in the system-call auditing support. For example, a reader-writer locked implementation of `audit_filter_task()` might be as follows:

```
static enum audit_state audit_filter_task(struct task_struct *tsk)
{
        struct audit_entry *e;
        enum audit_state   state;

        read_lock(&auditsc_lock);
        /* Note: audit_filter_mutex held by caller. */
        list_for_each_entry(e, &audit_tsklist, list) {
                if (audit_filter_rules(tsk, &e->rule, NULL, &
↪state)) {
                        read_unlock(&auditsc_lock);
                        return state;
                }
        }
        read_unlock(&auditsc_lock);
        return AUDIT_BUILD_CONTEXT;
}
```

Here the list is searched under the lock, but the lock is dropped before the corresponding value is returned. By the time that this value is acted on, the list may well have been modified. This makes sense, since if you are turning auditing off, it is OK to audit a few extra system calls.

This means that RCU can be easily applied to the read side, as follows:

```
static enum audit_state audit_filter_task(struct task_struct *tsk)
{
        struct audit_entry *e;
        enum audit_state   state;

        rcu_read_lock();
        /* Note: audit_filter_mutex held by caller. */
        list_for_each_entry_rcu(e, &audit_tsklist, list) {
                if (audit_filter_rules(tsk, &e->rule, NULL, &
↪state)) {
```

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```
                        rcu_read_unlock();
                        return state;
                }
        }
        rcu_read_unlock();
        return AUDIT_BUILD_CONTEXT;
}
```

The read_lock() and read_unlock() calls have become *rcu_read_lock()* and *rcu_read_unlock()*, respectively, and the *list_for_each_entry()* has become *list_for_each_entry_rcu()*. The **_rcu()** list-traversal primitives insert the read-side memory barriers that are required on DEC Alpha CPUs.

The changes to the update side are also straightforward. A reader-writer lock might be used as follows for deletion and insertion:

```
static inline int audit_del_rule(struct audit_rule *rule,
                                 struct list_head *list)
{
        struct audit_entry *e;

        write_lock(&auditsc_lock);
        list_for_each_entry(e, list, list) {
                if (!audit_compare_rule(rule, &e->rule)) {
                        list_del(&e->list);
                        write_unlock(&auditsc_lock);
                        return 0;
                }
        }
        write_unlock(&auditsc_lock);
        return -EFAULT;         /* No matching rule */
}

static inline int audit_add_rule(struct audit_entry *entry,
                                 struct list_head *list)
{
        write_lock(&auditsc_lock);
        if (entry->rule.flags & AUDIT_PREPEND) {
                entry->rule.flags &= ~AUDIT_PREPEND;
                list_add(&entry->list, list);
        } else {
                list_add_tail(&entry->list, list);
        }
        write_unlock(&auditsc_lock);
        return 0;
}
```

Following are the RCU equivalents for these two functions:

```
static inline int audit_del_rule(struct audit_rule *rule,
```

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```
                                    struct list_head *list)
{
        struct audit_entry *e;

        /* No need to use the _rcu iterator here, since this is the␣
↪only
         * deletion routine. */
        list_for_each_entry(e, list, list) {
                if (!audit_compare_rule(rule, &e->rule)) {
                        list_del_rcu(&e->list);
                        call_rcu(&e->rcu, audit_free_rule);
                        return 0;
                }
        }
        return -EFAULT;         /* No matching rule */
}

static inline int audit_add_rule(struct audit_entry *entry,
                                 struct list_head *list)
{
        if (entry->rule.flags & AUDIT_PREPEND) {
                entry->rule.flags &= ~AUDIT_PREPEND;
                list_add_rcu(&entry->list, list);
        } else {
                list_add_tail_rcu(&entry->list, list);
        }
        return 0;
}
```

Normally, the `write_lock()` and `write_unlock()` would be replaced by a spin_lock() and a spin_unlock(). But in this case, all callers hold `audit_filter_mutex`, so no additional locking is required. The `auditsc_lock` can therefore be eliminated, since use of RCU eliminates the need for writers to exclude readers.

The *list_del()*, *list_add()*, and *list_add_tail()* primitives have been replaced by *list_del_rcu()*, *list_add_rcu()*, and *list_add_tail_rcu()*. The **_rcu()** list-manipulation primitives add memory barriers that are needed on weakly ordered CPUs (most of them!). The *list_del_rcu()* primitive omits the pointer poisoning debug-assist code that would otherwise cause concurrent readers to fail spectacularly.

So, when readers can tolerate stale data and when entries are either added or deleted, without in-place modification, it is very easy to use RCU!

Example 3: Handling In-Place Updates

The system-call auditing code does not update auditing rules in place. However, if it did, the reader-writer-locked code to do so might look as follows (assuming only `field_count` is updated, otherwise, the added fields would need to be filled in):

```
static inline int audit_upd_rule(struct audit_rule *rule,
                                 struct list_head *list,
                                 __u32 newaction,
                                 __u32 newfield_count)
{
        struct audit_entry *e;
        struct audit_entry *ne;

        write_lock(&auditsc_lock);
        /* Note: audit_filter_mutex held by caller. */
        list_for_each_entry(e, list, list) {
                if (!audit_compare_rule(rule, &e->rule)) {
                        e->rule.action = newaction;
                        e->rule.field_count = newfield_count;
                        write_unlock(&auditsc_lock);
                        return 0;
                }
        }
        write_unlock(&auditsc_lock);
        return -EFAULT;         /* No matching rule */
}
```

The RCU version creates a copy, updates the copy, then replaces the old entry with the newly updated entry. This sequence of actions, allowing concurrent reads while making a copy to perform an update, is what gives RCU (*read-copy update*) its name. The RCU code is as follows:

```
static inline int audit_upd_rule(struct audit_rule *rule,
                                 struct list_head *list,
                                 __u32 newaction,
                                 __u32 newfield_count)
{
        struct audit_entry *e;
        struct audit_entry *ne;

        list_for_each_entry(e, list, list) {
                if (!audit_compare_rule(rule, &e->rule)) {
                        ne = kmalloc(sizeof(*entry), GFP_ATOMIC);
                        if (ne == NULL)
                                return -ENOMEM;
                        audit_copy_rule(&ne->rule, &e->rule);
                        ne->rule.action = newaction;
                        ne->rule.field_count = newfield_count;
                        list_replace_rcu(&e->list, &ne->list);
                        call_rcu(&e->rcu, audit_free_rule);
```

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```
                                return 0;
                        }
                }
                return -EFAULT;         /* No matching rule */
}
```

Again, this assumes that the caller holds `audit_filter_mutex`. Normally, the writer lock would become a spinlock in this sort of code.

Another use of this pattern can be found in the openswitch driver's *connection tracking table* code in `ct_limit_set()`. The table holds connection tracking entries and has a limit on the maximum entries. There is one such table per-zone and hence one *limit* per zone. The zones are mapped to their limits through a hashtable using an RCU-managed hlist for the hash chains. When a new limit is set, a new limit object is allocated and `ct_limit_set()` is called to replace the old limit object with the new one using *`list_replace_rcu()`*. The old limit object is then freed after a grace period using *`kfree_rcu()`*.

Example 4: Eliminating Stale Data

The auditing example above tolerates stale data, as do most algorithms that are tracking external state. Because there is a delay from the time the external state changes before Linux becomes aware of the change, additional RCU-induced staleness is generally not a problem.

However, there are many examples where stale data cannot be tolerated. One example in the Linux kernel is the System V IPC (see the shm_lock() function in ipc/shm.c). This code checks a *deleted* flag under a per-entry spinlock, and, if the *deleted* flag is set, pretends that the entry does not exist. For this to be helpful, the search function must return holding the per-entry spinlock, as shm_lock() does in fact do.

Quick Quiz:
: For the deleted-flag technique to be helpful, why is it necessary to hold the per-entry lock while returning from the search function?

Answer to Quick Quiz

If the system-call audit module were to ever need to reject stale data, one way to accomplish this would be to add a `deleted` flag and a `lock` spinlock to the audit_entry structure, and modify `audit_filter_task()` as follows:

```
static enum audit_state audit_filter_task(struct task_struct *tsk)
{
        struct audit_entry *e;
        enum audit_state   state;

        rcu_read_lock();
        list_for_each_entry_rcu(e, &audit_tsklist, list) {
                if (audit_filter_rules(tsk, &e->rule, NULL, &
↪state)) {
```

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```
                        spin_lock(&e->lock);
                        if (e->deleted) {
                                spin_unlock(&e->lock);
                                rcu_read_unlock();
                                return AUDIT_BUILD_CONTEXT;
                        }
                        rcu_read_unlock();
                        return state;
                }
        }
        rcu_read_unlock();
        return AUDIT_BUILD_CONTEXT;
}
```

Note that this example assumes that entries are only added and deleted. Additional mechanism is required to deal correctly with the update-in-place performed by `audit_upd_rule()`. For one thing, `audit_upd_rule()` would need additional memory barriers to ensure that the *list_add_rcu()* was really executed before the *list_del_rcu()*.

The `audit_del_rule()` function would need to set the `deleted` flag under the spinlock as follows:

```
static inline int audit_del_rule(struct audit_rule *rule,
                                 struct list_head *list)
{
        struct audit_entry *e;

        /* No need to use the _rcu iterator here, since this
         * is the only deletion routine. */
        list_for_each_entry(e, list, list) {
                if (!audit_compare_rule(rule, &e->rule)) {
                        spin_lock(&e->lock);
                        list_del_rcu(&e->list);
                        e->deleted = 1;
                        spin_unlock(&e->lock);
                        call_rcu(&e->rcu, audit_free_rule);
                        return 0;
                }
        }
        return -EFAULT;         /* No matching rule */
}
```

This too assumes that the caller holds `audit_filter_mutex`.

Example 5: Skipping Stale Objects

For some usecases, reader performance can be improved by skipping stale objects during read-side list traversal if the object in concern is pending destruction after one or more grace periods. One such example can be found in the timerfd subsystem. When a `CLOCK_REALTIME` clock is reprogrammed - for example due to setting of the system time, then all programmed timerfds that depend on this clock get triggered and processes waiting on them to expire are woken up in advance of their scheduled expiry. To facilitate this, all such timers are added to an RCU-managed `cancel_list` when they are setup in `timerfd_setup_cancel()`:

```
static void timerfd_setup_cancel(struct timerfd_ctx *ctx, int flags)
{
        spin_lock(&ctx->cancel_lock);
        if ((ctx->clockid == CLOCK_REALTIME &&
            (flags & TFD_TIMER_ABSTIME) && (flags & TFD_TIMER_
↪CANCEL_ON_SET)) {
                if (!ctx->might_cancel) {
                        ctx->might_cancel = true;
                        spin_lock(&cancel_lock);
                        list_add_rcu(&ctx->clist, &cancel_list);
                        spin_unlock(&cancel_lock);
                }
        }
        spin_unlock(&ctx->cancel_lock);
}
```

When a timerfd is freed (fd is closed), then the `might_cancel` flag of the timerfd object is cleared, the object removed from the `cancel_list` and destroyed:

```
int timerfd_release(struct inode *inode, struct file *file)
{
        struct timerfd_ctx *ctx = file->private_data;

        spin_lock(&ctx->cancel_lock);
        if (ctx->might_cancel) {
                ctx->might_cancel = false;
                spin_lock(&cancel_lock);
                list_del_rcu(&ctx->clist);
                spin_unlock(&cancel_lock);
        }
        spin_unlock(&ctx->cancel_lock);

        hrtimer_cancel(&ctx->t.tmr);
        kfree_rcu(ctx, rcu);
        return 0;
}
```

If the `CLOCK_REALTIME` clock is set, for example by a time server, the hrtimer framework calls `timerfd_clock_was_set()` which walks the `cancel_list` and wakes up processes waiting on the timerfd. While iterating the `cancel_list`, the `might_cancel` flag is consulted to skip stale objects:

```
void timerfd_clock_was_set(void)
{
        struct timerfd_ctx *ctx;
        unsigned long flags;

        rcu_read_lock();
        list_for_each_entry_rcu(ctx, &cancel_list, clist) {
                if (!ctx->might_cancel)
                        continue;
                spin_lock_irqsave(&ctx->wqh.lock, flags);
                if (ctx->moffs != ktime_mono_to_real(0)) {
                        ctx->moffs = KTIME_MAX;
                        ctx->ticks++;
                        wake_up_locked_poll(&ctx->wqh, EPOLLIN);
                }
                spin_unlock_irqrestore(&ctx->wqh.lock, flags);
        }
        rcu_read_unlock();
}
```

The key point here is, because RCU-traversal of the `cancel_list` happens while objects are being added and removed to the list, sometimes the traversal can step on an object that has been removed from the list. In this example, it is seen that it is better to skip such objects using a flag.

Summary

Read-mostly list-based data structures that can tolerate stale data are the most amenable to use of RCU. The simplest case is where entries are either added or deleted from the data structure (or atomically modified in place), but non-atomic in-place modifications can be handled by making a copy, updating the copy, then replacing the original with the copy. If stale data cannot be tolerated, then a *deleted* flag may be used in conjunction with a per-entry spinlock in order to allow the search function to reject newly deleted data.

Answer to Quick Quiz:

For the deleted-flag technique to be helpful, why is it necessary to hold the per-entry lock while returning from the search function?

If the search function drops the per-entry lock before returning, then the caller will be processing stale data in any case. If it is really OK to be processing stale data, then you don't need a *deleted* flag. If processing stale data really is a problem, then you need to hold the per-entry lock across all of the code that uses the value that was returned.

Back to Quick Quiz

3.6.14 Using RCU to Protect Dynamic NMI Handlers

Although RCU is usually used to protect read-mostly data structures, it is possible to use RCU to provide dynamic non-maskable interrupt handlers, as well as dynamic irq handlers. This document describes how to do this, drawing loosely from Zwane Mwaikambo's NMI-timer work in "arch/x86/oprofile/nmi_timer_int.c" and in "arch/x86/kernel/traps.c".

The relevant pieces of code are listed below, each followed by a brief explanation:

```
static int dummy_nmi_callback(struct pt_regs *regs, int cpu)
{
        return 0;
}
```

The dummy_nmi_callback() function is a "dummy" NMI handler that does nothing, but returns zero, thus saying that it did nothing, allowing the NMI handler to take the default machine-specific action:

```
static nmi_callback_t nmi_callback = dummy_nmi_callback;
```

This nmi_callback variable is a global function pointer to the current NMI handler:

```
void do_nmi(struct pt_regs * regs, long error_code)
{
        int cpu;

        nmi_enter();

        cpu = smp_processor_id();
        ++nmi_count(cpu);

        if (!rcu_dereference_sched(nmi_callback)(regs, cpu))
                default_do_nmi(regs);

        nmi_exit();
}
```

The do_nmi() function processes each NMI. It first disables preemption in the same way that a hardware irq would, then increments the per-CPU count of NMIs. It then invokes the NMI handler stored in the nmi_callback function pointer. If this handler returns zero, do_nmi() invokes the default_do_nmi() function to handle a machine-specific NMI. Finally, preemption is restored.

In theory, `rcu_dereference_sched()` is not needed, since this code runs only on i386, which in theory does not need `rcu_dereference_sched()` anyway. However, in practice it is a good documentation aid, particularly for anyone attempting to do something similar on Alpha or on systems with aggressive optimizing compilers.

Quick Quiz:

Why might the `rcu_dereference_sched()` be necessary on Alpha, given that the code referenced by the pointer is read-only?

Answer to Quick Quiz

Back to the discussion of NMI and RCU:

```
void set_nmi_callback(nmi_callback_t callback)
{
        rcu_assign_pointer(nmi_callback, callback);
}
```

The set_nmi_callback() function registers an NMI handler. Note that any data that is to be used by the callback must be initialized up -before- the call to set_nmi_callback(). On architectures that do not order writes, the *rcu_assign_pointer()* ensures that the NMI handler sees the initialized values:

```
void unset_nmi_callback(void)
{
        rcu_assign_pointer(nmi_callback, dummy_nmi_callback);
}
```

This function unregisters an NMI handler, restoring the original dummy_nmi_handler(). However, there may well be an NMI handler currently executing on some other CPU. We therefore cannot free up any data structures used by the old NMI handler until execution of it completes on all other CPUs.

One way to accomplish this is via *synchronize_rcu()*, perhaps as follows:

```
unset_nmi_callback();
synchronize_rcu();
kfree(my_nmi_data);
```

This works because (as of v4.20) *synchronize_rcu()* blocks until all CPUs complete any preemption-disabled segments of code that they were executing. Since NMI handlers disable preemption, *synchronize_rcu()* is guaranteed not to return until all ongoing NMI handlers exit. It is therefore safe to free up the handler's data as soon as *synchronize_rcu()* returns.

Important note: for this to work, the architecture in question must invoke nmi_enter() and nmi_exit() on NMI entry and exit, respectively.

Answer to Quick Quiz:

> Why might the *rcu_dereference_sched()* be necessary on Alpha, given that the code referenced by the pointer is read-only?
>
> The caller to set_nmi_callback() might well have initialized some data that is to be used by the new NMI handler. In this case, the *rcu_dereference_sched()* would be needed, because otherwise a CPU that received an NMI just after the new handler was set might see the pointer to the new NMI handler, but the old pre-initialized version of the handler's data.
>
> This same sad story can happen on other CPUs when using a compiler with aggressive pointer-value speculation optimizations.
>
> More important, the *rcu_dereference_sched()* makes it clear to someone reading the code that the pointer is being protected by RCU-sched.

3.6.15 RCU on Uniprocessor Systems

A common misconception is that, on UP systems, the *call_rcu()* primitive may immediately invoke its function. The basis of this misconception is that since there is only one CPU, it should not be necessary to wait for anything else to get done, since there are no other CPUs for anything else to be happening on. Although this approach will *sort of* work a surprising amount of the time, it is a very bad idea in general. This document presents three examples that demonstrate exactly how bad an idea this is.

Example 1: softirq Suicide

Suppose that an RCU-based algorithm scans a linked list containing elements A, B, and C in process context, and can delete elements from this same list in softirq context. Suppose that the process-context scan is referencing element B when it is interrupted by softirq processing, which deletes element B, and then invokes *call_rcu()* to free element B after a grace period.

Now, if *call_rcu()* were to directly invoke its arguments, then upon return from softirq, the list scan would find itself referencing a newly freed element B. This situation can greatly decrease the life expectancy of your kernel.

This same problem can occur if *call_rcu()* is invoked from a hardware interrupt handler.

Example 2: Function-Call Fatality

Of course, one could avert the suicide described in the preceding example by having *call_rcu()* directly invoke its arguments only if it was called from process context. However, this can fail in a similar manner.

Suppose that an RCU-based algorithm again scans a linked list containing elements A, B, and C in process contexts, but that it invokes a function on each element as it is scanned. Suppose further that this function deletes element B from the list, then passes it to *call_rcu()* for deferred freeing. This may be a bit unconventional, but it is perfectly legal RCU usage, since *call_rcu()* must wait for a grace period to elapse. Therefore, in this case, allowing *call_rcu()* to immediately invoke its arguments would cause it to fail to make the fundamental guarantee underlying RCU, namely that *call_rcu()* defers invoking its arguments until all RCU read-side critical sections currently executing have completed.

Quick Quiz #1:

Why is it *not* legal to invoke *synchronize_rcu()* in this case?

Answers to Quick Quiz

Example 3: Death by Deadlock

Suppose that *call_rcu()* is invoked while holding a lock, and that the callback function must acquire this same lock. In this case, if *call_rcu()* were to directly invoke the callback, the result would be self-deadlock.

In some cases, it would possible to restructure to code so that the *call_rcu()* is delayed until after the lock is released. However, there are cases where this can be quite ugly:

1. If a number of items need to be passed to *call_rcu()* within the same critical section, then the code would need to create a list of them, then traverse the list once the lock was released.
2. In some cases, the lock will be held across some kernel API, so that delaying the *call_rcu()* until the lock is released requires that the data item be passed up via a common API. It is far better to guarantee that callbacks are invoked with no locks held than to have to modify such APIs to allow arbitrary data items to be passed back up through them.

If *call_rcu()* directly invokes the callback, painful locking restrictions or API changes would be required.

Quick Quiz #2:
What locking restriction must RCU callbacks respect?

Answers to Quick Quiz

Summary

Permitting *call_rcu()* to immediately invoke its arguments breaks RCU, even on a UP system. So do not do it! Even on a UP system, the RCU infrastructure *must* respect grace periods, and *must* invoke callbacks from a known environment in which no locks are held.

Note that it *is* safe for *synchronize_rcu()* to return immediately on UP systems, including PREEMPT SMP builds running on UP systems.

Quick Quiz #3:
Why can't *synchronize_rcu()* return immediately on UP systems running preemptable RCU?

Answer to Quick Quiz #1:
Why is it *not* legal to invoke *synchronize_rcu()* in this case?

Because the calling function is scanning an RCU-protected linked list, and is therefore within an RCU read-side critical section. Therefore, the called function has been invoked within an RCU read-side critical section, and is not permitted to block.

Answer to Quick Quiz #2:
What locking restriction must RCU callbacks respect?

Any lock that is acquired within an RCU callback must be acquired elsewhere using an _bh variant of the spinlock primitive. For example, if "mylock" is acquired by an RCU callback, then a process-context acquisition of this lock must use something like spin_lock_bh() to acquire the lock. Please note that it is also OK to use _irq variants of spinlocks, for example, spin_lock_irqsave().

If the process-context code were to simply use spin_lock(), then, since RCU callbacks can be invoked from softirq context, the callback might be called from a softirq that interrupted the process-context critical section. This would result in self-deadlock.

This restriction might seem gratuitous, since very few RCU callbacks acquire locks directly. However, a great many RCU callbacks do acquire locks *indirectly*, for example, via the `kfree()` primitive.

Answer to Quick Quiz #3:

Why can't `synchronize_rcu()` return immediately on UP systems running preemptable RCU?

Because some other task might have been preempted in the middle of an RCU read-side critical section. If `synchronize_rcu()` simply immediately returned, it would prematurely signal the end of the grace period, which would come as a nasty shock to that other thread when it started running again.

3.6.16 A Tour Through TREE_RCU's Grace-Period Memory Ordering

August 8, 2017

This article was contributed by Paul E. McKenney

Introduction

This document gives a rough visual overview of how Tree RCU's grace-period memory ordering guarantee is provided.

What Is Tree RCU's Grace Period Memory Ordering Guarantee?

RCU grace periods provide extremely strong memory-ordering guarantees for non-idle non-offline code. Any code that happens after the end of a given RCU grace period is guaranteed to see the effects of all accesses prior to the beginning of that grace period that are within RCU read-side critical sections. Similarly, any code that happens before the beginning of a given RCU grace period is guaranteed to see the effects of all accesses following the end of that grace period that are within RCU read-side critical sections.

Note well that RCU-sched read-side critical sections include any region of code for which preemption is disabled. Given that each individual machine instruction can be thought of as an extremely small region of preemption-disabled code, one can think of `synchronize_rcu()` as `smp_mb()` on steroids.

RCU updaters use this guarantee by splitting their updates into two phases, one of which is executed before the grace period and the other of which is executed after the grace period. In the most common use case, phase one removes an element from a linked RCU-protected data structure, and phase two frees that element. For this to work, any readers that have witnessed state prior to the phase-one update (in the common case, removal) must not witness state following the phase-two update (in the common case, freeing).

The RCU implementation provides this guarantee using a network of lock-based critical sections, memory barriers, and per-CPU processing, as is described in the following sections.

Tree RCU Grace Period Memory Ordering Building Blocks

The workhorse for RCU's grace-period memory ordering is the critical section for the `rcu_node` structure's `->lock`. These critical sections use helper functions for lock acquisition, including `raw_spin_lock_rcu_node()`, `raw_spin_lock_irq_rcu_node()`, and `raw_spin_lock_irqsave_rcu_node()`. Their lock-release counterparts are `raw_spin_unlock_rcu_node()`, `raw_spin_unlock_irq_rcu_node()`, and `raw_spin_unlock_irqrestore_rcu_node()`, respectively. For completeness, a `raw_spin_trylock_rcu_node()` is also provided. The key point is that the lock-acquisition functions, including `raw_spin_trylock_rcu_node()`, all invoke `smp_mb__after_unlock_lock()` immediately after successful acquisition of the lock.

Therefore, for any given `rcu_node` structure, any access happening before one of the above lock-release functions will be seen by all CPUs as happening before any access happening after a later one of the above lock-acquisition functions. Furthermore, any access happening before one of the above lock-release function on any given CPU will be seen by all CPUs as happening before any access happening after a later one of the above lock-acquisition functions executing on that same CPU, even if the lock-release and lock-acquisition functions are operating on different `rcu_node` structures. Tree RCU uses these two ordering guarantees to form an ordering network among all CPUs that were in any way involved in the grace period, including any CPUs that came online or went offline during the grace period in question.

The following litmus test exhibits the ordering effects of these lock-acquisition and lock-release functions:

```
int x, y, z;

void task0(void)
{
  raw_spin_lock_rcu_node(rnp);
  WRITE_ONCE(x, 1);
  r1 = READ_ONCE(y);
  raw_spin_unlock_rcu_node(rnp);
}

void task1(void)
{
  raw_spin_lock_rcu_node(rnp);
  WRITE_ONCE(y, 1);
  r2 = READ_ONCE(z);
  raw_spin_unlock_rcu_node(rnp);
```

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```
}

void task2(void)
{
  WRITE_ONCE(z, 1);
  smp_mb();
  r3 = READ_ONCE(x);
}

WARN_ON(r1 == 0 && r2 == 0 && r3 == 0);
```

The `WARN_ON()` is evaluated at "the end of time", after all changes have propagated throughout the system. Without the `smp_mb__after_unlock_lock()` provided by the acquisition functions, this `WARN_ON()` could trigger, for example on PowerPC. The `smp_mb__after_unlock_lock()` invocations prevent this `WARN_ON()` from triggering.

This approach must be extended to include idle CPUs, which need RCU’s grace-period memory ordering guarantee to extend to any RCU read-side critical sections preceding and following the current idle sojourn. This case is handled by calls to the strongly ordered `atomic_add_return()` read-modify-write atomic operation that is invoked within `rcu_dynticks_eqs_enter()` at idle-entry time and within `rcu_dynticks_eqs_exit()` at idle-exit time. The grace-period kthread invokes `rcu_dynticks_snap()` and `rcu_dynticks_in_eqs_since()` (both of which invoke an `atomic_add_return()` of zero) to detect idle CPUs.

Quick Quiz:

But what about CPUs that remain offline for the entire grace period?

Answer:

Such CPUs will be offline at the beginning of the grace period, so the grace period won’t expect quiescent states from them. Races between grace-period start and CPU-hotplug operations are mediated by the CPU’s leaf `rcu_node` structure’s `->lock` as described above.

The approach must be extended to handle one final case, that of waking a task blocked in `synchronize_rcu()`. This task might be affinitied to a CPU that is not yet aware that the grace period has ended, and thus might not yet be subject to the grace period’s memory ordering. Therefore, there is an `smp_mb()` after the return from `wait_for_completion()` in the `synchronize_rcu()` code path.

Quick Quiz:

What? Where??? I don’t see any `smp_mb()` after the return from `wait_for_completion()`!!!

Answer:

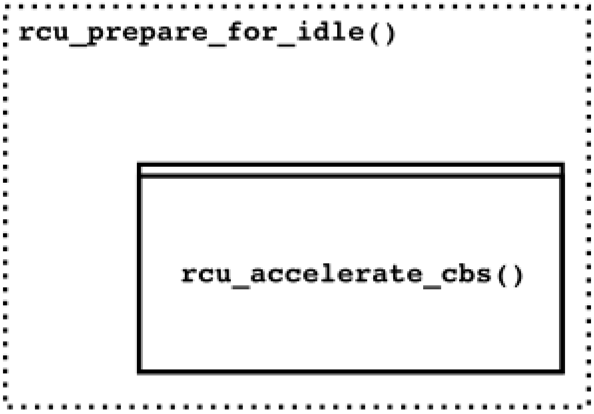
That would be because I spotted the need for that `smp_mb()` during the creation of this documentation, and it is therefore unlikely to hit mainline before v4.14. Kudos to Lance Roy, Will Deacon, Peter Zijlstra, and Jonathan Cameron for asking questions that sensitized me to the rather elaborate sequence of events that demonstrate the need for this memory barrier.

Tree RCU's grace-period memory-ordering guarantees rely most heavily on the rcu_node structure's ->lock field, so much so that it is necessary to abbreviate this pattern in the diagrams in the next section. For example, consider the rcu_prepare_for_idle() function shown below, which is one of several functions that enforce ordering of newly arrived RCU callbacks against future grace periods:

```
static void rcu_prepare_for_idle(void)
{
  bool needwake;
  struct rcu_data *rdp;
  struct rcu_dynticks *rdtp = this_cpu_ptr(&rcu_dynticks);
  struct rcu_node *rnp;
  struct rcu_state *rsp;
  int tne;

  if (IS_ENABLED(CONFIG_RCU_NOCB_CPU_ALL) ||
      rcu_is_nocb_cpu(smp_processor_id()))
    return;
  tne = READ_ONCE(tick_nohz_active);
  if (tne != rdtp->tick_nohz_enabled_snap) {
    if (rcu_cpu_has_callbacks(NULL))
      invoke_rcu_core();
    rdtp->tick_nohz_enabled_snap = tne;
    return;
  }
  if (!tne)
    return;
  if (rdtp->all_lazy &&
      rdtp->nonlazy_posted != rdtp->nonlazy_posted_snap) {
    rdtp->all_lazy = false;
    rdtp->nonlazy_posted_snap = rdtp->nonlazy_posted;
    invoke_rcu_core();
    return;
  }
  if (rdtp->last_accelerate == jiffies)
    return;
  rdtp->last_accelerate = jiffies;
  for_each_rcu_flavor(rsp) {
    rdp = this_cpu_ptr(rsp->rda);
    if (rcu_segcblist_pend_cbs(&rdp->cblist))
      continue;
    rnp = rdp->mynode;
    raw_spin_lock_rcu_node(rnp);
    needwake = rcu_accelerate_cbs(rsp, rnp, rdp);
    raw_spin_unlock_rcu_node(rnp);
    if (needwake)
      rcu_gp_kthread_wake(rsp);
  }
}
```

But the only part of rcu_prepare_for_idle() that really matters for this discussion are lines 37–39. We will therefore abbreviate this function as follows:



The box represents the `rcu_node` structure' s `->lock` critical section, with the double line on top representing the additional `smp_mb__after_unlock_lock()`.

Tree RCU Grace Period Memory Ordering Components

Tree RCU' s grace-period memory-ordering guarantee is provided by a number of RCU components:

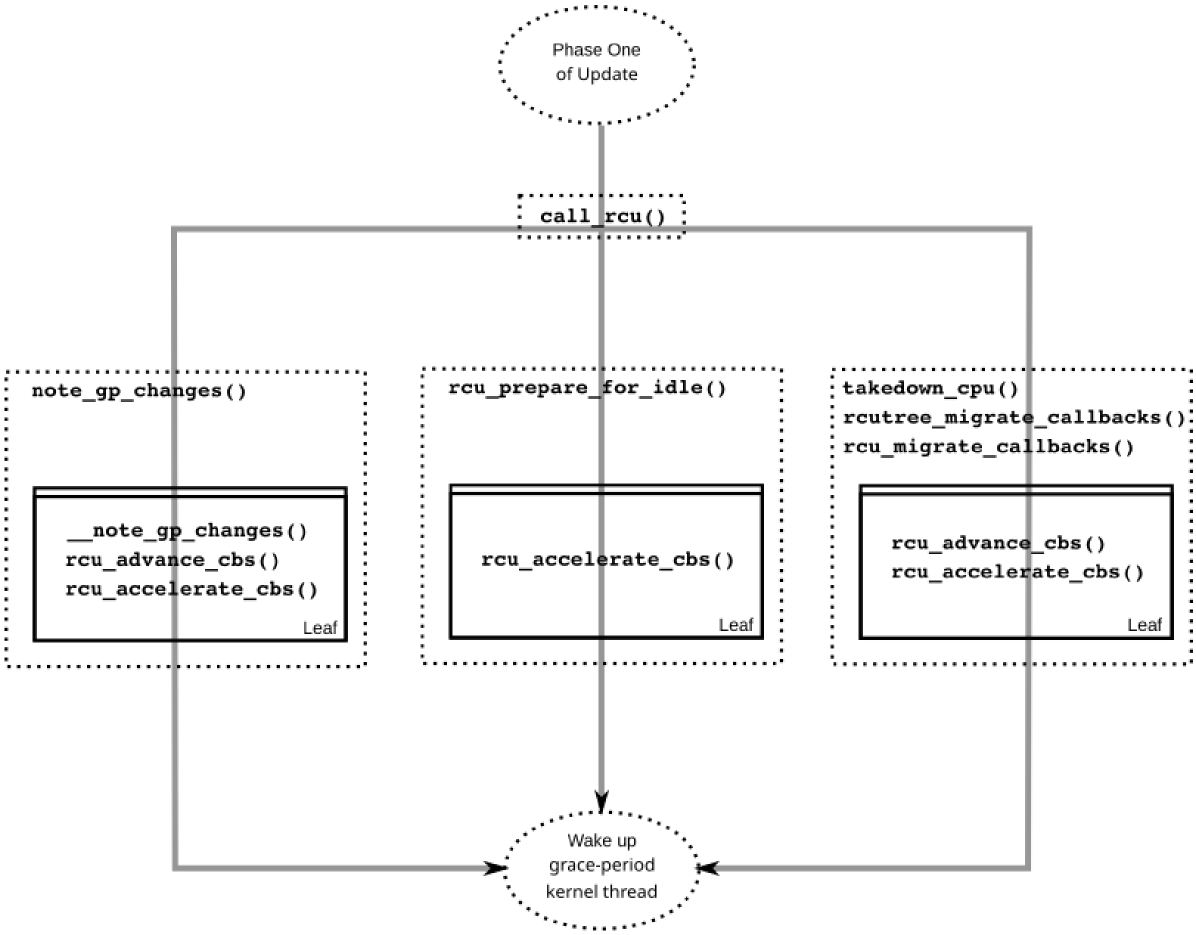
1. *Callback Registry*
2. *Grace-Period Initialization*
3. *Self-Reported Quiescent States*
4. *Dynamic Tick Interface*
5. *CPU-Hotplug Interface*
6. *Forcing Quiescent States*
7. *Grace-Period Cleanup*
8. *Callback Invocation*

Each of the following section looks at the corresponding component in detail.

Callback Registry

If RCU' s grace-period guarantee is to mean anything at all, any access that happens before a given invocation of `call_rcu()` must also happen before the corresponding grace period. The implementation of this portion of RCU' s grace period guarantee is shown in the following figure:

Because `call_rcu()` normally acts only on CPU-local state, it provides no ordering guarantees, either for itself or for phase one of the update (which again will usually be removal of an element from an RCU-protected data structure). It simply enqueues the `rcu_head` structure on a per-CPU list, which cannot become associated with a grace period until a later call to `rcu_accelerate_cbs()`, as shown in the diagram above.



Phase One
of Update
call_rcu()
note_gp_changes()
__note_gp_changes()
rcu_advance_cbs()
rcu_accelerate_cbs()
Leaf
rcu_prepare_for_idle()
rcu_accelerate_cbs()
Leaf
takedown_cpu()
rcutree_migrate_callbacks()
rcu_migrate_callbacks()
rcu_advance_cbs()
rcu_accelerate_cbs()
Leaf
Wake up
grace-period
kernel thread

One set of code paths shown on the left invokes `rcu_accelerate_cbs()` via `note_gp_changes()`, either directly from `call_rcu()` (if the current CPU is inundated with queued `rcu_head` structures) or more likely from an `RCU_SOFTIRQ` handler. Another code path in the middle is taken only in kernels built with `CONFIG_RCU_FAST_NO_HZ=y`, which invokes `rcu_accelerate_cbs()` via `rcu_prepare_for_idle()`. The final code path on the right is taken only in kernels built with `CONFIG_HOTPLUG_CPU=y`, which invokes `rcu_accelerate_cbs()` via `rcu_advance_cbs()`, `rcu_migrate_callbacks`, `rcutree_migrate_callbacks()`, and `takedown_cpu()`, which in turn is invoked on a surviving CPU after the outgoing CPU has been completely offlined.

There are a few other code paths within grace-period processing that opportunistically invoke `rcu_accelerate_cbs()`. However, either way, all of the CPU's recently queued `rcu_head` structures are associated with a future grace-period number under the protection of the CPU's lead `rcu_node` structure's `->lock`. In all cases, there is full ordering against any prior critical section for that same `rcu_node` structure's `->lock`, and also full ordering against any of the current task's or CPU's prior critical sections for any `rcu_node` structure's `->lock`.

The next section will show how this ordering ensures that any accesses prior to the `call_rcu()` (particularly including phase one of the update) happen before the start of the corresponding grace period.

Quick Quiz:
But what about `synchronize_rcu()`?
Answer:
The `synchronize_rcu()` passes `call_rcu()` to `wait_rcu_gp()`, which invokes it. So either way, it eventually comes down to `call_rcu()`.

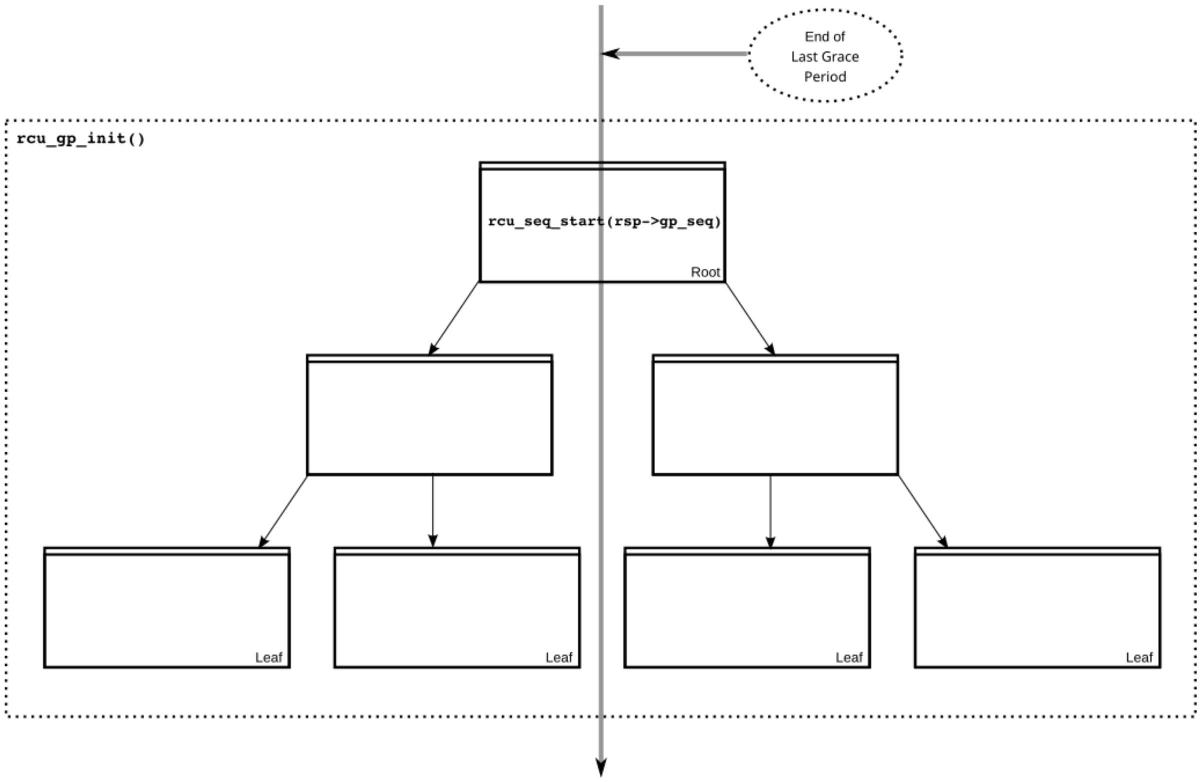
Grace-Period Initialization

Grace-period initialization is carried out by the grace-period kernel thread, which makes several passes over the `rcu_node` tree within the `rcu_gp_init()` function. This means that showing the full flow of ordering through the grace-period computation will require duplicating this tree. If you find this confusing, please note that the state of the `rcu_node` changes over time, just like Heraclitus's river. However, to keep the `rcu_node` river tractable, the grace-period kernel thread's traversals are presented in multiple parts, starting in this section with the various phases of grace-period initialization.

The first ordering-related grace-period initialization action is to advance the `rcu_state` structure's `->gp_seq` grace-period-number counter, as shown below:

The actual increment is carried out using `smp_store_release()`, which helps reject false-positive RCU CPU stall detection. Note that only the root `rcu_node` structure is touched.

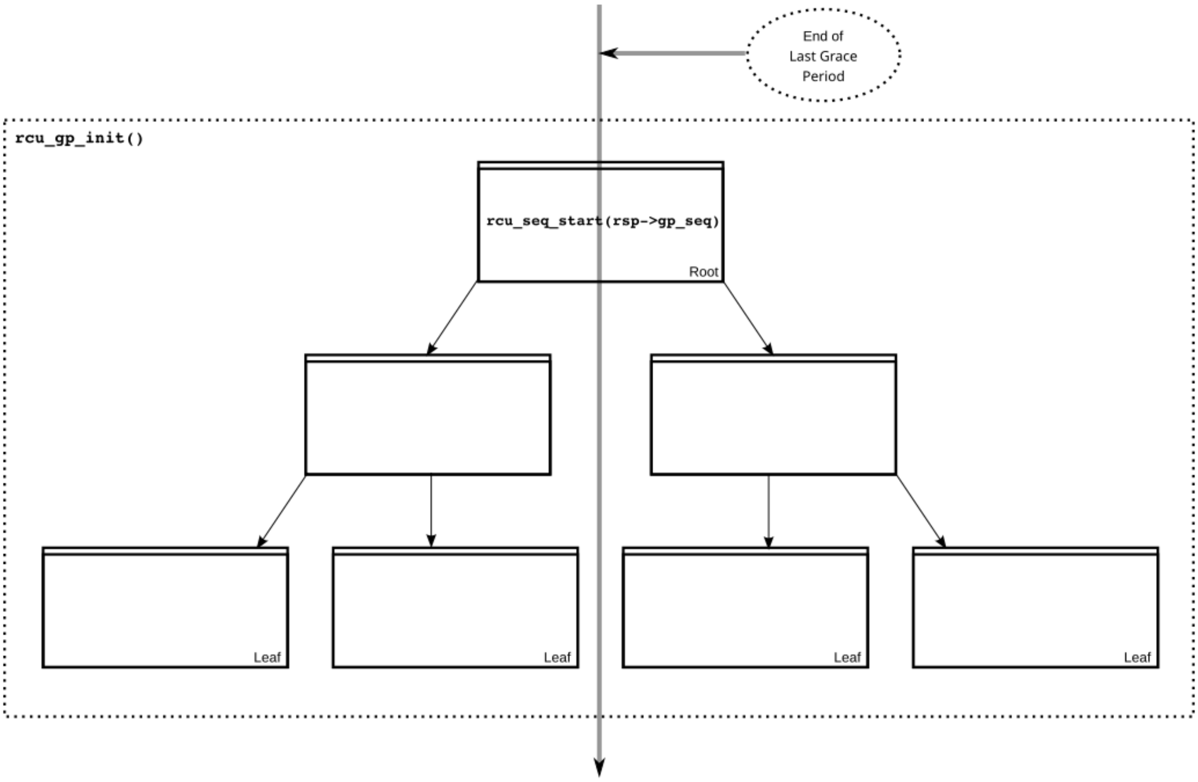
The first pass through the `rcu_node` tree updates bitmasks based on CPUs having come online or gone offline since the start of the previous grace period. In the common case where the number of online CPUs for this `rcu_node` structure has not transitioned to or from zero, this pass will scan only the leaf `rcu_node` structures. However, if the number of online CPUs for a given leaf `rcu_node` structure

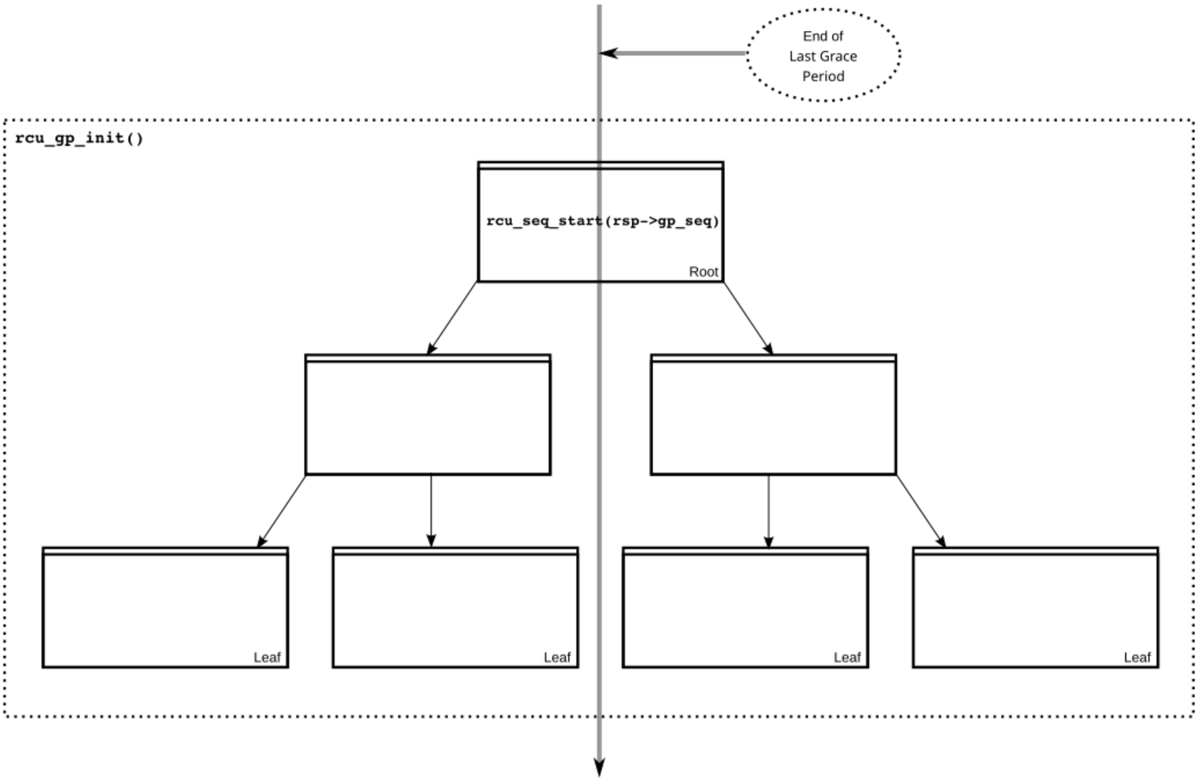


has transitioned from zero, `rcu_init_new_rnp()` will be invoked for the first incoming CPU. Similarly, if the number of online CPUs for a given leaf `rcu_node` structure has transitioned to zero, `rcu_cleanup_dead_rnp()` will be invoked for the last outgoing CPU. The diagram below shows the path of ordering if the leftmost `rcu_node` structure onlines its first CPU and if the next `rcu_node` structure has no online CPUs (or, alternatively if the leftmost `rcu_node` structure offlines its last CPU and if the next `rcu_node` structure has no online CPUs).

The final `rcu_gp_init()` pass through the `rcu_node` tree traverses breadth-first, setting each `rcu_node` structure's `->gp_seq` field to the newly advanced value from the `rcu_state` structure, as shown in the following diagram.

This change will also cause each CPU's next call to `__note_gp_changes()` to notice that a new grace period has started, as described in the next section. But because the grace-period kthread started the grace period at the root (with the advancing of the `rcu_state` structure's `->gp_seq` field) before setting each leaf `rcu_node` structure's `->gp_seq` field, each CPU's observation of the start of the grace period will happen after the actual start of the grace period.


End of
Last Grace
Period
rcu_gp_init()
rcu_seq_start(rsp->gp_seq)
Root
Leaf
Leaf
Leaf
Leaf


End of
Last Grace
Period
rcu_gp_init()
rcu_seq_start(rsp->gp_seq)
Root
Leaf
Leaf
Leaf
Leaf

Quick Quiz:
But what about the CPU that started the grace period? Why wouldn't it see the start of the grace period right when it started that grace period?

Answer:
In some deep philosophical and overly anthromorphized sense, yes, the CPU starting the grace period is immediately aware of having done so. However, if we instead assume that RCU is not self-aware, then even the CPU starting the grace period does not really become aware of the start of this grace period until its first call to `__note_gp_changes()`. On the other hand, this CPU potentially gets early notification because it invokes `__note_gp_changes()` during its last `rcu_gp_init()` pass through its leaf `rcu_node` structure.

Self-Reported Quiescent States

When all entities that might block the grace period have reported quiescent states (or as described in a later section, had quiescent states reported on their behalf), the grace period can end. Online non-idle CPUs report their own quiescent states, as shown in the following diagram:

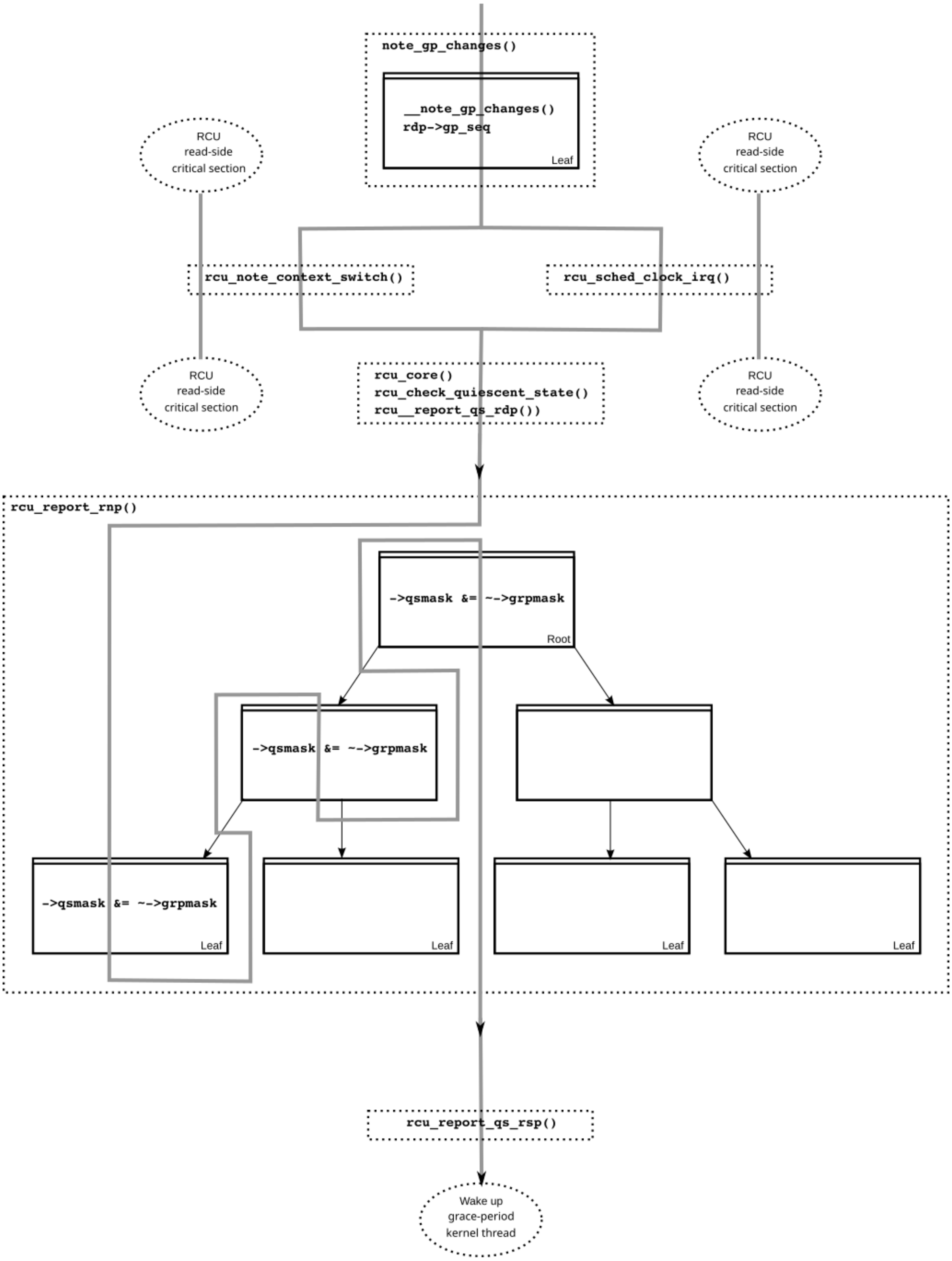
This is for the last CPU to report a quiescent state, which signals the end of the grace period. Earlier quiescent states would push up the `rcu_node` tree only until they encountered an `rcu_node` structure that is waiting for additional quiescent states. However, ordering is nevertheless preserved because some later quiescent state will acquire that `rcu_node` structure's `->lock`.

Any number of events can lead up to a CPU invoking `note_gp_changes` (or alternatively, directly invoking `__note_gp_changes()`), at which point that CPU will notice the start of a new grace period while holding its leaf `rcu_node` lock. Therefore, all execution shown in this diagram happens after the start of the grace period. In addition, this CPU will consider any RCU read-side critical section that started before the invocation of `__note_gp_changes()` to have started before the grace period, and thus a critical section that the grace period must wait on.

Quick Quiz:
But a RCU read-side critical section might have started after the beginning of the grace period (the advancing of `->gp_seq` from earlier), so why should the grace period wait on such a critical section?

Answer:
It is indeed not necessary for the grace period to wait on such a critical section. However, it is permissible to wait on it. And it is furthermore important to wait on it, as this lazy approach is far more scalable than a "big bang" all-at-once grace-period start could possibly be.

If the CPU does a context switch, a quiescent state will be noted by `rcu_note_context_switch()` on the left. On the other hand, if the CPU takes a scheduler-clock interrupt while executing in usermode, a quiescent state will be noted by `rcu_sched_clock_irq()` on the right. Either way, the passage through a quiescent state will be noted in a per-CPU variable.


note_gp_changes()
__note_gp_changes()
rdp->gp_seq
Leaf
RCU
read-side
critical section
RCU
read-side
critical section
rcu_note_context_switch()
rcu_sched_clock_irq()
RCU
read-side
critical section
rcu_core()
rcu_check_quiescent_state()
rcu__report_qs_rdp())
RCU
read-side
critical section
rcu_report_rnp()
->qsmask &= ~->grpmask
Root
->qsmask &= ~->grpmask
->qsmask &= ~->grpmask
Leaf
Leaf
Leaf
Leaf
rcu_report_qs_rsp()
Wake up
grace-period
kernel thread

The next time an `RCU_SOFTIRQ` handler executes on this CPU (for example, after the next scheduler-clock interrupt), `rcu_core()` will invoke `rcu_check_quiescent_state()`, which will notice the recorded quiescent state, and invoke `rcu_report_qs_rdp()`. If `rcu_report_qs_rdp()` verifies that the quiescent state really does apply to the current grace period, it invokes `rcu_report_rnp()` which traverses up the `rcu_node` tree as shown at the bottom of the diagram, clearing bits from each `rcu_node` structure's `->qsmask` field, and propagating up the tree when the result is zero.

Note that traversal passes upwards out of a given `rcu_node` structure only if the current CPU is reporting the last quiescent state for the subtree headed by that `rcu_node` structure. A key point is that if a CPU's traversal stops at a given `rcu_node` structure, then there will be a later traversal by another CPU (or perhaps the same one) that proceeds upwards from that point, and the `rcu_node` `->lock` guarantees that the first CPU's quiescent state happens before the remainder of the second CPU's traversal. Applying this line of thought repeatedly shows that all CPUs' quiescent states happen before the last CPU traverses through the root `rcu_node` structure, the "last CPU" being the one that clears the last bit in the root `rcu_node` structure's `->qsmask` field.

Dynamic Tick Interface

Due to energy-efficiency considerations, RCU is forbidden from disturbing idle CPUs. CPUs are therefore required to notify RCU when entering or leaving idle state, which they do via fully ordered value-returning atomic operations on a per-CPU variable. The ordering effects are as shown below:

The RCU grace-period kernel thread samples the per-CPU idleness variable while holding the corresponding CPU's leaf `rcu_node` structure's `->lock`. This means that any RCU read-side critical sections that precede the idle period (the oval near the top of the diagram above) will happen before the end of the current grace period. Similarly, the beginning of the current grace period will happen before any RCU read-side critical sections that follow the idle period (the oval near the bottom of the diagram above).

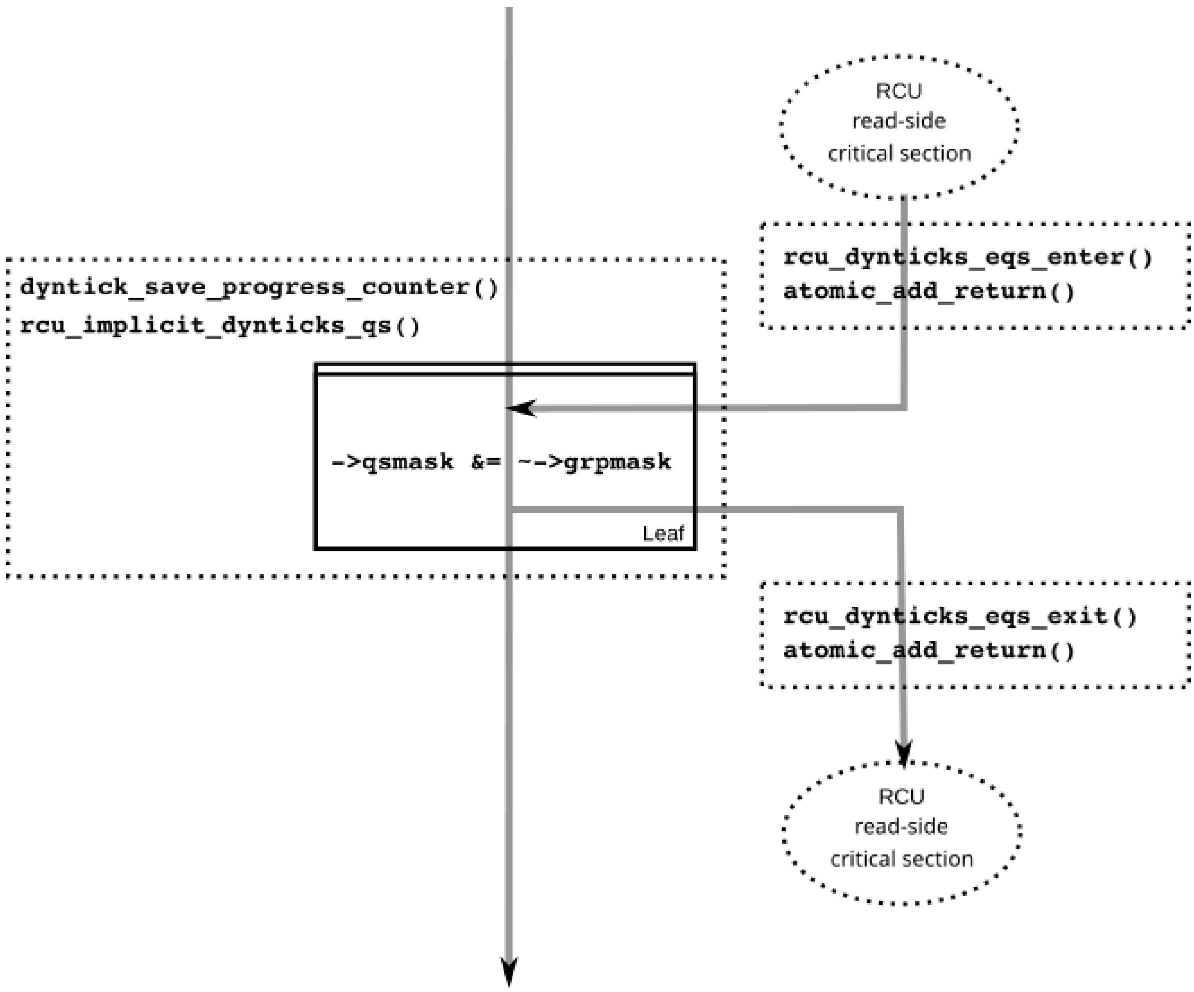
Plumbing this into the full grace-period execution is described *below*.

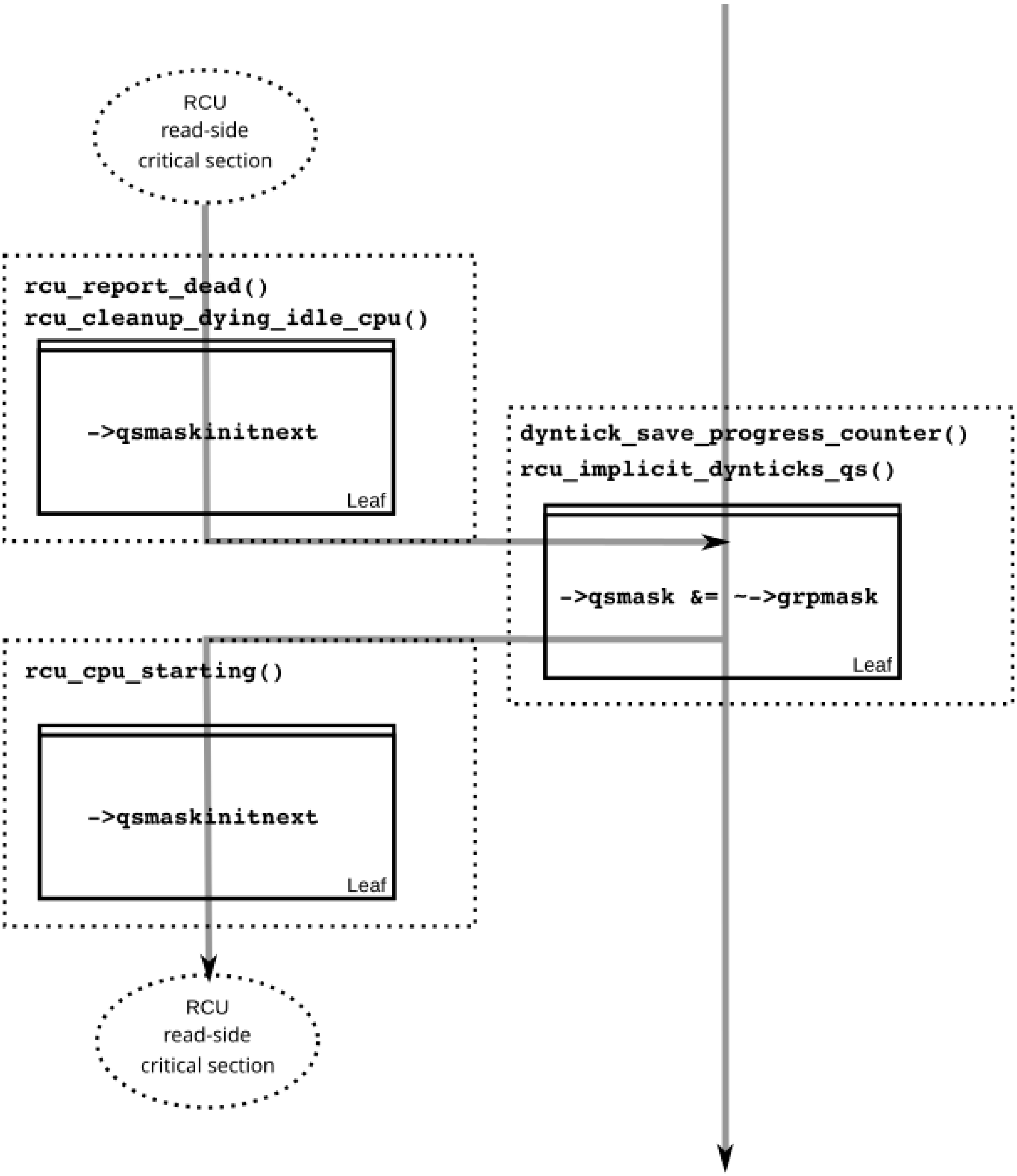
CPU-Hotplug Interface

RCU is also forbidden from disturbing offline CPUs, which might well be powered off and removed from the system completely. CPUs are therefore required to notify RCU of their comings and goings as part of the corresponding CPU hotplug operations. The ordering effects are shown below:

Because CPU hotplug operations are much less frequent than idle transitions, they are heavier weight, and thus acquire the CPU's leaf `rcu_node` structure's `->lock` and update this structure's `->qsmaskinitnext`. The RCU grace-period kernel thread samples this mask to detect CPUs having gone offline since the beginning of this grace period.

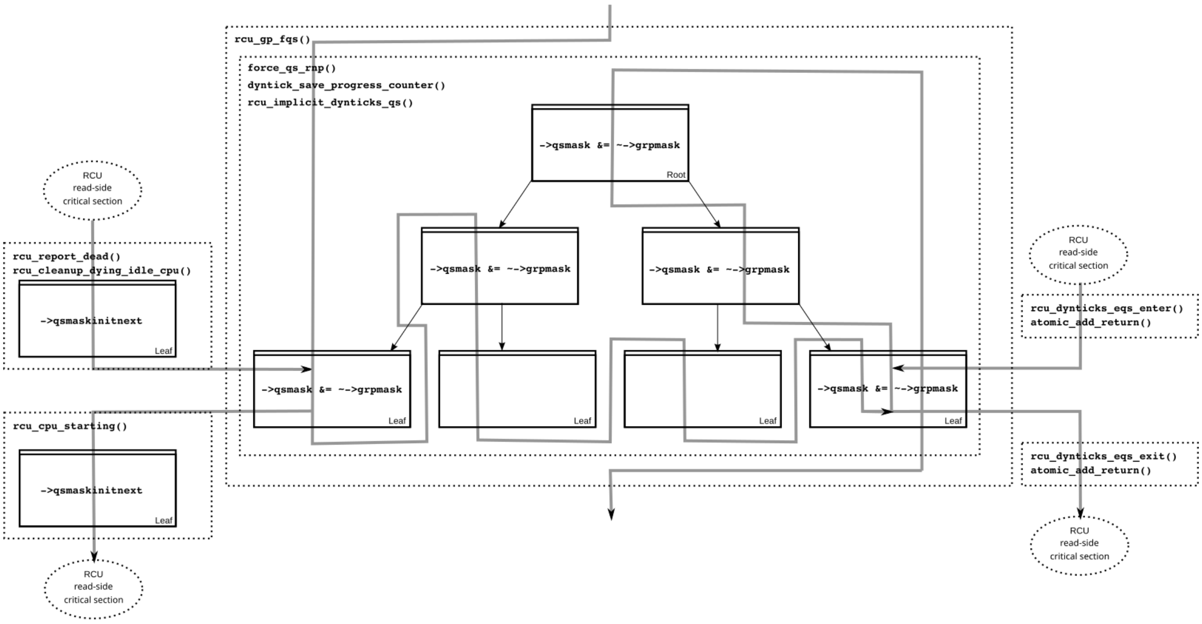
Plumbing this into the full grace-period execution is described *below*.


RCU
read-side
critical section
rcu_dynticks_eqs_enter()
atomic_add_return()
dyntick_save_progress_counter()
rcu_implicit_dynticks_qs()
->qsmask &= ~->grpmask
Leaf
rcu_dynticks_eqs_exit()
atomic_add_return()
RCU
read-side
critical section


RCU
read-side
critical section
rcu_report_dead()
rcu_cleanup_dying_idle_cpu()
->qsmaskinitnext
Leaf
dyntick_save_progress_counter()
rcu_implicit_dynticks_qs()
->qsmask &= ~->grpmask
Leaf
rcu_cpu_starting()
->qsmaskinitnext
Leaf
RCU
read-side
critical section

Forcing Quiescent States

As noted above, idle and offline CPUs cannot report their own quiescent states, and therefore the grace-period kernel thread must do the reporting on their behalf. This process is called "forcing quiescent states", it is repeated every few jiffies, and its ordering effects are shown below:



Each pass of quiescent state forcing is guaranteed to traverse the leaf `rcu_node` structures, and if there are no new quiescent states due to recently idled and/or offlined CPUs, then only the leaves are traversed. However, if there is a newly offlined CPU as illustrated on the left or a newly idled CPU as illustrated on the right, the corresponding quiescent state will be driven up towards the root. As with self-reported quiescent states, the upwards driving stops once it reaches an `rcu_node` structure that has quiescent states outstanding from other CPUs.

Quick Quiz:

The leftmost drive to root stopped before it reached the root `rcu_node` structure, which means that there are still CPUs subordinate to that structure on which the current grace period is waiting. Given that, how is it possible that the rightmost drive to root ended the grace period?

Answer:

Good analysis! It is in fact impossible in the absence of bugs in RCU. But this diagram is complex enough as it is, so simplicity overrode accuracy. You can think of it as poetic license, or you can think of it as misdirection that is resolved in the *stitched-together diagram*.

Grace-Period Cleanup

Grace-period cleanup first scans the `rcu_node` tree breadth-first advancing all the `->gp_seq` fields, then it advances the `rcu_state` structure's `->gp_seq` field. The ordering effects are shown below:

As indicated by the oval at the bottom of the diagram, once grace-period cleanup is complete, the next grace period can begin.

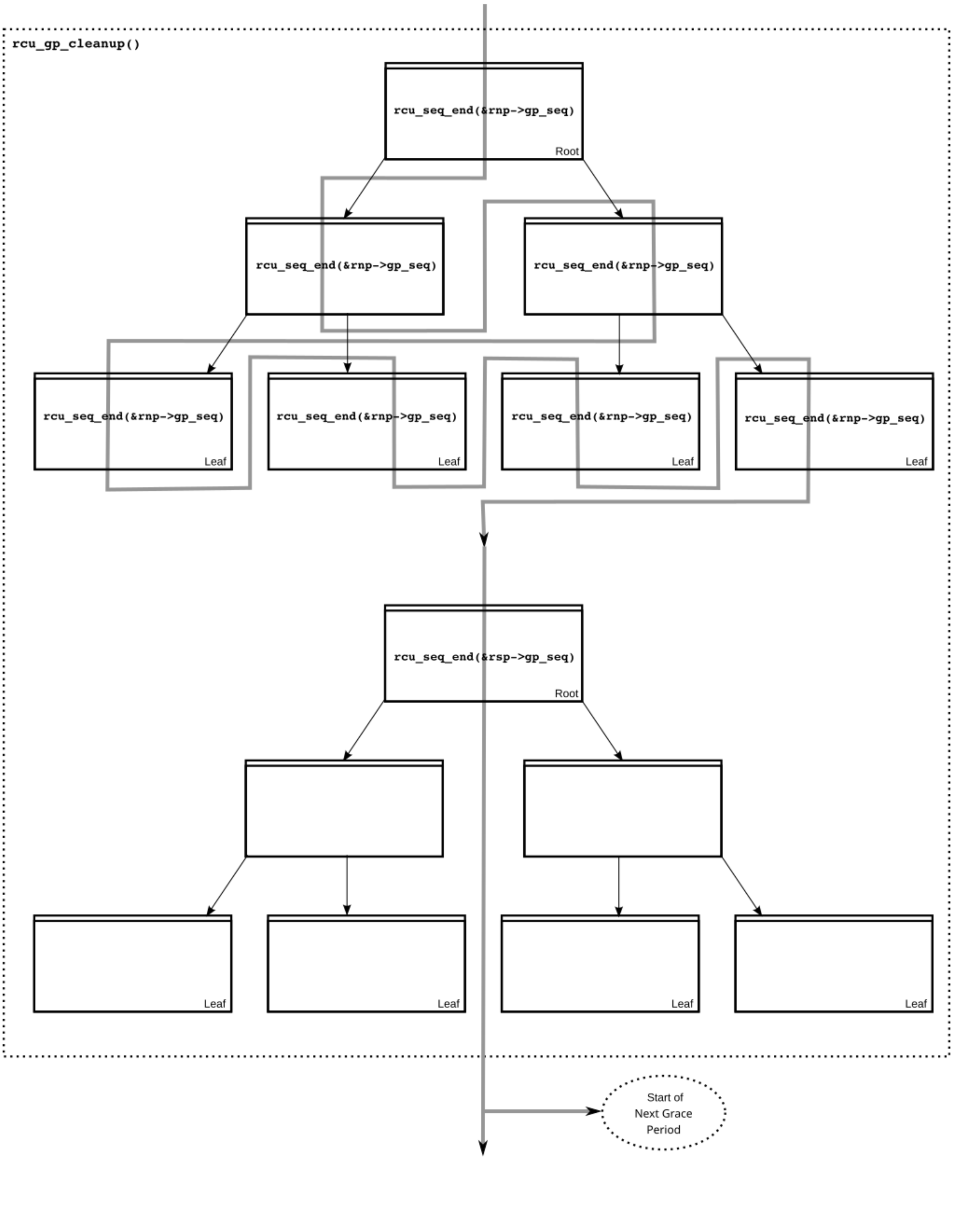
Quick Quiz:
But when precisely does the grace period end?
Answer:
There is no useful single point at which the grace period can be said to end. The earliest reasonable candidate is as soon as the last CPU has reported its quiescent state, but it may be some milliseconds before RCU becomes aware of this. The latest reasonable candidate is once the `rcu_state` structure's `->gp_seq` field has been updated, but it is quite possible that some CPUs have already completed phase two of their updates by that time. In short, if you are going to work with RCU, you need to learn to embrace uncertainty.

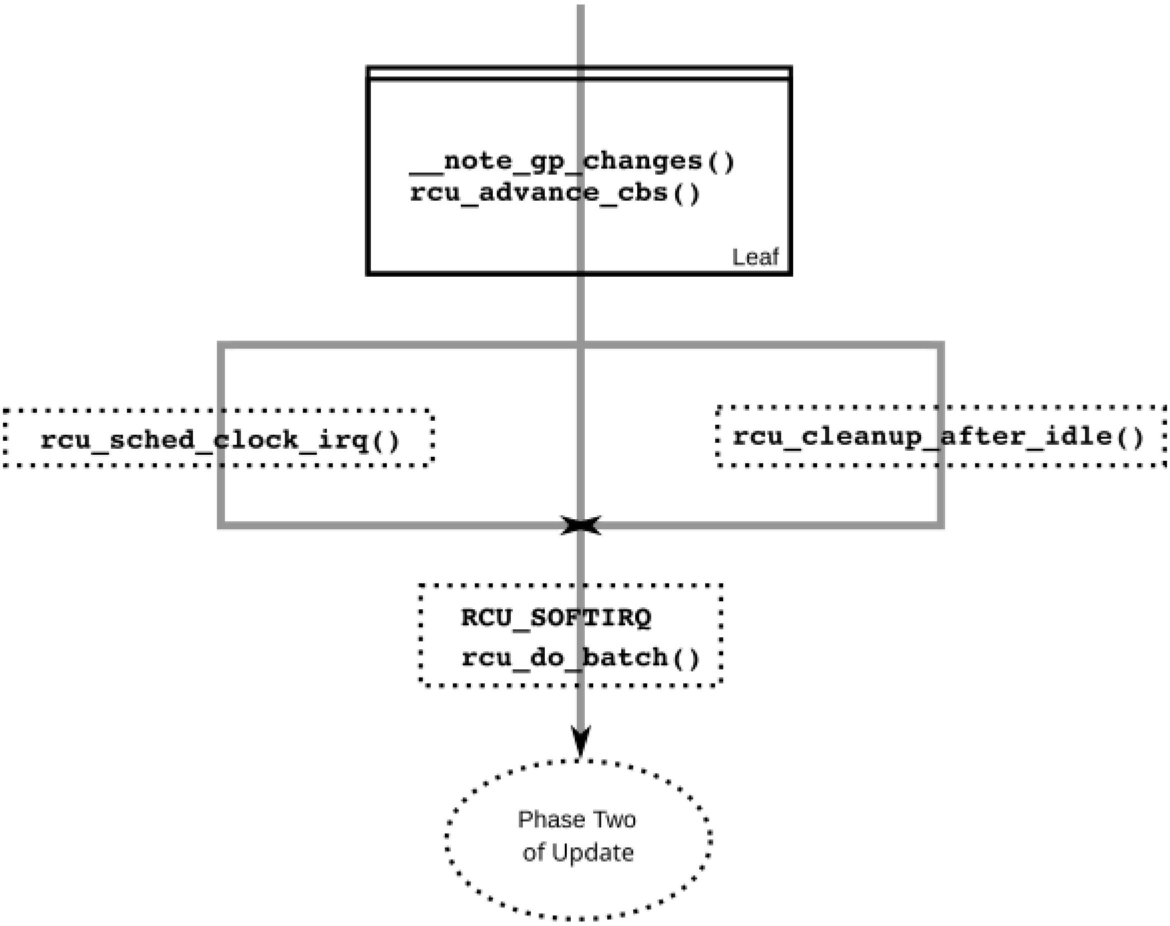
Callback Invocation

Once a given CPU's leaf `rcu_node` structure's `->gp_seq` field has been updated, that CPU can begin invoking its RCU callbacks that were waiting for this grace period to end. These callbacks are identified by `rcu_advance_cbs()`, which is usually invoked by `__note_gp_changes()`. As shown in the diagram below, this invocation can be triggered by the scheduling-clock interrupt (`rcu_sched_clock_irq()` on the left) or by idle entry (`rcu_cleanup_after_idle()` on the right, but only for kernels build with `CONFIG_RCU_FAST_NO_HZ=y`). Either way, `RCU_SOFTIRQ` is raised, which results in `rcu_do_batch()` invoking the callbacks, which in turn allows those callbacks to carry out (either directly or indirectly via wakeup) the needed phase-two processing for each update.

Please note that callback invocation can also be prompted by any number of corner-case code paths, for example, when a CPU notes that it has excessive numbers of callbacks queued. In all cases, the CPU acquires its leaf `rcu_node` structure's `->lock` before invoking callbacks, which preserves the required ordering against the newly completed grace period.

However, if the callback function communicates to other CPUs, for example, doing a wakeup, then it is that function's responsibility to maintain ordering. For example, if the callback function wakes up a task that runs on some other CPU, proper ordering must in place in both the callback function and the task being awakened. To see why this is important, consider the top half of the *grace-period cleanup* diagram. The callback might be running on a CPU corresponding to the leftmost leaf `rcu_node` structure, and awaken a task that is to run on a CPU corresponding to the rightmost leaf `rcu_node` structure, and the grace-period kernel thread might not yet have reached the rightmost leaf. In this case, the grace period's memory ordering might not yet have reached that CPU, so again the callback function and the awakened task must supply proper ordering.


rcu_gp_cleanup()
rcu_seq_end(&rnp->gp_seq)
Root
rcu_seq_end(&rnp->gp_seq)
rcu_seq_end(&rnp->gp_seq)
rcu_seq_end(&rnp->gp_seq)
Leaf
rcu_seq_end(&rnp->gp_seq)
Leaf
rcu_seq_end(&rnp->gp_seq)
Leaf
rcu_seq_end(&rnp->gp_seq)
Leaf
rcu_seq_end(&rsp->gp_seq)
Root
Leaf
Leaf
Leaf
Leaf
Start of
Next Grace
Period


__note_gp_changes()
rcu_advance_cbs()
Leaf
rcu_sched_clock_irq()
rcu_cleanup_after_idle()
RCU_SOFTIRQ
rcu_do_batch()
Phase Two
of Update

Putting It All Together

A stitched-together diagram is here:

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3.6.17 A Tour Through TREE_RCU's Expedited Grace Periods

Introduction

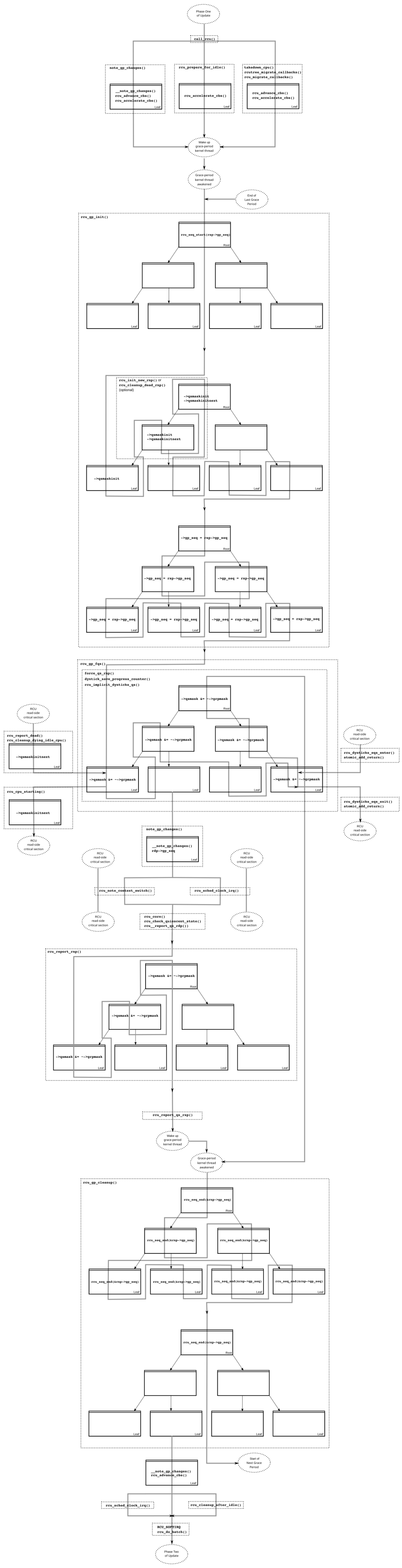
This document describes RCU's expedited grace periods. Unlike RCU's normal grace periods, which accept long latencies to attain high efficiency and minimal disturbance, expedited grace periods accept lower efficiency and significant disturbance to attain shorter latencies.

There are two flavors of RCU (RCU-preempt and RCU-sched), with an earlier third RCU-bh flavor having been implemented in terms of the other two. Each of the two implementations is covered in its own section.

Expedited Grace Period Design

The expedited RCU grace periods cannot be accused of being subtle, given that they for all intents and purposes hammer every CPU that has not yet provided a quiescent state for the current expedited grace period. The one saving grace is that the hammer has grown a bit smaller over time: The old call to `try_stop_cpus()` has been replaced with a set of calls to `smp_call_function_single()`, each of which results in an IPI to the target CPU. The corresponding handler function checks the CPU's state, motivating a faster quiescent state where possible, and triggering a report of that quiescent state. As always for RCU, once everything has spent some time in a quiescent state, the expedited grace period has completed.

The details of the `smp_call_function_single()` handler's operation depend on the RCU flavor, as described in the following sections.



RCU-preempt Expedited Grace Periods

`CONFIG_PREEMPT=y` kernels implement RCU-preempt. The overall flow of the handling of a given CPU by an RCU-preempt expedited grace period is shown in the following diagram:

The solid arrows denote direct action, for example, a function call. The dotted arrows denote indirect action, for example, an IPI or a state that is reached after some time.

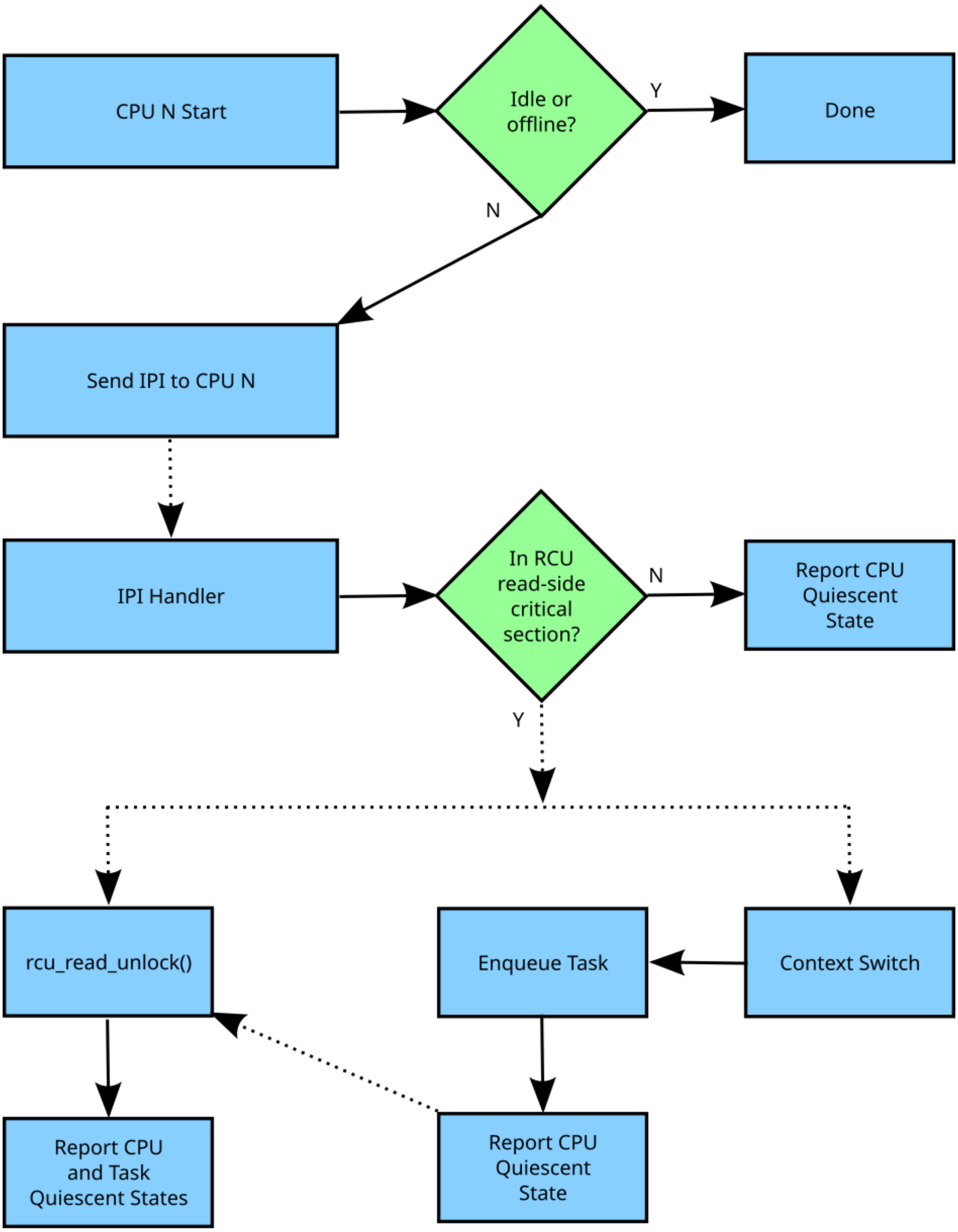
If a given CPU is offline or idle, `synchronize_rcu_expedited()` will ignore it because idle and offline CPUs are already residing in quiescent states. Otherwise, the expedited grace period will use `smp_call_function_single()` to send the CPU an IPI, which is handled by `rcu_exp_handler()`.

However, because this is preemptible RCU, `rcu_exp_handler()` can check to see if the CPU is currently running in an RCU read-side critical section. If not, the handler can immediately report a quiescent state. Otherwise, it sets flags so that the outermost `rcu_read_unlock()` invocation will provide the needed quiescent-state report. This flag-setting avoids the previous forced preemption of all CPUs that might have RCU read-side critical sections. In addition, this flag-setting is done so as to avoid increasing the overhead of the common-case fastpath through the scheduler.

Again because this is preemptible RCU, an RCU read-side critical section can be preempted. When that happens, RCU will enqueue the task, which will the continue to block the current expedited grace period until it resumes and finds its outermost `rcu_read_unlock()`. The CPU will report a quiescent state just after enqueuing the task because the CPU is no longer blocking the grace period. It is instead the preempted task doing the blocking. The list of blocked tasks is managed by `rcu_preempt_ctxt_queue()`, which is called from `rcu_preempt_note_context_switch()`, which in turn is called from `rcu_note_context_switch()`, which in turn is called from the scheduler.

Quick Quiz:
Why not just have the expedited grace period check the state of all the CPUs? After all, that would avoid all those real-time-unfriendly IPIs.
Answer:
Because we want the RCU read-side critical sections to run fast, which means no memory barriers. Therefore, it is not possible to safely check the state from some other CPU. And even if it was possible to safely check the state, it would still be necessary to IPI the CPU to safely interact with the upcoming `rcu_read_unlock()` invocation, which means that the remote state testing would not help the worst-case latency that real-time applications care about. One way to prevent your real-time application from getting hit with these IPIs is to build your kernel with `CONFIG_NO_HZ_FULL=y`. RCU would then perceive the CPU running your application as being idle, and it would be able to safely detect that state without needing to IPI the CPU.

Please note that this is just the overall flow: Additional complications can arise due to races with CPUs going idle or offline, among other things.


CPU N Start
Idle or offline?
Y
Done
N
Send IPI to CPU N
IPI Handler
In RCU read-side critical section?
N
Report CPU Quiescent State
Y
rcu_read_unlock()
Enqueue Task
Context Switch
Report CPU and Task Quiescent States
Report CPU Quiescent State

RCU-sched Expedited Grace Periods

CONFIG_PREEMPT=n kernels implement RCU-sched. The overall flow of the handling of a given CPU by an RCU-sched expedited grace period is shown in the following diagram:

As with RCU-preempt, RCU-sched's synchronize_rcu_expedited() ignores offline and idle CPUs, again because they are in remotely detectable quiescent states. However, because the rcu_read_lock_sched() and rcu_read_unlock_sched() leave no trace of their invocation, in general it is not possible to tell whether or not the current CPU is in an RCU read-side critical section. The best that RCU-sched's rcu_exp_handler() can do is to check for idle, on the off-chance that the CPU went idle while the IPI was in flight. If the CPU is idle, then rcu_exp_handler() reports the quiescent state.

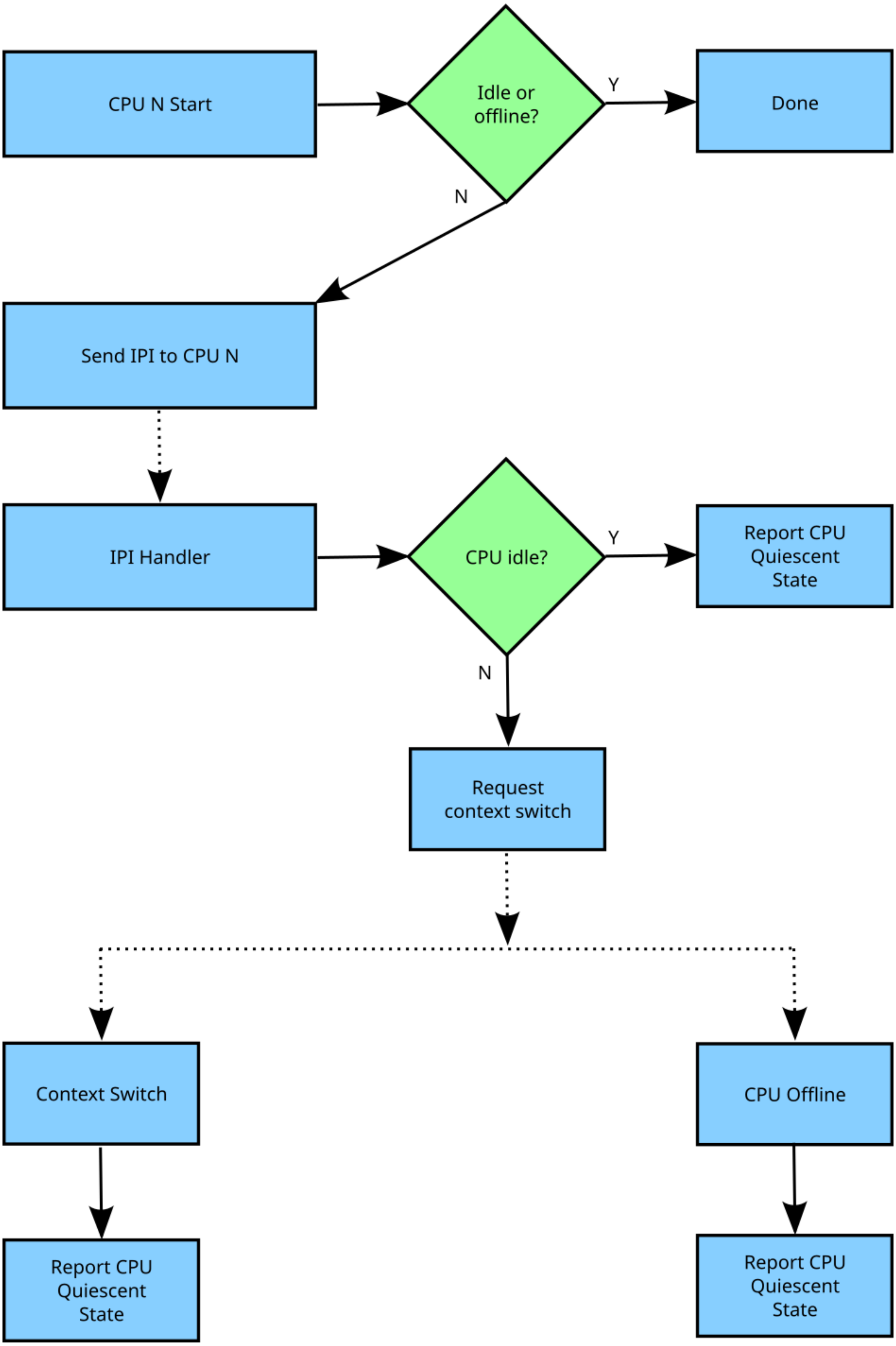
Otherwise, the handler forces a future context switch by setting the NEED_RESCHED flag of the current task's thread flag and the CPU preempt counter. At the time of the context switch, the CPU reports the quiescent state. Should the CPU go offline first, it will report the quiescent state at that time.

Expedited Grace Period and CPU Hotplug

The expedited nature of expedited grace periods require a much tighter interaction with CPU hotplug operations than is required for normal grace periods. In addition, attempting to IPI offline CPUs will result in splats, but failing to IPI online CPUs can result in too-short grace periods. Neither option is acceptable in production kernels.

The interaction between expedited grace periods and CPU hotplug operations is carried out at several levels:

1. The number of CPUs that have ever been online is tracked by the rcu_state structure's ->ncpus field. The rcu_state structure's ->ncpus_snap field tracks the number of CPUs that have ever been online at the beginning of an RCU expedited grace period. Note that this number never decreases, at least in the absence of a time machine.
2. The identities of the CPUs that have ever been online is tracked by the rcu_node structure's ->expmaskinitnext field. The rcu_node structure's ->expmaskinit field tracks the identities of the CPUs that were online at least once at the beginning of the most recent RCU expedited grace period. The rcu_state structure's ->ncpus and ->ncpus_snap fields are used to detect when new CPUs have come online for the first time, that is, when the rcu_node structure's ->expmaskinitnext field has changed since the beginning of the last RCU expedited grace period, which triggers an update of each rcu_node structure's ->expmaskinit field from its ->expmaskinitnext field.
3. Each rcu_node structure's ->expmaskinit field is used to initialize that structure's ->expmask at the beginning of each RCU expedited grace period. This means that only those CPUs that have been online at least once will be considered for a given grace period.


CPU N Start
Idle or
offline?
Y
Done
N
Send IPI to CPU N
IPI Handler
CPU idle?
Y
Report CPU
Quiescent
State
N
Request
context switch
Context Switch
CPU Offline
Report CPU
Quiescent
State
Report CPU
Quiescent
State

4. Any CPU that goes offline will clear its bit in its leaf `rcu_node` structure's `->qsmaskinitnext` field, so any CPU with that bit clear can safely be ignored. However, it is possible for a CPU coming online or going offline to have this bit set for some time while `cpu_online` returns `false`.
5. For each non-idle CPU that RCU believes is currently online, the grace period invokes `smp_call_function_single()`. If this succeeds, the CPU was fully online. Failure indicates that the CPU is in the process of coming online or going offline, in which case it is necessary to wait for a short time period and try again. The purpose of this wait (or series of waits, as the case may be) is to permit a concurrent CPU-hotplug operation to complete.
6. In the case of RCU-sched, one of the last acts of an outgoing CPU is to invoke `rcu_report_dead()`, which reports a quiescent state for that CPU. However, this is likely paranoia-induced redundancy.

Quick Quiz:
Why all the dancing around with multiple counters and masks tracking CPUs that were once online? Why not just have a single set of masks tracking the currently online CPUs and be done with it?

Answer:
Maintaining single set of masks tracking the online CPUs *sounds* easier, at least until you try working out all the race conditions between grace-period initialization and CPU-hotplug operations. For example, suppose initialization is progressing down the tree while a CPU-offline operation is progressing up the tree. This situation can result in bits set at the top of the tree that have no counterparts at the bottom of the tree. Those bits will never be cleared, which will result in grace-period hangs. In short, that way lies madness, to say nothing of a great many bugs, hangs, and deadlocks. In contrast, the current multi-mask multi-counter scheme ensures that grace-period initialization will always see consistent masks up and down the tree, which brings significant simplifications over the single-mask method.
This is an instance of deferring work in order to avoid synchronization. Lazily recording CPU-hotplug events at the beginning of the next grace period greatly simplifies maintenance of the CPU-tracking bitmasks in the `rcu_node` tree.

Expedited Grace Period Refinements

Idle-CPU Checks

Each expedited grace period checks for idle CPUs when initially forming the mask of CPUs to be IPIed and again just before IPIing a CPU (both checks are carried out by `sync_rcu_exp_select_cpus()`). If the CPU is idle at any time between those two times, the CPU will not be IPIed. Instead, the task pushing the grace period forward will include the idle CPUs in the mask passed to `rcu_report_exp_cpu_mult()`.

For RCU-sched, there is an additional check: If the IPI has interrupted the idle loop, then `rcu_exp_handler()` invokes `rcu_report_exp_rdp()` to report the corresponding quiescent state.

For RCU-preempt, there is no specific check for idle in the IPI handler (`rcu_exp_handler()`), but because RCU read-side critical sections are not permitted within the idle loop, if `rcu_exp_handler()` sees that the CPU is within RCU read-side critical section, the CPU cannot possibly be idle. Otherwise, `rcu_exp_handler()` invokes `rcu_report_exp_rdp()` to report the corresponding quiescent state, regardless of whether or not that quiescent state was due to the CPU being idle.

In summary, RCU expedited grace periods check for idle when building the bitmask of CPUs that must be IPIed, just before sending each IPI, and (either explicitly or implicitly) within the IPI handler.

Batching via Sequence Counter

If each grace-period request was carried out separately, expedited grace periods would have abysmal scalability and problematic high-load characteristics. Because each grace-period operation can serve an unlimited number of updates, it is important to *batch* requests, so that a single expedited grace-period operation will cover all requests in the corresponding batch.

This batching is controlled by a sequence counter named `->expedited_sequence` in the `rcu_state` structure. This counter has an odd value when there is an expedited grace period in progress and an even value otherwise, so that dividing the counter value by two gives the number of completed grace periods. During any given update request, the counter must transition from even to odd and then back to even, thus indicating that a grace period has elapsed. Therefore, if the initial value of the counter is `s`, the updater must wait until the counter reaches at least the value `(s+3)&~0x1`. This counter is managed by the following access functions:

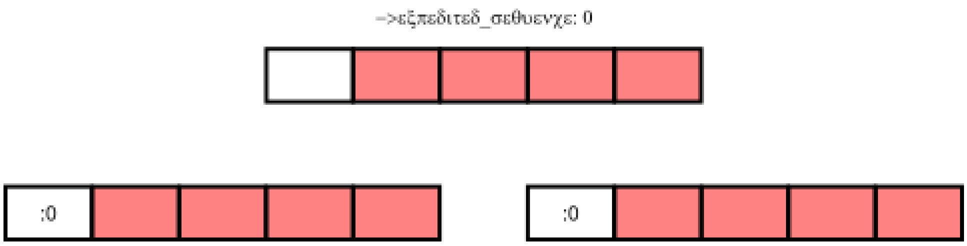
1. `rcu_exp_gp_seq_start()`, which marks the start of an expedited grace period.
2. `rcu_exp_gp_seq_end()`, which marks the end of an expedited grace period.
3. `rcu_exp_gp_seq_snap()`, which obtains a snapshot of the counter.
4. `rcu_exp_gp_seq_done()`, which returns `true` if a full expedited grace period has elapsed since the corresponding call to `rcu_exp_gp_seq_snap()`.

Again, only one request in a given batch need actually carry out a grace-period operation, which means there must be an efficient way to identify which of many concurrent reqeusts will initiate the grace period, and that there be an efficient way for the remaining requests to wait for that grace period to complete. However, that is the topic of the next section.

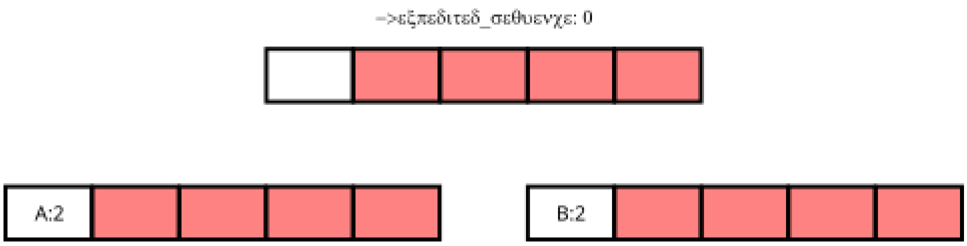
Funnel Locking and Wait/Wakeup

The natural way to sort out which of a batch of updaters will initiate the expedited grace period is to use the `rcu_node` combining tree, as implemented by the `exp_funnel_lock()` function. The first updater corresponding to a given grace period arriving at a given `rcu_node` structure records its desired grace-period sequence number in the `->exp_seq_rq` field and moves up to the next level in the tree. Otherwise, if the `->exp_seq_rq` field already contains the sequence number for the desired grace period or some later one, the updater blocks on one of four wait queues in the `->exp_wq[]` array, using the second-from-bottom and third-from bottom bits as an index. An `->exp_lock` field in the `rcu_node` structure synchronizes access to these fields.

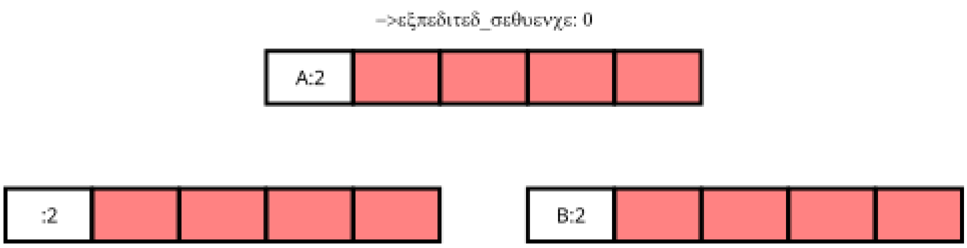
An empty `rcu_node` tree is shown in the following diagram, with the white cells representing the `->exp_seq_rq` field and the red cells representing the elements of the `->exp_wq[]` array.



The next diagram shows the situation after the arrival of Task A and Task B at the leftmost and rightmost leaf `rcu_node` structures, respectively. The current value of the `rcu_state` structure' s `->expedited_sequence` field is zero, so adding three and clearing the bottom bit results in the value two, which both tasks record in the `->exp_seq_rq` field of their respective `rcu_node` structures:



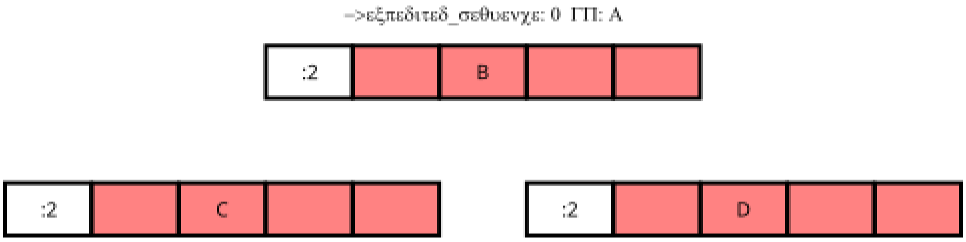
Each of Tasks A and B will move up to the root `rcu_node` structure. Suppose that Task A wins, recording its desired grace-period sequence number and resulting in the state shown below:



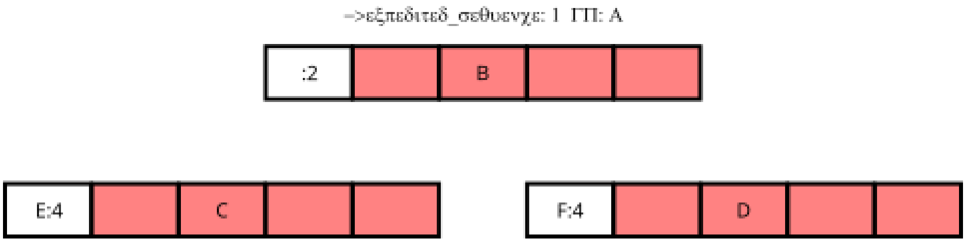
Task A now advances to initiate a new grace period, while Task B moves up to the root `rcu_node` structure, and, seeing that its desired sequence number is already recorded, blocks on ->exp_wq[1].

Quick Quiz:
Why ->exp_wq[1]? Given that the value of these tasks' desired sequence number is two, so shouldn't they instead block on ->exp_wq[2]?
Answer:
No. Recall that the bottom bit of the desired sequence number indicates whether or not a grace period is currently in progress. It is therefore necessary to shift the sequence number right one bit position to obtain the number of the grace period. This results in ->exp_wq[1].

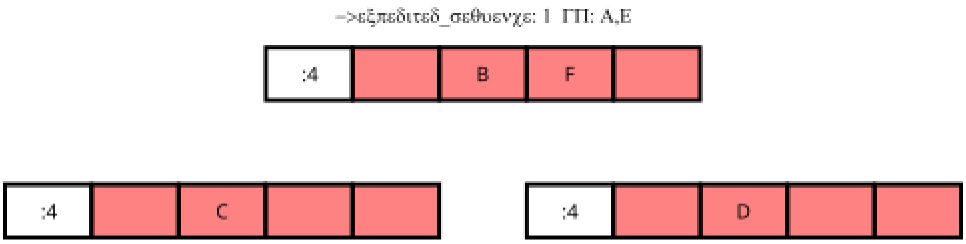
If Tasks C and D also arrive at this point, they will compute the same desired grace-period sequence number, and see that both leaf rcu_node structures already have that value recorded. They will therefore block on their respective rcu_node structures' ->exp_wq[1] fields, as shown below:



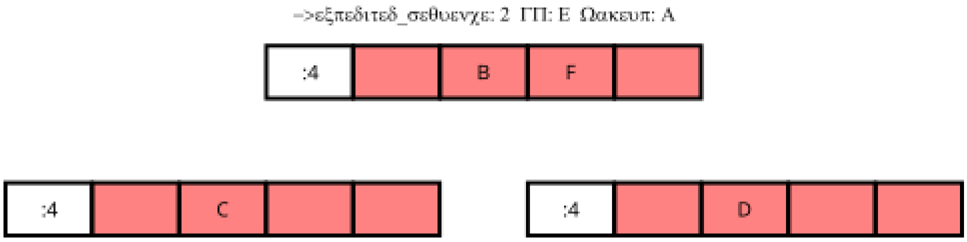
Task A now acquires the rcu_state structure's ->exp_mutex and initiates the grace period, which increments ->expedited_sequence. Therefore, if Tasks E and F arrive, they will compute a desired sequence number of 4 and will record this value as shown below:



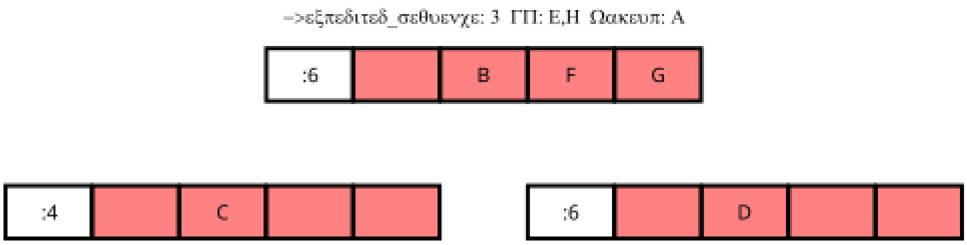
Tasks E and F will propagate up the rcu_node combining tree, with Task F blocking on the root rcu_node structure and Task E wait for Task A to finish so that it can start the next grace period. The resulting state is as shown below:



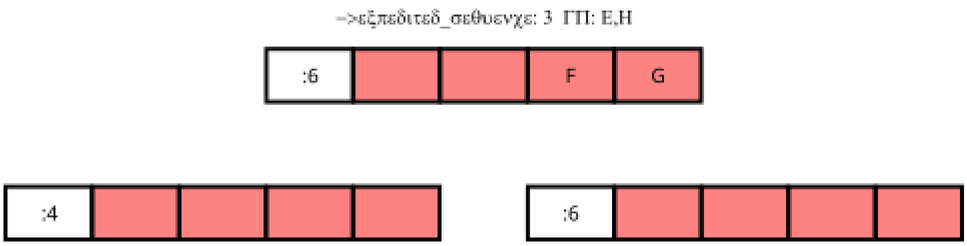
Once the grace period completes, Task A starts waking up the tasks waiting for this grace period to complete, increments the ->expedited_sequence, acquires the ->exp_wake_mutex and then releases the ->exp_mutex. This results in the following state:



Task E can then acquire ->exp_mutex and increment ->expedited_sequence to the value three. If new tasks G and H arrive and moves up the combining tree at the same time, the state will be as follows:



Note that three of the root rcu_node structure's waitqueues are now occupied. However, at some point, Task A will wake up the tasks blocked on the ->exp_wq waitqueues, resulting in the following state:



Execution will continue with Tasks E and H completing their grace periods and carrying out their wakeups.

Quick Quiz:
What happens if Task A takes so long to do its wakeups that Task E's grace period completes?
Answer:
Then Task E will block on the ->exp_wake_mutex, which will also prevent it from releasing ->exp_mutex, which in turn will prevent the next grace period from starting. This last is important in preventing overflow of the ->exp_wq[] array.

Use of Workqueues

In earlier implementations, the task requesting the expedited grace period also drove it to completion. This straightforward approach had the disadvantage of needing to account for POSIX signals sent to user tasks, so more recent implemementations use the Linux kernel's workqueues.

The requesting task still does counter snapshotting and funnel-lock processing, but the task reaching the top of the funnel lock does a `schedule_work()` (from `_synchronize_rcu_expedited()` so that a workqueue kthread does the actual grace-period processing. Because workqueue kthreads do not accept POSIX signals, grace-period-wait processing need not allow for POSIX signals. In addition, this approach allows wakeups for the previous expedited grace period to be overlapped with processing for the next expedited grace period. Because there are only four sets of waitqueues, it is necessary to ensure that the previous grace period's wakeups complete before the next grace period's wakeups start. This is handled by having the `->exp_mutex` guard expedited grace-period processing and the `->exp_wake_mutex` guard wakeups. The key point is that the `->exp_mutex` is not released until the first wakeup is complete, which means that the `->exp_wake_mutex` has already been acquired at that point. This approach ensures that the previous grace period's wakeups can be carried out while the current grace period is in process, but that these wakeups will complete before the next grace period starts. This means that only three waitqueues are required, guaranteeing that the four that are provided are sufficient.

Stall Warnings

Expediting grace periods does nothing to speed things up when RCU readers take too long, and therefore expedited grace periods check for stalls just as normal grace periods do.

Quick Quiz:
But why not just let the normal grace-period machinery detect the stalls, given that a given reader must block both normal and expedited grace periods?
Answer:
Because it is quite possible that at a given time there is no normal grace period in progress, in which case the normal grace period cannot emit a stall warning.

The `synchronize_sched_expedited_wait()` function loops waiting for the expedited grace period to end, but with a timeout set to the current RCU CPU stall-warning time. If this time is exceeded, any CPUs or `rcu_node` structures blocking the current grace period are printed. Each stall warning results in another pass through the loop, but the second and subsequent passes use longer stall times.

Mid-boot operation

The use of workqueues has the advantage that the expedited grace-period code need not worry about POSIX signals. Unfortunately, it has the corresponding disadvantage that workqueues cannot be used until they are initialized, which does not happen until some time after the scheduler spawns the first task. Given that there are parts of the kernel that really do want to execute grace periods during this mid-boot "dead zone", expedited grace periods must do something else during thie time.

What they do is to fall back to the old practice of requiring that the requesting task drive the expedited grace period, as was the case before the use of workqueues. However, the requesting task is only required to drive the grace period during the mid-boot dead zone. Before mid-boot, a synchronous grace period is a no-op. Some time after mid-boot, workqueues are used.

Non-expedited non-SRCU synchronous grace periods must also operate normally during mid-boot. This is handled by causing non-expedited grace periods to take the expedited code path during mid-boot.

The current code assumes that there are no POSIX signals during the mid-boot dead zone. However, if an overwhelming need for POSIX signals somehow arises, appropriate adjustments can be made to the expedited stall-warning code. One such adjustment would reinstate the pre-workqueue stall-warning checks, but only during the mid-boot dead zone.

With this refinement, synchronous grace periods can now be used from task context pretty much any time during the life of the kernel. That is, aside from some points in the suspend, hibernate, or shutdown code path.

Summary

Expedited grace periods use a sequence-number approach to promote batching, so that a single grace-period operation can serve numerous requests. A funnel lock is used to efficiently identify the one task out of a concurrent group that will request the grace period. All members of the group will block on waitqueues provided in the `rcu_node` structure. The actual grace-period processing is carried out by a workqueue.

CPU-hotplug operations are noted lazily in order to prevent the need for tight synchronization between expedited grace periods and CPU-hotplug operations. The dyntick-idle counters are used to avoid sending IPIs to idle CPUs, at least in the common case. RCU-preempt and RCU-sched use different IPI handlers and different code to respond to the state changes carried out by those handlers, but otherwise use common code.

Quiescent states are tracked using the `rcu_node` tree, and once all necessary quiescent states have been reported, all tasks waiting on this expedited grace period are awakened. A pair of mutexes are used to allow one grace period's wakeups to proceed concurrently with the next grace period's processing.

This combination of mechanisms allows expedited grace periods to run reasonably efficiently. However, for non-time-critical tasks, normal grace periods should be used instead because their longer duration permits much higher degrees of batching, and thus much lower per-request overheads.

3.6.18 A Tour Through RCU’s Requirements

Author: Paul E. McKenney

The initial version of this document appeared in the LWN on those articles: part 1, part 2, and part 3.

Introduction

Read-copy update (RCU) is a synchronization mechanism that is often used as a replacement for reader-writer locking. RCU is unusual in that updaters do not block readers, which means that RCU’s read-side primitives can be exceedingly fast and scalable. In addition, updaters can make useful forward progress concurrently with readers. However, all this concurrency between RCU readers and updaters does raise the question of exactly what RCU readers are doing, which in turn raises the question of exactly what RCU’s requirements are.

This document therefore summarizes RCU’s requirements, and can be thought of as an informal, high-level specification for RCU. It is important to understand that RCU’s specification is primarily empirical in nature; in fact, I learned about many of these requirements the hard way. This situation might cause some consternation, however, not only has this learning process been a lot of fun, but it has also been a great privilege to work with so many people willing to apply technologies in interesting new ways.

All that aside, here are the categories of currently known RCU requirements:

1. *Fundamental Requirements*
2. *Fundamental Non-Requirements*
3. *Parallelism Facts of Life*
4. *Quality-of-Implementation Requirements*
5. *Linux Kernel Complications*
6. *Software-Engineering Requirements*
7. *Other RCU Flavors*
8. *Possible Future Changes*

This is followed by a *summary*, however, the answers to each quick quiz immediately follows the quiz. Select the big white space with your mouse to see the answer.

Fundamental Requirements

RCU's fundamental requirements are the closest thing RCU has to hard mathematical requirements. These are:

1. *Grace-Period Guarantee*
2. *Publish/Subscribe Guarantee*
3. *Memory-Barrier Guarantees*
4. *RCU Primitives Guaranteed to Execute Unconditionally*
5. *Guaranteed Read-to-Write Upgrade*

Grace-Period Guarantee

RCU's grace-period guarantee is unusual in being premeditated: Jack Slingwine and I had this guarantee firmly in mind when we started work on RCU (then called "rclock") in the early 1990s. That said, the past two decades of experience with RCU have produced a much more detailed understanding of this guarantee.

RCU's grace-period guarantee allows updaters to wait for the completion of all pre-existing RCU read-side critical sections. An RCU read-side critical section begins with the marker `rcu_read_lock()` and ends with the marker `rcu_read_unlock()`. These markers may be nested, and RCU treats a nested set as one big RCU read-side critical section. Production-quality implementations of `rcu_read_lock()` and `rcu_read_unlock()` are extremely lightweight, and in fact have exactly zero overhead in Linux kernels built for production use with `CONFIG_PREEMPT=n`.

This guarantee allows ordering to be enforced with extremely low overhead to readers, for example:

```
 1 int x, y;
 2
 3 void thread0(void)
 4 {
 5   rcu_read_lock();
 6   r1 = READ_ONCE(x);
 7   r2 = READ_ONCE(y);
 8   rcu_read_unlock();
 9 }
10
11 void thread1(void)
12 {
13   WRITE_ONCE(x, 1);
14   synchronize_rcu();
15   WRITE_ONCE(y, 1);
16 }
```

Because the `synchronize_rcu()` on line 14 waits for all pre-existing readers, any instance of `thread0()` that loads a value of zero from `x` must complete before `thread1()` stores to `y`, so that instance must also load a value of zero from `y`. Similarly, any instance of `thread0()` that loads a value of one from `y` must have started after the `synchronize_rcu()` started, and must therefore also load a value of one from `x`. Therefore, the outcome:

```
(r1 == 0 && r2 == 1)
```

cannot happen.

Quick Quiz:

Wait a minute! You said that updaters can make useful forward progress concurrently with readers, but pre-existing readers will block `synchronize_rcu()`!!! Just who are you trying to fool???

Answer:

First, if updaters do not wish to be blocked by readers, they can use `call_rcu()` or `kfree_rcu()`, which will be discussed later. Second, even when using `synchronize_rcu()`, the other update-side code does run concurrently with readers, whether pre-existing or not.

This scenario resembles one of the first uses of RCU in DYNIX/ptx, which managed a distributed lock manager' s transition into a state suitable for handling recovery from node failure, more or less as follows:

```
#define STATE_NORMAL        0
#define STATE_WANT_RECOVERY 1
#define STATE_RECOVERING    2
#define STATE_WANT_NORMAL   3

int state = STATE_NORMAL;

void do_something_dlm(void)
{
  int state_snap;

  rcu_read_lock();
  state_snap = READ_ONCE(state);
  if (state_snap == STATE_NORMAL)
    do_something();
  else
    do_something_carefully();
  rcu_read_unlock();
}

void start_recovery(void)
{
  WRITE_ONCE(state, STATE_WANT_RECOVERY);
  synchronize_rcu();
  WRITE_ONCE(state, STATE_RECOVERING);
  recovery();
  WRITE_ONCE(state, STATE_WANT_NORMAL);
  synchronize_rcu();
  WRITE_ONCE(state, STATE_NORMAL);
```

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```
30 }
```

The RCU read-side critical section in `do_something_dlm()` works with the `synchronize_rcu()` in `start_recovery()` to guarantee that `do_something()` never runs concurrently with `recovery()`, but with little or no synchronization overhead in `do_something_dlm()`.

Quick Quiz:

Why is the `synchronize_rcu()` on line 28 needed?

Answer:

Without that extra grace period, memory reordering could result in `do_something_dlm()` executing `do_something()` concurrently with the last bits of `recovery()`.

In order to avoid fatal problems such as deadlocks, an RCU read-side critical section must not contain calls to `synchronize_rcu()`. Similarly, an RCU read-side critical section must not contain anything that waits, directly or indirectly, on completion of an invocation of `synchronize_rcu()`.

Although RCU' s grace-period guarantee is useful in and of itself, with quite a few use cases, it would be good to be able to use RCU to coordinate read-side access to linked data structures. For this, the grace-period guarantee is not sufficient, as can be seen in function `add_gp_buggy()` below. We will look at the reader' s code later, but in the meantime, just think of the reader as locklessly picking up the `gp` pointer, and, if the value loaded is non-`NULL`, locklessly accessing the `->a` and `->b` fields.

```
bool add_gp_buggy(int a, int b)
{
  p = kmalloc(sizeof(*p), GFP_KERNEL);
  if (!p)
    return -ENOMEM;
  spin_lock(&gp_lock);
  if (rcu_access_pointer(gp)) {
    spin_unlock(&gp_lock);
    return false;
  }
  p->a = a;
  p->b = a;
  gp = p; /* ORDERING BUG */
  spin_unlock(&gp_lock);
  return true;
}
```

The problem is that both the compiler and weakly ordered CPUs are within their rights to reorder this code as follows:

```
bool add_gp_buggy_optimized(int a, int b)
{
```

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```
 3   p = kmalloc(sizeof(*p), GFP_KERNEL);
 4   if (!p)
 5     return -ENOMEM;
 6   spin_lock(&gp_lock);
 7   if (rcu_access_pointer(gp)) {
 8     spin_unlock(&gp_lock);
 9     return false;
10   }
11   gp = p; /* ORDERING BUG */
12   p->a = a;
13   p->b = a;
14   spin_unlock(&gp_lock);
15   return true;
16 }
```

If an RCU reader fetches `gp` just after `add_gp_buggy_optimized` executes line 11, it will see garbage in the `->a` and `->b` fields. And this is but one of many ways in which compiler and hardware optimizations could cause trouble. Therefore, we clearly need some way to prevent the compiler and the CPU from reordering in this manner, which brings us to the publish-subscribe guarantee discussed in the next section.

Publish/Subscribe Guarantee

RCU's publish-subscribe guarantee allows data to be inserted into a linked data structure without disrupting RCU readers. The updater uses `rcu_assign_pointer()` to insert the new data, and readers use `rcu_dereference()` to access data, whether new or old. The following shows an example of insertion:

```
 1 bool add_gp(int a, int b)
 2 {
 3   p = kmalloc(sizeof(*p), GFP_KERNEL);
 4   if (!p)
 5     return -ENOMEM;
 6   spin_lock(&gp_lock);
 7   if (rcu_access_pointer(gp)) {
 8     spin_unlock(&gp_lock);
 9     return false;
10   }
11   p->a = a;
12   p->b = a;
13   rcu_assign_pointer(gp, p);
14   spin_unlock(&gp_lock);
15   return true;
16 }
```

The `rcu_assign_pointer()` on line 13 is conceptually equivalent to a simple assignment statement, but also guarantees that its assignment will happen after the two assignments in lines 11 and 12, similar to the C11 `memory_order_release` store operation. It also prevents any number of "interesting" compiler optimizations, for example, the use of `gp` as a scratch location immediately preceding the assignment.

Quick Quiz:

But `rcu_assign_pointer()` does nothing to prevent the two assignments to `p->a` and `p->b` from being reordered. Can't that also cause problems?

Answer:

No, it cannot. The readers cannot see either of these two fields until the assignment to `gp`, by which time both fields are fully initialized. So reordering the assignments to `p->a` and `p->b` cannot possibly cause any problems.

It is tempting to assume that the reader need not do anything special to control its accesses to the RCU-protected data, as shown in `do_something_gp_buggy()` below:

```
bool do_something_gp_buggy(void)
{
  rcu_read_lock();
  p = gp;  /* OPTIMIZATIONS GALORE!!! */
  if (p) {
    do_something(p->a, p->b);
    rcu_read_unlock();
    return true;
  }
  rcu_read_unlock();
  return false;
}
```

However, this temptation must be resisted because there are a surprisingly large number of ways that the compiler (to say nothing of DEC Alpha CPUs) can trip this code up. For but one example, if the compiler were short of registers, it might choose to refetch from `gp` rather than keeping a separate copy in `p` as follows:

```
bool do_something_gp_buggy_optimized(void)
{
  rcu_read_lock();
  if (gp) { /* OPTIMIZATIONS GALORE!!! */
    do_something(gp->a, gp->b);
    rcu_read_unlock();
    return true;
  }
  rcu_read_unlock();
  return false;
}
```

If this function ran concurrently with a series of updates that replaced the current structure with a new one, the fetches of `gp->a` and `gp->b` might well come from two different structures, which could cause serious confusion. To prevent this (and much else besides), `do_something_gp()` uses `rcu_dereference()` to fetch from gp:

```
bool do_something_gp(void)
{
  rcu_read_lock();
  p = rcu_dereference(gp);
  if (p) {
    do_something(p->a, p->b);
    rcu_read_unlock();
    return true;
  }
  rcu_read_unlock();
  return false;
}
```

The rcu_dereference() uses volatile casts and (for DEC Alpha) memory barriers in the Linux kernel. Should a *high-quality implementation of C11 ``memory_order_consume`* [PDF] <http://www.rdrop.com/users/paulmck/RCU/consume.2015.07.13a.pdf>`__ ever appear, then rcu_dereference() could be implemented as a memory_order_consume load. Regardless of the exact implementation, a pointer fetched by rcu_dereference() may not be used outside of the outermost RCU read-side critical section containing that rcu_dereference(), unless protection of the corresponding data element has been passed from RCU to some other synchronization mechanism, most commonly locking or reference counting.

In short, updaters use rcu_assign_pointer() and readers use rcu_dereference(), and these two RCU API elements work together to ensure that readers have a consistent view of newly added data elements.

Of course, it is also necessary to remove elements from RCU-protected data structures, for example, using the following process:

1. Remove the data element from the enclosing structure.
2. Wait for all pre-existing RCU read-side critical sections to complete (because only pre-existing readers can possibly have a reference to the newly removed data element).
3. At this point, only the updater has a reference to the newly removed data element, so it can safely reclaim the data element, for example, by passing it to kfree().

This process is implemented by remove_gp_synchronous():

```
bool remove_gp_synchronous(void)
{
  struct foo *p;

  spin_lock(&gp_lock);
  p = rcu_access_pointer(gp);
  if (!p) {
    spin_unlock(&gp_lock);
    return false;
  }
```

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```
11   rcu_assign_pointer(gp, NULL);
12   spin_unlock(&gp_lock);
13   synchronize_rcu();
14   kfree(p);
15   return true;
16 }
```

This function is straightforward, with line 13 waiting for a grace period before line 14 frees the old data element. This waiting ensures that readers will reach line 7 of `do_something_gp()` before the data element referenced by `p` is freed. The `rcu_access_pointer()` on line 6 is similar to `rcu_dereference()`, except that:

1. The value returned by `rcu_access_pointer()` cannot be dereferenced. If you want to access the value pointed to as well as the pointer itself, use `rcu_dereference()` instead of `rcu_access_pointer()`.
2. The call to `rcu_access_pointer()` need not be protected. In contrast, `rcu_dereference()` must either be within an RCU read-side critical section or in a code segment where the pointer cannot change, for example, in code protected by the corresponding update-side lock.

Quick Quiz:

Without the `rcu_dereference()` or the `rcu_access_pointer()`, what destructive optimizations might the compiler make use of?

Answer:

Let' s start with what happens to `do_something_gp()` if it fails to use `rcu_dereference()`. It could reuse a value formerly fetched from this same pointer. It could also fetch the pointer from `gp` in a byte-at-a-time manner, resulting in *load tearing*, in turn resulting a bytewise mash-up of two distinct pointer values. It might even use value-speculation optimizations, where it makes a wrong guess, but by the time it gets around to checking the value, an update has changed the pointer to match the wrong guess. Too bad about any dereferences that returned pre-initialization garbage in the meantime! For `remove_gp_synchronous()`, as long as all modifications to `gp` are carried out while holding `gp_lock`, the above optimizations are harmless. However, `sparse` will complain if you define `gp` with `__rcu` and then access it without using either `rcu_access_pointer()` or `rcu_dereference()`.

In short, RCU' s publish-subscribe guarantee is provided by the combination of `rcu_assign_pointer()` and `rcu_dereference()`. This guarantee allows data elements to be safely added to RCU-protected linked data structures without disrupting RCU readers. This guarantee can be used in combination with the grace-period guarantee to also allow data elements to be removed from RCU-protected linked data structures, again without disrupting RCU readers.

This guarantee was only partially premeditated. DYNIX/ptx used an explicit memory barrier for publication, but had nothing resembling `rcu_dereference()` for subscription, nor did it have anything resembling the dependency-ordering barrier that was later subsumed into `rcu_dereference()` and later still into `READ_ONCE()`. The need for these operations made itself known quite suddenly at a late-1990s meeting with the DEC Alpha architects, back in the days when DEC was still a free-standing company. It took the Alpha architects a good hour to convince me that any sort of barrier would ever be needed, and it then took me a good *two* hours to convince them that their documentation did not make this point clear. More recent work with the C and C++ standards committees have provided much education on tricks and traps from the compiler. In short, compilers were much less tricky in the early 1990s, but in 2015, don't even think about omitting `rcu_dereference()`!

Memory-Barrier Guarantees

The previous section's simple linked-data-structure scenario clearly demonstrates the need for RCU's stringent memory-ordering guarantees on systems with more than one CPU:

1. Each CPU that has an RCU read-side critical section that begins before `synchronize_rcu()` starts is guaranteed to execute a full memory barrier between the time that the RCU read-side critical section ends and the time that `synchronize_rcu()` returns. Without this guarantee, a pre-existing RCU read-side critical section might hold a reference to the newly removed `struct foo` after the `kfree()` on line 14 of `remove_gp_synchronous()`.
2. Each CPU that has an RCU read-side critical section that ends after `synchronize_rcu()` returns is guaranteed to execute a full memory barrier between the time that `synchronize_rcu()` begins and the time that the RCU read-side critical section begins. Without this guarantee, a later RCU read-side critical section running after the `kfree()` on line 14 of `remove_gp_synchronous()` might later run `do_something_gp()` and find the newly deleted `struct foo`.
3. If the task invoking `synchronize_rcu()` remains on a given CPU, then that CPU is guaranteed to execute a full memory barrier sometime during the execution of `synchronize_rcu()`. This guarantee ensures that the `kfree()` on line 14 of `remove_gp_synchronous()` really does execute after the removal on line 11.
4. If the task invoking `synchronize_rcu()` migrates among a group of CPUs during that invocation, then each of the CPUs in that group is guaranteed to execute a full memory barrier sometime during the execution of `synchronize_rcu()`. This guarantee also ensures that the `kfree()` on line 14 of `remove_gp_synchronous()` really does execute after the removal on line 11, but also in the case where the thread executing the `synchronize_rcu()` migrates in the meantime.

Quick Quiz:
Given that multiple CPUs can start RCU read-side critical sections at any time without any ordering whatsoever, how can RCU possibly tell whether or not a given RCU read-side critical section starts before a given instance of `synchronize_rcu()`?

Answer:
If RCU cannot tell whether or not a given RCU read-side critical section starts before a given instance of `synchronize_rcu()`, then it must assume that the RCU read-side critical section started first. In other words, a given instance of `synchronize_rcu()` can avoid waiting on a given RCU read-side critical section only if it can prove that `synchronize_rcu()` started first. A related question is "When `rcu_read_lock()` doesn't generate any code, why does it matter how it relates to a grace period?" The answer is that it is not the relationship of `rcu_read_lock()` itself that is important, but rather the relationship of the code within the enclosed RCU read-side critical section to the code preceding and following the grace period. If we take this viewpoint, then a given RCU read-side critical section begins before a given grace period when some access preceding the grace period observes the effect of some access within the critical section, in which case none of the accesses within the critical section may observe the effects of any access following the grace period.
As of late 2016, mathematical models of RCU take this viewpoint, for example, see slides 62 and 63 of the 2016 LinuxCon EU presentation.

Quick Quiz:

The first and second guarantees require unbelievably strict ordering! Are all these memory barriers *really* required?

Answer:

Yes, they really are required. To see why the first guarantee is required, consider the following sequence of events:

1. CPU 1: `rcu_read_lock()`
2. CPU 1: `q = rcu_dereference(gp); /* Very likely to return p. */`
3. CPU 0: `list_del_rcu(p);`
4. CPU 0: `synchronize_rcu()` starts.
5. CPU 1: `do_something_with(q->a); /* No smp_mb(), so might happen after kfree(). */`
6. CPU 1: `rcu_read_unlock()`
7. CPU 0: `synchronize_rcu()` returns.
8. CPU 0: `kfree(p);`

Therefore, there absolutely must be a full memory barrier between the end of the RCU read-side critical section and the end of the grace period.

The sequence of events demonstrating the necessity of the second rule is roughly similar:

1. CPU 0: `list_del_rcu(p);`
2. CPU 0: `synchronize_rcu()` starts.
3. CPU 1: `rcu_read_lock()`
4. CPU 1: `q = rcu_dereference(gp); /* Might return p if no memory barrier. */`
5. CPU 0: `synchronize_rcu()` returns.
6. CPU 0: `kfree(p);`
7. CPU 1: `do_something_with(q->a); /* Boom!!! */`
8. CPU 1: `rcu_read_unlock()`

And similarly, without a memory barrier between the beginning of the grace period and the beginning of the RCU read-side critical section, CPU 1 might end up accessing the freelist.

The "as if" rule of course applies, so that any implementation that acts as if the appropriate memory barriers were in place is a correct implementation. That said, it is much easier to fool yourself into believing that you have adhered to the as-if rule than it is to actually adhere to it!

Quick Quiz:

You claim that `rcu_read_lock()` and `rcu_read_unlock()` generate absolutely no code in some kernel builds. This means that the compiler might arbitrarily rearrange consecutive RCU read-side critical sections. Given such rearrangement, if a given RCU read-side critical section is done, how can you be sure that all prior RCU read-side critical sections are done? Won't the compiler rearrangements make that impossible to determine?

Answer:

In cases where `rcu_read_lock()` and `rcu_read_unlock()` generate absolutely no code, RCU infers quiescent states only at special locations, for example, within the scheduler. Because calls to `schedule()` had better prevent calling-code accesses to shared variables from being rearranged across the call to `schedule()`, if RCU detects the end of a given RCU read-side critical section, it will necessarily detect the end of all prior RCU read-side critical sections, no matter how aggressively the compiler scrambles the code. Again, this all assumes that the compiler cannot scramble code across calls to the scheduler, out of interrupt handlers, into the idle loop, into user-mode code, and so on. But if your kernel build allows that sort of scrambling, you have broken far more than just RCU!

Note that these memory-barrier requirements do not replace the fundamental RCU requirement that a grace period wait for all pre-existing readers. On the contrary, the memory barriers called out in this section must operate in such a way as to *enforce* this fundamental requirement. Of course, different implementations enforce this requirement in different ways, but enforce it they must.

RCU Primitives Guaranteed to Execute Unconditionally

The common-case RCU primitives are unconditional. They are invoked, they do their job, and they return, with no possibility of error, and no need to retry. This is a key RCU design philosophy.

However, this philosophy is pragmatic rather than pigheaded. If someone comes up with a good justification for a particular conditional RCU primitive, it might well be implemented and added. After all, this guarantee was reverse-engineered, not premeditated. The unconditional nature of the RCU primitives was initially an accident of implementation, and later experience with synchronization primitives with conditional primitives caused me to elevate this accident to a guarantee. Therefore, the justification for adding a conditional primitive to RCU would need to be based on detailed and compelling use cases.

Guaranteed Read-to-Write Upgrade

As far as RCU is concerned, it is always possible to carry out an update within an RCU read-side critical section. For example, that RCU read-side critical section might search for a given data element, and then might acquire the update-side spinlock in order to update that element, all while remaining in that RCU read-side critical section. Of course, it is necessary to exit the RCU read-side critical section before invoking `synchronize_rcu()`, however, this inconvenience can be avoided through use of the `call_rcu()` and `kfree_rcu()` API members described later in this document.

Quick Quiz:
But how does the upgrade-to-write operation exclude other readers?
Answer:
It doesn't, just like normal RCU updates, which also do not exclude RCU readers.

This guarantee allows lookup code to be shared between read-side and update-side code, and was premeditated, appearing in the earliest DYNIX/ptx RCU documentation.

Fundamental Non-Requirements

RCU provides extremely lightweight readers, and its read-side guarantees, though quite useful, are correspondingly lightweight. It is therefore all too easy to assume that RCU is guaranteeing more than it really is. Of course, the list of things that RCU does not guarantee is infinitely long, however, the following sections list a few non-guarantees that have caused confusion. Except where otherwise noted, these non-guarantees were premeditated.

1. *Readers Impose Minimal Ordering*
2. *Readers Do Not Exclude Updaters*
3. *Updaters Only Wait For Old Readers*
4. *Grace Periods Don't Partition Read-Side Critical Sections*
5. *Read-Side Critical Sections Don't Partition Grace Periods*

Readers Impose Minimal Ordering

Reader-side markers such as `rcu_read_lock()` and `rcu_read_unlock()` provide absolutely no ordering guarantees except through their interaction with the grace-period APIs such as `synchronize_rcu()`. To see this, consider the following pair of threads:

```
void thread0(void)
{
  rcu_read_lock();
  WRITE_ONCE(x, 1);
```

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```
  rcu_read_unlock();
  rcu_read_lock();
  WRITE_ONCE(y, 1);
  rcu_read_unlock();
}

void thread1(void)
{
  rcu_read_lock();
  r1 = READ_ONCE(y);
  rcu_read_unlock();
  rcu_read_lock();
  r2 = READ_ONCE(x);
  rcu_read_unlock();
}
```

After `thread0()` and `thread1()` execute concurrently, it is quite possible to have

```
(r1 == 1 && r2 == 0)
```

(that is, `y` appears to have been assigned before `x`), which would not be possible if `rcu_read_lock()` and `rcu_read_unlock()` had much in the way of ordering properties. But they do not, so the CPU is within its rights to do significant reordering. This is by design: Any significant ordering constraints would slow down these fast-path APIs.

Quick Quiz:
Can't the compiler also reorder this code?
Answer:
No, the volatile casts in `READ_ONCE()` and `WRITE_ONCE()` prevent the compiler from reordering in this particular case.

Readers Do Not Exclude Updaters

Neither `rcu_read_lock()` nor `rcu_read_unlock()` exclude updates. All they do is to prevent grace periods from ending. The following example illustrates this:

```
void thread0(void)
{
  rcu_read_lock();
  r1 = READ_ONCE(y);
  if (r1) {
    do_something_with_nonzero_x();
    r2 = READ_ONCE(x);
    WARN_ON(!r2); /* BUG!!! */
  }
  rcu_read_unlock();
}
```

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```

void thread1(void)
{
  spin_lock(&my_lock);
  WRITE_ONCE(x, 1);
  WRITE_ONCE(y, 1);
  spin_unlock(&my_lock);
}
```

If the `thread0()` function's `rcu_read_lock()` excluded the `thread1()` function's update, the `WARN_ON()` could never fire. But the fact is that `rcu_read_lock()` does not exclude much of anything aside from subsequent grace periods, of which `thread1()` has none, so the `WARN_ON()` can and does fire.

Updaters Only Wait For Old Readers

It might be tempting to assume that after `synchronize_rcu()` completes, there are no readers executing. This temptation must be avoided because new readers can start immediately after `synchronize_rcu()` starts, and `synchronize_rcu()` is under no obligation to wait for these new readers.

Quick Quiz:
Suppose that *`synchronize_rcu()`* did wait until *all* readers had completed instead of waiting only on pre-existing readers. For how long would the updater be able to rely on there being no readers?
Answer:
For no time at all. Even if `synchronize_rcu()` were to wait until all readers had completed, a new reader might start immediately after `synchronize_rcu()` completed. Therefore, the code following `synchronize_rcu()` can *never* rely on there being no readers.

Grace Periods Don't Partition Read-Side Critical Sections

It is tempting to assume that if any part of one RCU read-side critical section precedes a given grace period, and if any part of another RCU read-side critical section follows that same grace period, then all of the first RCU read-side critical section must precede all of the second. However, this just isn't the case: A single grace period does not partition the set of RCU read-side critical sections. An example of this situation can be illustrated as follows, where `x`, `y`, and `z` are initially all zero:

```
void thread0(void)
{
  rcu_read_lock();
  WRITE_ONCE(a, 1);
  WRITE_ONCE(b, 1);
  rcu_read_unlock();
```

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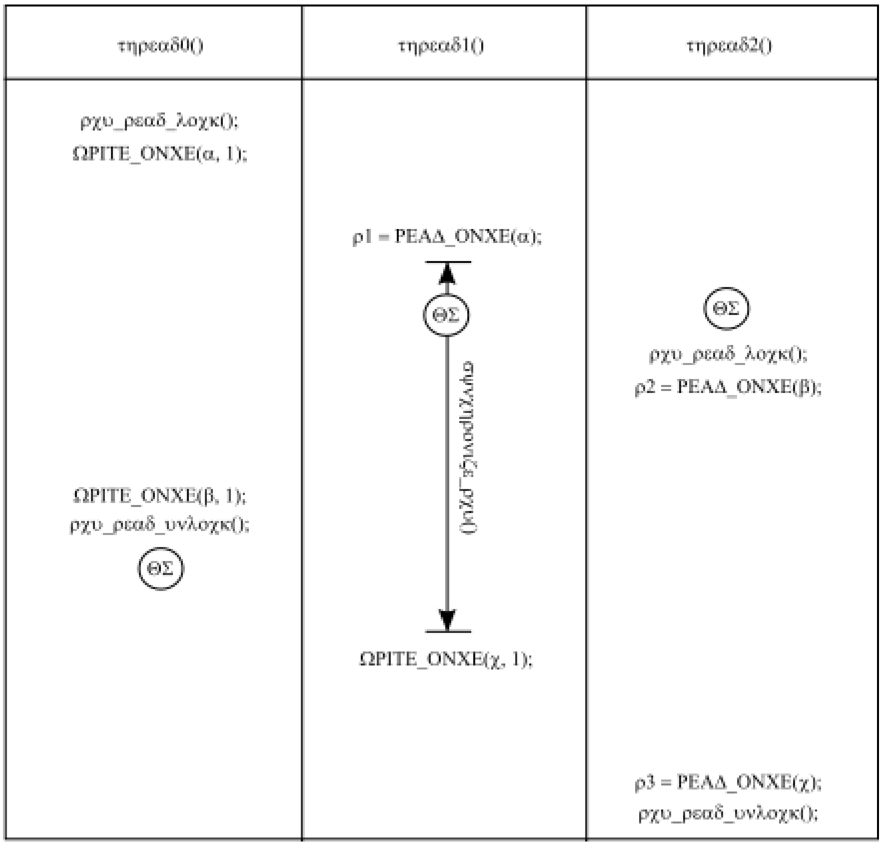
```
}

void thread1(void)
{
  r1 = READ_ONCE(a);
  synchronize_rcu();
  WRITE_ONCE(c, 1);
}

void thread2(void)
{
  rcu_read_lock();
  r2 = READ_ONCE(b);
  r3 = READ_ONCE(c);
  rcu_read_unlock();
}
```

It turns out that the outcome:

```
(r1 == 1 && r2 == 0 && r3 == 1)
```

is entirely possible. The following figure show how this can happen, with each circled `QS` indicating the point at which RCU recorded a *quiescent state* for each thread, that is, a state in which RCU knows that the thread cannot be in the midst of an RCU read-side critical section that started before the current grace period:



If it is necessary to partition RCU read-side critical sections in this manner, it is necessary to use two grace periods, where the first grace period is known to end before the second grace period starts:

```
void thread0(void)
{
  rcu_read_lock();
  WRITE_ONCE(a, 1);
  WRITE_ONCE(b, 1);
  rcu_read_unlock();
}

void thread1(void)
{
  r1 = READ_ONCE(a);
  synchronize_rcu();
  WRITE_ONCE(c, 1);
}

void thread2(void)
{
  r2 = READ_ONCE(c);
  synchronize_rcu();
  WRITE_ONCE(d, 1);
}

void thread3(void)
{
  rcu_read_lock();
  r3 = READ_ONCE(b);
  r4 = READ_ONCE(d);
  rcu_read_unlock();
}
```

Here, if `(r1 == 1)`, then `thread0()`'s write to `b` must happen before the end of `thread1()`'s grace period. If in addition `(r4 == 1)`, then `thread3()`'s read from `b` must happen after the beginning of `thread2()`'s grace period. If it is also the case that `(r2 == 1)`, then the end of `thread1()`'s grace period must precede the beginning of `thread2()`'s grace period. This mean that the two RCU read-side critical sections cannot overlap, guaranteeing that `(r3 == 1)`. As a result, the outcome:

```
(r1 == 1 && r2 == 1 && r3 == 0 && r4 == 1)
```

cannot happen.

This non-requirement was also non-premeditated, but became apparent when studying RCU's interaction with memory ordering.

Read-Side Critical Sections Don’t Partition Grace Periods

It is also tempting to assume that if an RCU read-side critical section happens between a pair of grace periods, then those grace periods cannot overlap. However, this temptation leads nowhere good, as can be illustrated by the following, with all variables initially zero:

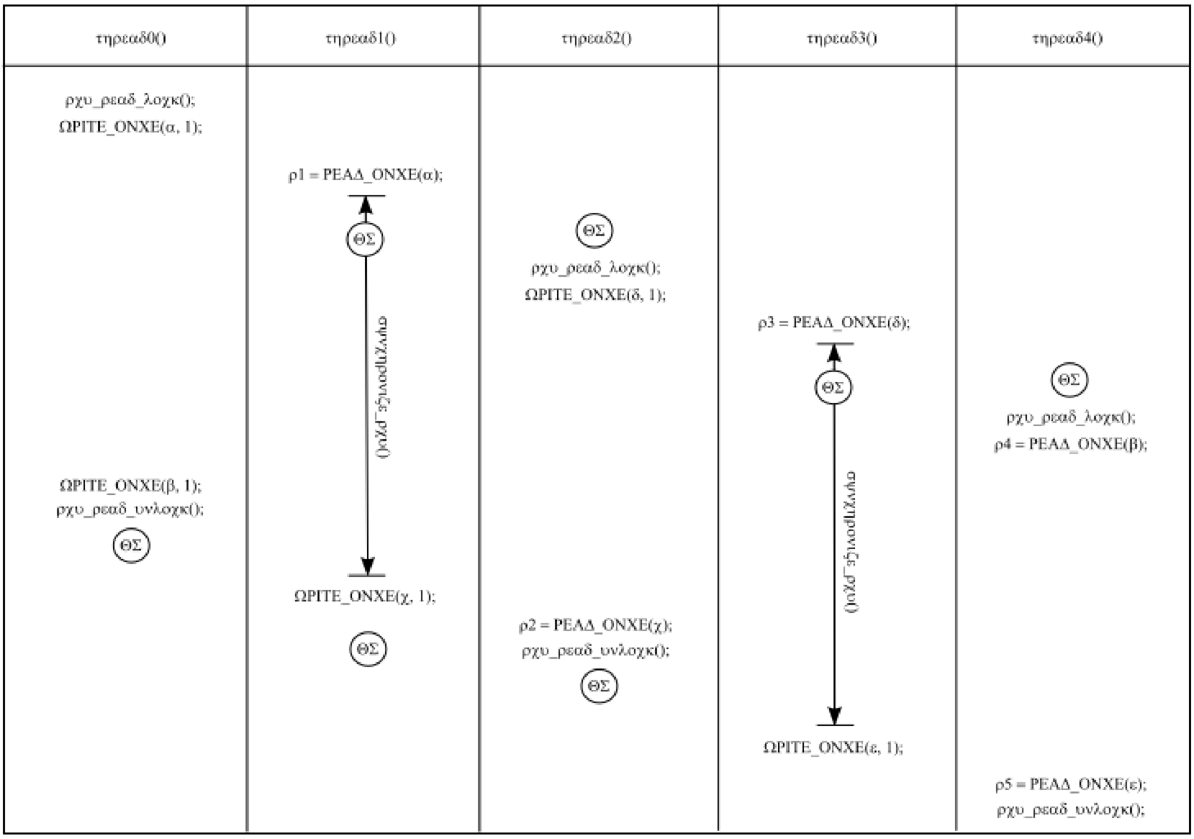
```
void thread0(void)
{
  rcu_read_lock();
  WRITE_ONCE(a, 1);
  WRITE_ONCE(b, 1);
  rcu_read_unlock();
}

void thread1(void)
{
  r1 = READ_ONCE(a);
  synchronize_rcu();
  WRITE_ONCE(c, 1);
}

void thread2(void)
{
  rcu_read_lock();
  WRITE_ONCE(d, 1);
  r2 = READ_ONCE(c);
  rcu_read_unlock();
}

void thread3(void)
{
  r3 = READ_ONCE(d);
  synchronize_rcu();
  WRITE_ONCE(e, 1);
}

void thread4(void)
{
  rcu_read_lock();
  r4 = READ_ONCE(b);
  r5 = READ_ONCE(e);
  rcu_read_unlock();
}
```

In this case, the outcome:

```
(r1 == 1 && r2 == 1 && r3 == 1 && r4 == 0 && r5 == 1)
```

is entirely possible, as illustrated below:

Again, an RCU read-side critical section can overlap almost all of a given grace



period, just so long as it does not overlap the entire grace period. As a result, an RCU read-side critical section cannot partition a pair of RCU grace periods.

Quick Quiz:

How long a sequence of grace periods, each separated by an RCU read-side critical section, would be required to partition the RCU read-side critical sections at the beginning and end of the chain?

Answer:

In theory, an infinite number. In practice, an unknown number that is sensitive to both implementation details and timing considerations. Therefore, even in practice, RCU users must abide by the theoretical rather than the practical answer.

Parallelism Facts of Life

These parallelism facts of life are by no means specific to RCU, but the RCU implementation must abide by them. They therefore bear repeating:

1. Any CPU or task may be delayed at any time, and any attempts to avoid these delays by disabling preemption, interrupts, or whatever are completely futile. This is most obvious in preemptible user-level environments and in virtualized environments (where a given guest OS's VCPUs can be preempted at any time by the underlying hypervisor), but can also happen in bare-metal environments due to ECC errors, NMIs, and other hardware events. Although a delay of more than about 20 seconds can result in splats, the RCU implemen-

tation is obligated to use algorithms that can tolerate extremely long delays, but where "extremely long" is not long enough to allow wrap-around when incrementing a 64-bit counter.

2. Both the compiler and the CPU can reorder memory accesses. Where it matters, RCU must use compiler directives and memory-barrier instructions to preserve ordering.

3. Conflicting writes to memory locations in any given cache line will result in expensive cache misses. Greater numbers of concurrent writes and more-frequent concurrent writes will result in more dramatic slowdowns. RCU is therefore obligated to use algorithms that have sufficient locality to avoid significant performance and scalability problems.

4. As a rough rule of thumb, only one CPU's worth of processing may be carried out under the protection of any given exclusive lock. RCU must therefore use scalable locking designs.

5. Counters are finite, especially on 32-bit systems. RCU's use of counters must therefore tolerate counter wrap, or be designed such that counter wrap would take way more time than a single system is likely to run. An uptime of ten years is quite possible, a runtime of a century much less so. As an example of the latter, RCU's dyntick-idle nesting counter allows 54 bits for interrupt nesting level (this counter is 64 bits even on a 32-bit system). Overflowing this counter requires 2^{54} half-interrupts on a given CPU without that CPU ever going idle. If a half-interrupt happened every microsecond, it would take 570 years of runtime to overflow this counter, which is currently believed to be an acceptably long time.

6. Linux systems can have thousands of CPUs running a single Linux kernel in a single shared-memory environment. RCU must therefore pay close attention to high-end scalability.

This last parallelism fact of life means that RCU must pay special attention to the preceding facts of life. The idea that Linux might scale to systems with thousands of CPUs would have been met with some skepticism in the 1990s, but these requirements would have otherwise have been unsurprising, even in the early 1990s.

Quality-of-Implementation Requirements

These sections list quality-of-implementation requirements. Although an RCU implementation that ignores these requirements could still be used, it would likely be subject to limitations that would make it inappropriate for industrial-strength production use. Classes of quality-of-implementation requirements are as follows:

1. *Specialization*
2. *Performance and Scalability*
3. *Forward Progress*
4. *Composability*
5. *Corner Cases*

These classes is covered in the following sections.

Specialization

RCU is and always has been intended primarily for read-mostly situations, which means that RCU’s read-side primitives are optimized, often at the expense of its update-side primitives. Experience thus far is captured by the following list of situations:

1. Read-mostly data, where stale and inconsistent data is not a problem: RCU works great!
2. Read-mostly data, where data must be consistent: RCU works well.
3. Read-write data, where data must be consistent: RCU *might* work OK. Or not.
4. Write-mostly data, where data must be consistent: RCU is very unlikely to be the right tool for the job, with the following exceptions, where RCU can provide:
   a. Existence guarantees for update-friendly mechanisms.
   b. Wait-free read-side primitives for real-time use.

This focus on read-mostly situations means that RCU must interoperate with other synchronization primitives. For example, the `add_gp()` and `remove_gp_synchronous()` examples discussed earlier use RCU to protect readers and locking to coordinate updaters. However, the need extends much farther, requiring that a variety of synchronization primitives be legal within RCU read-side critical sections, including spinlocks, sequence locks, atomic operations, reference counters, and memory barriers.

Quick Quiz:

What about sleeping locks?

Answer:

These are forbidden within Linux-kernel RCU read-side critical sections because it is not legal to place a quiescent state (in this case, voluntary context switch) within an RCU read-side critical section. However, sleeping locks may be used within userspace RCU read-side critical sections, and also within Linux-kernel sleepable RCU *(SRCU)* read-side critical sections. In addition, the -rt patchset turns spinlocks into a sleeping locks so that the corresponding critical sections can be preempted, which also means that these sleeplockified spinlocks (but not other sleeping locks!) may be acquire within -rt-Linux-kernel RCU read-side critical sections. Note that it *is* legal for a normal RCU read-side critical section to conditionally acquire a sleeping locks (as in `mutex_trylock()`), but only as long as it does not loop indefinitely attempting to conditionally acquire that sleeping locks. The key point is that things like `mutex_trylock()` either return with the mutex held, or return an error indication if the mutex was not immediately available. Either way, `mutex_trylock()` returns immediately without sleeping.

It often comes as a surprise that many algorithms do not require a consistent view of data, but many can function in that mode, with network routing being the poster child. Internet routing algorithms take significant time to propagate updates, so that by the time an update arrives at a given system, that system has been sending network traffic the wrong way for a considerable length of time. Having a few threads continue to send traffic the wrong way for a few more milliseconds is clearly not a problem: In the worst case, TCP retransmissions will eventually get the data where it needs to go. In general, when tracking the state of the universe outside of the computer, some level of inconsistency must be tolerated due to speed-of-light delays if nothing else.

Furthermore, uncertainty about external state is inherent in many cases. For example, a pair of veterinarians might use heartbeat to determine whether or not a given cat was alive. But how long should they wait after the last heartbeat to decide that the cat is in fact dead? Waiting less than 400 milliseconds makes no sense because this would mean that a relaxed cat would be considered to cycle between death and life more than 100 times per minute. Moreover, just as with human beings, a cat's heart might stop for some period of time, so the exact wait period is a judgment call. One of our pair of veterinarians might wait 30 seconds before pronouncing the cat dead, while the other might insist on waiting a full minute. The two veterinarians would then disagree on the state of the cat during the final 30 seconds of the minute following the last heartbeat.

Interestingly enough, this same situation applies to hardware. When push comes to shove, how do we tell whether or not some external server has failed? We send messages to it periodically, and declare it failed if we don't receive a response within a given period of time. Policy decisions can usually tolerate short periods of inconsistency. The policy was decided some time ago, and is only now being put into effect, so a few milliseconds of delay is normally inconsequential.

However, there are algorithms that absolutely must see consistent data. For example, the translation between a user-level SystemV semaphore ID to the corresponding in-kernel data structure is protected by RCU, but it is absolutely forbidden to update a semaphore that has just been removed. In the Linux kernel, this need for consistency is accommodated by acquiring spinlocks located in the in-kernel data structure from within the RCU read-side critical section, and this is indicated by the green box in the figure above. Many other techniques may be used, and are in fact used within the Linux kernel.

In short, RCU is not required to maintain consistency, and other mechanisms may be used in concert with RCU when consistency is required. RCU's specialization allows it to do its job extremely well, and its ability to interoperate with other synchronization mechanisms allows the right mix of synchronization tools to be used for a given job.

Performance and Scalability

Energy efficiency is a critical component of performance today, and Linux-kernel RCU implementations must therefore avoid unnecessarily awakening idle CPUs. I cannot claim that this requirement was premeditated. In fact, I learned of it during a telephone conversation in which I was given "frank and open" feedback on the importance of energy efficiency in battery-powered systems and on specific energy-efficiency shortcomings of the Linux-kernel RCU implementation. In my experience, the battery-powered embedded community will consider any unnecessary wakeups to be extremely unfriendly acts. So much so that mere Linux-kernel-mailing-list posts are insufficient to vent their ire.

Memory consumption is not particularly important for in most situations, and has become decreasingly so as memory sizes have expanded and memory costs have plummeted. However, as I learned from Matt Mackall's bloatwatch efforts, memory footprint is critically important on single-CPU systems with non-preemptible (CONFIG_PREEMPT=n) kernels, and thus tiny RCU was born. Josh Triplett has since taken over the small-memory banner with his Linux kernel tinification project, which resulted in *SRCU* becoming optional for those kernels not needing it.

The remaining performance requirements are, for the most part, unsurprising. For example, in keeping with RCU's read-side specialization, `rcu_dereference()` should have negligible overhead (for example, suppression of a few minor compiler optimizations). Similarly, in non-preemptible environments, `rcu_read_lock()` and `rcu_read_unlock()` should have exactly zero overhead.

In preemptible environments, in the case where the RCU read-side critical section was not preempted (as will be the case for the highest-priority real-time process), `rcu_read_lock()` and `rcu_read_unlock()` should have minimal overhead. In particular, they should not contain atomic read-modify-write operations, memory-barrier instructions, preemption disabling, interrupt disabling, or backwards branches. However, in the case where the RCU read-side critical section was preempted, `rcu_read_unlock()` may acquire spinlocks and disable interrupts. This is why it is better to nest an RCU read-side critical section within a preempt-disable region than vice versa, at least in cases where that critical section is short enough to avoid unduly degrading real-time latencies.

The `synchronize_rcu()` grace-period-wait primitive is optimized for throughput. It may therefore incur several milliseconds of latency in addition to the duration of the longest RCU read-side critical section. On the other hand, multiple concurrent invocations of `synchronize_rcu()` are required to use batching optimizations so that they can be satisfied by a single underlying grace-period-wait operation. For example, in the Linux kernel, it is not unusual for a single grace-period-wait operation to serve more than 1,000 separate invocations of `synchronize_rcu()`, thus amortizing the per-invocation overhead down to nearly zero. However, the grace-period optimization is also required to avoid measurable degradation of real-time scheduling and interrupt latencies.

In some cases, the multi-millisecond `synchronize_rcu()` latencies are unacceptable. In these cases, `synchronize_rcu_expedited()` may be used instead, reducing the grace-period latency down to a few tens of microseconds on small systems, at least in cases where the RCU read-side critical sections are short. There are currently no special latency requirements for `synchronize_rcu_expedited()` on large systems, but, consistent with the empirical nature of the RCU specification, that is subject to change. However, there most definitely are scalability requirements: A storm of `synchronize_rcu_expedited()` invocations on 4096 CPUs should at least make reasonable forward progress. In return for its shorter latencies, `synchronize_rcu_expedited()` is permitted to impose modest degradation of real-time latency on non-idle online CPUs. Here, "modest" means roughly the same latency degradation as a scheduling-clock interrupt.

There are a number of situations where even `synchronize_rcu_expedited()`'s reduced grace-period latency is unacceptable. In these situations, the asynchronous `call_rcu()` can be used in place of `synchronize_rcu()` as follows:

```
struct foo {
  int a;
```

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```
 3   int b;
 4   struct rcu_head rh;
 5 };
 6
 7 static void remove_gp_cb(struct rcu_head *rhp)
 8 {
 9   struct foo *p = container_of(rhp, struct foo, rh);
10
11   kfree(p);
12 }
13
14 bool remove_gp_asynchronous(void)
15 {
16   struct foo *p;
17
18   spin_lock(&gp_lock);
19   p = rcu_access_pointer(gp);
20   if (!p) {
21     spin_unlock(&gp_lock);
22     return false;
23   }
24   rcu_assign_pointer(gp, NULL);
25   call_rcu(&p->rh, remove_gp_cb);
26   spin_unlock(&gp_lock);
27   return true;
28 }
```

A definition of `struct foo` is finally needed, and appears on lines 1-5. The function `remove_gp_cb()` is passed to `call_rcu()` on line 25, and will be invoked after the end of a subsequent grace period. This gets the same effect as `remove_gp_synchronous()`, but without forcing the updater to wait for a grace period to elapse. The `call_rcu()` function may be used in a number of situations where neither `synchronize_rcu()` nor `synchronize_rcu_expedited()` would be legal, including within preempt-disable code, `local_bh_disable()` code, interrupt-disable code, and interrupt handlers. However, even `call_rcu()` is illegal within NMI handlers and from idle and offline CPUs. The callback function (`remove_gp_cb()` in this case) will be executed within softirq (software interrupt) environment within the Linux kernel, either within a real softirq handler or under the protection of `local_bh_disable()`. In both the Linux kernel and in userspace, it is bad practice to write an RCU callback function that takes too long. Long-running operations should be relegated to separate threads or (in the Linux kernel) workqueues.

Quick Quiz:

Why does line 19 use `rcu_access_pointer()`? After all, `call_rcu()` on line 25 stores into the structure, which would interact badly with concurrent insertions. Doesn't this mean that `rcu_dereference()` is required?

Answer:

Presumably the `->gp_lock` acquired on line 18 excludes any changes, including any insertions that `rcu_dereference()` would protect against. Therefore, any insertions will be delayed until after `->gp_lock` is released on line 25, which in turn means that `rcu_access_pointer()` suffices.

However, all that `remove_gp_cb()` is doing is invoking `kfree()` on the data element. This is a common idiom, and is supported by `kfree_rcu()`, which allows "fire and forget" operation as shown below:

```
struct foo {
  int a;
  int b;
  struct rcu_head rh;
};

bool remove_gp_faf(void)
{
  struct foo *p;

  spin_lock(&gp_lock);
  p = rcu_dereference(gp);
  if (!p) {
    spin_unlock(&gp_lock);
    return false;
  }
  rcu_assign_pointer(gp, NULL);
  kfree_rcu(p, rh);
  spin_unlock(&gp_lock);
  return true;
}
```

Note that `remove_gp_faf()` simply invokes `kfree_rcu()` and proceeds, without any need to pay any further attention to the subsequent grace period and `kfree()`. It is permissible to invoke `kfree_rcu()` from the same environments as for `call_rcu()`. Interestingly enough, DYNIX/ptx had the equivalents of `call_rcu()` and `kfree_rcu()`, but not `synchronize_rcu()`. This was due to the fact that RCU was not heavily used within DYNIX/ptx, so the very few places that needed something like `synchronize_rcu()` simply open-coded it.

Quick Quiz:

Earlier it was claimed that `call_rcu()` and `kfree_rcu()` allowed updaters to avoid being blocked by readers. But how can that be correct, given that the invocation of the callback and the freeing of the memory (respectively) must still wait for a grace period to elapse?

Answer:

We could define things this way, but keep in mind that this sort of definition would say that updates in garbage-collected languages cannot complete until the next time the garbage collector runs, which does not seem at all reasonable. The key point is that in most cases, an updater using either `call_rcu()` or `kfree_rcu()` can proceed to the next update as soon as it has invoked `call_rcu()` or `kfree_rcu()`, without having to wait for a subsequent grace period.

But what if the updater must wait for the completion of code to be executed after the end of the grace period, but has other tasks that can be carried out in the meantime? The polling-style `get_state_synchronize_rcu()` and `cond_synchronize_rcu()` functions may be used for this purpose, as shown below:

```
 1 bool remove_gp_poll(void)
 2 {
 3   struct foo *p;
 4   unsigned long s;
 5
 6   spin_lock(&gp_lock);
 7   p = rcu_access_pointer(gp);
 8   if (!p) {
 9     spin_unlock(&gp_lock);
10     return false;
11   }
12   rcu_assign_pointer(gp, NULL);
13   spin_unlock(&gp_lock);
14   s = get_state_synchronize_rcu();
15   do_something_while_waiting();
16   cond_synchronize_rcu(s);
17   kfree(p);
18   return true;
19 }
```

On line 14, `get_state_synchronize_rcu()` obtains a "cookie" from RCU, then line 15 carries out other tasks, and finally, line 16 returns immediately if a grace period has elapsed in the meantime, but otherwise waits as required. The need for `get_state_synchronize_rcu` and `cond_synchronize_rcu()` has appeared quite recently, so it is too early to tell whether they will stand the test of time.

RCU thus provides a range of tools to allow updaters to strike the required tradeoff between latency, flexibility and CPU overhead.

Forward Progress

In theory, delaying grace-period completion and callback invocation is harmless. In practice, not only are memory sizes finite but also callbacks sometimes do wakeups, and sufficiently deferred wakeups can be difficult to distinguish from system hangs. Therefore, RCU must provide a number of mechanisms to promote forward progress.

These mechanisms are not foolproof, nor can they be. For one simple example, an infinite loop in an RCU read-side critical section must by definition prevent later grace periods from ever completing. For a more involved example, consider a 64-CPU system built with `CONFIG_RCU_NOCB_CPU=y` and booted with `rcu_nocbs=1-63`, where CPUs 1 through 63 spin in tight loops that invoke `call_rcu()`. Even if these tight loops also contain calls to `cond_resched()` (thus allowing grace periods to complete), CPU 0 simply will not be able to invoke callbacks as fast as the other 63 CPUs can register them, at least not until the system runs out of memory. In both of these examples, the Spiderman principle applies: With great power comes great responsibility. However, short of this level of abuse, RCU is required to ensure timely completion of grace periods and timely invocation of callbacks.

RCU takes the following steps to encourage timely completion of grace periods:

1. If a grace period fails to complete within 100 milliseconds, RCU causes future invocations of `cond_resched()` on the holdout CPUs to provide an RCU quiescent state. RCU also causes those CPUs' `need_resched()` invocations to return `true`, but only after the corresponding CPU' s next scheduling-clock.
2. CPUs mentioned in the `nohz_full` kernel boot parameter can run indefinitely in the kernel without scheduling-clock interrupts, which defeats the above `need_resched()` strategem. RCU will therefore invoke `resched_cpu()` on any `nohz_full` CPUs still holding out after 109 milliseconds.
3. In kernels built with `CONFIG_RCU_BOOST=y`, if a given task that has been preempted within an RCU read-side critical section is holding out for more than 500 milliseconds, RCU will resort to priority boosting.
4. If a CPU is still holding out 10 seconds into the grace period, RCU will invoke `resched_cpu()` on it regardless of its `nohz_full` state.

The above values are defaults for systems running with `HZ=1000`. They will vary as the value of `HZ` varies, and can also be changed using the relevant Kconfig options and kernel boot parameters. RCU currently does not do much sanity checking of these parameters, so please use caution when changing them. Note that these forward-progress measures are provided only for RCU, not for *SRCU* or *Tasks RCU*.

RCU takes the following steps in `call_rcu()` to encourage timely invocation of callbacks when any given non-`rcu_nocbs` CPU has 10,000 callbacks, or has 10,000 more callbacks than it had the last time encouragement was provided:

1. Starts a grace period, if one is not already in progress.
2. Forces immediate checking for quiescent states, rather than waiting for three milliseconds to have elapsed since the beginning of the grace period.
3. Immediately tags the CPU' s callbacks with their grace period completion numbers, rather than waiting for the `RCU_SOFTIRQ` handler to get around to

it.

4. Lifts callback-execution batch limits, which speeds up callback invocation at the expense of degrading realtime response.

Again, these are default values when running at `HZ=1000`, and can be overridden. Again, these forward-progress measures are provided only for RCU, not for *SRCU* or *Tasks RCU*. Even for RCU, callback-invocation forward progress for `rcu_nocbs` CPUs is much less well-developed, in part because workloads benefiting from `rcu_nocbs` CPUs tend to invoke `call_rcu()` relatively infrequently. If workloads emerge that need both `rcu_nocbs` CPUs and high `call_rcu()` invocation rates, then additional forward-progress work will be required.

Composability

Composability has received much attention in recent years, perhaps in part due to the collision of multicore hardware with object-oriented techniques designed in single-threaded environments for single-threaded use. And in theory, RCU read-side critical sections may be composed, and in fact may be nested arbitrarily deeply. In practice, as with all real-world implementations of composable constructs, there are limitations.

Implementations of RCU for which `rcu_read_lock()` and `rcu_read_unlock()` generate no code, such as Linux-kernel RCU when `CONFIG_PREEMPT=n`, can be nested arbitrarily deeply. After all, there is no overhead. Except that if all these instances of `rcu_read_lock()` and `rcu_read_unlock()` are visible to the compiler, compilation will eventually fail due to exhausting memory, mass storage, or user patience, whichever comes first. If the nesting is not visible to the compiler, as is the case with mutually recursive functions each in its own translation unit, stack overflow will result. If the nesting takes the form of loops, perhaps in the guise of tail recursion, either the control variable will overflow or (in the Linux kernel) you will get an RCU CPU stall warning. Nevertheless, this class of RCU implementations is one of the most composable constructs in existence.

RCU implementations that explicitly track nesting depth are limited by the nesting-depth counter. For example, the Linux kernel's preemptible RCU limits nesting to `INT_MAX`. This should suffice for almost all practical purposes. That said, a consecutive pair of RCU read-side critical sections between which there is an operation that waits for a grace period cannot be enclosed in another RCU read-side critical section. This is because it is not legal to wait for a grace period within an RCU read-side critical section: To do so would result either in deadlock or in RCU implicitly splitting the enclosing RCU read-side critical section, neither of which is conducive to a long-lived and prosperous kernel.

It is worth noting that RCU is not alone in limiting composability. For example, many transactional-memory implementations prohibit composing a pair of transactions separated by an irrevocable operation (for example, a network receive operation). For another example, lock-based critical sections can be composed surprisingly freely, but only if deadlock is avoided.

In short, although RCU read-side critical sections are highly composable, care is required in some situations, just as is the case for any other composable synchronization mechanism.

Corner Cases

A given RCU workload might have an endless and intense stream of RCU read-side critical sections, perhaps even so intense that there was never a point in time during which there was not at least one RCU read-side critical section in flight. RCU cannot allow this situation to block grace periods: As long as all the RCU read-side critical sections are finite, grace periods must also be finite.

That said, preemptible RCU implementations could potentially result in RCU read-side critical sections being preempted for long durations, which has the effect of creating a long-duration RCU read-side critical section. This situation can arise only in heavily loaded systems, but systems using real-time priorities are of course more vulnerable. Therefore, RCU priority boosting is provided to help deal with this case. That said, the exact requirements on RCU priority boosting will likely evolve as more experience accumulates.

Other workloads might have very high update rates. Although one can argue that such workloads should instead use something other than RCU, the fact remains that RCU must handle such workloads gracefully. This requirement is another factor driving batching of grace periods, but it is also the driving force behind the checks for large numbers of queued RCU callbacks in the `call_rcu()` code path. Finally, high update rates should not delay RCU read-side critical sections, although some small read-side delays can occur when using `synchronize_rcu_expedited()`, courtesy of this function's use of `smp_call_function_single()`.

Although all three of these corner cases were understood in the early 1990s, a simple user-level test consisting of `close(open(path))` in a tight loop in the early 2000s suddenly provided a much deeper appreciation of the high-update-rate corner case. This test also motivated addition of some RCU code to react to high update rates, for example, if a given CPU finds itself with more than 10,000 RCU callbacks queued, it will cause RCU to take evasive action by more aggressively starting grace periods and more aggressively forcing completion of grace-period processing. This evasive action causes the grace period to complete more quickly, but at the cost of restricting RCU's batching optimizations, thus increasing the CPU overhead incurred by that grace period.

Software-Engineering Requirements

Between Murphy's Law and "To err is human", it is necessary to guard against mishaps and misuse:

1. It is all too easy to forget to use `rcu_read_lock()` everywhere that it is needed, so kernels built with `CONFIG_PROVE_RCU=y` will splat if `rcu_dereference()` is used outside of an RCU read-side critical section. Update-side code can use `rcu_dereference_protected()`, which takes a lockdep expression to indicate what is providing the protection. If the indicated protection is not provided, a lockdep splat is emitted. Code shared between readers and updaters can use `rcu_dereference_check()`, which also takes a lockdep expression, and emits a lockdep splat if neither `rcu_read_lock()` nor the indicated protection is in place. In addition, `rcu_dereference_raw()` is used in those (hopefully rare) cases

where the required protection cannot be easily described. Finally, `rcu_read_lock_held()` is provided to allow a function to verify that it has been invoked within an RCU read-side critical section. I was made aware of this set of requirements shortly after Thomas Gleixner audited a number of RCU uses.

2. A given function might wish to check for RCU-related preconditions upon entry, before using any other RCU API. The `rcu_lockdep_assert()` does this job, asserting the expression in kernels having lockdep enabled and doing nothing otherwise.

3. It is also easy to forget to use `rcu_assign_pointer()` and `rcu_dereference()`, perhaps (incorrectly) substituting a simple assignment. To catch this sort of error, a given RCU-protected pointer may be tagged with `__rcu`, after which sparse will complain about simple-assignment accesses to that pointer. Arnd Bergmann made me aware of this requirement, and also supplied the needed patch series.

4. Kernels built with `CONFIG_DEBUG_OBJECTS_RCU_HEAD=y` will splat if a data element is passed to `call_rcu()` twice in a row, without a grace period in between. (This error is similar to a double free.) The corresponding `rcu_head` structures that are dynamically allocated are automatically tracked, but `rcu_head` structures allocated on the stack must be initialized with `init_rcu_head_on_stack()` and cleaned up with `destroy_rcu_head_on_stack()`. Similarly, statically allocated non-stack `rcu_head` structures must be initialized with `init_rcu_head()` and cleaned up with `destroy_rcu_head()`. Mathieu Desnoyers made me aware of this requirement, and also supplied the needed patch.

5. An infinite loop in an RCU read-side critical section will eventually trigger an RCU CPU stall warning splat, with the duration of "eventually" being controlled by the `RCU_CPU_STALL_TIMEOUT` `Kconfig` option, or, alternatively, by the `rcupdate.rcu_cpu_stall_timeout` boot/sysfs parameter. However, RCU is not obligated to produce this splat unless there is a grace period waiting on that particular RCU read-side critical section.

   Some extreme workloads might intentionally delay RCU grace periods, and systems running those workloads can be booted with `rcupdate.rcu_cpu_stall_suppress` to suppress the splats. This kernel parameter may also be set via `sysfs`. Furthermore, RCU CPU stall warnings are counter-productive during sysrq dumps and during panics. RCU therefore supplies the `rcu_sysrq_start()` and `rcu_sysrq_end()` API members to be called before and after long sysrq dumps. RCU also supplies the `rcu_panic()` notifier that is automatically invoked at the beginning of a panic to suppress further RCU CPU stall warnings.

   This requirement made itself known in the early 1990s, pretty much the first time that it was necessary to debug a CPU stall. That said, the initial implementation in DYNIX/ptx was quite generic in comparison with that of Linux.

6. Although it would be very good to detect pointers leaking out of RCU read-side critical sections, there is currently no good way of doing this. One complication is the need to distinguish between pointers leaking and pointers that have been handed off from RCU to some other synchronization mechanism, for example, reference counting.

7. In kernels built with `CONFIG_RCU_TRACE=y`, RCU-related information is provided via event tracing.
8. Open-coded use of `rcu_assign_pointer()` and `rcu_dereference()` to create typical linked data structures can be surprisingly error-prone. Therefore, RCU-protected linked lists and, more recently, RCU-protected hash tables are available. Many other special-purpose RCU-protected data structures are available in the Linux kernel and the userspace RCU library.
9. Some linked structures are created at compile time, but still require `__rcu` checking. The `RCU_POINTER_INITIALIZER()` macro serves this purpose.
10. It is not necessary to use `rcu_assign_pointer()` when creating linked structures that are to be published via a single external pointer. The `RCU_INIT_POINTER()` macro is provided for this task and also for assigning `NULL` pointers at runtime.

This not a hard-and-fast list: RCU' s diagnostic capabilities will continue to be guided by the number and type of usage bugs found in real-world RCU usage.

Linux Kernel Complications

The Linux kernel provides an interesting environment for all kinds of software, including RCU. Some of the relevant points of interest are as follows:

1. *Configuration*
2. *Firmware Interface*
3. *Early Boot*
4. *Interrupts and NMIs*
5. *Loadable Modules*
6. *Hotplug CPU*
7. *Scheduler and RCU*
8. *Tracing and RCU*
9. *Accesses to User Memory and RCU*
10. *Energy Efficiency*
11. *Scheduling-Clock Interrupts and RCU*
12. *Memory Efficiency*
13. *Performance, Scalability, Response Time, and Reliability*

This list is probably incomplete, but it does give a feel for the most notable Linux-kernel complications. Each of the following sections covers one of the above topics.

Configuration

RCU's goal is automatic configuration, so that almost nobody needs to worry about RCU's `Kconfig` options. And for almost all users, RCU does in fact work well "out of the box."

However, there are specialized use cases that are handled by kernel boot parameters and `Kconfig` options. Unfortunately, the `Kconfig` system will explicitly ask users about new `Kconfig` options, which requires almost all of them be hidden behind a `CONFIG_RCU_EXPERT` `Kconfig` option.

This all should be quite obvious, but the fact remains that Linus Torvalds recently had to remind me of this requirement.

Firmware Interface

In many cases, kernel obtains information about the system from the firmware, and sometimes things are lost in translation. Or the translation is accurate, but the original message is bogus.

For example, some systems' firmware overreports the number of CPUs, sometimes by a large factor. If RCU naively believed the firmware, as it used to do, it would create too many per-CPU kthreads. Although the resulting system will still run correctly, the extra kthreads needlessly consume memory and can cause confusion when they show up in `ps` listings.

RCU must therefore wait for a given CPU to actually come online before it can allow itself to believe that the CPU actually exists. The resulting "ghost CPUs" (which are never going to come online) cause a number of interesting complications.

Early Boot

The Linux kernel's boot sequence is an interesting process, and RCU is used early, even before `rcu_init()` is invoked. In fact, a number of RCU's primitives can be used as soon as the initial task's `task_struct` is available and the boot CPU's per-CPU variables are set up. The read-side primitives (`rcu_read_lock()`, `rcu_read_unlock()`, `rcu_dereference()`, and `rcu_access_pointer()`) will operate normally very early on, as will `rcu_assign_pointer()`.

Although `call_rcu()` may be invoked at any time during boot, callbacks are not guaranteed to be invoked until after all of RCU's kthreads have been spawned, which occurs at `early_initcall()` time. This delay in callback invocation is due to the fact that RCU does not invoke callbacks until it is fully initialized, and this full initialization cannot occur until after the scheduler has initialized itself to the point where RCU can spawn and run its kthreads. In theory, it would be possible to invoke callbacks earlier, however, this is not a panacea because there would be severe restrictions on what operations those callbacks could invoke.

Perhaps surprisingly, `synchronize_rcu()` and `synchronize_rcu_expedited()`, will operate normally during very early boot, the reason being that there is only one CPU and preemption is disabled. This means that the call `synchronize_rcu()`

(or friends) itself is a quiescent state and thus a grace period, so the early-boot implementation can be a no-op.

However, once the scheduler has spawned its first kthread, this early boot trick fails for `synchronize_rcu()` (as well as for `synchronize_rcu_expedited()`) in `CONFIG_PREEMPT=y` kernels. The reason is that an RCU read-side critical section might be preempted, which means that a subsequent `synchronize_rcu()` really does have to wait for something, as opposed to simply returning immediately. Unfortunately, `synchronize_rcu()` can't do this until all of its kthreads are spawned, which doesn't happen until some time during `early_initcalls()` time. But this is no excuse: RCU is nevertheless required to correctly handle synchronous grace periods during this time period. Once all of its kthreads are up and running, RCU starts running normally.

Quick Quiz:

How can RCU possibly handle grace periods before all of its kthreads have been spawned???

Answer:

Very carefully! During the "dead zone" between the time that the scheduler spawns the first task and the time that all of RCU's kthreads have been spawned, all synchronous grace periods are handled by the expedited grace-period mechanism. At runtime, this expedited mechanism relies on workqueues, but during the dead zone the requesting task itself drives the desired expedited grace period. Because dead-zone execution takes place within task context, everything works. Once the dead zone ends, expedited grace periods go back to using workqueues, as is required to avoid problems that would otherwise occur when a user task received a POSIX signal while driving an expedited grace period.

And yes, this does mean that it is unhelpful to send POSIX signals to random tasks between the time that the scheduler spawns its first kthread and the time that RCU's kthreads have all been spawned. If there ever turns out to be a good reason for sending POSIX signals during that time, appropriate adjustments will be made. (If it turns out that POSIX signals are sent during this time for no good reason, other adjustments will be made, appropriate or otherwise.)

I learned of these boot-time requirements as a result of a series of system hangs.

Interrupts and NMIs

The Linux kernel has interrupts, and RCU read-side critical sections are legal within interrupt handlers and within interrupt-disabled regions of code, as are invocations of `call_rcu()`.

Some Linux-kernel architectures can enter an interrupt handler from non-idle process context, and then just never leave it, instead stealthily transitioning back to process context. This trick is sometimes used to invoke system calls from inside the kernel. These "half-interrupts" mean that RCU has to be very careful about how it counts interrupt nesting levels. I learned of this requirement the hard way during a rewrite of RCU's dyntick-idle code.

The Linux kernel has non-maskable interrupts (NMIs), and RCU read-side critical sections are legal within NMI handlers. Thankfully, RCU update-side primitives, including `call_rcu()`, are prohibited within NMI handlers.

The name notwithstanding, some Linux-kernel architectures can have nested NMIs, which RCU must handle correctly. Andy Lutomirski surprised me with this requirement; he also kindly surprised me with an algorithm that meets this requirement.

Furthermore, NMI handlers can be interrupted by what appear to RCU to be normal interrupts. One way that this can happen is for code that directly invokes `rcu_irq_enter()` and `rcu_irq_exit()` to be called from an NMI handler. This astonishing fact of life prompted the current code structure, which has `rcu_irq_enter()` invoking `rcu_nmi_enter()` and `rcu_irq_exit()` invoking `rcu_nmi_exit()`. And yes, I also learned of this requirement the hard way.

Loadable Modules

The Linux kernel has loadable modules, and these modules can also be unloaded. After a given module has been unloaded, any attempt to call one of its functions results in a segmentation fault. The module-unload functions must therefore cancel any delayed calls to loadable-module functions, for example, any outstanding `mod_timer()` must be dealt with via `del_timer_sync()` or similar.

Unfortunately, there is no way to cancel an RCU callback; once you invoke `call_rcu()`, the callback function is eventually going to be invoked, unless the system goes down first. Because it is normally considered socially irresponsible to crash the system in response to a module unload request, we need some other way to deal with in-flight RCU callbacks.

RCU therefore provides `rcu_barrier()`, which waits until all in-flight RCU callbacks have been invoked. If a module uses `call_rcu()`, its exit function should therefore prevent any future invocation of `call_rcu()`, then invoke `rcu_barrier()`. In theory, the underlying module-unload code could invoke `rcu_barrier()` unconditionally, but in practice this would incur unacceptable latencies.

Nikita Danilov noted this requirement for an analogous filesystem-unmount situation, and Dipankar Sarma incorporated `rcu_barrier()` into RCU. The need for `rcu_barrier()` for module unloading became apparent later.

Important: The `rcu_barrier()` function is not, repeat, *not*, obligated to wait for a grace period. It is instead only required to wait for RCU callbacks that have already been posted. Therefore, if there are no RCU callbacks posted anywhere in the system, `rcu_barrier()` is within its rights to return immediately. Even if there are callbacks posted, `rcu_barrier()` does not necessarily need to wait for a grace period.

Quick Quiz:

Wait a minute! Each RCU callbacks must wait for a grace period to complete, and `rcu_barrier()` must wait for each pre-existing callback to be invoked. Doesn't `rcu_barrier()` therefore need to wait for a full grace period if there is even one callback posted anywhere in the system?

Answer:

Absolutely not!!! Yes, each RCU callbacks must wait for a grace period to complete, but it might well be partly (or even completely) finished waiting by the time `rcu_barrier()` is invoked. In that case, `rcu_barrier()` need only wait for the remaining portion of the grace period to elapse. So even if there are quite a few callbacks posted, `rcu_barrier()` might well return quite quickly.

So if you need to wait for a grace period as well as for all pre-existing callbacks, you will need to invoke both `synchronize_rcu()` and `rcu_barrier()`. If latency is a concern, you can always use workqueues to invoke them concurrently.

Hotplug CPU

The Linux kernel supports CPU hotplug, which means that CPUs can come and go. It is of course illegal to use any RCU API member from an offline CPU, with the exception of *SRCU* read-side critical sections. This requirement was present from day one in DYNIX/ptx, but on the other hand, the Linux kernel's CPU-hotplug implementation is "interesting."

The Linux-kernel CPU-hotplug implementation has notifiers that are used to allow the various kernel subsystems (including RCU) to respond appropriately to a given CPU-hotplug operation. Most RCU operations may be invoked from CPU-hotplug notifiers, including even synchronous grace-period operations such as `synchronize_rcu()` and `synchronize_rcu_expedited()`.

However, all-callback-wait operations such as `rcu_barrier()` are also not supported, due to the fact that there are phases of CPU-hotplug operations where the outgoing CPU's callbacks will not be invoked until after the CPU-hotplug operation ends, which could also result in deadlock. Furthermore, `rcu_barrier()` blocks CPU-hotplug operations during its execution, which results in another type of deadlock when invoked from a CPU-hotplug notifier.

Scheduler and RCU

RCU makes use of kthreads, and it is necessary to avoid excessive CPU-time accumulation by these kthreads. This requirement was no surprise, but RCU's violation of it when running context-switch-heavy workloads when built with `CONFIG_NO_HZ_FULL=y` did come as a surprise [PDF]. RCU has made good progress towards meeting this requirement, even for context-switch-heavy `CONFIG_NO_HZ_FULL=y` workloads, but there is room for further improvement.

There is no longer any prohibition against holding any of scheduler's runqueue or priority-inheritance spinlocks across an `rcu_read_unlock()`, even if interrupts and preemption were enabled somewhere within the corresponding RCU read-side critical section. Therefore, it is now perfectly legal to execute `rcu_read_lock()`

with preemption enabled, acquire one of the scheduler locks, and hold that lock across the matching `rcu_read_unlock()`.

Similarly, the RCU flavor consolidation has removed the need for negative nesting. The fact that interrupt-disabled regions of code act as RCU read-side critical sections implicitly avoids earlier issues that used to result in destructive recursion via interrupt handler's use of RCU.

Tracing and RCU

It is possible to use tracing on RCU code, but tracing itself uses RCU. For this reason, `rcu_dereference_raw_check()` is provided for use by tracing, which avoids the destructive recursion that could otherwise ensue. This API is also used by virtualization in some architectures, where RCU readers execute in environments in which tracing cannot be used. The tracing folks both located the requirement and provided the needed fix, so this surprise requirement was relatively painless.

Accesses to User Memory and RCU

The kernel needs to access user-space memory, for example, to access data referenced by system-call parameters. The `get_user()` macro does this job.

However, user-space memory might well be paged out, which means that `get_user()` might well page-fault and thus block while waiting for the resulting I/O to complete. It would be a very bad thing for the compiler to reorder a `get_user()` invocation into an RCU read-side critical section.

For example, suppose that the source code looked like this:

```
1 rcu_read_lock();
2 p = rcu_dereference(gp);
3 v = p->value;
4 rcu_read_unlock();
5 get_user(user_v, user_p);
6 do_something_with(v, user_v);
```

The compiler must not be permitted to transform this source code into the following:

```
1 rcu_read_lock();
2 p = rcu_dereference(gp);
3 get_user(user_v, user_p); // BUG: POSSIBLE PAGE FAULT!!!
4 v = p->value;
5 rcu_read_unlock();
6 do_something_with(v, user_v);
```

If the compiler did make this transformation in a `CONFIG_PREEMPT=n` kernel build, and if `get_user()` did page fault, the result would be a quiescent state in the middle of an RCU read-side critical section. This misplaced quiescent state could result in line 4 being a use-after-free access, which could be bad for your kernel's actuarial statistics. Similar examples can be constructed with the call to `get_user()` preceding the `rcu_read_lock()`.

Unfortunately, `get_user()` doesn't have any particular ordering properties, and in some architectures the underlying `asm` isn't even marked `volatile`. And even if it was marked `volatile`, the above access to `p->value` is not volatile, so the compiler would not have any reason to keep those two accesses in order.

Therefore, the Linux-kernel definitions of `rcu_read_lock()` and `rcu_read_unlock()` must act as compiler barriers, at least for outermost instances of `rcu_read_lock()` and `rcu_read_unlock()` within a nested set of RCU read-side critical sections.

Energy Efficiency

Interrupting idle CPUs is considered socially unacceptable, especially by people with battery-powered embedded systems. RCU therefore conserves energy by detecting which CPUs are idle, including tracking CPUs that have been interrupted from idle. This is a large part of the energy-efficiency requirement, so I learned of this via an irate phone call.

Because RCU avoids interrupting idle CPUs, it is illegal to execute an RCU read-side critical section on an idle CPU. (Kernels built with `CONFIG_PROVE_RCU=y` will splat if you try it.) The `RCU_NONIDLE()` macro and `_rcuidle` event tracing is provided to work around this restriction. In addition, `rcu_is_watching()` may be used to test whether or not it is currently legal to run RCU read-side critical sections on this CPU. I learned of the need for diagnostics on the one hand and `RCU_NONIDLE()` on the other while inspecting idle-loop code. Steven Rostedt supplied `_rcuidle` event tracing, which is used quite heavily in the idle loop. However, there are some restrictions on the code placed within `RCU_NONIDLE()`:

1. Blocking is prohibited. In practice, this is not a serious restriction given that idle tasks are prohibited from blocking to begin with.
2. Although nesting `RCU_NONIDLE()` is permitted, they cannot nest indefinitely deeply. However, given that they can be nested on the order of a million deep, even on 32-bit systems, this should not be a serious restriction. This nesting limit would probably be reached long after the compiler OOMed or the stack overflowed.
3. Any code path that enters `RCU_NONIDLE()` must sequence out of that same `RCU_NONIDLE()`. For example, the following is grossly illegal:

   ```
     RCU_NONIDLE({
       do_something();
       goto bad_idea;  /* BUG!!! */
       do_something_else();});
   bad_idea:
   ```

   It is just as illegal to transfer control into the middle of `RCU_NONIDLE()`'s argument. Yes, in theory, you could transfer in as long as you also transferred out, but in practice you could also expect to get sharply worded review comments.

It is similarly socially unacceptable to interrupt an `nohz_full` CPU running in userspace. RCU must therefore track `nohz_full` userspace execution. RCU must therefore be able to sample state at two points in time, and be able to determine whether or not some other CPU spent any time idle and/or executing in userspace.

These energy-efficiency requirements have proven quite difficult to understand and to meet, for example, there have been more than five clean-sheet rewrites of RCU's energy-efficiency code, the last of which was finally able to demonstrate real energy savings running on real hardware [PDF]. As noted earlier, I learned of many of these requirements via angry phone calls: Flaming me on the Linux-kernel mailing list was apparently not sufficient to fully vent their ire at RCU's energy-efficiency bugs!

Scheduling-Clock Interrupts and RCU

The kernel transitions between in-kernel non-idle execution, userspace execution, and the idle loop. Depending on kernel configuration, RCU handles these states differently:

HZ Kconfig	In-Kernel	Usermode	Idle
HZ_P	Can rely on scheduling-clock interrupt.	Can rely on scheduling-clock interrupt and its detection of interrupt from usermode.	Can rely on RCU's dyntick-idle detection.
NO_H	Can rely on scheduling-clock interrupt.	Can rely on scheduling-clock interrupt and its detection of interrupt from usermode.	Can rely on RCU's dyntick-idle detection.
NO_H	Can only sometimes rely on scheduling-clock interrupt. In other cases, it is necessary to bound kernel execution times and/or use IPIs.	Can rely on RCU's dyntick-idle detection.	Can rely on RCU's dyntick-idle detection.

Quick Quiz:

Why can't NO_HZ_FULL in-kernel execution rely on the scheduling-clock interrupt, just like HZ_PERIODIC and NO_HZ_IDLE do?

Answer:

Because, as a performance optimization, NO_HZ_FULL does not necessarily re-enable the scheduling-clock interrupt on entry to each and every system call.

However, RCU must be reliably informed as to whether any given CPU is currently in the idle loop, and, for NO_HZ_FULL, also whether that CPU is executing in usermode, as discussed *earlier*. It also requires that the scheduling-clock interrupt be enabled when RCU needs it to be:

1. If a CPU is either idle or executing in usermode, and RCU believes it is non-idle, the scheduling-clock tick had better be running. Otherwise, you will get

RCU CPU stall warnings. Or at best, very long (11-second) grace periods, with a pointless IPI waking the CPU from time to time.

2. If a CPU is in a portion of the kernel that executes RCU read-side critical sections, and RCU believes this CPU to be idle, you will get random memory corruption. **DON' T DO THIS!!!** This is one reason to test with lockdep, which will complain about this sort of thing.

3. If a CPU is in a portion of the kernel that is absolutely positively no-joking guaranteed to never execute any RCU read-side critical sections, and RCU believes this CPU to be idle, no problem. This sort of thing is used by some architectures for light-weight exception handlers, which can then avoid the overhead of `rcu_irq_enter()` and `rcu_irq_exit()` at exception entry and exit, respectively. Some go further and avoid the entireties of `irq_enter()` and `irq_exit()`. Just make very sure you are running some of your tests with `CONFIG_PROVE_RCU=y`, just in case one of your code paths was in fact joking about not doing RCU read-side critical sections.

4. If a CPU is executing in the kernel with the scheduling-clock interrupt disabled and RCU believes this CPU to be non-idle, and if the CPU goes idle (from an RCU perspective) every few jiffies, no problem. It is usually OK for there to be the occasional gap between idle periods of up to a second or so. If the gap grows too long, you get RCU CPU stall warnings.

5. If a CPU is either idle or executing in usermode, and RCU believes it to be idle, of course no problem.

6. If a CPU is executing in the kernel, the kernel code path is passing through quiescent states at a reasonable frequency (preferably about once per few jiffies, but the occasional excursion to a second or so is usually OK) and the scheduling-clock interrupt is enabled, of course no problem. If the gap between a successive pair of quiescent states grows too long, you get RCU CPU stall warnings.

Quick Quiz:

But what if my driver has a hardware interrupt handler that can run for many seconds? I cannot invoke `schedule()` from an hardware interrupt handler, after all!

Answer:

One approach is to do `rcu_irq_exit();rcu_irq_enter();` every so often. But given that long-running interrupt handlers can cause other problems, not least for response time, shouldn' t you work to keep your interrupt handler' s runtime within reasonable bounds?

But as long as RCU is properly informed of kernel state transitions between in-kernel execution, usermode execution, and idle, and as long as the scheduling-clock interrupt is enabled when RCU needs it to be, you can rest assured that the bugs you encounter will be in some other part of RCU or some other part of the kernel!

Memory Efficiency

Although small-memory non-realtime systems can simply use Tiny RCU, code size is only one aspect of memory efficiency. Another aspect is the size of the `rcu_head` structure used by `call_rcu()` and `kfree_rcu()`. Although this structure contains nothing more than a pair of pointers, it does appear in many RCU-protected data structures, including some that are size critical. The `page` structure is a case in point, as evidenced by the many occurrences of the `union` keyword within that structure.

This need for memory efficiency is one reason that RCU uses hand-crafted singly linked lists to track the `rcu_head` structures that are waiting for a grace period to elapse. It is also the reason why `rcu_head` structures do not contain debug information, such as fields tracking the file and line of the `call_rcu()` or `kfree_rcu()` that posted them. Although this information might appear in debug-only kernel builds at some point, in the meantime, the `->func` field will often provide the needed debug information.

However, in some cases, the need for memory efficiency leads to even more extreme measures. Returning to the `page` structure, the `rcu_head` field shares storage with a great many other structures that are used at various points in the corresponding page's lifetime. In order to correctly resolve certain race conditions, the Linux kernel's memory-management subsystem needs a particular bit to remain zero during all phases of grace-period processing, and that bit happens to map to the bottom bit of the `rcu_head` structure's `->next` field. RCU makes this guarantee as long as `call_rcu()` is used to post the callback, as opposed to `kfree_rcu()` or some future "lazy" variant of `call_rcu()` that might one day be created for energy-efficiency purposes.

That said, there are limits. RCU requires that the `rcu_head` structure be aligned to a two-byte boundary, and passing a misaligned `rcu_head` structure to one of the `call_rcu()` family of functions will result in a splat. It is therefore necessary to exercise caution when packing structures containing fields of type `rcu_head`. Why not a four-byte or even eight-byte alignment requirement? Because the m68k architecture provides only two-byte alignment, and thus acts as alignment's least common denominator.

The reason for reserving the bottom bit of pointers to `rcu_head` structures is to leave the door open to "lazy" callbacks whose invocations can safely be deferred. Deferring invocation could potentially have energy-efficiency benefits, but only if the rate of non-lazy callbacks decreases significantly for some important workload. In the meantime, reserving the bottom bit keeps this option open in case it one day becomes useful.

Performance, Scalability, Response Time, and Reliability

Expanding on the *earlier discussion*, RCU is used heavily by hot code paths in performance-critical portions of the Linux kernel's networking, security, virtualization, and scheduling code paths. RCU must therefore use efficient implementations, especially in its read-side primitives. To that end, it would be good if preemptible RCU's implementation of `rcu_read_lock()` could be inlined, however, doing this requires resolving `#include` issues with the `task_struct` structure.

The Linux kernel supports hardware configurations with up to 4096 CPUs, which means that RCU must be extremely scalable. Algorithms that involve frequent acquisitions of global locks or frequent atomic operations on global variables simply cannot be tolerated within the RCU implementation. RCU therefore makes heavy use of a combining tree based on the `rcu_node` structure. RCU is required to tolerate all CPUs continuously invoking any combination of RCU's runtime primitives with minimal per-operation overhead. In fact, in many cases, increasing load must *decrease* the per-operation overhead, witness the batching optimizations for `synchronize_rcu()`, `call_rcu()`, `synchronize_rcu_expedited()`, and `rcu_barrier()`. As a general rule, RCU must cheerfully accept whatever the rest of the Linux kernel decides to throw at it.

The Linux kernel is used for real-time workloads, especially in conjunction with the -rt patchset. The real-time-latency response requirements are such that the traditional approach of disabling preemption across RCU read-side critical sections is inappropriate. Kernels built with `CONFIG_PREEMPT=y` therefore use an RCU implementation that allows RCU read-side critical sections to be preempted. This requirement made its presence known after users made it clear that an earlier real-time patch did not meet their needs, in conjunction with some RCU issues encountered by a very early version of the -rt patchset.

In addition, RCU must make do with a sub-100-microsecond real-time latency budget. In fact, on smaller systems with the -rt patchset, the Linux kernel provides sub-20-microsecond real-time latencies for the whole kernel, including RCU. RCU's scalability and latency must therefore be sufficient for these sorts of configurations. To my surprise, the sub-100-microsecond real-time latency budget applies to even the largest systems [PDF], up to and including systems with 4096 CPUs. This real-time requirement motivated the grace-period kthread, which also simplified handling of a number of race conditions.

RCU must avoid degrading real-time response for CPU-bound threads, whether executing in usermode (which is one use case for `CONFIG_NO_HZ_FULL=y`) or in the kernel. That said, CPU-bound loops in the kernel must execute `cond_resched()` at least once per few tens of milliseconds in order to avoid receiving an IPI from RCU.

Finally, RCU's status as a synchronization primitive means that any RCU failure can result in arbitrary memory corruption that can be extremely difficult to debug. This means that RCU must be extremely reliable, which in practice also means that RCU must have an aggressive stress-test suite. This stress-test suite is called `rcutorture`.

Although the need for `rcutorture` was no surprise, the current immense popularity of the Linux kernel is posing interesting—and perhaps unprecedented—validation challenges. To see this, keep in mind that there are well over one billion instances of the Linux kernel running today, given Android smartphones, Linux-powered televisions, and servers. This number can be expected to increase sharply with the advent of the celebrated Internet of Things.

Suppose that RCU contains a race condition that manifests on average once per million years of runtime. This bug will be occurring about three times per *day* across the installed base. RCU could simply hide behind hardware error rates, given that no one should really expect their smartphone to last for a million years. However, anyone taking too much comfort from this thought should consider the fact that in most jurisdictions, a successful multi-year test of a given mechanism, which might include a Linux kernel, suffices for a number of types of safety-critical certifications. In fact, rumor has it that the Linux kernel is already being used in production for safety-critical applications. I don't know about you, but I would feel quite bad if a bug in RCU killed someone. Which might explain my recent focus on validation and verification.

Other RCU Flavors

One of the more surprising things about RCU is that there are now no fewer than five *flavors*, or API families. In addition, the primary flavor that has been the sole focus up to this point has two different implementations, non-preemptible and preemptible. The other four flavors are listed below, with requirements for each described in a separate section.

1. *Bottom-Half Flavor (Historical)*
2. *Sched Flavor (Historical)*
3. *Sleepable RCU*
4. *Tasks RCU*

Bottom-Half Flavor (Historical)

The RCU-bh flavor of RCU has since been expressed in terms of the other RCU flavors as part of a consolidation of the three flavors into a single flavor. The read-side API remains, and continues to disable softirq and to be accounted for by lockdep. Much of the material in this section is therefore strictly historical in nature.

The softirq-disable (AKA "bottom-half", hence the "_bh" abbreviations) flavor of RCU, or *RCU-bh*, was developed by Dipankar Sarma to provide a flavor of RCU that could withstand the network-based denial-of-service attacks researched by Robert Olsson. These attacks placed so much networking load on the system that some of the CPUs never exited softirq execution, which in turn prevented those CPUs from ever executing a context switch, which, in the RCU implementation of that time, prevented grace periods from ever ending. The result was an out-of-memory condition and a system hang.

The solution was the creation of RCU-bh, which does `local_bh_disable()` across its read-side critical sections, and which uses the transition from one type of softirq processing to another as a quiescent state in addition to context switch, idle, user mode, and offline. This means that RCU-bh grace periods can complete even when some of the CPUs execute in softirq indefinitely, thus allowing algorithms based on RCU-bh to withstand network-based denial-of-service attacks.

Because `rcu_read_lock_bh()` and `rcu_read_unlock_bh()` disable and re-enable softirq handlers, any attempt to start a softirq handlers during the RCU-bh read-side critical section will be deferred. In this case, `rcu_read_unlock_bh()` will invoke softirq processing, which can take considerable time. One can of course argue that this softirq overhead should be associated with the code following the RCU-bh read-side critical section rather than `rcu_read_unlock_bh()`, but the fact is that most profiling tools cannot be expected to make this sort of fine distinction. For example, suppose that a three-millisecond-long RCU-bh read-side critical section executes during a time of heavy networking load. There will very likely be an attempt to invoke at least one softirq handler during that three milliseconds, but any such invocation will be delayed until the time of the `rcu_read_unlock_bh()`. This can of course make it appear at first glance as if `rcu_read_unlock_bh()` was executing very slowly.

The RCU-bh API includes `rcu_read_lock_bh()`, `rcu_read_unlock_bh()`, `rcu_dereference_bh()`, `rcu_dereference_bh_check()`, `synchronize_rcu_bh()`, `synchronize_rcu_bh_expedited()`, `call_rcu_bh()`, `rcu_barrier_bh()`, and `rcu_read_lock_bh_held()`. However, the update-side APIs are now simple wrappers for other RCU flavors, namely RCU-sched in CONFIG_PREEMPT=n kernels and RCU-preempt otherwise.

Sched Flavor (Historical)

The RCU-sched flavor of RCU has since been expressed in terms of the other RCU flavors as part of a consolidation of the three flavors into a single flavor. The read-side API remains, and continues to disable preemption and to be accounted for by lockdep. Much of the material in this section is therefore strictly historical in nature.

Before preemptible RCU, waiting for an RCU grace period had the side effect of also waiting for all pre-existing interrupt and NMI handlers. However, there are legitimate preemptible-RCU implementations that do not have this property, given that any point in the code outside of an RCU read-side critical section can be a quiescent state. Therefore, *RCU-sched* was created, which follows "classic" RCU in that an RCU-sched grace period waits for pre-existing interrupt and NMI handlers. In kernels built with `CONFIG_PREEMPT=n`, the RCU and RCU-sched APIs have identical implementations, while kernels built with `CONFIG_PREEMPT=y` provide a separate implementation for each.

Note well that in `CONFIG_PREEMPT=y` kernels, `rcu_read_lock_sched()` and `rcu_read_unlock_sched()` disable and re-enable preemption, respectively. This means that if there was a preemption attempt during the RCU-sched read-side critical section, `rcu_read_unlock_sched()` will enter the scheduler, with all the latency and overhead entailed. Just as with `rcu_read_unlock_bh()`, this can make it look as if `rcu_read_unlock_sched()` was executing very slowly. However, the highest-priority task won't be preempted, so that task will enjoy low-overhead `rcu_read_unlock_sched()` invocations.

The RCU-sched API includes `rcu_read_lock_sched()`, `rcu_read_unlock_sched()`, `rcu_read_lock_sched_notrace()`, rcu_read_unlock_sched_notrace(), rcu_dereference_sched(), rcu_dereference_sched_check(), synchronize_sched(), synchronize_rcu_sched_expedited(), call_rcu_sched(), rcu_barrier_sched(), and rcu_read_lock_sched_held(). However, anything that disables preemption also marks an RCU-sched read-side critical section, including preempt_disable() and preempt_enable(), local_irq_save() and local_irq_restore(), and so on.

Sleepable RCU

For well over a decade, someone saying "I need to block within an RCU read-side critical section" was a reliable indication that this someone did not understand RCU. After all, if you are always blocking in an RCU read-side critical section, you can probably afford to use a higher-overhead synchronization mechanism. However, that changed with the advent of the Linux kernel's notifiers, whose RCU read-side critical sections almost never sleep, but sometimes need to. This resulted in the introduction of sleepable RCU, or *SRCU*.

SRCU allows different domains to be defined, with each such domain defined by an instance of an srcu_struct structure. A pointer to this structure must be passed in to each SRCU function, for example, synchronize_srcu(&ss), where ss is the srcu_struct structure. The key benefit of these domains is that a slow SRCU reader in one domain does not delay an SRCU grace period in some other domain. That said, one consequence of these domains is that read-side code must pass a "cookie" from srcu_read_lock() to srcu_read_unlock(), for example, as follows:

```
int idx;

idx = srcu_read_lock(&ss);
do_something();
srcu_read_unlock(&ss, idx);
```

As noted above, it is legal to block within SRCU read-side critical sections, however, with great power comes great responsibility. If you block forever in one of a given domain's SRCU read-side critical sections, then that domain's grace periods will also be blocked forever. Of course, one good way to block forever is to deadlock, which can happen if any operation in a given domain's SRCU read-side critical section can wait, either directly or indirectly, for that domain's grace period to elapse. For example, this results in a self-deadlock:

```
1 int idx;
2
3 idx = srcu_read_lock(&ss);
4 do_something();
5 synchronize_srcu(&ss);
6 srcu_read_unlock(&ss, idx);
```

However, if line 5 acquired a mutex that was held across a synchronize_srcu() for domain ss, deadlock would still be possible. Furthermore, if line 5 acquired a mutex that was held across a synchronize_srcu() for some other domain ss1, and if an ss1-domain SRCU read-side critical section acquired another mutex that was held across as ss-domain `synchronize_srcu()`, deadlock would again be possible. Such a deadlock cycle could extend across an arbitrarily large number of different SRCU domains. Again, with great power comes great responsibility.

Unlike the other RCU flavors, SRCU read-side critical sections can run on idle and even offline CPUs. This ability requires that `srcu_read_lock()` and `srcu_read_unlock()` contain memory barriers, which means that SRCU readers will run a bit slower than would RCU readers. It also motivates the `smp_mb__after_srcu_read_unlock()` API, which, in combination with `srcu_read_unlock()`, guarantees a full memory barrier.

Also unlike other RCU flavors, `synchronize_srcu()` may **not** be invoked from CPU-hotplug notifiers, due to the fact that SRCU grace periods make use of timers and the possibility of timers being temporarily "stranded" on the outgoing CPU. This stranding of timers means that timers posted to the outgoing CPU will not fire until late in the CPU-hotplug process. The problem is that if a notifier is waiting on an SRCU grace period, that grace period is waiting on a timer, and that timer is stranded on the outgoing CPU, then the notifier will never be awakened, in other words, deadlock has occurred. This same situation of course also prohibits `srcu_barrier()` from being invoked from CPU-hotplug notifiers.

SRCU also differs from other RCU flavors in that SRCU's expedited and non-expedited grace periods are implemented by the same mechanism. This means that in the current SRCU implementation, expediting a future grace period has the side effect of expediting all prior grace periods that have not yet completed. (But please note that this is a property of the current implementation, not necessarily of future implementations.) In addition, if SRCU has been idle for longer than the interval specified by the `srcutree.exp_holdoff` kernel boot parameter (25 microseconds by default), and if a `synchronize_srcu()` invocation ends this idle period, that invocation will be automatically expedited.

As of v4.12, SRCU's callbacks are maintained per-CPU, eliminating a locking bottleneck present in prior kernel versions. Although this will allow users to put much heavier stress on `call_srcu()`, it is important to note that SRCU does not yet take any special steps to deal with callback flooding. So if you are posting (say) 10,000 SRCU callbacks per second per CPU, you are probably totally OK, but if you intend to post (say) 1,000,000 SRCU callbacks per second per CPU, please run some tests first. SRCU just might need a few adjustment to deal with that sort of load. Of course, your mileage may vary based on the speed of your CPUs and the size of your memory.

The SRCU API includes `srcu_read_lock()`, `srcu_read_unlock()`, `srcu_dereference()`, `srcu_dereference_check()`, `synchronize_srcu()`, `synchronize_srcu_expedited()`, `call_srcu()`, `srcu_barrier()`, and `srcu_read_lock_held()`. It also includes `DEFINE_SRCU()`, `DEFINE_STATIC_SRCU()`, and `init_srcu_struct()` APIs for defining and initializing `srcu_struct` structures.

Tasks RCU

Some forms of tracing use "trampolines" to handle the binary rewriting required to install different types of probes. It would be good to be able to free old trampolines, which sounds like a job for some form of RCU. However, because it is necessary to be able to install a trace anywhere in the code, it is not possible to use read-side markers such as `rcu_read_lock()` and `rcu_read_unlock()`. In addition, it does not work to have these markers in the trampoline itself, because there would need to be instructions following `rcu_read_unlock()`. Although `synchronize_rcu()` would guarantee that execution reached the `rcu_read_unlock()`, it would not be able to guarantee that execution had completely left the trampoline. Worse yet, in some situations the trampoline's protection must extend a few instructions *prior* to execution reaching the trampoline. For example, these few instructions might calculate the address of the trampoline, so that entering the trampoline would be pre-ordained a surprisingly long time before execution actually reached the trampoline itself.

The solution, in the form of Tasks RCU, is to have implicit read-side critical sections that are delimited by voluntary context switches, that is, calls to `schedule()`, `cond_resched()`, and `synchronize_rcu_tasks()`. In addition, transitions to and from userspace execution also delimit tasks-RCU read-side critical sections.

The tasks-RCU API is quite compact, consisting only of `call_rcu_tasks()`, `synchronize_rcu_tasks()`, and `rcu_barrier_tasks()`. In `CONFIG_PREEMPT=n` kernels, trampolines cannot be preempted, so these APIs map to `call_rcu()`, `synchronize_rcu()`, and `rcu_barrier()`, respectively. In `CONFIG_PREEMPT=y` kernels, trampolines can be preempted, and these three APIs are therefore implemented by separate functions that check for voluntary context switches.

Possible Future Changes

One of the tricks that RCU uses to attain update-side scalability is to increase grace-period latency with increasing numbers of CPUs. If this becomes a serious problem, it will be necessary to rework the grace-period state machine so as to avoid the need for the additional latency.

RCU disables CPU hotplug in a few places, perhaps most notably in the `rcu_barrier()` operations. If there is a strong reason to use `rcu_barrier()` in CPU-hotplug notifiers, it will be necessary to avoid disabling CPU hotplug. This would introduce some complexity, so there had better be a *very* good reason.

The tradeoff between grace-period latency on the one hand and interruptions of other CPUs on the other hand may need to be re-examined. The desire is of course for zero grace-period latency as well as zero interprocessor interrupts undertaken during an expedited grace period operation. While this ideal is unlikely to be achievable, it is quite possible that further improvements can be made.

The multiprocessor implementations of RCU use a combining tree that groups CPUs so as to reduce lock contention and increase cache locality. However, this combining tree does not spread its memory across NUMA nodes nor does it align the CPU groups with hardware features such as sockets or cores. Such spreading and alignment is currently believed to be unnecessary because the hot-path read-side primitives do not access the combining tree, nor does `call_rcu()`

in the common case. If you believe that your architecture needs such spreading and alignment, then your architecture should also benefit from the `rcutree.rcu_fanout_leaf` boot parameter, which can be set to the number of CPUs in a socket, NUMA node, or whatever. If the number of CPUs is too large, use a fraction of the number of CPUs. If the number of CPUs is a large prime number, well, that certainly is an "interesting" architectural choice! More flexible arrangements might be considered, but only if `rcutree.rcu_fanout_leaf` has proven inadequate, and only if the inadequacy has been demonstrated by a carefully run and realistic system-level workload.

Please note that arrangements that require RCU to remap CPU numbers will require extremely good demonstration of need and full exploration of alternatives.

RCU's various kthreads are reasonably recent additions. It is quite likely that adjustments will be required to more gracefully handle extreme loads. It might also be necessary to be able to relate CPU utilization by RCU's kthreads and softirq handlers to the code that instigated this CPU utilization. For example, RCU callback overhead might be charged back to the originating `call_rcu()` instance, though probably not in production kernels.

Additional work may be required to provide reasonable forward-progress guarantees under heavy load for grace periods and for callback invocation.

Summary

This document has presented more than two decade's worth of RCU requirements. Given that the requirements keep changing, this will not be the last word on this subject, but at least it serves to get an important subset of the requirements set forth.

Acknowledgments

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3.6.19 A Tour Through TREE_RCU's Data Structures [LWN.net]

December 18, 2016

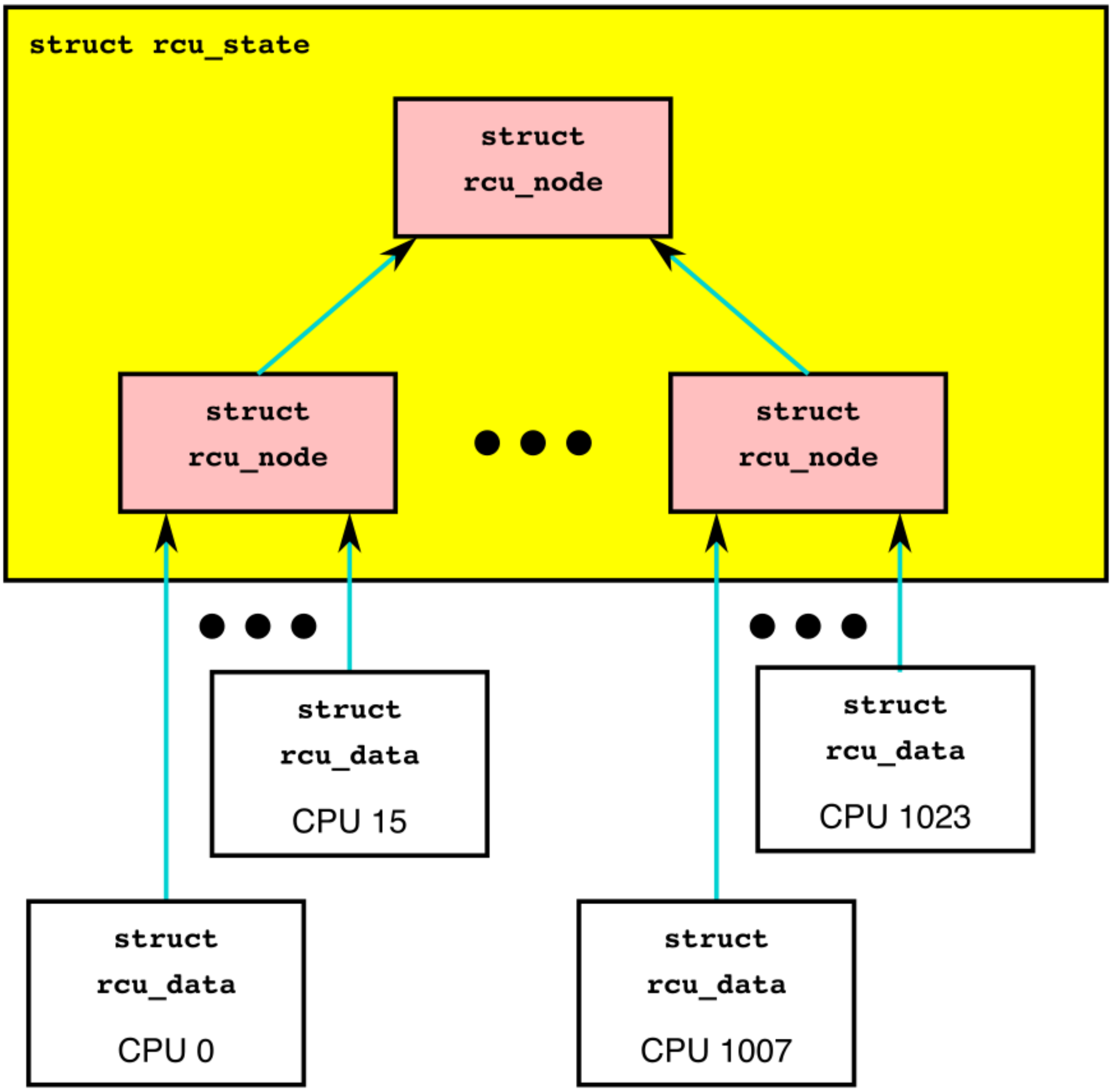
This article was contributed by Paul E. McKenney

Introduction

This document describes RCU's major data structures and their relationship to each other.

Data-Structure Relationships

RCU is for all intents and purposes a large state machine, and its data structures maintain the state in such a way as to allow RCU readers to execute extremely quickly, while also processing the RCU grace periods requested by updaters in an efficient and extremely scalable fashion. The efficiency and scalability of RCU updaters is provided primarily by a combining tree, as shown below:



This diagram shows an enclosing `rcu_state` structure containing a tree of `rcu_node` structures. Each leaf node of the `rcu_node` tree has up to 16 `rcu_data` structures associated with it, so that there are `NR_CPUS` number of `rcu_data` structures, one for each possible CPU. This structure is adjusted at boot time, if needed, to handle the common case where nr_cpu_ids is much less than NR_CPUs. For example, a number of Linux distributions set NR_CPUs=4096, which results in a three-level rcu_node tree. If the actual hardware has only 16 CPUs, RCU will adjust itself at boot time, resulting in an rcu_node tree with only a single node.

The purpose of this combining tree is to allow per-CPU events such as quiescent states, dyntick-idle transitions, and CPU hotplug operations to be processed efficiently and scalably. Quiescent states are recorded by the per-CPU rcu_data structures, and other events are recorded by the leaf-level rcu_node structures. All of these events are combined at each level of the tree until finally grace periods are completed at the tree's root rcu_node structure. A grace period can be completed at the root once every CPU (or, in the case of CONFIG_PREEMPT_RCU, task) has passed through a quiescent state. Once a grace period has completed, record of that fact is propagated back down the tree.

As can be seen from the diagram, on a 64-bit system a two-level tree with 64 leaves can accommodate 1,024 CPUs, with a fanout of 64 at the root and a fanout of 16 at the leaves.

Quick Quiz:

Why isn't the fanout at the leaves also 64?

Answer:

Because there are more types of events that affect the leaf-level rcu_node structures than further up the tree. Therefore, if the leaf rcu_node structures have fanout of 64, the contention on these structures' ->structures becomes excessive. Experimentation on a wide variety of systems has shown that a fanout of 16 works well for the leaves of the rcu_node tree.

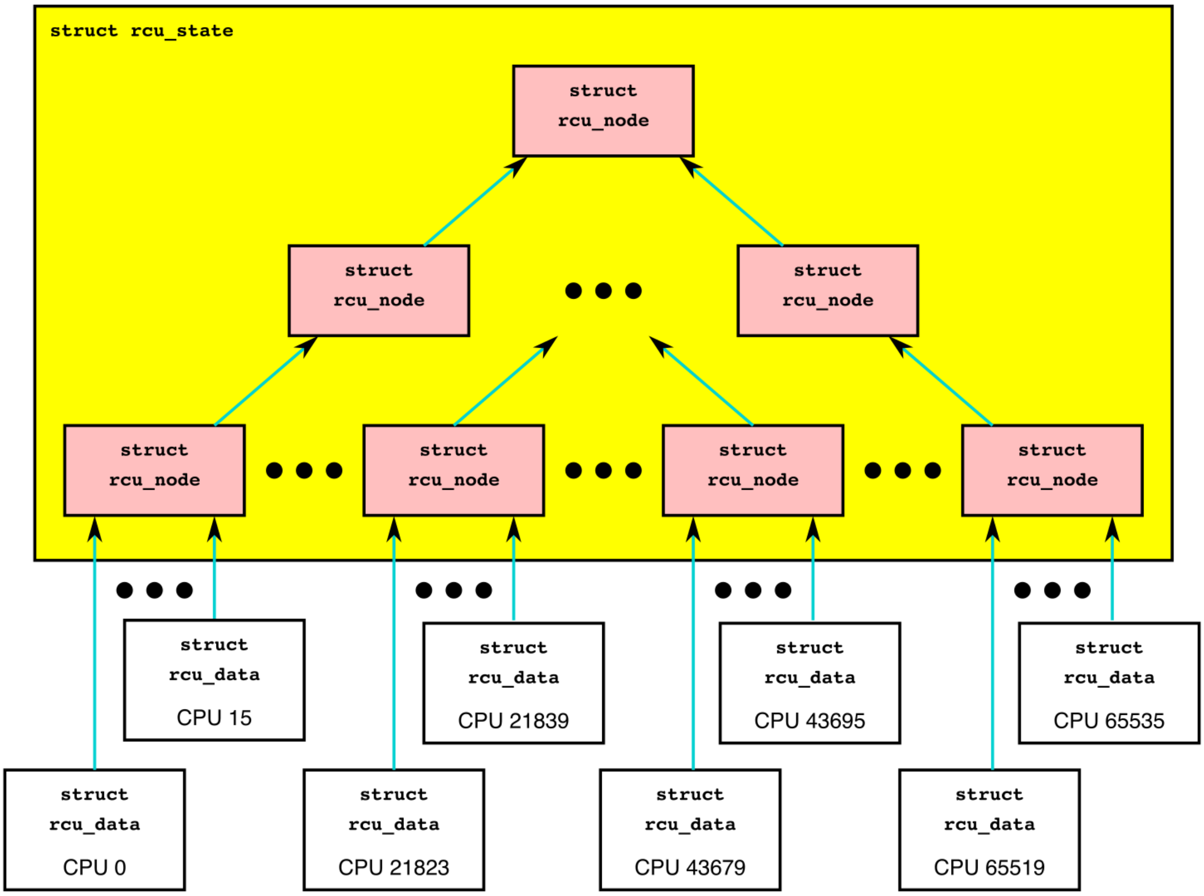
Of course, further experience with systems having hundreds or thousands of CPUs may demonstrate that the fanout for the non-leaf rcu_node structures must also be reduced. Such reduction can be easily carried out when and if it proves necessary. In the meantime, if you are using such a system and running into contention problems on the non-leaf rcu_node structures, you may use the CONFIG_RCU_FANOUT kernel configuration parameter to reduce the non-leaf fanout as needed.

Kernels built for systems with strong NUMA characteristics might also need to adjust CONFIG_RCU_FANOUT so that the domains of the rcu_node structures align with hardware boundaries. However, there has thus far been no need for this.

If your system has more than 1,024 CPUs (or more than 512 CPUs on a 32-bit system), then RCU will automatically add more levels to the tree. For example, if you are crazy enough to build a 64-bit system with 65,536 CPUs, RCU would configure the rcu_node tree as follows:

RCU currently permits up to a four-level tree, which on a 64-bit system accommodates up to 4,194,304 CPUs, though only a mere 524,288 CPUs for 32-bit systems. On the other hand, you can set both CONFIG_RCU_FANOUT and CONFIG_RCU_FANOUT_LEAF to be as small as 2, which would result in a 16-CPU test using a 4-level tree. This can be useful for testing large-system capabilities on small test machines.

This multi-level combining tree allows us to get most of the performance and scalability benefits of partitioning, even though RCU grace-period detection is inher-



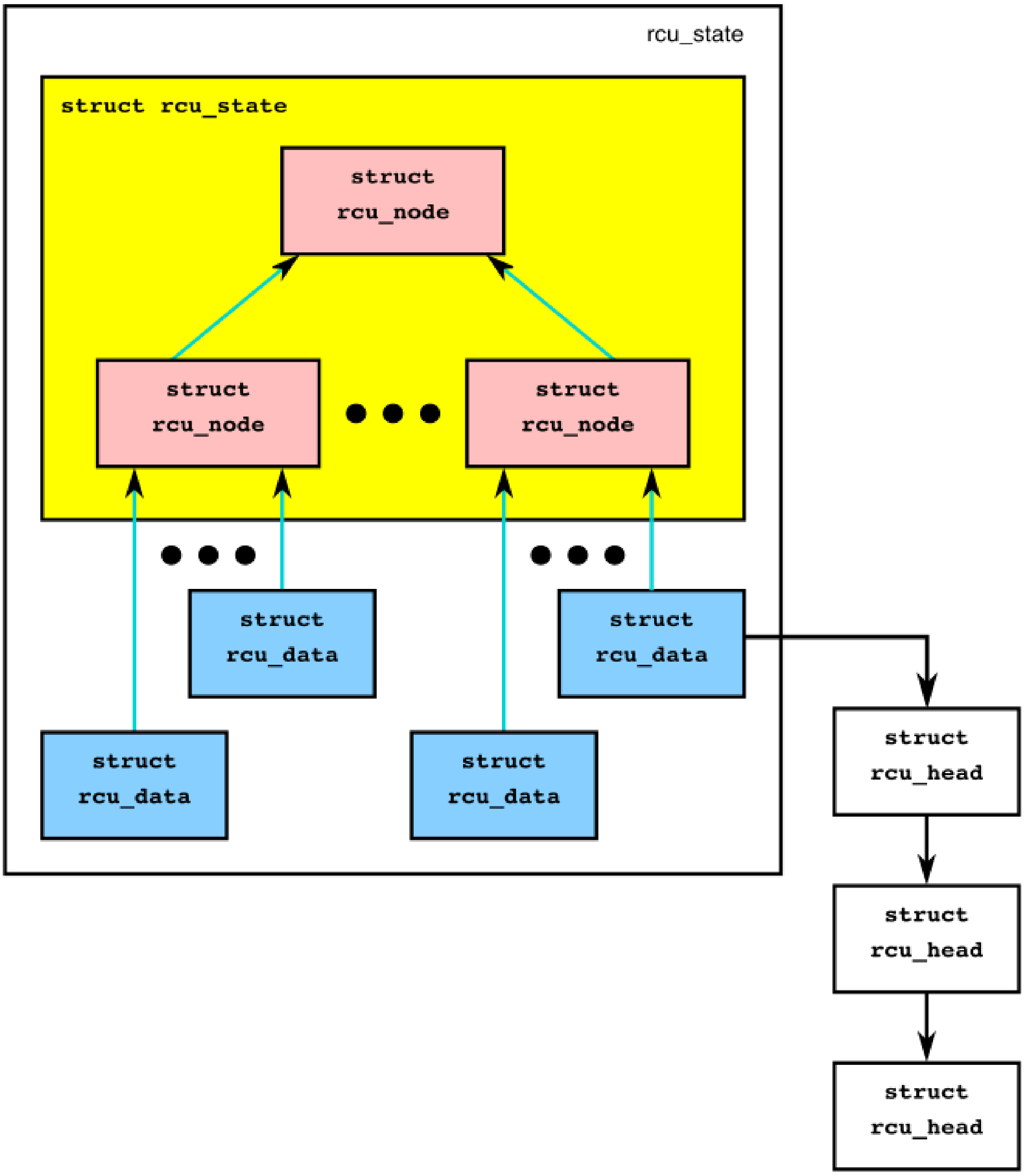
ently a global operation. The trick here is that only the last CPU to report a quiescent state into a given `rcu_node` structure need advance to the `rcu_node` structure at the next level up the tree. This means that at the leaf-level `rcu_node` structure, only one access out of sixteen will progress up the tree. For the internal `rcu_node` structures, the situation is even more extreme: Only one access out of sixty-four will progress up the tree. Because the vast majority of the CPUs do not progress up the tree, the lock contention remains roughly constant up the tree. No matter how many CPUs there are in the system, at most 64 quiescent-state reports per grace period will progress all the way to the root `rcu_node` structure, thus ensuring that the lock contention on that root `rcu_node` structure remains acceptably low.

In effect, the combining tree acts like a big shock absorber, keeping lock contention under control at all tree levels regardless of the level of loading on the system.

RCU updaters wait for normal grace periods by registering RCU callbacks, either directly via `call_rcu()` or indirectly via `synchronize_rcu()` and friends. RCU callbacks are represented by `rcu_head` structures, which are queued on `rcu_data` structures while they are waiting for a grace period to elapse, as shown in the following figure:

This figure shows how `TREE_RCU`' s and `PREEMPT_RCU`' s major data structures are related. Lesser data structures will be introduced with the algorithms that make use of them.

Note that each of the data structures in the above figure has its own synchronization:


rcu_state
struct rcu_state
struct
rcu_node
struct
rcu_node
struct
rcu_node
struct
rcu_data
struct
rcu_data
struct
rcu_data
struct
rcu_data
struct
rcu_head
struct
rcu_head
struct
rcu_head

1. Each `rcu_state` structures has a lock and a mutex, and some fields are protected by the corresponding root `rcu_node` structure's lock.
2. Each `rcu_node` structure has a spinlock.
3. The fields in `rcu_data` are private to the corresponding CPU, although a few can be read and written by other CPUs.

It is important to note that different data structures can have very different ideas about the state of RCU at any given time. For but one example, awareness of the start or end of a given RCU grace period propagates slowly through the data structures. This slow propagation is absolutely necessary for RCU to have good read-side performance. If this balkanized implementation seems foreign to you, one useful trick is to consider each instance of these data structures to be a different person, each having the usual slightly different view of reality.

The general role of each of these data structures is as follows:

1. `rcu_state`: This structure forms the interconnection between the `rcu_node` and `rcu_data` structures, tracks grace periods, serves as short-term repository for callbacks orphaned by CPU-hotplug events, maintains `rcu_barrier()` state, tracks expedited grace-period state, and maintains state used to force quiescent states when grace periods extend too long,
2. `rcu_node`: This structure forms the combining tree that propagates quiescent-state information from the leaves to the root, and also propagates grace-period information from the root to the leaves. It provides local copies of the grace-period state in order to allow this information to be accessed in a synchronized manner without suffering the scalability limitations that would otherwise be imposed by global locking. In `CONFIG_PREEMPT_RCU` kernels, it manages the lists of tasks that have blocked while in their current RCU read-side critical section. In `CONFIG_PREEMPT_RCU` with `CONFIG_RCU_BOOST`, it manages the per-`rcu_node` priority-boosting kernel threads (kthreads) and state. Finally, it records CPU-hotplug state in order to determine which CPUs should be ignored during a given grace period.
3. `rcu_data`: This per-CPU structure is the focus of quiescent-state detection and RCU callback queuing. It also tracks its relationship to the corresponding leaf `rcu_node` structure to allow more-efficient propagation of quiescent states up the `rcu_node` combining tree. Like the `rcu_node` structure, it provides a local copy of the grace-period information to allow for-free synchronized access to this information from the corresponding CPU. Finally, this structure records past dyntick-idle state for the corresponding CPU and also tracks statistics.
4. `rcu_head`: This structure represents RCU callbacks, and is the only structure allocated and managed by RCU users. The `rcu_head` structure is normally embedded within the RCU-protected data structure.

If all you wanted from this article was a general notion of how RCU's data structures are related, you are done. Otherwise, each of the following sections give more details on the `rcu_state`, `rcu_node` and `rcu_data` data structures.

The `rcu_state` Structure

The `rcu_state` structure is the base structure that represents the state of RCU in the system. This structure forms the interconnection between the `rcu_node` and `rcu_data` structures, tracks grace periods, contains the lock used to synchronize with CPU-hotplug events, and maintains state used to force quiescent states when grace periods extend too long,

A few of the `rcu_state` structure' s fields are discussed, singly and in groups, in the following sections. The more specialized fields are covered in the discussion of their use.

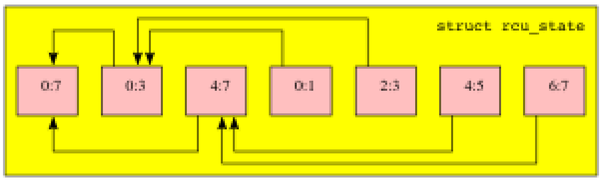
Relationship to rcu_node and rcu_data Structures

This portion of the `rcu_state` structure is declared as follows:

```
struct rcu_node node[NUM_RCU_NODES];
struct rcu_node *level[NUM_RCU_LVLS + 1];
struct rcu_data __percpu *rda;
```

Quick Quiz:
Wait a minute! You said that the `rcu_node` structures formed a tree, but they are declared as a flat array! What gives?
Answer:
The tree is laid out in the array. The first node In the array is the head, the next set of nodes in the array are children of the head node, and so on until the last set of nodes in the array are the leaves. See the following diagrams to see how this works.

The `rcu_node` tree is embedded into the `->node[]` array as shown in the following figure:

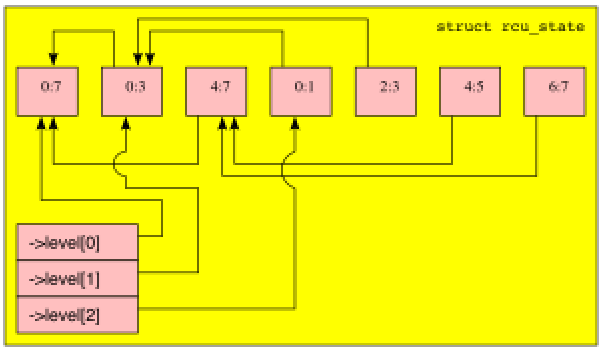


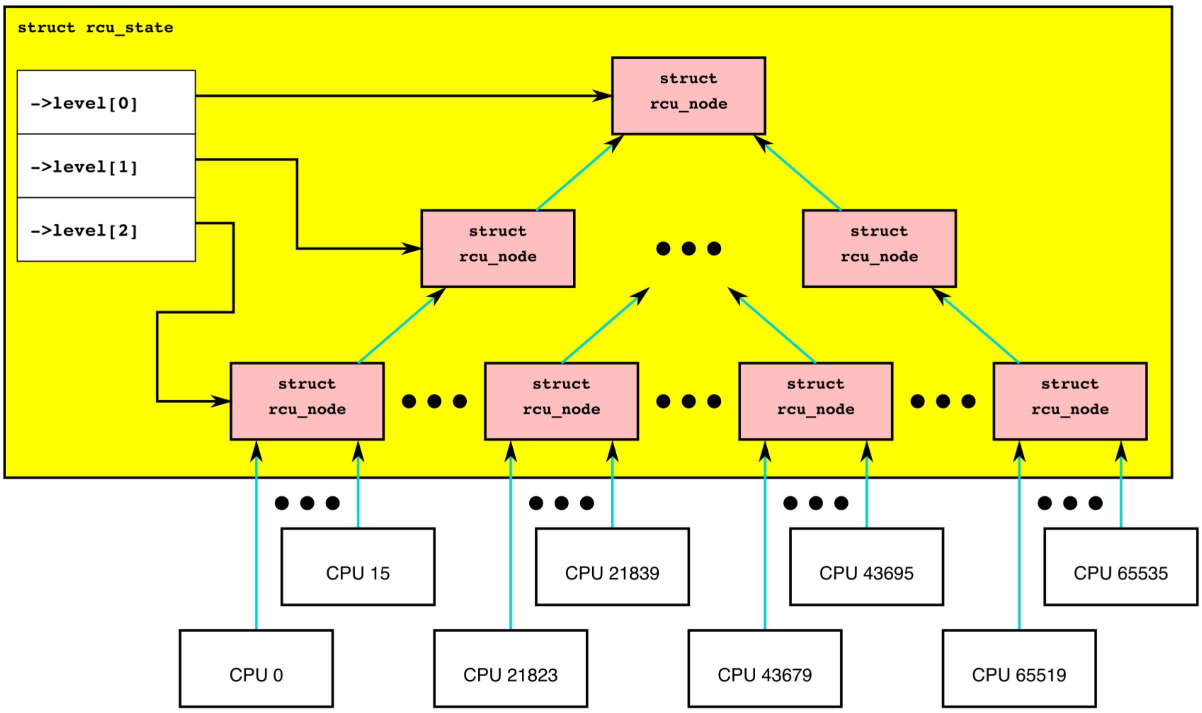
One interesting consequence of this mapping is that a breadth-first traversal of the tree is implemented as a simple linear scan of the array, which is in fact what the `rcu_for_each_node_breadth_first()` macro does. This macro is used at the beginning and ends of grace periods.

Each entry of the `->level` array references the first `rcu_node` structure on the corresponding level of the tree, for example, as shown below:

The zeroth element of the array references the root `rcu_node` structure, the first element references the first child of the root `rcu_node`, and finally the second element references the first leaf `rcu_node` structure.

For whatever it is worth, if you draw the tree to be tree-shaped rather than array-shaped, it is easy to draw a planar representation:


struct rcu_state
0:7
0:3
4:7
0:1
2:3
4:5
6:7
->level[0]
->level[1]
->level[2]


struct rcu_state
->level[0]
->level[1]
->level[2]
struct rcu_node
CPU 15
CPU 21839
CPU 43695
CPU 65535
CPU 0
CPU 21823
CPU 43679
CPU 65519

Finally, the ->rda field references a per-CPU pointer to the corresponding CPU's rcu_data structure.

All of these fields are constant once initialization is complete, and therefore need no protection.

Grace-Period Tracking

This portion of the rcu_state structure is declared as follows:

```
unsigned long gp_seq;
```

RCU grace periods are numbered, and the ->gp_seq field contains the current grace-period sequence number. The bottom two bits are the state of the current grace period, which can be zero for not yet started or one for in progress. In other words, if the bottom two bits of ->gp_seq are zero, then RCU is idle. Any other value in the bottom two bits indicates that something is broken. This field is protected by the root rcu_node structure's ->lock field.

There are ->gp_seq fields in the rcu_node and rcu_data structures as well. The fields in the rcu_state structure represent the most current value, and those of the other structures are compared in order to detect the beginnings and ends of grace periods in a distributed fashion. The values flow from rcu_state to rcu_node (down the tree from the root to the leaves) to rcu_data.

Miscellaneous

This portion of the rcu_state structure is declared as follows:

```
unsigned long gp_max;
char abbr;
char *name;
```

The ->gp_max field tracks the duration of the longest grace period in jiffies. It is protected by the root rcu_node's ->lock.

The ->name and ->abbr fields distinguish between preemptible RCU ("rcu_preempt" and "p") and non-preemptible RCU ("rcu_sched" and "s"). These fields are used for diagnostic and tracing purposes.

The rcu_node Structure

The rcu_node structures form the combining tree that propagates quiescent-state information from the leaves to the root and also that propagates grace-period information from the root down to the leaves. They provides local copies of the grace-period state in order to allow this information to be accessed in a synchronized manner without suffering the scalability limitations that would otherwise be imposed by global locking. In CONFIG_PREEMPT_RCU kernels, they manage the lists of tasks that have blocked while in their current RCU read-side critical section. In CONFIG_PREEMPT_RCU with CONFIG_RCU_BOOST, they manage the per-rcu_node priority-boosting kernel threads (kthreads) and state. Finally, they record CPU-hotplug state in order to determine which CPUs should be ignored during a given grace period.

The rcu_node structure's fields are discussed, singly and in groups, in the following sections.

Connection to Combining Tree

This portion of the rcu_node structure is declared as follows:

```
struct rcu_node *parent;
u8 level;
u8 grpnum;
unsigned long grpmask;
int grplo;
int grphi;
```

The ->parent pointer references the rcu_node one level up in the tree, and is NULL for the root rcu_node. The RCU implementation makes heavy use of this field to push quiescent states up the tree. The ->level field gives the level in the tree, with the root being at level zero, its children at level one, and so on. The ->grpnum field gives this node's position within the children of its parent, so this number can range between 0 and 31 on 32-bit systems and between 0 and 63 on 64-bit systems. The ->level and ->grpnum fields are used only during initialization and for tracing. The ->grpmask field is the bitmask counterpart of ->grpnum, and therefore always has exactly one bit set. This mask is used to clear the bit corresponding to this rcu_node structure in its parent's bitmasks, which are described later. Finally, the ->grplo and ->grphi fields contain the lowest and highest numbered CPU served by this rcu_node structure, respectively.

All of these fields are constant, and thus do not require any synchronization.

Synchronization

This field of the rcu_node structure is declared as follows:

```
raw_spinlock_t lock;
```

This field is used to protect the remaining fields in this structure, unless otherwise stated. That said, all of the fields in this structure can be accessed without locking for tracing purposes. Yes, this can result in confusing traces, but better some tracing confusion than to be heisenbugged out of existence.

Grace-Period Tracking

This portion of the rcu_node structure is declared as follows:

```
unsigned long gp_seq;
unsigned long gp_seq_needed;
```

The rcu_node structures' ->gp_seq fields are the counterparts of the field of the same name in the rcu_state structure. They each may lag up to one step behind their rcu_state counterpart. If the bottom two bits of a given rcu_node structure's ->gp_seq field is zero, then this rcu_node structure believes that RCU is idle.

The >gp_seq field of each rcu_node structure is updated at the beginning and the end of each grace period.

The ->gp_seq_needed fields record the furthest-in-the-future grace period request seen by the corresponding rcu_node structure. The request is considered fulfilled when the value of the ->gp_seq field equals or exceeds that of the ->gp_seq_needed field.

Quick Quiz:

Suppose that this rcu_node structure doesn't see a request for a very long time. Won't wrapping of the ->gp_seq field cause problems?

Answer:

No, because if the ->gp_seq_needed field lags behind the ->gp_seq field, the ->gp_seq_needed field will be updated at the end of the grace period. Modulo-arithmetic comparisons therefore will always get the correct answer, even with wrapping.

Quiescent-State Tracking

These fields manage the propagation of quiescent states up the combining tree.

This portion of the rcu_node structure has fields as follows:

```
unsigned long qsmask;
unsigned long expmask;
unsigned long qsmaskinit;
unsigned long expmaskinit;
```

The ->qsmask field tracks which of this rcu_node structure's children still need to report quiescent states for the current normal grace period. Such children will have a value of 1 in their corresponding bit. Note that the leaf rcu_node structures should be thought of as having rcu_data structures as their children. Similarly, the ->expmask field tracks which of this rcu_node structure's children still need to report quiescent states for the current expedited grace period. An expedited grace period has the same conceptual properties as a normal grace period, but the expedited implementation accepts extreme CPU overhead to obtain much lower grace-period latency, for example, consuming a few tens of microseconds worth of CPU time to reduce grace-period duration from milliseconds to tens of microseconds. The ->qsmaskinit field tracks which of this rcu_node structure's children cover for at least one online CPU. This mask is used to initialize `->qsmask`, and `->expmaskinit` is used to initialize `->expmask` and the beginning of the normal and expedited grace periods, respectively.

Quick Quiz:
Why are these bitmasks protected by locking? Come on, haven't you heard of atomic instructions???

Answer:
Lockless grace-period computation! Such a tantalizing possibility! But consider the following sequence of events:

1. CPU 0 has been in dyntick-idle mode for quite some time. When it wakes up, it notices that the current RCU grace period needs it to report in, so it sets a flag where the scheduling clock interrupt will find it.
2. Meanwhile, CPU 1 is running `force_quiescent_state()`, and notices that CPU 0 has been in dyntick idle mode, which qualifies as an extended quiescent state.
3. CPU 0's scheduling clock interrupt fires in the middle of an RCU read-side critical section, and notices that the RCU core needs something, so commences RCU softirq processing.
4. CPU 0's softirq handler executes and is just about ready to report its quiescent state up the `rcu_node` tree.
5. But CPU 1 beats it to the punch, completing the current grace period and starting a new one.
6. CPU 0 now reports its quiescent state for the wrong grace period. That grace period might now end before the RCU read-side critical section. If that happens, disaster will ensue.

So the locking is absolutely required in order to coordinate clearing of the bits with updating of the grace-period sequence number in `->gp_seq`.

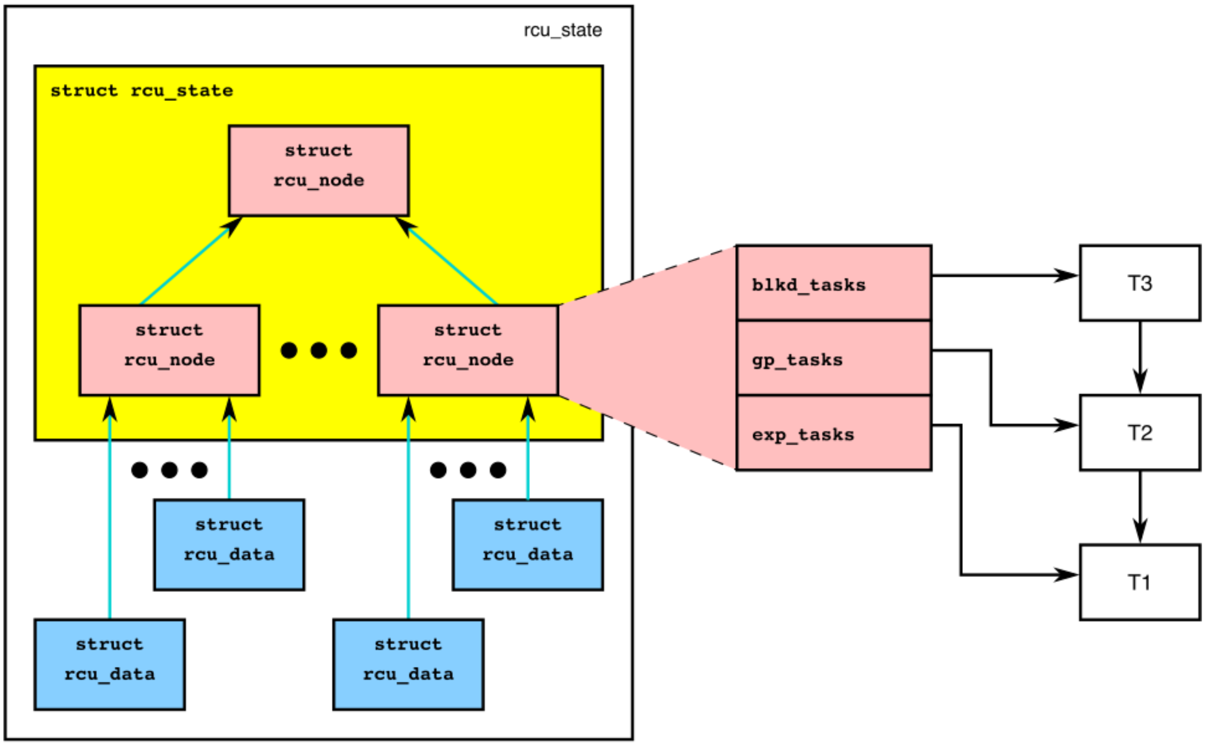
Blocked-Task Management

`PREEMPT_RCU` allows tasks to be preempted in the midst of their RCU read-side critical sections, and these tasks must be tracked explicitly. The details of exactly why and how they are tracked will be covered in a separate article on RCU read-side processing. For now, it is enough to know that the `rcu_node` structure tracks them.

```
struct list_head blkd_tasks;
struct list_head *gp_tasks;
struct list_head *exp_tasks;
bool wait_blkd_tasks;
```

The `->blkd_tasks` field is a list header for the list of blocked and preempted tasks. As tasks undergo context switches within RCU read-side critical sections, their `task_struct` structures are enqueued (via the `task_struct`'s `->rcu_node_entry` field) onto the head of the `->blkd_tasks` list for the leaf `rcu_node` structure corresponding to the CPU on which the outgoing context switch executed. As these tasks later exit their RCU read-side critical sections, they remove themselves from the list. This list is therefore in reverse time order, so that if one of the tasks is blocking the current grace period, all subsequent tasks must also be blocking that same grace period. Therefore, a single pointer into this list suffices to track all tasks blocking a given grace period. That pointer is stored in `->gp_tasks` for normal grace periods and in `->exp_tasks` for expedited grace periods. These last two fields are `NULL` if either there is no grace period in flight or if there are no blocked tasks preventing that grace period from completing. If either of these two pointers is referencing a task that removes itself from the `->blkd_tasks` list, then that task must advance the pointer to the next task on the list, or set the pointer to `NULL` if there are no subsequent tasks on the list.

For example, suppose that tasks T1, T2, and T3 are all hard-affinitied to the largest-numbered CPU in the system. Then if task T1 blocked in an RCU read-side critical section, then an expedited grace period started, then task T2 blocked in an RCU read-side critical section, then a normal grace period started, and finally task 3 blocked in an RCU read-side critical section, then the state of the last leaf `rcu_node` structure' s blocked-task list would be as shown below:



Task T1 is blocking both grace periods, task T2 is blocking only the normal grace period, and task T3 is blocking neither grace period. Note that these tasks will not remove themselves from this list immediately upon resuming execution. They will instead remain on the list until they execute the outermost `rcu_read_unlock()` that ends their RCU read-side critical section.

The `->wait_blkd_tasks` field indicates whether or not the current grace period is waiting on a blocked task.

Sizing the rcu_node Array

The rcu_node array is sized via a series of C-preprocessor expressions as follows:

```
#ifdef CONFIG_RCU_FANOUT
#define RCU_FANOUT CONFIG_RCU_FANOUT
#else
# ifdef CONFIG_64BIT
# define RCU_FANOUT 64
# else
# define RCU_FANOUT 32
# endif
#endif

#ifdef CONFIG_RCU_FANOUT_LEAF
#define RCU_FANOUT_LEAF CONFIG_RCU_FANOUT_LEAF
#else
# ifdef CONFIG_64BIT
# define RCU_FANOUT_LEAF 64
# else
# define RCU_FANOUT_LEAF 32
# endif
#endif

#define RCU_FANOUT_1        (RCU_FANOUT_LEAF)
#define RCU_FANOUT_2        (RCU_FANOUT_1 * RCU_FANOUT)
#define RCU_FANOUT_3        (RCU_FANOUT_2 * RCU_FANOUT)
#define RCU_FANOUT_4        (RCU_FANOUT_3 * RCU_FANOUT)

#if NR_CPUS <= RCU_FANOUT_1
#  define RCU_NUM_LVLS       1
#  define NUM_RCU_LVL_0       1
#  define NUM_RCU_NODES       NUM_RCU_LVL_0
#  define NUM_RCU_LVL_INIT    { NUM_RCU_LVL_0 }
#  define RCU_NODE_NAME_INIT  { "rcu_node_0" }
#  define RCU_FQS_NAME_INIT   { "rcu_node_fqs_0" }
#  define RCU_EXP_NAME_INIT   { "rcu_node_exp_0" }
#elif NR_CPUS <= RCU_FANOUT_2
#  define RCU_NUM_LVLS       2
#  define NUM_RCU_LVL_0       1
#  define NUM_RCU_LVL_1       DIV_ROUND_UP(NR_CPUS, RCU_FANOUT_1)
#  define NUM_RCU_NODES       (NUM_RCU_LVL_0 + NUM_RCU_LVL_1)
#  define NUM_RCU_LVL_INIT    { NUM_RCU_LVL_0, NUM_RCU_LVL_1 }
#  define RCU_NODE_NAME_INIT  { "rcu_node_0", "rcu_node_1" }
#  define RCU_FQS_NAME_INIT   { "rcu_node_fqs_0", "rcu_node_fqs_1" }
#  define RCU_EXP_NAME_INIT   { "rcu_node_exp_0", "rcu_node_exp_1" }
#elif NR_CPUS <= RCU_FANOUT_3
```

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```
44 #  define RCU_NUM_LVLS        3
45 #  define NUM_RCU_LVL_0        1
46 #  define NUM_RCU_LVL_1        DIV_ROUND_UP(NR_CPUS, RCU_FANOUT_2)
47 #  define NUM_RCU_LVL_2        DIV_ROUND_UP(NR_CPUS, RCU_FANOUT_1)
48 #  define NUM_RCU_NODES        (NUM_RCU_LVL_0 + NUM_RCU_LVL_1 + NUM_RCU_LVL_2)
49 #  define NUM_RCU_LVL_INIT    { NUM_RCU_LVL_0, NUM_RCU_LVL_1, NUM_RCU_LVL_2 }
50 #  define RCU_NODE_NAME_INIT  { "rcu_node_0", "rcu_node_1", "rcu_node_2" }
51 #  define RCU_FQS_NAME_INIT   { "rcu_node_fqs_0", "rcu_node_fqs_1", "rcu_node_fqs_2" }
52 #  define RCU_EXP_NAME_INIT   { "rcu_node_exp_0", "rcu_node_exp_1", "rcu_node_exp_2" }
53 #elif NR_CPUS <= RCU_FANOUT_4
54 #  define RCU_NUM_LVLS        4
55 #  define NUM_RCU_LVL_0        1
56 #  define NUM_RCU_LVL_1        DIV_ROUND_UP(NR_CPUS, RCU_FANOUT_3)
57 #  define NUM_RCU_LVL_2        DIV_ROUND_UP(NR_CPUS, RCU_FANOUT_2)
58 #  define NUM_RCU_LVL_3        DIV_ROUND_UP(NR_CPUS, RCU_FANOUT_1)
59 #  define NUM_RCU_NODES        (NUM_RCU_LVL_0 + NUM_RCU_LVL_1 + NUM_RCU_LVL_2 + NUM_RCU_LVL_3)
60 #  define NUM_RCU_LVL_INIT    { NUM_RCU_LVL_0, NUM_RCU_LVL_1, NUM_RCU_LVL_2, NUM_RCU_LVL_3 }
61 #  define RCU_NODE_NAME_INIT  { "rcu_node_0", "rcu_node_1", "rcu_node_2", "rcu_node_3" }
62 #  define RCU_FQS_NAME_INIT   { "rcu_node_fqs_0", "rcu_node_fqs_1", "rcu_node_fqs_2", "rcu_node_fqs_3" }
63 #  define RCU_EXP_NAME_INIT   { "rcu_node_exp_0", "rcu_node_exp_1", "rcu_node_exp_2", "rcu_node_exp_3" }
64 #else
65 # error "CONFIG_RCU_FANOUT insufficient for NR_CPUS"
66 #endif
```

The maximum number of levels in the `rcu_node` structure is currently limited to four, as specified by lines 21-24 and the structure of the subsequent "if" statement. For 32-bit systems, this allows 16*32*32*32=524,288 CPUs, which should be sufficient for the next few years at least. For 64-bit systems, 16*64*64*64=4,194,304 CPUs is allowed, which should see us through the next decade or so. This four-level tree also allows kernels built with `CONFIG_RCU_FANOUT=8` to support up to 4096 CPUs, which might be useful in very large systems having eight CPUs per socket (but please note that no one has yet shown any measurable performance degradation due to misaligned socket and `rcu_node` boundaries). In addition, building kernels with a full four levels of `rcu_node` tree permits better testing of RCU's combining-tree code.

The RCU_FANOUT symbol controls how many children are permitted at each non-leaf level of the rcu_node tree. If the CONFIG_RCU_FANOUT Kconfig option is not specified, it is set based on the word size of the system, which is also the Kconfig default.

The RCU_FANOUT_LEAF symbol controls how many CPUs are handled by each leaf rcu_node structure. Experience has shown that allowing a given leaf rcu_node structure to handle 64 CPUs, as permitted by the number of bits in the ->qsmask field on a 64-bit system, results in excessive contention for the leaf rcu_node structures' ->lock fields. The number of CPUs per leaf rcu_node structure is therefore limited to 16 given the default value of CONFIG_RCU_FANOUT_LEAF. If CONFIG_RCU_FANOUT_LEAF is unspecified, the value selected is based on the word size of the system, just as for CONFIG_RCU_FANOUT. Lines 11-19 perform this computation.

Lines 21-24 compute the maximum number of CPUs supported by a single-level (which contains a single rcu_node structure), two-level, three-level, and four-level rcu_node tree, respectively, given the fanout specified by RCU_FANOUT and RCU_FANOUT_LEAF. These numbers of CPUs are retained in the RCU_FANOUT_1, RCU_FANOUT_2, RCU_FANOUT_3, and RCU_FANOUT_4 C-preprocessor variables, respectively.

These variables are used to control the C-preprocessor #if statement spanning lines 26-66 that computes the number of rcu_node structures required for each level of the tree, as well as the number of levels required. The number of levels is placed in the NUM_RCU_LVLS C-preprocessor variable by lines 27, 35, 44, and 54. The number of rcu_node structures for the topmost level of the tree is always exactly one, and this value is unconditionally placed into NUM_RCU_LVL_0 by lines 28, 36, 45, and 55. The rest of the levels (if any) of the rcu_node tree are computed by dividing the maximum number of CPUs by the fanout supported by the number of levels from the current level down, rounding up. This computation is performed by lines 37, 46-47, and 56-58. Lines 31-33, 40-42, 50-52, and 62-63 create initializers for lockdep lock-class names. Finally, lines 64-66 produce an error if the maximum number of CPUs is too large for the specified fanout.

The rcu_segcblist Structure

The rcu_segcblist structure maintains a segmented list of callbacks as follows:

```
#define RCU_DONE_TAIL        0
#define RCU_WAIT_TAIL        1
#define RCU_NEXT_READY_TAIL  2
#define RCU_NEXT_TAIL        3
#define RCU_CBLIST_NSEGS     4

struct rcu_segcblist {
  struct rcu_head *head;
  struct rcu_head **tails[RCU_CBLIST_NSEGS];
  unsigned long gp_seq[RCU_CBLIST_NSEGS];
  long len;
  long len_lazy;
};
```

The segments are as follows:

1. `RCU_DONE_TAIL`: Callbacks whose grace periods have elapsed. These callbacks are ready to be invoked.
2. `RCU_WAIT_TAIL`: Callbacks that are waiting for the current grace period. Note that different CPUs can have different ideas about which grace period is current, hence the `->gp_seq` field.
3. `RCU_NEXT_READY_TAIL`: Callbacks waiting for the next grace period to start.
4. `RCU_NEXT_TAIL`: Callbacks that have not yet been associated with a grace period.

The `->head` pointer references the first callback or is `NULL` if the list contains no callbacks (which is *not* the same as being empty). Each element of the `->tails[]` array references the `->next` pointer of the last callback in the corresponding segment of the list, or the list' s `->head` pointer if that segment and all previous segments are empty. If the corresponding segment is empty but some previous segment is not empty, then the array element is identical to its predecessor. Older callbacks are closer to the head of the list, and new callbacks are added at the tail. This relationship between the `->head` pointer, the `->tails[]` array, and the callbacks is shown in this diagram:

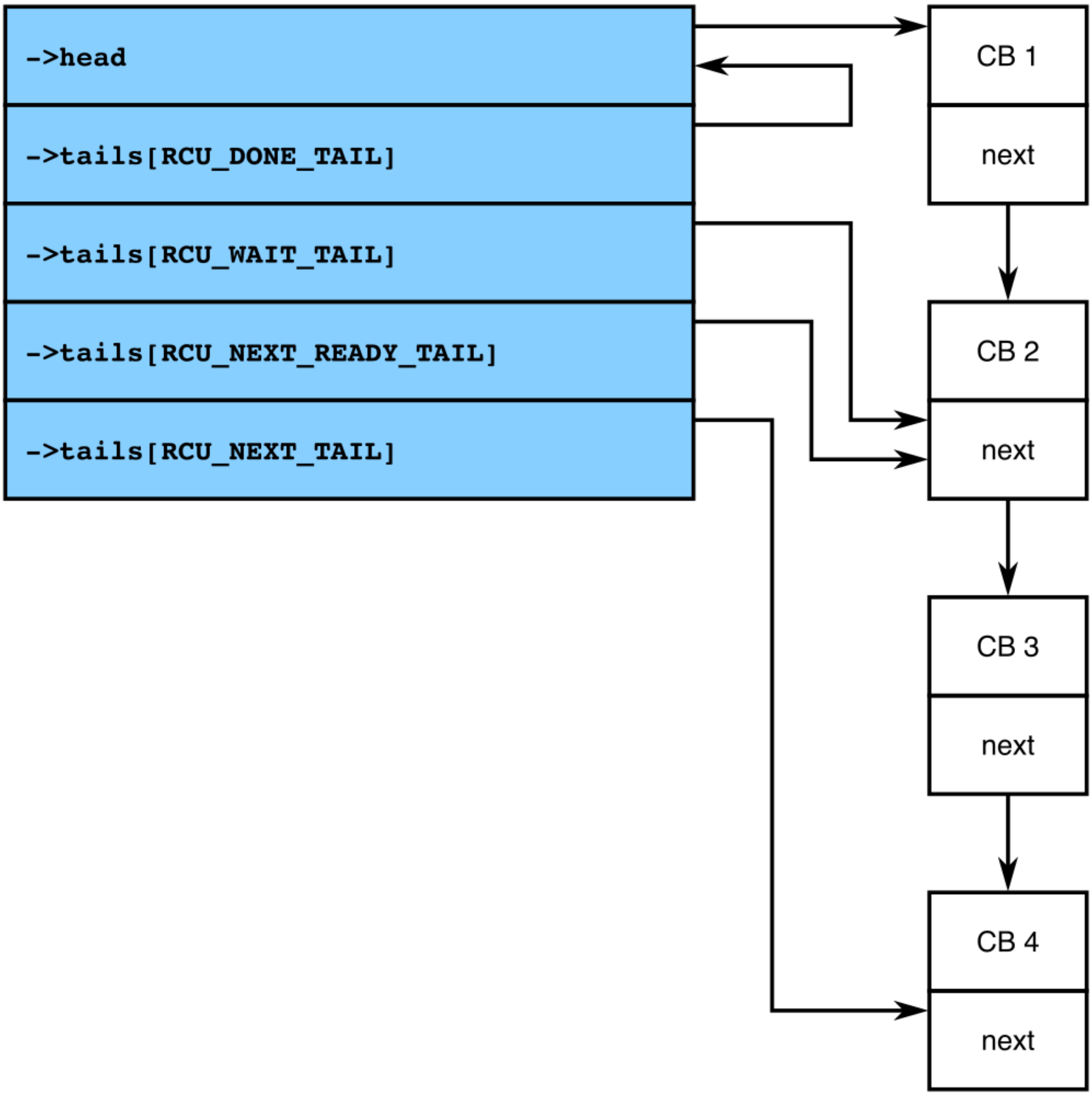
In this figure, the `->head` pointer references the first RCU callback in the list. The `->tails[RCU_DONE_TAIL]` array element references the `->head` pointer itself, indicating that none of the callbacks is ready to invoke. The `->tails[RCU_WAIT_TAIL]` array element references callback CB 2' s `->next` pointer, which indicates that CB 1 and CB 2 are both waiting on the current grace period, give or take possible disagreements about exactly which grace period is the current one. The `->tails[RCU_NEXT_READY_TAIL]` array element references the same RCU callback that `->tails[RCU_WAIT_TAIL]` does, which indicates that there are no callbacks waiting on the next RCU grace period. The `->tails[RCU_NEXT_TAIL]` array element references CB 4' s `->next` pointer, indicating that all the remaining RCU callbacks have not yet been assigned to an RCU grace period. Note that the `->tails[RCU_NEXT_TAIL]` array element always references the last RCU callback' s `->next` pointer unless the callback list is empty, in which case it references the `->head` pointer.

There is one additional important special case for the `->tails[RCU_NEXT_TAIL]` array element: It can be `NULL` when this list is *disabled*. Lists are disabled when the corresponding CPU is offline or when the corresponding CPU' s callbacks are offloaded to a kthread, both of which are described elsewhere.

CPUs advance their callbacks from the `RCU_NEXT_TAIL` to the `RCU_NEXT_READY_TAIL` to the `RCU_WAIT_TAIL` to the `RCU_DONE_TAIL` list segments as grace periods advance.

The `->gp_seq[]` array records grace-period numbers corresponding to the list segments. This is what allows different CPUs to have different ideas as to which is the current grace period while still avoiding premature invocation of their callbacks. In particular, this allows CPUs that go idle for extended periods to determine which of their callbacks are ready to be invoked after reawakening.

The `->len` counter contains the number of callbacks in `->head`, and the `->len_lazy` contains the number of those callbacks that are known to only free


->head
->tails[RCU_DONE_TAIL]
->tails[RCU_WAIT_TAIL]
->tails[RCU_NEXT_READY_TAIL]
->tails[RCU_NEXT_TAIL]
CB 1
next
CB 2
next
CB 3
next
CB 4
next

memory, and whose invocation can therefore be safely deferred.

Important: It is the `->len` field that determines whether or not there are callbacks associated with this `rcu_segcblist` structure, *not* the `->head` pointer. The reason for this is that all the ready-to-invoke callbacks (that is, those in the `RCU_DONE_TAIL` segment) are extracted all at once at callback-invocation time (`rcu_do_batch`), due to which `->head` may be set to NULL if there are no not-done callbacks remaining in the `rcu_segcblist`. If callback invocation must be postponed, for example, because a high-priority process just woke up on this CPU, then the remaining callbacks are placed back on the `RCU_DONE_TAIL` segment and `->head` once again points to the start of the segment. In short, the head field can briefly be `NULL` even though the CPU has callbacks present the entire time. Therefore, it is not appropriate to test the `->head` pointer for `NULL`.

In contrast, the `->len` and `->len_lazy` counts are adjusted only after the corresponding callbacks have been invoked. This means that the `->len` count is zero only if the `rcu_segcblist` structure really is devoid of callbacks. Of course, off-CPU sampling of the `->len` count requires careful use of appropriate synchronization, for example, memory barriers. This synchronization can be a bit subtle, particularly in the case of `rcu_barrier()`.

The `rcu_data` Structure

The `rcu_data` maintains the per-CPU state for the RCU subsystem. The fields in this structure may be accessed only from the corresponding CPU (and from tracing) unless otherwise stated. This structure is the focus of quiescent-state detection and RCU callback queuing. It also tracks its relationship to the corresponding leaf `rcu_node` structure to allow more-efficient propagation of quiescent states up the `rcu_node` combining tree. Like the `rcu_node` structure, it provides a local copy of the grace-period information to allow for-free synchronized access to this information from the corresponding CPU. Finally, this structure records past dyntick-idle state for the corresponding CPU and also tracks statistics.

The `rcu_data` structure' s fields are discussed, singly and in groups, in the following sections.

Connection to Other Data Structures

This portion of the `rcu_data` structure is declared as follows:

```
int cpu;
struct rcu_node *mynode;
unsigned long grpmask;
bool beenonline;
```

The `->cpu` field contains the number of the corresponding CPU and the `->mynode` field references the corresponding `rcu_node` structure. The `->mynode` is used to propagate quiescent states up the combining tree. These two fields are constant and therefore do not require synchronization.

The ->grpmask field indicates the bit in the ->mynode->qsmask corresponding to this rcu_data structure, and is also used when propagating quiescent states. The ->beenonline flag is set whenever the corresponding CPU comes online, which means that the debugfs tracing need not dump out any rcu_data structure for which this flag is not set.

Quiescent-State and Grace-Period Tracking

This portion of the rcu_data structure is declared as follows:

```
unsigned long gp_seq;
unsigned long gp_seq_needed;
bool cpu_no_qs;
bool core_needs_qs;
bool gpwrap;
```

The ->gp_seq field is the counterpart of the field of the same name in the rcu_state and rcu_node structures. The ->gp_seq_needed field is the counterpart of the field of the same name in the rcu_node structure. They may each lag up to one behind their rcu_node counterparts, but in CONFIG_NO_HZ_IDLE and CONFIG_NO_HZ_FULL kernels can lag arbitrarily far behind for CPUs in dyntick-idle mode (but these counters will catch up upon exit from dyntick-idle mode). If the lower two bits of a given rcu_data structure's ->gp_seq are zero, then this rcu_data structure believes that RCU is idle.

Quick Quiz:

All this replication of the grace period numbers can only cause massive confusion. Why not just keep a global sequence number and be done with it???

Answer:

Because if there was only a single global sequence numbers, there would need to be a single global lock to allow safely accessing and updating it. And if we are not going to have a single global lock, we need to carefully manage the numbers on a per-node basis. Recall from the answer to a previous Quick Quiz that the consequences of applying a previously sampled quiescent state to the wrong grace period are quite severe.

The ->cpu_no_qs flag indicates that the CPU has not yet passed through a quiescent state, while the ->core_needs_qs flag indicates that the RCU core needs a quiescent state from the corresponding CPU. The ->gpwrap field indicates that the corresponding CPU has remained idle for so long that the gp_seq counter is in danger of overflow, which will cause the CPU to disregard the values of its counters on its next exit from idle.

RCU Callback Handling

In the absence of CPU-hotplug events, RCU callbacks are invoked by the same CPU that registered them. This is strictly a cache-locality optimization: callbacks can and do get invoked on CPUs other than the one that registered them. After all, if the CPU that registered a given callback has gone offline before the callback can be invoked, there really is no other choice.

This portion of the `rcu_data` structure is declared as follows:

```
struct rcu_segcblist cblist;
long qlen_last_fqs_check;
unsigned long n_cbs_invoked;
unsigned long n_nocbs_invoked;
unsigned long n_cbs_orphaned;
unsigned long n_cbs_adopted;
unsigned long n_force_qs_snap;
long blimit;
```

The `->cblist` structure is the segmented callback list described earlier. The CPU advances the callbacks in its `rcu_data` structure whenever it notices that another RCU grace period has completed. The CPU detects the completion of an RCU grace period by noticing that the value of its `rcu_data` structure’ s `->gp_seq` field differs from that of its leaf `rcu_node` structure. Recall that each `rcu_node` structure’ s `->gp_seq` field is updated at the beginnings and ends of each grace period.

The `->qlen_last_fqs_check` and `->n_force_qs_snap` coordinate the forcing of quiescent states from `call_rcu()` and friends when callback lists grow excessively long.

The `->n_cbs_invoked`, `->n_cbs_orphaned`, and `->n_cbs_adopted` fields count the number of callbacks invoked, sent to other CPUs when this CPU goes offline, and received from other CPUs when those other CPUs go offline. The `->n_nocbs_invoked` is used when the CPU’ s callbacks are offloaded to a kthread.

Finally, the `->blimit` counter is the maximum number of RCU callbacks that may be invoked at a given time.

Dyntick-Idle Handling

This portion of the `rcu_data` structure is declared as follows:

```
  int dynticks_snap;
  unsigned long dynticks_fqs;
```

The `->dynticks_snap` field is used to take a snapshot of the corresponding CPU’ s dyntick-idle state when forcing quiescent states, and is therefore accessed from other CPUs. Finally, the `->dynticks_fqs` field is used to count the number of times this CPU is determined to be in dyntick-idle state, and is used for tracing and debugging purposes.

This portion of the rcu_data structure is declared as follows:

```
long dynticks_nesting;
long dynticks_nmi_nesting;
atomic_t dynticks;
bool rcu_need_heavy_qs;
bool rcu_urgent_qs;
```

These fields in the rcu_data structure maintain the per-CPU dyntick-idle state for the corresponding CPU. The fields may be accessed only from the corresponding CPU (and from tracing) unless otherwise stated.

The `->dynticks_nesting` field counts the nesting depth of process execution, so that in normal circumstances this counter has value zero or one. NMIs, irqs, and tracers are counted by the `->dynticks_nmi_nesting` field. Because NMIs cannot be masked, changes to this variable have to be undertaken carefully using an algorithm provided by Andy Lutomirski. The initial transition from idle adds one, and nested transitions add two, so that a nesting level of five is represented by a `->dynticks_nmi_nesting` value of nine. This counter can therefore be thought of as counting the number of reasons why this CPU cannot be permitted to enter dyntick-idle mode, aside from process-level transitions.

However, it turns out that when running in non-idle kernel context, the Linux kernel is fully capable of entering interrupt handlers that never exit and perhaps also vice versa. Therefore, whenever the `->dynticks_nesting` field is incremented up from zero, the `->dynticks_nmi_nesting` field is set to a large positive number, and whenever the `->dynticks_nesting` field is decremented down to zero, the `->dynticks_nmi_nesting` field is set to zero. Assuming that the number of misnested interrupts is not sufficient to overflow the counter, this approach corrects the `->dynticks_nmi_nesting` field every time the corresponding CPU enters the idle loop from process context.

The `->dynticks` field counts the corresponding CPU’s transitions to and from either dyntick-idle or user mode, so that this counter has an even value when the CPU is in dyntick-idle mode or user mode and an odd value otherwise. The transitions to/from user mode need to be counted for user mode adaptive-ticks support (see timers/NO_HZ.txt).

The `->rcu_need_heavy_qs` field is used to record the fact that the RCU core code would really like to see a quiescent state from the corresponding CPU, so much so that it is willing to call for heavy-weight dyntick-counter operations. This flag is checked by RCU’s context-switch and `cond_resched()` code, which provide a momentary idle sojourn in response.

Finally, the `->rcu_urgent_qs` field is used to record the fact that the RCU core code would really like to see a quiescent state from the corresponding CPU, with the various other fields indicating just how badly RCU wants this quiescent state. This flag is checked by RCU’s context-switch path (`rcu_note_context_switch`) and the cond_resched code.

Quick Quiz:
Why not simply combine the `->dynticks_nesting` and `->dynticks_nmi_nesting` counters into a single counter that just counts the number of reasons that the corresponding CPU is non-idle?
Answer:
Because this would fail in the presence of interrupts whose handlers never return and of handlers that manage to return from a made-up interrupt.

Additional fields are present for some special-purpose builds, and are discussed separately.

The `rcu_head` Structure

Each `rcu_head` structure represents an RCU callback. These structures are normally embedded within RCU-protected data structures whose algorithms use asynchronous grace periods. In contrast, when using algorithms that block waiting for RCU grace periods, RCU users need not provide `rcu_head` structures.

The `rcu_head` structure has fields as follows:

```
1   struct rcu_head *next;
2   void (*func)(struct rcu_head *head);
```

The `->next` field is used to link the `rcu_head` structures together in the lists within the `rcu_data` structures. The `->func` field is a pointer to the function to be called when the callback is ready to be invoked, and this function is passed a pointer to the `rcu_head` structure. However, `kfree_rcu()` uses the `->func` field to record the offset of the `rcu_head` structure within the enclosing RCU-protected data structure.

Both of these fields are used internally by RCU. From the viewpoint of RCU users, this structure is an opaque "cookie".

Quick Quiz:
Given that the callback function `->func` is passed a pointer to the `rcu_head` structure, how is that function supposed to find the beginning of the enclosing RCU-protected data structure?
Answer:
In actual practice, there is a separate callback function per type of RCU-protected data structure. The callback function can therefore use the `container_of()` macro in the Linux kernel (or other pointer-manipulation facilities in other software environments) to find the beginning of the enclosing structure.

RCU-Specific Fields in the task_struct Structure

The CONFIG_PREEMPT_RCU implementation uses some additional fields in the task_struct structure:

```
#ifdef CONFIG_PREEMPT_RCU
  int rcu_read_lock_nesting;
  union rcu_special rcu_read_unlock_special;
  struct list_head rcu_node_entry;
  struct rcu_node *rcu_blocked_node;
#endif /* #ifdef CONFIG_PREEMPT_RCU */
#ifdef CONFIG_TASKS_RCU
  unsigned long rcu_tasks_nvcsw;
  bool rcu_tasks_holdout;
  struct list_head rcu_tasks_holdout_list;
  int rcu_tasks_idle_cpu;
#endif /* #ifdef CONFIG_TASKS_RCU */
```

The ->rcu_read_lock_nesting field records the nesting level for RCU read-side critical sections, and the ->rcu_read_unlock_special field is a bitmask that records special conditions that require rcu_read_unlock() to do additional work. The ->rcu_node_entry field is used to form lists of tasks that have blocked within preemptible-RCU read-side critical sections and the ->rcu_blocked_node field references the rcu_node structure whose list this task is a member of, or NULL if it is not blocked within a preemptible-RCU read-side critical section.

The ->rcu_tasks_nvcsw field tracks the number of voluntary context switches that this task had undergone at the beginning of the current tasks-RCU grace period, ->rcu_tasks_holdout is set if the current tasks-RCU grace period is waiting on this task, ->rcu_tasks_holdout_list is a list element enqueuing this task on the holdout list, and ->rcu_tasks_idle_cpu tracks which CPU this idle task is running, but only if the task is currently running, that is, if the CPU is currently idle.

Accessor Functions

The following listing shows the rcu_get_root(), rcu_for_each_node_breadth_first and rcu_for_each_leaf_node() function and macros:

```
static struct rcu_node *rcu_get_root(struct rcu_state *rsp)
{
  return &rsp->node[0];
}

#define rcu_for_each_node_breadth_first(rsp, rnp) \
  for ((rnp) = &(rsp)->node[0]; \
       (rnp) < &(rsp)->node[NUM_RCU_NODES]; (rnp)++)

#define rcu_for_each_leaf_node(rsp, rnp) \
  for ((rnp) = (rsp)->level[NUM_RCU_LVLS - 1]; \
       (rnp) < &(rsp)->node[NUM_RCU_NODES]; (rnp)++)
```

The `rcu_get_root()` simply returns a pointer to the first element of the specified `rcu_state` structure' s `->node[]` array, which is the root `rcu_node` structure.

As noted earlier, the `rcu_for_each_node_breadth_first()` macro takes advantage of the layout of the `rcu_node` structures in the `rcu_state` structure' s `->node[]` array, performing a breadth-first traversal by simply traversing the array in order. Similarly, the `rcu_for_each_leaf_node()` macro traverses only the last part of the array, thus traversing only the leaf `rcu_node` structures.

Quick Quiz:
What does `rcu_for_each_leaf_node()` do if the `rcu_node` tree contains only a single node?
Answer:
In the single-node case, `rcu_for_each_leaf_node()` traverses the single node.

Summary

So the state of RCU is represented by an `rcu_state` structure, which contains a combining tree of `rcu_node` and `rcu_data` structures. Finally, in `CONFIG_NO_HZ_IDLE` kernels, each CPU' s dyntick-idle state is tracked by dynticks-related fields in the `rcu_data` structure. If you made it this far, you are well prepared to read the code walkthroughs in the other articles in this series.

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CHAPTER

FOUR

LOW-LEVEL HARDWARE MANAGEMENT

Cache management, managing CPU hotplug, etc.

4.1 Cache and TLB Flushing Under Linux

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This document describes the cache/tlb flushing interfaces called by the Linux VM subsystem. It enumerates over each interface, describes its intended purpose, and what side effect is expected after the interface is invoked.

The side effects described below are stated for a uniprocessor implementation, and what is to happen on that single processor. The SMP cases are a simple extension, in that you just extend the definition such that the side effect for a particular interface occurs on all processors in the system. Don't let this scare you into thinking SMP cache/tlb flushing must be so inefficient, this is in fact an area where many optimizations are possible. For example, if it can be proven that a user address space has never executed on a cpu (see mm_cpumask()), one need not perform a flush for this address space on that cpu.

First, the TLB flushing interfaces, since they are the simplest. The "TLB" is abstracted under Linux as something the cpu uses to cache virtual–>physical address translations obtained from the software page tables. Meaning that if the software page tables change, it is possible for stale translations to exist in this "TLB" cache. Therefore when software page table changes occur, the kernel will invoke one of the following flush methods _after_ the page table changes occur:

1) `void flush_tlb_all(void)`

   The most severe flush of all. After this interface runs, any previous page table modification whatsoever will be visible to the cpu.

   This is usually invoked when the kernel page tables are changed, since such translations are "global" in nature.

2) `void flush_tlb_mm(struct mm_struct *mm)`

   This interface flushes an entire user address space from the TLB. After running, this interface must make sure that any previous page table modifications for the address space 'mm' will be visible to the cpu. That is, after running, there will be no entries in the TLB for 'mm'.

This interface is used to handle whole address space page table operations such as what happens during fork, and exec.

3) `void flush_tlb_range(struct vm_area_struct *vma, unsigned long start, unsigned long end)`

   Here we are flushing a specific range of (user) virtual address translations from the TLB. After running, this interface must make sure that any previous page table modifications for the address space 'vma->vm_mm' in the range 'start' to 'end-1' will be visible to the cpu. That is, after running, there will be no entries in the TLB for 'mm' for virtual addresses in the range 'start' to 'end-1'.

   The "vma" is the backing store being used for the region. Primarily, this is used for munmap() type operations.

   The interface is provided in hopes that the port can find a suitably efficient method for removing multiple page sized translations from the TLB, instead of having the kernel call flush_tlb_page (see below) for each entry which may be modified.

4) `void flush_tlb_page(struct vm_area_struct *vma, unsigned long addr)`

   This time we need to remove the PAGE_SIZE sized translation from the TLB. The 'vma' is the backing structure used by Linux to keep track of mmap'd regions for a process, the address space is available via vma->vm_mm. Also, one may test (vma->vm_flags & VM_EXEC) to see if this region is executable (and thus could be in the 'instruction TLB' in split-tlb type setups).

   After running, this interface must make sure that any previous page table modification for address space 'vma->vm_mm' for user virtual address 'addr' will be visible to the cpu. That is, after running, there will be no entries in the TLB for 'vma->vm_mm' for virtual address 'addr'.

   This is used primarily during fault processing.

5) `void update_mmu_cache(struct vm_area_struct *vma, unsigned long address, pte_t *ptep)`

   At the end of every page fault, this routine is invoked to tell the architecture specific code that a translation now exists at virtual address "address" for address space "vma->vm_mm", in the software page tables.

   A port may use this information in any way it so chooses. For example, it could use this event to pre-load TLB translations for software managed TLB configurations. The sparc64 port currently does this.

Next, we have the cache flushing interfaces. In general, when Linux is changing an existing virtual–>physical mapping to a new value, the sequence will be in one of the following forms:

```
1) flush_cache_mm(mm);
   change_all_page_tables_of(mm);
```

(continues on next page)

(continued from previous page)

```
   flush_tlb_mm(mm);

2) flush_cache_range(vma, start, end);
   change_range_of_page_tables(mm, start, end);
   flush_tlb_range(vma, start, end);

3) flush_cache_page(vma, addr, pfn);
   set_pte(pte_pointer, new_pte_val);
   flush_tlb_page(vma, addr);
```

The cache level flush will always be first, because this allows us to properly handle systems whose caches are strict and require a virtual–>physical translation to exist for a virtual address when that virtual address is flushed from the cache. The HyperSparc cpu is one such cpu with this attribute.

The cache flushing routines below need only deal with cache flushing to the extent that it is necessary for a particular cpu. Mostly, these routines must be implemented for cpus which have virtually indexed caches which must be flushed when virtual–>physical translations are changed or removed. So, for example, the physically indexed physically tagged caches of IA32 processors have no need to implement these interfaces since the caches are fully synchronized and have no dependency on translation information.

Here are the routines, one by one:

1) `void flush_cache_mm(struct mm_struct *mm)`

   This interface flushes an entire user address space from the caches. That is, after running, there will be no cache lines associated with 'mm'.

   This interface is used to handle whole address space page table operations such as what happens during exit and exec.

2) `void flush_cache_dup_mm(struct mm_struct *mm)`

   This interface flushes an entire user address space from the caches. That is, after running, there will be no cache lines associated with 'mm'.

   This interface is used to handle whole address space page table operations such as what happens during fork.

   This option is separate from flush_cache_mm to allow some optimizations for VIPT caches.

3) `void flush_cache_range(struct vm_area_struct *vma, unsigned long start, unsigned long end)`

   Here we are flushing a specific range of (user) virtual addresses from the cache. After running, there will be no entries in the cache for 'vma->vm_mm' for virtual addresses in the range 'start' to 'end-1'.

   The "vma" is the backing store being used for the region. Primarily, this is used for munmap() type operations.

The interface is provided in hopes that the port can find a suitably efficient method for removing multiple page sized regions from the cache, instead of having the kernel call flush_cache_page (see below) for each entry which may be modified.

4) `void flush_cache_page(struct vm_area_struct *vma, unsigned long addr, unsigned long pfn)`

   This time we need to remove a PAGE_SIZE sized range from the cache. The 'vma' is the backing structure used by Linux to keep track of mmap'd regions for a process, the address space is available via vma->vm_mm. Also, one may test (vma->vm_flags & VM_EXEC) to see if this region is executable (and thus could be in the 'instruction cache' in "Harvard" type cache layouts).

   The 'pfn' indicates the physical page frame (shift this value left by PAGE_SHIFT to get the physical address) that 'addr' translates to. It is this mapping which should be removed from the cache.

   After running, there will be no entries in the cache for 'vma->vm_mm' for virtual address 'addr' which translates to 'pfn'.

   This is used primarily during fault processing.

5) `void flush_cache_kmaps(void)`

   This routine need only be implemented if the platform utilizes highmem. It will be called right before all of the kmaps are invalidated.

   After running, there will be no entries in the cache for the kernel virtual address range PKMAP_ADDR(0) to PKMAP_ADDR(LAST_PKMAP).

   This routing should be implemented in asm/highmem.h

6) `void flush_cache_vmap(unsigned long start, unsigned long end)` `void flush_cache_vunmap(unsigned long start, unsigned long end)`

   Here in these two interfaces we are flushing a specific range of (kernel) virtual addresses from the cache. After running, there will be no entries in the cache for the kernel address space for virtual addresses in the range 'start' to 'end-1'.

   The first of these two routines is invoked after map_kernel_range() has installed the page table entries. The second is invoked before unmap_kernel_range() deletes the page table entries.

There exists another whole class of cpu cache issues which currently require a whole different set of interfaces to handle properly. The biggest problem is that of virtual aliasing in the data cache of a processor.

Is your port susceptible to virtual aliasing in its D-cache? Well, if your D-cache is virtually indexed, is larger in size than PAGE_SIZE, and does not prevent multiple cache lines for the same physical address from existing at once, you have this problem.

If your D-cache has this problem, first define asm/shmparam.h SHMLBA properly, it should essentially be the size of your virtually addressed D-cache (or if the size is variable, the largest possible size). This setting will force the SYSv IPC layer to only allow user processes to mmap shared memory at address which are a multiple of this value.

Note: This does not fix shared mmaps, check out the sparc64 port for one way to solve this (in particular SPARC_FLAG_MMAPSHARED).

Next, you have to solve the D-cache aliasing issue for all other cases. Please keep in mind that fact that, for a given page mapped into some user address space, there is always at least one more mapping, that of the kernel in its linear mapping starting at PAGE_OFFSET. So immediately, once the first user maps a given physical page into its address space, by implication the D-cache aliasing problem has the potential to exist since the kernel already maps this page at its virtual address.

`void copy_user_page(void *to, void *from, unsigned long addr, struct page *page) void clear_user_page(void *to, unsigned long addr, struct page *page)`

These two routines store data in user anonymous or COW pages. It allows a port to efficiently avoid D-cache alias issues between userspace and the kernel.

For example, a port may temporarily map 'from' and 'to' to kernel virtual addresses during the copy. The virtual address for these two pages is chosen in such a way that the kernel load/store instructions happen to virtual addresses which are of the same "color" as the user mapping of the page. Sparc64 for example, uses this technique.

The 'addr' parameter tells the virtual address where the user will ultimately have this page mapped, and the 'page' parameter gives a pointer to the struct page of the target.

If D-cache aliasing is not an issue, these two routines may simply call memcpy/memset directly and do nothing more.

`void flush_dcache_page(struct page *page)`

Any time the kernel writes to a page cache page, _OR_ the kernel is about to read from a page cache page and user space shared/writable mappings of this page potentially exist, this routine is called.

Note: This routine need only be called for page cache pages which can potentially ever be mapped into the address space of a user process. So for example, VFS layer code handling vfs symlinks in the page cache need not call this interface at all.

The phrase "kernel writes to a page cache page" means, specifically, that the kernel executes store instructions that dirty data in that page at the page->virtual mapping of that page. It is important to flush here to handle D-cache aliasing, to make sure these kernel stores are visible to user space mappings of that page.

The corollary case is just as important, if there are users which have shared+writable mappings of this file, we must make sure that kernel reads of these pages will see the most recent stores done by the user.

If D-cache aliasing is not an issue, this routine may simply be defined as a nop on that architecture.

There is a bit set aside in page->flags (PG_arch_1) as "architecture private". The kernel guarantees that, for pagecache pages, it will clear this bit when such a page first enters the pagecache.

This allows these interfaces to be implemented much more efficiently. It allows one to "defer" (perhaps indefinitely) the actual flush if there are currently no user processes mapping this page. See sparc64's flush_dcache_page and update_mmu_cache implementations for an example of how to go about doing this.

The idea is, first at flush_dcache_page() time, if page->mapping->i_mmap is an empty tree, just mark the architecture private page flag bit. Later, in update_mmu_cache(), a check is made of this flag bit, and if set the flush is done and the flag bit is cleared.

Important: It is often important, if you defer the flush, that the actual flush occurs on the same CPU as did the cpu stores into the page to make it dirty. Again, see sparc64 for examples of how to deal with this.

`void copy_to_user_page(struct vm_area_struct *vma, struct page *page, unsigned long user_vaddr, void *dst, void *src, int len)` `void copy_from_user_page(struct vm_area_struct *vma, struct page *page, unsigned long user_vaddr, void *dst, void *src, int len)`

When the kernel needs to copy arbitrary data in and out of arbitrary user pages (f.e. for ptrace()) it will use these two routines.

Any necessary cache flushing or other coherency operations that need to occur should happen here. If the processor's instruction cache does not snoop cpu stores, it is very likely that you will need to flush the instruction cache for copy_to_user_page().

`void flush_anon_page(struct vm_area_struct *vma, struct page *page, unsigned long vmaddr)`

When the kernel needs to access the contents of an anonymous page, it calls this function (currently only get_user_pages()). Note: flush_dcache_page() deliberately doesn't work for an anonymous page. The default implementation is a nop (and should remain so for all coherent architectures). For incoherent architectures, it should flush the cache of the page at vmaddr.

`void flush_kernel_dcache_page(struct page *page)`

When the kernel needs to modify a user page is has obtained with kmap, it calls this function after all modifications are complete (but before kunmapping it) to bring the underlying page up to date. It is assumed here that the user has no incoherent cached copies (i.e. the original page was obtained from a mechanism like get_user_pages()). The default implementation is a nop and should remain so on all coherent architectures. On incoherent architectures, this should flush the kernel cache for page (using page_address(page)).

`void flush_icache_range(unsigned long start, unsigned long end)`

When the kernel stores into addresses that it will execute out of (eg when loading modules), this function is called.

If the icache does not snoop stores then this routine will need to flush it.

`void flush_icache_page(struct vm_area_struct *vma, struct page *page)`

All the functionality of flush_icache_page can be implemented in flush_dcache_page and update_mmu_cache. In the future, the hope is to remove this interface completely.

The final category of APIs is for I/O to deliberately aliased address ranges inside the kernel. Such aliases are set up by use of the vmap/vmalloc API. Since kernel I/O goes via physical pages, the I/O subsystem assumes that the user mapping and kernel offset mapping are the only aliases. This isn't true for vmap aliases, so anything in the kernel trying to do I/O to vmap areas must manually manage coherency. It must do this by flushing the vmap range before doing I/O and invalidating it after the I/O returns.

`void flush_kernel_vmap_range(void *vaddr, int size)`

flushes the kernel cache for a given virtual address range in the vmap area. This is to make sure that any data the kernel modified in the vmap range is made visible to the physical page. The design is to make this area safe to perform I/O on. Note that this API does *not* also flush the offset map alias of the area.

`void invalidate_kernel_vmap_range(void *vaddr, int size) invalidates`

the cache for a given virtual address range in the vmap area which prevents the processor from making the cache stale by speculatively reading data while the I/O was occurring to the physical pages. This is only necessary for data reads into the vmap area.

4.2 CPU hotplug in the Kernel

Date
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4.2.1 Introduction

Modern advances in system architectures have introduced advanced error reporting and correction capabilities in processors. There are couple OEMS that support NUMA hardware which are hot pluggable as well, where physical node insertion and removal require support for CPU hotplug.

Such advances require CPUs available to a kernel to be removed either for provisioning reasons, or for RAS purposes to keep an offending CPU off system execution path. Hence the need for CPU hotplug support in the Linux kernel.

A more novel use of CPU-hotplug support is its use today in suspend resume support for SMP. Dual-core and HT support makes even a laptop run SMP kernels which didn' t support these methods.

4.2.2 Command Line Switches

`maxcpus=n`
Restrict boot time CPUs to *n*. Say if you have four CPUs, using `maxcpus=2` will only boot two. You can choose to bring the other CPUs later online.

`nr_cpus=n`
Restrict the total amount of CPUs the kernel will support. If the number supplied here is lower than the number of physically available CPUs, then those CPUs can not be brought online later.

`additional_cpus=n`
Use this to limit hotpluggable CPUs. This option sets `cpu_possible_mask = cpu_present_mask + additional_cpus`

This option is limited to the IA64 architecture.

`possible_cpus=n`
This option sets `possible_cpus` bits in `cpu_possible_mask`.

This option is limited to the X86 and S390 architecture.

`cpu0_hotplug`
Allow to shutdown CPU0.

This option is limited to the X86 architecture.

4.2.3 CPU maps

cpu_possible_mask
Bitmap of possible CPUs that can ever be available in the system. This is used to allocate some boot time memory for per_cpu variables that aren't designed to grow/shrink as CPUs are made available or removed. Once set during boot time discovery phase, the map is static, i.e no bits are added or removed anytime. Trimming it accurately for your system needs upfront can save some boot time memory.

cpu_online_mask
Bitmap of all CPUs currently online. Its set in `__cpu_up()` after a CPU is available for kernel scheduling and ready to receive interrupts from devices. Its cleared when a CPU is brought down using `__cpu_disable()`, before which all OS services including interrupts are migrated to another target CPU.

cpu_present_mask
Bitmap of CPUs currently present in the system. Not all of them may be online. When physical hotplug is processed by the relevant subsystem (e.g ACPI) can change and new bit either be added or removed from the map depending on the event is hot-add/hot-remove. There are currently no locking rules as of now. Typical usage is to init topology during boot, at which time hotplug is disabled.

You really don't need to manipulate any of the system CPU maps. They should be read-only for most use. When setting up per-cpu resources almost always use `cpu_possible_mask` or `for_each_possible_cpu()` to iterate. To macro `for_each_cpu()` can be used to iterate over a custom CPU mask.

Never use anything other than `cpumask_t` to represent bitmap of CPUs.

4.2.4 Using CPU hotplug

The kernel option *CONFIG_HOTPLUG_CPU* needs to be enabled. It is currently available on multiple architectures including ARM, MIPS, PowerPC and X86. The configuration is done via the sysfs interface:

```
$ ls -lh /sys/devices/system/cpu
total 0
drwxr-xr-x  9 root root    0 Dec 21 16:33 cpu0
drwxr-xr-x  9 root root    0 Dec 21 16:33 cpu1
drwxr-xr-x  9 root root    0 Dec 21 16:33 cpu2
drwxr-xr-x  9 root root    0 Dec 21 16:33 cpu3
drwxr-xr-x  9 root root    0 Dec 21 16:33 cpu4
drwxr-xr-x  9 root root    0 Dec 21 16:33 cpu5
drwxr-xr-x  9 root root    0 Dec 21 16:33 cpu6
drwxr-xr-x  9 root root    0 Dec 21 16:33 cpu7
drwxr-xr-x  2 root root    0 Dec 21 16:33 hotplug
-r--r--r--  1 root root 4.0K Dec 21 16:33 offline
-r--r--r--  1 root root 4.0K Dec 21 16:33 online
-r--r--r--  1 root root 4.0K Dec 21 16:33 possible
-r--r--r--  1 root root 4.0K Dec 21 16:33 present
```

The files *offline*, *online*, *possible*, *present* represent the CPU masks. Each CPU folder contains an *online* file which controls the logical on (1) and off (0) state. To logically shutdown CPU4:

```
$ echo 0 > /sys/devices/system/cpu/cpu4/online
 smpboot: CPU 4 is now offline
```

Once the CPU is shutdown, it will be removed from */proc/interrupts*, */proc/cpuinfo* and should also not be shown visible by the *top* command. To bring CPU4 back online:

```
$ echo 1 > /sys/devices/system/cpu/cpu4/online
smpboot: Booting Node 0 Processor 4 APIC 0x1
```

The CPU is usable again. This should work on all CPUs. CPU0 is often special and excluded from CPU hotplug. On X86 the kernel option *CONFIG_BOOTPARAM_HOTPLUG_CPU0* has to be enabled in order to be able to shutdown CPU0. Alternatively the kernel command option *cpu0_hotplug* can be used. Some known dependencies of CPU0:

- Resume from hibernate/suspend. Hibernate/suspend will fail if CPU0 is offline.
- PIC interrupts. CPU0 can't be removed if a PIC interrupt is detected.

Please let Fenghua Yu <fenghua.yu@intel.com> know if you find any dependencies on CPU0.

4.2.5 The CPU hotplug coordination

The offline case

Once a CPU has been logically shutdown the teardown callbacks of registered hotplug states will be invoked, starting with `CPUHP_ONLINE` and terminating at state `CPUHP_OFFLINE`. This includes:

- If tasks are frozen due to a suspend operation then *cpuhp_tasks_frozen* will be set to true.
- All processes are migrated away from this outgoing CPU to new CPUs. The new CPU is chosen from each process' current cpuset, which may be a subset of all online CPUs.
- All interrupts targeted to this CPU are migrated to a new CPU
- timers are also migrated to a new CPU
- Once all services are migrated, kernel calls an arch specific routine `__cpu_disable()` to perform arch specific cleanup.

Using the hotplug API

It is possible to receive notifications once a CPU is offline or onlined. This might be important to certain drivers which need to perform some kind of setup or clean up functions based on the number of available CPUs:

```
#include <linux/cpuhotplug.h>

ret = cpuhp_setup_state(CPUHP_AP_ONLINE_DYN, "X/Y:online",
                        Y_online, Y_prepare_down);
```

X is the subsystem and *Y* the particular driver. The *Y_online* callback will be invoked during registration on all online CPUs. If an error occurs during the online callback the *Y_prepare_down* callback will be invoked on all CPUs on which the online callback was previously invoked. After registration completed, the *Y_online* callback will be invoked once a CPU is brought online and *Y_prepare_down* will be invoked when a CPU is shutdown. All resources which were previously allocated in *Y_online* should be released in *Y_prepare_down*. The return value *ret* is negative if an error occurred during the registration process. Otherwise a positive value is returned which contains the allocated hotplug for dynamically allocated states (*CPUHP_AP_ONLINE_DYN*). It will return zero for predefined states.

The callback can be remove by invoking `cpuhp_remove_state()`. In case of a dynamically allocated state (*CPUHP_AP_ONLINE_DYN*) use the returned state. During the removal of a hotplug state the teardown callback will be invoked.

Multiple instances

If a driver has multiple instances and each instance needs to perform the callback independently then it is likely that a " multi-state' ' should be used. First a multi-state state needs to be registered:

```
ret = cpuhp_setup_state_multi(CPUHP_AP_ONLINE_DYN, "X/Y:online,
                              Y_online, Y_prepare_down);
Y_hp_online = ret;
```

The `cpuhp_setup_state_multi()` behaves similar to `cpuhp_setup_state()` except it prepares the callbacks for a multi state and does not invoke the callbacks. This is a one time setup. Once a new instance is allocated, you need to register this new instance:

```
ret = cpuhp_state_add_instance(Y_hp_online, &d->node);
```

This function will add this instance to your previously allocated *Y_hp_online* state and invoke the previously registered callback (*Y_online*) on all online CPUs. The *node* element is a `struct hlist_node` member of your per-instance data structure.

On removal of the instance: ::
cpuhp_state_remove_instance(Y_hp_online, &d->node)

should be invoked which will invoke the teardown callback on all online CPUs.

Manual setup

Usually it is handy to invoke setup and teardown callbacks on registration or removal of a state because usually the operation needs to performed once a CPU goes online (offline) and during initial setup (shutdown) of the driver. However each registration and removal function is also available with a `_nocalls` suffix which does not invoke the provided callbacks if the invocation of the callbacks is not desired. During the manual setup (or teardown) the functions `get_online_cpus()` and `put_online_cpus()` should be used to inhibit CPU hotplug operations.

The ordering of the events

The hotplug states are defined in `include/linux/cpuhotplug.h`:

- The states *CPUHP_OFFLINE* …*CPUHP_AP_OFFLINE* are invoked before the CPU is up.
- The states *CPUHP_AP_OFFLINE* …*CPUHP_AP_ONLINE* are invoked just the after the CPU has been brought up. The interrupts are off and the scheduler is not yet active on this CPU. Starting with *CPUHP_AP_OFFLINE* the callbacks are invoked on the target CPU.
- The states between *CPUHP_AP_ONLINE_DYN* and *CPUHP_AP_ONLINE_DYN_END* are reserved for the dynamic allocation.
- The states are invoked in the reverse order on CPU shutdown starting with *CPUHP_ONLINE* and stopping at *CPUHP_OFFLINE*. Here the callbacks are invoked on the CPU that will be shutdown until *CPUHP_AP_OFFLINE*.

A dynamically allocated state via *CPUHP_AP_ONLINE_DYN* is often enough. However if an earlier invocation during the bring up or shutdown is required then an explicit state should be acquired. An explicit state might also be required if the hotplug event requires specific ordering in respect to another hotplug event.

4.2.6 Testing of hotplug states

One way to verify whether a custom state is working as expected or not is to shutdown a CPU and then put it online again. It is also possible to put the CPU to certain state (for instance *CPUHP_AP_ONLINE*) and then go back to *CPUHP_ONLINE*. This would simulate an error one state after *CPUHP_AP_ONLINE* which would lead to rollback to the online state.

All registered states are enumerated in `/sys/devices/system/cpu/hotplug/states`:

```
$ tail /sys/devices/system/cpu/hotplug/states
138: mm/vmscan:online
139: mm/vmstat:online
140: lib/percpu_cnt:online
141: acpi/cpu-drv:online
142: base/cacheinfo:online
143: virtio/net:online
```

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```
144: x86/mce:online
145: printk:online
168: sched:active
169: online
```

To rollback CPU4 to `lib/percpu_cnt:online` and back online just issue:

```
$ cat /sys/devices/system/cpu/cpu4/hotplug/state
169
$ echo 140 > /sys/devices/system/cpu/cpu4/hotplug/target
$ cat /sys/devices/system/cpu/cpu4/hotplug/state
140
```

It is important to note that the teardown callbac of state 140 have been invoked. And now get back online:

```
$ echo 169 > /sys/devices/system/cpu/cpu4/hotplug/target
$ cat /sys/devices/system/cpu/cpu4/hotplug/state
169
```

With trace events enabled, the individual steps are visible, too:

```
#  TASK-PID   CPU#    TIMESTAMP  FUNCTION
#     | |       |         |          |
    bash-394  [001]  22.976: cpuhp_enter: cpu: 0004 target: 140␣
↪step: 169 (cpuhp_kick_ap_work)
 cpuhp/4-31   [004]  22.977: cpuhp_enter: cpu: 0004 target: 140␣
↪step: 168 (sched_cpu_deactivate)
 cpuhp/4-31   [004]  22.990: cpuhp_exit:  cpu: 0004  state: 168␣
↪step: 168 ret: 0
 cpuhp/4-31   [004]  22.991: cpuhp_enter: cpu: 0004 target: 140␣
↪step: 144 (mce_cpu_pre_down)
 cpuhp/4-31   [004]  22.992: cpuhp_exit:  cpu: 0004  state: 144␣
↪step: 144 ret: 0
 cpuhp/4-31   [004]  22.993: cpuhp_multi_enter: cpu: 0004 target:␣
↪140 step: 143 (virtnet_cpu_down_prep)
 cpuhp/4-31   [004]  22.994: cpuhp_exit:  cpu: 0004  state: 143␣
↪step: 143 ret: 0
 cpuhp/4-31   [004]  22.995: cpuhp_enter: cpu: 0004 target: 140␣
↪step: 142 (cacheinfo_cpu_pre_down)
 cpuhp/4-31   [004]  22.996: cpuhp_exit:  cpu: 0004  state: 142␣
↪step: 142 ret: 0
    bash-394  [001]  22.997: cpuhp_exit:  cpu: 0004  state: 140␣
↪step: 169 ret: 0
    bash-394  [005]  95.540: cpuhp_enter: cpu: 0004 target: 169␣
↪step: 140 (cpuhp_kick_ap_work)
 cpuhp/4-31   [004]  95.541: cpuhp_enter: cpu: 0004 target: 169␣
↪step: 141 (acpi_soft_cpu_online)
 cpuhp/4-31   [004]  95.542: cpuhp_exit:  cpu: 0004  state: 141␣
↪step: 141 ret: 0
```

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```
cpuhp/4-31   [004]  95.543: cpuhp_enter: cpu: 0004 target: 169␣
↪step: 142 (cacheinfo_cpu_online)
cpuhp/4-31   [004]  95.544: cpuhp_exit:  cpu: 0004  state: 142␣
↪step: 142 ret: 0
cpuhp/4-31   [004]  95.545: cpuhp_multi_enter: cpu: 0004 target:␣
↪169 step: 143 (virtnet_cpu_online)
cpuhp/4-31   [004]  95.546: cpuhp_exit:  cpu: 0004  state: 143␣
↪step: 143 ret: 0
cpuhp/4-31   [004]  95.547: cpuhp_enter: cpu: 0004 target: 169␣
↪step: 144 (mce_cpu_online)
cpuhp/4-31   [004]  95.548: cpuhp_exit:  cpu: 0004  state: 144␣
↪step: 144 ret: 0
cpuhp/4-31   [004]  95.549: cpuhp_enter: cpu: 0004 target: 169␣
↪step: 145 (console_cpu_notify)
cpuhp/4-31   [004]  95.550: cpuhp_exit:  cpu: 0004  state: 145␣
↪step: 145 ret: 0
cpuhp/4-31   [004]  95.551: cpuhp_enter: cpu: 0004 target: 169␣
↪step: 168 (sched_cpu_activate)
cpuhp/4-31   [004]  95.552: cpuhp_exit:  cpu: 0004  state: 168␣
↪step: 168 ret: 0
   bash-394  [005]  95.553: cpuhp_exit:  cpu: 0004  state: 169␣
↪step: 140 ret: 0
```

As it an be seen, CPU4 went down until timestamp 22.996 and then back up until 95.552. All invoked callbacks including their return codes are visible in the trace.

4.2.7 Architecture's requirements

The following functions and configurations are required:

CONFIG_HOTPLUG_CPU
: This entry needs to be enabled in Kconfig

__cpu_up()
: Arch interface to bring up a CPU

__cpu_disable()
: Arch interface to shutdown a CPU, no more interrupts can be handled by the kernel after the routine returns. This includes the shutdown of the timer.

__cpu_die()
: This actually supposed to ensure death of the CPU. Actually look at some example code in other arch that implement CPU hotplug. The processor is taken down from the `idle()` loop for that specific architecture. `__cpu_die()` typically waits for some per_cpu state to be set, to ensure the processor dead routine is called to be sure positively.

4.2.8 User Space Notification

After CPU successfully onlined or offline udev events are sent. A udev rule like:

```
SUBSYSTEM=="cpu", DRIVERS=="processor", DEVPATH=="/devices/system/
↪cpu/*", RUN+="the_hotplug_receiver.sh"
```

will receive all events. A script like:

```
#!/bin/sh

if [ "${ACTION}" = "offline" ]
then
    echo "CPU ${DEVPATH##*/} offline"

elif [ "${ACTION}" = "online" ]
then
    echo "CPU ${DEVPATH##*/} online"

fi
```

can process the event further.

4.2.9 Kernel Inline Documentations Reference

int **cpuhp_setup_state**(enum cpuhp_state state, const char *name, int (*startup)(unsigned int cpu), int (*teardown)(unsigned int cpu))

Setup hotplug state callbacks with calling the callbacks

Parameters

enum cpuhp_state state
The state for which the calls are installed

const char *name
Name of the callback (will be used in debug output)

int (*startup)(unsigned int cpu)
startup callback function

int (*teardown)(unsigned int cpu)
teardown callback function

Description

Installs the callback functions and invokes the startup callback on the present cpus which have already reached the **state**.

int **cpuhp_setup_state_nocalls**(enum cpuhp_state state, const char *name, int (*startup)(unsigned int cpu), int (*teardown)(unsigned int cpu))

Setup hotplug state callbacks without calling the callbacks

Parameters

enum cpuhp_state state
The state for which the calls are installed

const char *name
Name of the callback.

int (*startup)(unsigned int cpu)
startup callback function

int (*teardown)(unsigned int cpu)
teardown callback function

Description

Same as **cpuhp_setup_state** except that no calls are executed are invoked during installation of this callback. NOP if SMP=n or HOTPLUG_CPU=n.

int **cpuhp_setup_state_multi**(enum cpuhp_state state, const char *name, int (*startup)(unsigned int cpu, struct hlist_node *node), int (*teardown)(unsigned int cpu, struct hlist_node *node))

Add callbacks for multi state

Parameters

enum cpuhp_state state
The state for which the calls are installed

const char *name
Name of the callback.

int (*startup)(unsigned int cpu, struct hlist_node *node)
startup callback function

int (*teardown)(unsigned int cpu, struct hlist_node *node)
teardown callback function

Description

Sets the internal multi_instance flag and prepares a state to work as a multi instance callback. No callbacks are invoked at this point. The callbacks are invoked once an instance for this state are registered via **cpuhp_state_add_instance** or **cpuhp_state_add_instance_nocalls**.

int **cpuhp_state_add_instance**(enum cpuhp_state state, struct hlist_node *node)

Add an instance for a state and invoke startup callback.

Parameters

enum cpuhp_state state
The state for which the instance is installed

struct hlist_node *node
The node for this individual state.

Description

Installs the instance for the **state** and invokes the startup callback on the present cpus which have already reached the **state**. The **state** must have been earlier marked as multi-instance by **cpuhp_setup_state_multi**.

int **cpuhp_state_add_instance_nocalls**(enum cpuhp_state state, struct hlist_node *node)

Add an instance for a state without invoking the startup callback.

Parameters

enum cpuhp_state state
The state for which the instance is installed

struct hlist_node *node
The node for this individual state.

Description

Installs the instance for the **state** The **state** must have been earlier marked as multi-instance by **cpuhp_setup_state_multi**.

void **cpuhp_remove_state**(enum cpuhp_state state)

Remove hotplug state callbacks and invoke the teardown

Parameters

enum cpuhp_state state
The state for which the calls are removed

Description

Removes the callback functions and invokes the teardown callback on the present cpus which have already reached the **state**.

void **cpuhp_remove_state_nocalls**(enum cpuhp_state state)

Remove hotplug state callbacks without invoking teardown

Parameters

enum cpuhp_state state
The state for which the calls are removed

void **cpuhp_remove_multi_state**(enum cpuhp_state state)

Remove hotplug multi state callback

Parameters

enum cpuhp_state state
The state for which the calls are removed

Description

Removes the callback functions from a multi state. This is the reverse of *cpuhp_setup_state_multi()*. All instances should have been removed before invoking this function.

int **cpuhp_state_remove_instance**(enum cpuhp_state state, struct hlist_node *node)

Remove hotplug instance from state and invoke the teardown callback

Parameters

enum cpuhp_state state
The state from which the instance is removed

struct hlist_node *node
The node for this individual state.

Description

Removes the instance and invokes the teardown callback on the present cpus which have already reached the **state**.

int **cpuhp_state_remove_instance_nocalls**(enum cpuhp_state state, struct hlist_node *node)

Remove hotplug instance from state without invoking the reatdown callback

Parameters

enum cpuhp_state state
The state from which the instance is removed

struct hlist_node *node
The node for this individual state.

Description

Removes the instance without invoking the teardown callback.

4.3 Memory hotplug

4.3.1 Memory hotplug event notifier

Hotplugging events are sent to a notification queue.

There are six types of notification defined in `include/linux/memory.h`:

MEM_GOING_ONLINE
Generated before new memory becomes available in order to be able to prepare subsystems to handle memory. The page allocator is still unable to allocate from the new memory.

MEM_CANCEL_ONLINE
Generated if MEM_GOING_ONLINE fails.

MEM_ONLINE
Generated when memory has successfully brought online. The callback may allocate pages from the new memory.

MEM_GOING_OFFLINE
Generated to begin the process of offlining memory. Allocations are no longer possible from the memory but some of the memory to be offlined is still in use. The callback can be used to free memory known to a subsystem from the indicated memory block.

MEM_CANCEL_OFFLINE
Generated if MEM_GOING_OFFLINE fails. Memory is available again from the memory block that we attempted to offline.

MEM_OFFLINE
Generated after offlining memory is complete.

A callback routine can be registered by calling:

```
hotplug_memory_notifier(callback_func, priority)
```

Callback functions with higher values of priority are called before callback functions with lower values.

A callback function must have the following prototype:

```
int callback_func(
  struct notifier_block *self, unsigned long action, void *arg);
```

The first argument of the callback function (self) is a pointer to the block of the notifier chain that points to the callback function itself. The second argument (action) is one of the event types described above. The third argument (arg) passes a pointer of struct memory_notify:

```
struct memory_notify {
        unsigned long start_pfn;
        unsigned long nr_pages;
        int status_change_nid_normal;
        int status_change_nid_high;
        int status_change_nid;
}
```

- start_pfn is start_pfn of online/offline memory.
- nr_pages is # of pages of online/offline memory.
- status_change_nid_normal is set node id when N_NORMAL_MEMORY of nodemask is (will be) set/clear, if this is -1, then nodemask status is not changed.
- status_change_nid_high is set node id when N_HIGH_MEMORY of nodemask is (will be) set/clear, if this is -1, then nodemask status is not changed.
- status_change_nid is set node id when N_MEMORY of nodemask is (will be) set/clear. It means a new(memoryless) node gets new memory by online and a node loses all memory. If this is -1, then nodemask status is not changed.

  If status_changed_nid* >= 0, callback should create/discard structures for the node if necessary.

The callback routine shall return one of the values NOTIFY_DONE, NOTIFY_OK, NOTIFY_BAD, NOTIFY_STOP defined in `include/linux/notifier.h`

NOTIFY_DONE and NOTIFY_OK have no effect on the further processing.

NOTIFY_BAD is used as response to the MEM_GOING_ONLINE, MEM_GOING_OFFLINE, MEM_ONLINE, or MEM_OFFLINE action to cancel hotplugging. It stops further processing of the notification queue.

NOTIFY_STOP stops further processing of the notification queue.

4.3.2 Locking Internals

When adding/removing memory that uses memory block devices (i.e. ordinary RAM), the device_hotplug_lock should be held to:

- synchronize against online/offline requests (e.g. via sysfs). This way, memory block devices can only be accessed (.online/.state attributes) by user space once memory has been fully added. And when removing memory, we know nobody is in critical sections.
- synchronize against CPU hotplug and similar (e.g. relevant for ACPI and PPC)

Especially, there is a possible lock inversion that is avoided using device_hotplug_lock when adding memory and user space tries to online that memory faster than expected:

- device_online() will first take the device_lock(), followed by mem_hotplug_lock
- add_memory_resource() will first take the mem_hotplug_lock, followed by the device_lock() (while creating the devices, during bus_add_device()).

As the device is visible to user space before taking the device_lock(), this can result in a lock inversion.

onlining/offlining of memory should be done via device_online()/ device_offline() - to make sure it is properly synchronized to actions via sysfs. Holding device_hotplug_lock is advised (to e.g. protect online_type)

When adding/removing/onlining/offlining memory or adding/removing heterogeneous/device memory, we should always hold the mem_hotplug_lock in write mode to serialise memory hotplug (e.g. access to global/zone variables).

In addition, mem_hotplug_lock (in contrast to device_hotplug_lock) in read mode allows for a quite efficient get_online_mems/put_online_mems implementation, so code accessing memory can protect from that memory vanishing.

4.4 Linux generic IRQ handling

4.4.1 Introduction

The generic interrupt handling layer is designed to provide a complete abstraction of interrupt handling for device drivers. It is able to handle all the different types of interrupt controller hardware. Device drivers use generic API functions to request, enable, disable and free interrupts. The drivers do not have to know anything about interrupt hardware details, so they can be used on different platforms without code changes.

This documentation is provided to developers who want to implement an interrupt subsystem based for their architecture, with the help of the generic IRQ handling layer.

4.4.2 Rationale

The original implementation of interrupt handling in Linux uses the __do_IRQ() super-handler, which is able to deal with every type of interrupt logic.

Originally, Russell King identified different types of handlers to build a quite universal set for the ARM interrupt handler implementation in Linux 2.5/2.6. He distinguished between:

- Level type
- Edge type
- Simple type

During the implementation we identified another type:

- Fast EOI type

In the SMP world of the __do_IRQ() super-handler another type was identified:

- Per CPU type

This split implementation of high-level IRQ handlers allows us to optimize the flow of the interrupt handling for each specific interrupt type. This reduces complexity in that particular code path and allows the optimized handling of a given type.

The original general IRQ implementation used hw_interrupt_type structures and their `->ack`, `->end` [etc.] callbacks to differentiate the flow control in the super-handler. This leads to a mix of flow logic and low-level hardware logic, and it also leads to unnecessary code duplication: for example in i386, there is an `ioapic_level_irq` and an `ioapic_edge_irq` IRQ-type which share many of the low-level details but have different flow handling.

A more natural abstraction is the clean separation of the 'irq flow' and the 'chip details'.

Analysing a couple of architecture's IRQ subsystem implementations reveals that most of them can use a generic set of 'irq flow' methods and only need to add the chip-level specific code. The separation is also valuable for (sub)architectures which need specific quirks in the IRQ flow itself but not in the chip details - and thus provides a more transparent IRQ subsystem design.

Each interrupt descriptor is assigned its own high-level flow handler, which is normally one of the generic implementations. (This high-level flow handler implementation also makes it simple to provide demultiplexing handlers which can be found in embedded platforms on various architectures.)

The separation makes the generic interrupt handling layer more flexible and extensible. For example, an (sub)architecture can use a generic IRQ-flow implementation for 'level type' interrupts and add a (sub)architecture specific 'edge type' implementation.

To make the transition to the new model easier and prevent the breakage of existing implementations, the __do_IRQ() super-handler is still available. This leads to a kind of duality for the time being. Over time the new model should be used in more and more architectures, as it enables smaller and cleaner IRQ subsystems. It's deprecated for three years now and about to be removed.

4.4.3 Known Bugs And Assumptions

None (knock on wood).

4.4.4 Abstraction layers

There are three main levels of abstraction in the interrupt code:

1. High-level driver API
2. High-level IRQ flow handlers
3. Chip-level hardware encapsulation

Interrupt control flow

Each interrupt is described by an interrupt descriptor structure irq_desc. The interrupt is referenced by an 'unsigned int' numeric value which selects the corresponding interrupt description structure in the descriptor structures array. The descriptor structure contains status information and pointers to the interrupt flow method and the interrupt chip structure which are assigned to this interrupt.

Whenever an interrupt triggers, the low-level architecture code calls into the generic interrupt code by calling desc->handle_irq(). This high-level IRQ handling function only uses desc->irq_data.chip primitives referenced by the assigned chip descriptor structure.

High-level Driver API

The high-level Driver API consists of following functions:

- *request_irq()*
- *request_threaded_irq()*
- *free_irq()*
- *disable_irq()*
- *enable_irq()*
- *disable_irq_nosync()* (SMP only)
- *synchronize_irq()* (SMP only)
- *irq_set_irq_type()*
- *irq_set_irq_wake()*
- *irq_set_handler_data()*
- *irq_set_chip()*
- *irq_set_chip_data()*

See the autogenerated function documentation for details.

High-level IRQ flow handlers

The generic layer provides a set of pre-defined irq-flow methods:

- *handle_level_irq()*
- *handle_edge_irq()*
- *handle_fasteoi_irq()*
- *handle_simple_irq()*
- *handle_percpu_irq()*
- *handle_edge_eoi_irq()*
- *handle_bad_irq()*

The interrupt flow handlers (either pre-defined or architecture specific) are assigned to specific interrupts by the architecture either during bootup or during device initialization.

Default flow implementations

Helper functions

The helper functions call the chip primitives and are used by the default flow implementations. The following helper functions are implemented (simplified excerpt):

```
default_enable(struct irq_data *data)
{
    desc->irq_data.chip->irq_unmask(data);
}

default_disable(struct irq_data *data)
{
    if (!delay_disable(data))
        desc->irq_data.chip->irq_mask(data);
}

default_ack(struct irq_data *data)
{
    chip->irq_ack(data);
}

default_mask_ack(struct irq_data *data)
{
    if (chip->irq_mask_ack) {
        chip->irq_mask_ack(data);
    } else {
        chip->irq_mask(data);
        chip->irq_ack(data);
    }
}

noop(struct irq_data *data))
{
}
```

Default flow handler implementations

Default Level IRQ flow handler

handle_level_irq provides a generic implementation for level-triggered interrupts.

The following control flow is implemented (simplified excerpt):

```
desc->irq_data.chip->irq_mask_ack();
handle_irq_event(desc->action);
desc->irq_data.chip->irq_unmask();
```

Default Fast EOI IRQ flow handler

handle_fasteoi_irq provides a generic implementation for interrupts, which only need an EOI at the end of the handler.

The following control flow is implemented (simplified excerpt):

```
handle_irq_event(desc->action);
desc->irq_data.chip->irq_eoi();
```

Default Edge IRQ flow handler

handle_edge_irq provides a generic implementation for edge-triggered interrupts.

The following control flow is implemented (simplified excerpt):

```
if (desc->status & running) {
    desc->irq_data.chip->irq_mask_ack();
    desc->status |= pending | masked;
    return;
}
desc->irq_data.chip->irq_ack();
desc->status |= running;
do {
    if (desc->status & masked)
        desc->irq_data.chip->irq_unmask();
    desc->status &= ~pending;
    handle_irq_event(desc->action);
} while (status & pending);
desc->status &= ~running;
```

Default simple IRQ flow handler

handle_simple_irq provides a generic implementation for simple interrupts.

Note: The simple flow handler does not call any handler/chip primitives.

The following control flow is implemented (simplified excerpt):

```
handle_irq_event(desc->action);
```

Default per CPU flow handler

handle_percpu_irq provides a generic implementation for per CPU interrupts.

Per CPU interrupts are only available on SMP and the handler provides a simplified version without locking.

The following control flow is implemented (simplified excerpt):

```
if (desc->irq_data.chip->irq_ack)
    desc->irq_data.chip->irq_ack();
handle_irq_event(desc->action);
if (desc->irq_data.chip->irq_eoi)
    desc->irq_data.chip->irq_eoi();
```

EOI Edge IRQ flow handler

handle_edge_eoi_irq provides an abnomination of the edge handler which is solely used to tame a badly wreckaged irq controller on powerpc/cell.

Bad IRQ flow handler

handle_bad_irq is used for spurious interrupts which have no real handler assigned..

Quirks and optimizations

The generic functions are intended for 'clean' architectures and chips, which have no platform-specific IRQ handling quirks. If an architecture needs to implement quirks on the 'flow' level then it can do so by overriding the high-level irq-flow handler.

Delayed interrupt disable

This per interrupt selectable feature, which was introduced by Russell King in the ARM interrupt implementation, does not mask an interrupt at the hardware level when *disable_irq()* is called. The interrupt is kept enabled and is masked in the flow handler when an interrupt event happens. This prevents losing edge interrupts on hardware which does not store an edge interrupt event while the interrupt is disabled at the hardware level. When an interrupt arrives while the IRQ_DISABLED flag is set, then the interrupt is masked at the hardware level and the IRQ_PENDING bit is set. When the interrupt is re-enabled by *enable_irq()* the pending bit is checked and if it is set, the interrupt is resent either via hardware or by a software resend mechanism. (It's necessary to enable CONFIG_HARDIRQS_SW_RESEND when you want to use the delayed interrupt disable feature and your hardware is not capable of retriggering an interrupt.) The delayed interrupt disable is not configurable.

Chip-level hardware encapsulation

The chip-level hardware descriptor structure `irq_chip` contains all the direct chip relevant functions, which can be utilized by the irq flow implementations.

- `irq_ack`
- `irq_mask_ack` - Optional, recommended for performance
- `irq_mask`
- `irq_unmask`
- `irq_eoi` - Optional, required for EOI flow handlers
- `irq_retrigger` - Optional
- `irq_set_type` - Optional
- `irq_set_wake` - Optional

These primitives are strictly intended to mean what they say: ack means ACK, masking means masking of an IRQ line, etc. It is up to the flow handler(s) to use these basic units of low-level functionality.

4.4.5 __do_IRQ entry point

The original implementation __do_IRQ() was an alternative entry point for all types of interrupts. It no longer exists.

This handler turned out to be not suitable for all interrupt hardware and was therefore reimplemented with split functionality for edge/level/simple/percpu interrupts. This is not only a functional optimization. It also shortens code paths for interrupts.

4.4.6 Locking on SMP

The locking of chip registers is up to the architecture that defines the chip primitives. The per-irq structure is protected via desc->lock, by the generic layer.

4.4.7 Generic interrupt chip

To avoid copies of identical implementations of IRQ chips the core provides a configurable generic interrupt chip implementation. Developers should check carefully whether the generic chip fits their needs before implementing the same functionality slightly differently themselves.

void **irq_gc_mask_set_bit**(struct *irq_data* *d)

Mask chip via setting bit in mask register

Parameters

struct irq_data *d

irq_data

Description

Chip has a single mask register. Values of this register are cached and protected by gc->lock

void **irq_gc_mask_clr_bit**(struct *irq_data* *d)
Mask chip via clearing bit in mask register

Parameters

struct irq_data *d
irq_data

Description

Chip has a single mask register. Values of this register are cached and protected by gc->lock

void **irq_gc_ack_set_bit**(struct *irq_data* *d)
Ack pending interrupt via setting bit

Parameters

struct irq_data *d
irq_data

struct *irq_chip_generic* ***irq_alloc_generic_chip**(const char *name, int num_ct, unsigned int irq_base, void __iomem *reg_base, irq_flow_handler_t handler)
Allocate a generic chip and initialize it

Parameters

const char *name
Name of the irq chip

int num_ct
Number of irq_chip_type instances associated with this

unsigned int irq_base
Interrupt base nr for this chip

void __iomem *reg_base
Register base address (virtual)

irq_flow_handler_t handler
Default flow handler associated with this chip

Description

Returns an initialized irq_chip_generic structure. The chip defaults to the primary (index 0) irq_chip_type and **handler**

int **__irq_alloc_domain_generic_chips**(struct irq_domain *d, int irqs_per_chip, int num_ct, const char *name, irq_flow_handler_t handler, unsigned int clr, unsigned int set, enum *irq_gc_flags* gcflags)

Allocate generic chips for an irq domain

Parameters

struct irq_domain *d
irq domain for which to allocate chips

int irqs_per_chip
Number of interrupts each chip handles (max 32)

int num_ct
Number of irq_chip_type instances associated with this

const char *name
Name of the irq chip

irq_flow_handler_t handler
Default flow handler associated with these chips

unsigned int clr
IRQ_* bits to clear in the mapping function

unsigned int set
IRQ_* bits to set in the mapping function

enum irq_gc_flags gcflags
Generic chip specific setup flags

struct *irq_chip_generic* ***irq_get_domain_generic_chip**(struct irq_domain *d, unsigned int hw_irq)

Get a pointer to the generic chip of a hw_irq

Parameters

struct irq_domain *d
irq domain pointer

unsigned int hw_irq
Hardware interrupt number

void **irq_setup_generic_chip**(struct *irq_chip_generic* *gc, u32 msk, enum *irq_gc_flags* flags, unsigned int clr, unsigned int set)

Setup a range of interrupts with a generic chip

Parameters

struct irq_chip_generic *gc
Generic irq chip holding all data

u32 msk
Bitmask holding the irqs to initialize relative to gc->irq_base

enum irq_gc_flags flags
Flags for initialization

unsigned int clr
IRQ_* bits to clear

unsigned int set
IRQ_* bits to set

Description

Set up max. 32 interrupts starting from gc->irq_base. Note, this initializes all interrupts to the primary irq_chip_type and its associated handler.

int **irq_setup_alt_chip**(struct *irq_data* *d, unsigned int type)
Switch to alternative chip

Parameters

struct irq_data *d
irq_data for this interrupt

unsigned int type
Flow type to be initialized

Description

Only to be called from chip->irq_set_type() callbacks.

void **irq_remove_generic_chip**(struct *irq_chip_generic* *gc, u32 msk, unsigned int clr, unsigned int set)
Remove a chip

Parameters

struct irq_chip_generic *gc
Generic irq chip holding all data

u32 msk
Bitmask holding the irqs to initialize relative to gc->irq_base

unsigned int clr
IRQ_* bits to clear

unsigned int set
IRQ_* bits to set

Description

Remove up to 32 interrupts starting from gc->irq_base.

4.4.8 Structures

This chapter contains the autogenerated documentation of the structures which are used in the generic IRQ layer.

struct **irq_common_data**
per irq data shared by all irqchips

Definition

```
struct irq_common_data {
  unsigned int            __private state_use_accessors;
#ifdef CONFIG_NUMA;
```

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```
  unsigned int            node;
#endif;
  void *handler_data;
  struct msi_desc         *msi_desc;
  cpumask_var_t affinity;
#ifdef CONFIG_GENERIC_IRQ_EFFECTIVE_AFF_MASK;
  cpumask_var_t effective_affinity;
#endif;
#ifdef CONFIG_GENERIC_IRQ_IPI;
  unsigned int            ipi_offset;
#endif;
};
```

Members

state_use_accessors
status information for irq chip functions. Use accessor functions to deal with it

node
node index useful for balancing

handler_data
per-IRQ data for the irq_chip methods

msi_desc
MSI descriptor

affinity
IRQ affinity on SMP. If this is an IPI related irq, then this is the mask of the CPUs to which an IPI can be sent.

effective_affinity
The effective IRQ affinity on SMP as some irq chips do not allow multi CPU destinations. A subset of **affinity**.

ipi_offset
Offset of first IPI target cpu in **affinity**. Optional.

struct **irq_data**
per irq chip data passed down to chip functions

Definition

```
struct irq_data {
  u32 mask;
  unsigned int            irq;
  unsigned long           hwirq;
  struct irq_common_data  *common;
  struct irq_chip         *chip;
  struct irq_domain       *domain;
#ifdef CONFIG_IRQ_DOMAIN_HIERARCHY;
  struct irq_data         *parent_data;
#endif;
```

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```
  void *chip_data;
};
```

Members

mask
precomputed bitmask for accessing the chip registers

irq
interrupt number

hwirq
hardware interrupt number, local to the interrupt domain

common
point to data shared by all irqchips

chip
low level interrupt hardware access

domain
Interrupt translation domain; responsible for mapping between hwirq number and linux irq number.

parent_data
pointer to parent *struct irq_data* to support hierarchy irq_domain

chip_data
platform-specific per-chip private data for the chip methods, to allow shared chip implementations

struct **irq_chip**

hardware interrupt chip descriptor

Definition

```
struct irq_chip {
  struct device   *parent_device;
  const char      *name;
  unsigned int    (*irq_startup)(struct irq_data *data);
  void (*irq_shutdown)(struct irq_data *data);
  void (*irq_enable)(struct irq_data *data);
  void (*irq_disable)(struct irq_data *data);
  void (*irq_ack)(struct irq_data *data);
  void (*irq_mask)(struct irq_data *data);
  void (*irq_mask_ack)(struct irq_data *data);
  void (*irq_unmask)(struct irq_data *data);
  void (*irq_eoi)(struct irq_data *data);
  int (*irq_set_affinity)(struct irq_data *data, const struct␣
→cpumask *dest, bool force);
  int (*irq_retrigger)(struct irq_data *data);
  int (*irq_set_type)(struct irq_data *data, unsigned int flow_
→type);
  int (*irq_set_wake)(struct irq_data *data, unsigned int on);
```

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```
  void (*irq_bus_lock)(struct irq_data *data);
  void (*irq_bus_sync_unlock)(struct irq_data *data);
  void (*irq_cpu_online)(struct irq_data *data);
  void (*irq_cpu_offline)(struct irq_data *data);
  void (*irq_suspend)(struct irq_data *data);
  void (*irq_resume)(struct irq_data *data);
  void (*irq_pm_shutdown)(struct irq_data *data);
  void (*irq_calc_mask)(struct irq_data *data);
  void (*irq_print_chip)(struct irq_data *data, struct seq_file *p);
  int (*irq_request_resources)(struct irq_data *data);
  void (*irq_release_resources)(struct irq_data *data);
  void (*irq_compose_msi_msg)(struct irq_data *data, struct msi_msg␣
↪*msg);
  void (*irq_write_msi_msg)(struct irq_data *data, struct msi_msg␣
↪*msg);
  int (*irq_get_irqchip_state)(struct irq_data *data, enum irqchip_
↪irq_state which, bool *state);
  int (*irq_set_irqchip_state)(struct irq_data *data, enum irqchip_
↪irq_state which, bool state);
  int (*irq_set_vcpu_affinity)(struct irq_data *data, void *vcpu_
↪info);
  void (*ipi_send_single)(struct irq_data *data, unsigned int cpu);
  void (*ipi_send_mask)(struct irq_data *data, const struct cpumask␣
↪*dest);
  int (*irq_nmi_setup)(struct irq_data *data);
  void (*irq_nmi_teardown)(struct irq_data *data);
  unsigned long   flags;
};
```

Members

parent_device
    pointer to parent device for irqchip

name
    name for /proc/interrupts

irq_startup
    start up the interrupt (defaults to ->enable if NULL)

irq_shutdown
    shut down the interrupt (defaults to ->disable if NULL)

irq_enable
    enable the interrupt (defaults to chip->unmask if NULL)

irq_disable
    disable the interrupt

irq_ack
    start of a new interrupt

irq_mask
    mask an interrupt source

irq_mask_ack
ack and mask an interrupt source

irq_unmask
unmask an interrupt source

irq_eoi
end of interrupt

irq_set_affinity
Set the CPU affinity on SMP machines. If the force argument is true, it tells the driver to unconditionally apply the affinity setting. Sanity checks against the supplied affinity mask are not required. This is used for CPU hotplug where the target CPU is not yet set in the cpu_online_mask.

irq_retrigger
resend an IRQ to the CPU

irq_set_type
set the flow type (IRQ_TYPE_LEVEL/etc.) of an IRQ

irq_set_wake
enable/disable power-management wake-on of an IRQ

irq_bus_lock
function to lock access to slow bus (i2c) chips

irq_bus_sync_unlock
function to sync and unlock slow bus (i2c) chips

irq_cpu_online
configure an interrupt source for a secondary CPU

irq_cpu_offline
un-configure an interrupt source for a secondary CPU

irq_suspend
function called from core code on suspend once per chip, when one or more interrupts are installed

irq_resume
function called from core code on resume once per chip, when one ore more interrupts are installed

irq_pm_shutdown
function called from core code on shutdown once per chip

irq_calc_mask
Optional function to set irq_data.mask for special cases

irq_print_chip
optional to print special chip info in show_interrupts

irq_request_resources
optional to request resources before calling any other callback related to this irq

irq_release_resources
optional to release resources acquired with irq_request_resources

irq_compose_msi_msg
optional to compose message content for MSI

irq_write_msi_msg
optional to write message content for MSI

irq_get_irqchip_state
return the internal state of an interrupt

irq_set_irqchip_state
set the internal state of a interrupt

irq_set_vcpu_affinity
optional to target a vCPU in a virtual machine

ipi_send_single
send a single IPI to destination cpus

ipi_send_mask
send an IPI to destination cpus in cpumask

irq_nmi_setup
function called from core code before enabling an NMI

irq_nmi_teardown
function called from core code after disabling an NMI

flags
chip specific flags

struct **irq_chip_regs**

register offsets for struct irq_gci

Definition

```
struct irq_chip_regs {
  unsigned long           enable;
  unsigned long           disable;
  unsigned long           mask;
  unsigned long           ack;
  unsigned long           eoi;
  unsigned long           type;
  unsigned long           polarity;
};
```

Members

enable
Enable register offset to reg_base

disable
Disable register offset to reg_base

mask
Mask register offset to reg_base

ack
Ack register offset to reg_base

eoi
Eoi register offset to reg_base

type
Type configuration register offset to reg_base

polarity
Polarity configuration register offset to reg_base

struct **irq_chip_type**
Generic interrupt chip instance for a flow type

Definition

```
struct irq_chip_type {
  struct irq_chip         chip;
  struct irq_chip_regs    regs;
  irq_flow_handler_t handler;
  u32 type;
  u32 mask_cache_priv;
  u32 *mask_cache;
};
```

Members

chip
The real interrupt chip which provides the callbacks

regs
Register offsets for this chip

handler
Flow handler associated with this chip

type
Chip can handle these flow types

mask_cache_priv
Cached mask register private to the chip type

mask_cache
Pointer to cached mask register

Description

A irq_generic_chip can have several instances of irq_chip_type when it requires different functions and register offsets for different flow types.

struct **irq_chip_generic**
Generic irq chip data structure

Definition

```
struct irq_chip_generic {
  raw_spinlock_t lock;
  void __iomem            *reg_base;
  u32 (*reg_readl)(void __iomem *addr);
```

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```
  void (*reg_writel)(u32 val, void __iomem *addr);
  void (*suspend)(struct irq_chip_generic *gc);
  void (*resume)(struct irq_chip_generic *gc);
  unsigned int            irq_base;
  unsigned int            irq_cnt;
  u32 mask_cache;
  u32 type_cache;
  u32 polarity_cache;
  u32 wake_enabled;
  u32 wake_active;
  unsigned int            num_ct;
  void *private;
  unsigned long           installed;
  unsigned long           unused;
  struct irq_domain       *domain;
  struct list_head        list;
  struct irq_chip_type    chip_types[];
};
```

Members

lock
Lock to protect register and cache data access

reg_base
Register base address (virtual)

reg_readl
Alternate I/O accessor (defaults to readl if NULL)

reg_writel
Alternate I/O accessor (defaults to writel if NULL)

suspend
Function called from core code on suspend once per chip; can be useful instead of irq_chip::suspend to handle chip details even when no interrupts are in use

resume
Function called from core code on resume once per chip; can be useful instead of irq_chip::suspend to handle chip details even when no interrupts are in use

irq_base
Interrupt base nr for this chip

irq_cnt
Number of interrupts handled by this chip

mask_cache
Cached mask register shared between all chip types

type_cache
Cached type register

polarity_cache
Cached polarity register

wake_enabled
Interrupt can wakeup from suspend

wake_active
Interrupt is marked as an wakeup from suspend source

num_ct
Number of available irq_chip_type instances (usually 1)

private
Private data for non generic chip callbacks

installed
bitfield to denote installed interrupts

unused
bitfield to denote unused interrupts

domain
irq domain pointer

list
List head for keeping track of instances

chip_types
Array of interrupt irq_chip_types

Description

Note, that irq_chip_generic can have multiple irq_chip_type implementations which can be associated to a particular irq line of an irq_chip_generic instance. That allows to share and protect state in an irq_chip_generic instance when we need to implement different flow mechanisms (level/edge) for it.

enum **irq_gc_flags**

Initialization flags for generic irq chips

Constants

IRQ_GC_INIT_MASK_CACHE
Initialize the mask_cache by reading mask reg

IRQ_GC_INIT_NESTED_LOCK
Set the lock class of the irqs to nested for irq chips which need to call irq_set_wake() on the parent irq. Usually GPIO implementations

IRQ_GC_MASK_CACHE_PER_TYPE
Mask cache is chip type private

IRQ_GC_NO_MASK
Do not calculate irq_data->mask

IRQ_GC_BE_IO
Use big-endian register accesses (default: LE)

struct **irqaction**

per interrupt action descriptor

Definition

```
struct irqaction {
  irq_handler_t handler;
  void *dev_id;
  void __percpu           *percpu_dev_id;
  struct irqaction        *next;
  irq_handler_t thread_fn;
  struct task_struct      *thread;
  struct irqaction        *secondary;
  unsigned int            irq;
  unsigned int            flags;
  unsigned long           thread_flags;
  unsigned long           thread_mask;
  const char              *name;
  struct proc_dir_entry   *dir;
};
```

Members

handler
interrupt handler function

dev_id
cookie to identify the device

percpu_dev_id
cookie to identify the device

next
pointer to the next irqaction for shared interrupts

thread_fn
interrupt handler function for threaded interrupts

thread
thread pointer for threaded interrupts

secondary
pointer to secondary irqaction (force threading)

irq
interrupt number

flags
flags (see IRQF_* above)

thread_flags
flags related to **thread**

thread_mask
bitmask for keeping track of **thread** activity

name
name of the device

dir
pointer to the proc/irq/NN/name entry

int **request_irq**(unsigned int irq, irq_handler_t handler, unsigned long flags, const char *name, void *dev)

Add a handler for an interrupt line

Parameters

unsigned int irq
The interrupt line to allocate

irq_handler_t handler
Function to be called when the IRQ occurs. Primary handler for threaded interrupts If NULL, the default primary handler is installed

unsigned long flags
Handling flags

const char *name
Name of the device generating this interrupt

void *dev
A cookie passed to the handler function

Description

This call allocates an interrupt and establishes a handler; see the documentation for *request_threaded_irq()* for details.

struct **irq_affinity_notify**

context for notification of IRQ affinity changes

Definition

```
struct irq_affinity_notify {
  unsigned int irq;
  struct kref kref;
  struct work_struct work;
  void (*notify)(struct irq_affinity_notify *, const cpumask_t␣
↪*mask);
  void (*release)(struct kref *ref);
};
```

Members

irq
Interrupt to which notification applies

kref
Reference count, for internal use

work
Work item, for internal use

notify
Function to be called on change. This will be called in process context.

release
Function to be called on release. This will be called in process context. Once registered, the structure must only be freed when this function is called or later.

struct **irq_affinity**

Description for automatic irq affinity assignements

Definition

```
struct irq_affinity {
  unsigned int    pre_vectors;
  unsigned int    post_vectors;
  unsigned int    nr_sets;
  unsigned int    set_size[IRQ_AFFINITY_MAX_SETS];
  void (*calc_sets)(struct irq_affinity *, unsigned int nvecs);
  void *priv;
};
```

Members

pre_vectors
Don't apply affinity to **pre_vectors** at beginning of the MSI(-X) vector space

post_vectors
Don't apply affinity to **post_vectors** at end of the MSI(-X) vector space

nr_sets
The number of interrupt sets for which affinity spreading is required

set_size
Array holding the size of each interrupt set

calc_sets
Callback for calculating the number and size of interrupt sets

priv
Private data for usage by **calc_sets**, usually a pointer to driver/device specific data.

struct **irq_affinity_desc**

Interrupt affinity descriptor

Definition

```
struct irq_affinity_desc {
  struct cpumask  mask;
  unsigned int    is_managed : 1;
};
```

Members

mask
cpumask to hold the affinity assignment

is_managed
1 if the interrupt is managed internally

int **irq_set_affinity**(unsigned int irq, const struct *cpumask* *cpumask)

Set the irq affinity of a given irq

Parameters

unsigned int irq
Interrupt to set affinity

const struct cpumask *cpumask
cpumask

Description

Fails if cpumask does not contain an online CPU

int **irq_force_affinity**(unsigned int irq, const struct *cpumask* *cpumask)
Force the irq affinity of a given irq

Parameters

unsigned int irq
Interrupt to set affinity

const struct cpumask *cpumask
cpumask

Description

Same as irq_set_affinity, but without checking the mask against online cpus.

Solely for low level cpu hotplug code, where we need to make per cpu interrupts affine before the cpu becomes online.

4.4.9 Public Functions Provided

This chapter contains the autogenerated documentation of the kernel API functions which are exported.

bool **synchronize_hardirq**(unsigned int irq)
wait for pending hard IRQ handlers (on other CPUs)

Parameters

unsigned int irq
interrupt number to wait for

This function waits for any pending hard IRQ handlers for this interrupt to complete before returning. If you use this function while holding a resource the IRQ handler may need you will deadlock. It does not take associated threaded handlers into account.

Do not use this for shutdown scenarios where you must be sure that all parts (hardirq and threaded handler) have completed.

Return

false if a threaded handler is active.

This function may be called - with care - from IRQ context.

It does not check whether there is an interrupt in flight at the hardware level, but not serviced yet, as this might deadlock when called with interrupts disabled and the target CPU of the interrupt is the current CPU.

void **synchronize_irq**(unsigned int irq)
wait for pending IRQ handlers (on other CPUs)

Parameters

unsigned int irq
interrupt number to wait for

This function waits for any pending IRQ handlers for this interrupt to complete before returning. If you use this function while holding a resource the IRQ handler may need you will deadlock.

Can only be called from preemptible code as it might sleep when an interrupt thread is associated to **irq**.

It optionally makes sure (when the irq chip supports that method) that the interrupt is not pending in any CPU and waiting for service.

int **irq_can_set_affinity**(unsigned int irq)
Check if the affinity of a given irq can be set

Parameters

unsigned int irq
Interrupt to check

bool **irq_can_set_affinity_usr**(unsigned int irq)
Check if affinity of a irq can be set from user space

Parameters

unsigned int irq
Interrupt to check

Description

Like *irq_can_set_affinity()* above, but additionally checks for the AFFINITY_MANAGED flag.

void **irq_set_thread_affinity**(struct irq_desc *desc)
Notify irq threads to adjust affinity

Parameters

struct irq_desc *desc
irq descriptor which has affitnity changed

We just set IRQTF_AFFINITY and delegate the affinity setting to the interrupt thread itself. We can not call set_cpus_allowed_ptr() here as we hold desc->lock and this code can be called from hard interrupt context.

int **irq_set_affinity_notifier**(unsigned int irq, struct *irq_affinity_notify* *notify)
control notification of IRQ affinity changes

Parameters

unsigned int irq
Interrupt for which to enable/disable notification

struct irq_affinity_notify *notify
Context for notification, or `NULL` to disable notification. Function pointers must be initialised; the other fields will be initialised by this function.

> Must be called in process context. Notification may only be enabled after the IRQ is allocated and must be disabled before the IRQ is freed using *free_irq()*.

int **irq_set_vcpu_affinity**(unsigned int irq, void *vcpu_info)
Set vcpu affinity for the interrupt

Parameters

unsigned int irq
interrupt number to set affinity

void *vcpu_info
vCPU specific data or pointer to a percpu array of vCPU specific data for percpu_devid interrupts

> This function uses the vCPU specific data to set the vCPU affinity for an irq. The vCPU specific data is passed from outside, such as KVM. One example code path is as below: KVM -> IOMMU -> *irq_set_vcpu_affinity()*.

void **disable_irq_nosync**(unsigned int irq)
disable an irq without waiting

Parameters

unsigned int irq
Interrupt to disable

Disable the selected interrupt line. Disables and Enables are nested. Unlike *disable_irq()*, this function does not ensure existing instances of the IRQ handler have completed before returning.

This function may be called from IRQ context.

void **disable_irq**(unsigned int irq)
disable an irq and wait for completion

Parameters

unsigned int irq
Interrupt to disable

Disable the selected interrupt line. Enables and Disables are nested. This function waits for any pending IRQ handlers for this interrupt to complete before returning. If you use this function while holding a resource the IRQ handler may need you will deadlock.

This function may be called - with care - from IRQ context.

bool **disable_hardirq**(unsigned int irq)
disables an irq and waits for hardirq completion

Parameters

unsigned int irq
Interrupt to disable

Disable the selected interrupt line. Enables and Disables are nested. This function waits for any pending hard IRQ handlers for this interrupt to complete before returning. If you use this function while holding a resource the hard IRQ handler may need you will deadlock.

When used to optimistically disable an interrupt from atomic context the return value must be checked.

Return

false if a threaded handler is active.

This function may be called - with care - from IRQ context.

void **disable_nmi_nosync**(unsigned int irq)
disable an nmi without waiting

Parameters

unsigned int irq
Interrupt to disable

Disable the selected interrupt line. Disables and enables are nested. The interrupt to disable must have been requested through request_nmi. Unlike disable_nmi(), this function does not ensure existing instances of the IRQ handler have completed before returning.

void **enable_irq**(unsigned int irq)
enable handling of an irq

Parameters

unsigned int irq
Interrupt to enable

Undoes the effect of one call to *disable_irq()*. If this matches the last disable, processing of interrupts on this IRQ line is re-enabled.

This function may be called from IRQ context only when desc->irq_data.chip->bus_lock and desc->chip->bus_sync_unlock are NULL !

void **enable_nmi**(unsigned int irq)
enable handling of an nmi

Parameters

unsigned int irq
Interrupt to enable

The interrupt to enable must have been requested through request_nmi. Undoes the effect of one call to disable_nmi(). If this matches the last disable, processing of interrupts on this IRQ line is re-enabled.

int **irq_set_irq_wake**(unsigned int irq, unsigned int on)
control irq power management wakeup

Parameters

unsigned int irq
interrupt to control

unsigned int on
enable/disable power management wakeup

Enable/disable power management wakeup mode, which is disabled by default. Enables and disables must match, just as they match for non-wakeup mode support.

Wakeup mode lets this IRQ wake the system from sleep states like "suspend to RAM".

Note

irq enable/disable state is completely orthogonal
to the enable/disable state of irq wake. An irq can be disabled with *disable_irq()* and still wake the system as long as the irq has wake enabled. If this does not hold, then the underlying irq chip and the related driver need to be investigated.

void **irq_wake_thread**(unsigned int irq, void *dev_id)
wake the irq thread for the action identified by dev_id

Parameters

unsigned int irq
Interrupt line

void *dev_id
Device identity for which the thread should be woken

const void ***free_irq**(unsigned int irq, void *dev_id)
free an interrupt allocated with request_irq

Parameters

unsigned int irq
Interrupt line to free

void *dev_id
Device identity to free

Remove an interrupt handler. The handler is removed and if the interrupt line is no longer in use by any driver it is disabled. On a shared IRQ the caller must ensure the interrupt is disabled on the card it drives before calling this function. The function does not return until any executing interrupts for this IRQ have completed.

This function must not be called from interrupt context.

Returns the devname argument passed to request_irq.

int **request_threaded_irq**(unsigned int irq, irq_handler_t handler, irq_handler_t thread_fn, unsigned long irqflags, const char *devname, void *dev_id)
allocate an interrupt line

Parameters

unsigned int irq
Interrupt line to allocate

irq_handler_t handler
Function to be called when the IRQ occurs. Primary handler for threaded interrupts If NULL and thread_fn != NULL the default primary handler is installed

irq_handler_t thread_fn
Function called from the irq handler thread If NULL, no irq thread is created

unsigned long irqflags
Interrupt type flags

const char *devname
An ascii name for the claiming device

void *dev_id
A cookie passed back to the handler function

This call allocates interrupt resources and enables the interrupt line and IRQ handling. From the point this call is made your handler function may be invoked. Since your handler function must clear any interrupt the board raises, you must take care both to initialise your hardware and to set up the interrupt handler in the right order.

If you want to set up a threaded irq handler for your device then you need to supply **handler** and **thread_fn**. **handler** is still called in hard interrupt context and has to check whether the interrupt originates from the device. If yes it needs to disable the interrupt on the device and return IRQ_WAKE_THREAD which will wake up the handler thread and run **thread_fn**. This split handler design is necessary to support shared interrupts.

Dev_id must be globally unique. Normally the address of the device data structure is used as the cookie. Since the handler receives this value it makes sense to use it.

If your interrupt is shared you must pass a non NULL dev_id as this is required when freeing the interrupt.

Flags:

IRQF_SHARED Interrupt is shared IRQF_TRIGGER_* Specify active edge(s) or level

int **request_any_context_irq**(unsigned int irq, irq_handler_t handler, unsigned long flags, const char *name, void *dev_id)

allocate an interrupt line

Parameters

unsigned int irq
Interrupt line to allocate

irq_handler_t handler
Function to be called when the IRQ occurs. Threaded handler for threaded interrupts.

unsigned long flags
Interrupt type flags

const char *name
An ascii name for the claiming device

void *dev_id
A cookie passed back to the handler function

This call allocates interrupt resources and enables the interrupt line and IRQ handling. It selects either a hardirq or threaded handling method depending on the context.

On failure, it returns a negative value. On success, it returns either IRQC_IS_HARDIRQ or IRQC_IS_NESTED.

int **request_nmi**(unsigned int irq, irq_handler_t handler, unsigned long irqflags, const char *name, void *dev_id)

allocate an interrupt line for NMI delivery

Parameters

unsigned int irq
Interrupt line to allocate

irq_handler_t handler
Function to be called when the IRQ occurs. Threaded handler for threaded interrupts.

unsigned long irqflags
Interrupt type flags

const char *name
An ascii name for the claiming device

void *dev_id
A cookie passed back to the handler function

This call allocates interrupt resources and enables the interrupt line and IRQ handling. It sets up the IRQ line to be handled as an NMI.

An interrupt line delivering NMIs cannot be shared and IRQ handling cannot be threaded.

Interrupt lines requested for NMI delivering must produce per cpu interrupts and have auto enabling setting disabled.

Dev_id must be globally unique. Normally the address of the device data structure is used as the cookie. Since the handler receives this value it makes sense to use it.

If the interrupt line cannot be used to deliver NMIs, function will fail and return a negative value.

bool **irq_percpu_is_enabled**(unsigned int irq)

Check whether the per cpu irq is enabled

Parameters

unsigned int irq
Linux irq number to check for

Description

Must be called from a non migratable context. Returns the enable state of a per cpu interrupt on the current cpu.

void **remove_percpu_irq**(unsigned int irq, struct *irqaction* *act)
free a per-cpu interrupt

Parameters

unsigned int irq
Interrupt line to free

struct irqaction *act
irqaction for the interrupt

Description

Used to remove interrupts statically setup by the early boot process.

void **free_percpu_irq**(unsigned int irq, void __percpu *dev_id)
free an interrupt allocated with request_percpu_irq

Parameters

unsigned int irq
Interrupt line to free

void __percpu *dev_id
Device identity to free

Remove a percpu interrupt handler. The handler is removed, but the interrupt line is not disabled. This must be done on each CPU before calling this function. The function does not return until any executing interrupts for this IRQ have completed.

This function must not be called from interrupt context.

int **setup_percpu_irq**(unsigned int irq, struct *irqaction* *act)
setup a per-cpu interrupt

Parameters

unsigned int irq
Interrupt line to setup

struct irqaction *act
irqaction for the interrupt

Description

Used to statically setup per-cpu interrupts in the early boot process.

int **__request_percpu_irq**(unsigned int irq, irq_handler_t handler, unsigned long flags, const char *devname, void __percpu *dev_id)
allocate a percpu interrupt line

Parameters

unsigned int irq
Interrupt line to allocate

irq_handler_t handler
Function to be called when the IRQ occurs.

unsigned long flags
Interrupt type flags (IRQF_TIMER only)

const char *devname
An ascii name for the claiming device

void __percpu *dev_id
A percpu cookie passed back to the handler function

This call allocates interrupt resources and enables the interrupt on the local CPU. If the interrupt is supposed to be enabled on other CPUs, it has to be done on each CPU using enable_percpu_irq().

Dev_id must be globally unique. It is a per-cpu variable, and the handler gets called with the interrupted CPU's instance of that variable.

int **request_percpu_nmi**(unsigned int irq, irq_handler_t handler, const char *name, void __percpu *dev_id)

allocate a percpu interrupt line for NMI delivery

Parameters

unsigned int irq
Interrupt line to allocate

irq_handler_t handler
Function to be called when the IRQ occurs.

const char *name
An ascii name for the claiming device

void __percpu *dev_id
A percpu cookie passed back to the handler function

This call allocates interrupt resources for a per CPU NMI. Per CPU NMIs have to be setup on each CPU by calling *prepare_percpu_nmi()* before being enabled on the same CPU by using enable_percpu_nmi().

Dev_id must be globally unique. It is a per-cpu variable, and the handler gets called with the interrupted CPU's instance of that variable.

Interrupt lines requested for NMI delivering should have auto enabling setting disabled.

If the interrupt line cannot be used to deliver NMIs, function will fail returning a negative value.

int **prepare_percpu_nmi**(unsigned int irq)

performs CPU local setup for NMI delivery

Parameters

unsigned int irq
Interrupt line to prepare for NMI delivery

This call prepares an interrupt line to deliver NMI on the current CPU, before that interrupt line gets enabled with enable_percpu_nmi().

As a CPU local operation, this should be called from non-preemptible context.

If the interrupt line cannot be used to deliver NMIs, function will fail returning a negative value.

void **teardown_percpu_nmi**(unsigned int irq)
undoes NMI setup of IRQ line

Parameters

unsigned int irq
Interrupt line from which CPU local NMI configuration should be removed

This call undoes the setup done by *prepare_percpu_nmi()*.

IRQ line should not be enabled for the current CPU.

As a CPU local operation, this should be called from non-preemptible context.

int **irq_get_irqchip_state**(unsigned int irq, enum irqchip_irq_state which, bool *state)
returns the irqchip state of a interrupt.

Parameters

unsigned int irq
Interrupt line that is forwarded to a VM

enum irqchip_irq_state which
One of IRQCHIP_STATE_* the caller wants to know about

bool *state
a pointer to a boolean where the state is to be storeed

This call snapshots the internal irqchip state of an interrupt, returning into **state** the bit corresponding to stage **which**

This function should be called with preemption disabled if the interrupt controller has per-cpu registers.

int **irq_set_irqchip_state**(unsigned int irq, enum irqchip_irq_state which, bool val)
set the state of a forwarded interrupt.

Parameters

unsigned int irq
Interrupt line that is forwarded to a VM

enum irqchip_irq_state which
State to be restored (one of IRQCHIP_STATE_*)

bool val
Value corresponding to **which**

This call sets the internal irqchip state of an interrupt, depending on the value of **which**.

This function should be called with preemption disabled if the interrupt controller has per-cpu registers.

int **irq_set_chip**(unsigned int irq, struct *irq_chip* *chip)

set the irq chip for an irq

Parameters

unsigned int irq
irq number

struct irq_chip *chip
pointer to irq chip description structure

int **irq_set_irq_type**(unsigned int irq, unsigned int type)

set the irq trigger type for an irq

Parameters

unsigned int irq
irq number

unsigned int type
IRQ_TYPE_{LEVEL,EDGE}_* value - see include/linux/irq.h

int **irq_set_handler_data**(unsigned int irq, void *data)

set irq handler data for an irq

Parameters

unsigned int irq
Interrupt number

void *data
Pointer to interrupt specific data

Set the hardware irq controller data for an irq

int **irq_set_chip_data**(unsigned int irq, void *data)

set irq chip data for an irq

Parameters

unsigned int irq
Interrupt number

void *data
Pointer to chip specific data

Set the hardware irq chip data for an irq

void **handle_simple_irq**(struct irq_desc *desc)

Simple and software-decoded IRQs.

Parameters

struct irq_desc *desc
the interrupt description structure for this irq

Simple interrupts are either sent from a demultiplexing interrupt handler or come from hardware, where no interrupt hardware control is necessary.

Note

The caller is expected to handle the ack, clear, mask and
unmask issues if necessary.

void **handle_untracked_irq**(struct irq_desc *desc)

Simple and software-decoded IRQs.

Parameters

struct irq_desc *desc
the interrupt description structure for this irq

Untracked interrupts are sent from a demultiplexing interrupt handler when the demultiplexer does not know which device it its multiplexed irq domain generated the interrupt. IRQ's handled through here are not subjected to stats tracking, randomness, or spurious interrupt detection.

Note

Like handle_simple_irq, the caller is expected to handle
the ack, clear, mask and unmask issues if necessary.

void **handle_level_irq**(struct irq_desc *desc)

Level type irq handler

Parameters

struct irq_desc *desc
the interrupt description structure for this irq

Level type interrupts are active as long as the hardware line has the active level. This may require to mask the interrupt and unmask it after the associated handler has acknowledged the device, so the interrupt line is back to inactive.

void **handle_fasteoi_irq**(struct irq_desc *desc)

irq handler for transparent controllers

Parameters

struct irq_desc *desc
the interrupt description structure for this irq

Only a single callback will be issued to the chip: an ->eoi() call when the interrupt has been serviced. This enables support for modern forms of interrupt handlers, which handle the flow details in hardware, transparently.

void **handle_fasteoi_nmi**(struct irq_desc *desc)

irq handler for NMI interrupt lines

Parameters

struct irq_desc *desc
the interrupt description structure for this irq

A simple NMI-safe handler, considering the restrictions from request_nmi.

Only a single callback will be issued to the chip: an ->eoi() call when the interrupt has been serviced. This enables support for modern forms of interrupt handlers, which handle the flow details in hardware, transparently.

void **handle_edge_irq**(struct irq_desc *desc)

edge type IRQ handler

Parameters

struct irq_desc *desc
the interrupt description structure for this irq

Interrupt occures on the falling and/or rising edge of a hardware signal. The occurrence is latched into the irq controller hardware and must be acked in order to be reenabled. After the ack another interrupt can happen on the same source even before the first one is handled by the associated event handler. If this happens it might be necessary to disable (mask) the interrupt depending on the controller hardware. This requires to reenable the interrupt inside of the loop which handles the interrupts which have arrived while the handler was running. If all pending interrupts are handled, the loop is left.

void **handle_fasteoi_ack_irq**(struct irq_desc *desc)

irq handler for edge hierarchy stacked on transparent controllers

Parameters

struct irq_desc *desc
the interrupt description structure for this irq

Like *handle_fasteoi_irq()*, but for use with hierarchy where the irq_chip also needs to have its ->irq_ack() function called.

void **handle_fasteoi_mask_irq**(struct irq_desc *desc)

irq handler for level hierarchy stacked on transparent controllers

Parameters

struct irq_desc *desc
the interrupt description structure for this irq

Like *handle_fasteoi_irq()*, but for use with hierarchy where the irq_chip also needs to have its ->irq_mask_ack() function called.

int **irq_chip_set_parent_state**(struct *irq_data* *data, enum irqchip_irq_state which, bool val)

set the state of a parent interrupt.

Parameters

struct irq_data *data
Pointer to interrupt specific data

enum irqchip_irq_state which
State to be restored (one of IRQCHIP_STATE_*)

bool val
Value corresponding to **which**

Description

Conditional success, if the underlying irqchip does not implement it.

int **irq_chip_get_parent_state**(struct *irq_data* *data, enum irqchip_irq_state which, bool *state)

get the state of a parent interrupt.

Parameters

struct irq_data *data
Pointer to interrupt specific data

enum irqchip_irq_state which
one of IRQCHIP_STATE_* the caller wants to know

bool *state
a pointer to a boolean where the state is to be stored

Description

Conditional success, if the underlying irqchip does not implement it.

void **irq_chip_enable_parent**(struct *irq_data* *data)

Enable the parent interrupt (defaults to unmask if NULL)

Parameters

struct irq_data *data
Pointer to interrupt specific data

void **irq_chip_disable_parent**(struct *irq_data* *data)

Disable the parent interrupt (defaults to mask if NULL)

Parameters

struct irq_data *data
Pointer to interrupt specific data

void **irq_chip_ack_parent**(struct *irq_data* *data)

Acknowledge the parent interrupt

Parameters

struct irq_data *data
Pointer to interrupt specific data

void **irq_chip_mask_parent**(struct *irq_data* *data)

Mask the parent interrupt

Parameters

struct irq_data *data
Pointer to interrupt specific data

void **irq_chip_mask_ack_parent**(struct *irq_data* *data)

Mask and acknowledge the parent interrupt

Parameters

struct irq_data *data
Pointer to interrupt specific data

void **irq_chip_unmask_parent**(struct *irq_data* *data)
Unmask the parent interrupt

Parameters

struct irq_data *data
Pointer to interrupt specific data

void **irq_chip_eoi_parent**(struct *irq_data* *data)
Invoke EOI on the parent interrupt

Parameters

struct irq_data *data
Pointer to interrupt specific data

int **irq_chip_set_affinity_parent**(struct *irq_data* *data, const struct cpumask *dest, bool force)

Set affinity on the parent interrupt

Parameters

struct irq_data *data
Pointer to interrupt specific data

const struct cpumask *dest
The affinity mask to set

bool force
Flag to enforce setting (disable online checks)

Description

Conditinal, as the underlying parent chip might not implement it.

int **irq_chip_set_type_parent**(struct *irq_data* *data, unsigned int type)
Set IRQ type on the parent interrupt

Parameters

struct irq_data *data
Pointer to interrupt specific data

unsigned int type
IRQ_TYPE_{LEVEL,EDGE}_* value - see include/linux/irq.h

Description

Conditional, as the underlying parent chip might not implement it.

int **irq_chip_retrigger_hierarchy**(struct *irq_data* *data)
Retrigger an interrupt in hardware

Parameters

struct irq_data *data
Pointer to interrupt specific data

Description

Iterate through the domain hierarchy of the interrupt and check whether a hw retrigger function exists. If yes, invoke it.

int **irq_chip_set_vcpu_affinity_parent**(struct *irq_data* *data, void *vcpu_info)

Set vcpu affinity on the parent interrupt

Parameters

struct irq_data *data
Pointer to interrupt specific data

void *vcpu_info
The vcpu affinity information

int **irq_chip_set_wake_parent**(struct *irq_data* *data, unsigned int on)

Set/reset wake-up on the parent interrupt

Parameters

struct irq_data *data
Pointer to interrupt specific data

unsigned int on
Whether to set or reset the wake-up capability of this irq

Description

Conditional, as the underlying parent chip might not implement it.

int **irq_chip_request_resources_parent**(struct *irq_data* *data)

Request resources on the parent interrupt

Parameters

struct irq_data *data
Pointer to interrupt specific data

void **irq_chip_release_resources_parent**(struct *irq_data* *data)

Release resources on the parent interrupt

Parameters

struct irq_data *data
Pointer to interrupt specific data

4.4.10 Internal Functions Provided

This chapter contains the autogenerated documentation of the internal functions.

int **generic_handle_irq**(unsigned int irq)

Invoke the handler for a particular irq

Parameters

unsigned int irq
The irq number to handle

int **__handle_domain_irq**(struct irq_domain *domain, unsigned int hwirq, bool lookup, struct pt_regs *regs)

Invoke the handler for a HW irq belonging to a domain

Parameters

struct irq_domain *domain
: The domain where to perform the lookup

unsigned int hwirq
: The HW irq number to convert to a logical one

bool lookup
: Whether to perform the domain lookup or not

struct pt_regs *regs
: Register file coming from the low-level handling code

Return

0 on success, or -EINVAL if conversion has failed

int **handle_domain_nmi**(struct irq_domain *domain, unsigned int hwirq, struct pt_regs *regs)

Invoke the handler for a HW irq belonging to a domain

Parameters

struct irq_domain *domain
: The domain where to perform the lookup

unsigned int hwirq
: The HW irq number to convert to a logical one

struct pt_regs *regs
: Register file coming from the low-level handling code

This function must be called from an NMI context.

Return

0 on success, or -EINVAL if conversion has failed

void **irq_free_descs**(unsigned int from, unsigned int cnt)

free irq descriptors

Parameters

unsigned int from
: Start of descriptor range

unsigned int cnt
: Number of consecutive irqs to free

int __ref **__irq_alloc_descs**(int irq, unsigned int from, unsigned int cnt, int node, struct module *owner, const struct *irq_affinity_desc* *affinity)

allocate and initialize a range of irq descriptors

Parameters

int irq
: Allocate for specific irq number if irq >= 0

unsigned int from
: Start the search from this irq number

unsigned int cnt
Number of consecutive irqs to allocate.

int node
Preferred node on which the irq descriptor should be allocated

struct module *owner
Owning module (can be NULL)

const struct irq_affinity_desc *affinity
Optional pointer to an affinity mask array of size **cnt** which hints where the irq descriptors should be allocated and which default affinities to use

Description

Returns the first irq number or error code

unsigned int **irq_alloc_hwirqs**(int cnt, int node)
Allocate an irq descriptor and initialize the hardware

Parameters

int cnt
number of interrupts to allocate

int node
node on which to allocate

Description

Returns an interrupt number > 0 or 0, if the allocation fails.

void **irq_free_hwirqs**(unsigned int from, int cnt)
Free irq descriptor and cleanup the hardware

Parameters

unsigned int from
Free from irq number

int cnt
number of interrupts to free

unsigned int **irq_get_next_irq**(unsigned int offset)
get next allocated irq number

Parameters

unsigned int offset
where to start the search

Description

Returns next irq number after offset or nr_irqs if none is found.

unsigned int **kstat_irqs_cpu**(unsigned int irq, int cpu)
Get the statistics for an interrupt on a cpu

Parameters

unsigned int irq
The interrupt number

int cpu
The cpu number

Description

Returns the sum of interrupt counts on **cpu** since boot for **irq**. The caller must ensure that the interrupt is not removed concurrently.

unsigned int **kstat_irqs**(unsigned int irq)
Get the statistics for an interrupt

Parameters

unsigned int irq
The interrupt number

Description

Returns the sum of interrupt counts on all cpus since boot for **irq**. The caller must ensure that the interrupt is not removed concurrently.

unsigned int **kstat_irqs_usr**(unsigned int irq)
Get the statistics for an interrupt

Parameters

unsigned int irq
The interrupt number

Description

Returns the sum of interrupt counts on all cpus since boot for **irq**. Contrary to *kstat_irqs()* this can be called from any context. It uses rcu since a concurrent removal of an interrupt descriptor is observing an rcu grace period before delayed_free_desc()/irq_kobj_release().

void **handle_bad_irq**(struct irq_desc *desc)
handle spurious and unhandled irqs

Parameters

struct irq_desc *desc
description of the interrupt

Description

Handles spurious and unhandled IRQ's. It also prints a debugmessage.

int **irq_set_msi_desc_off**(unsigned int irq_base, unsigned int irq_offset, struct msi_desc *entry)
set MSI descriptor data for an irq at offset

Parameters

unsigned int irq_base
Interrupt number base

unsigned int irq_offset
Interrupt number offset

struct msi_desc *entry
Pointer to MSI descriptor data

Set the MSI descriptor entry for an irq at offset

int **irq_set_msi_desc**(unsigned int irq, struct msi_desc *entry)
set MSI descriptor data for an irq

Parameters

unsigned int irq
Interrupt number

struct msi_desc *entry
Pointer to MSI descriptor data

Set the MSI descriptor entry for an irq

void **irq_disable**(struct irq_desc *desc)
Mark interrupt disabled

Parameters

struct irq_desc *desc
irq descriptor which should be disabled

Description

If the chip does not implement the irq_disable callback, we use a lazy disable approach. That means we mark the interrupt disabled, but leave the hardware unmasked. That's an optimization because we avoid the hardware access for the common case where no interrupt happens after we marked it disabled. If an interrupt happens, then the interrupt flow handler masks the line at the hardware level and marks it pending.

If the interrupt chip does not implement the irq_disable callback, a driver can disable the lazy approach for a particular irq line by calling 'irq_set_status_flags(irq, IRQ_DISABLE_UNLAZY)'. This can be used for devices which cannot disable the interrupt at the device level under certain circumstances and have to use disable_irq[_nosync] instead.

void **handle_edge_eoi_irq**(struct irq_desc *desc)
edge eoi type IRQ handler

Parameters

struct irq_desc *desc
the interrupt description structure for this irq

Description

Similar as the above handle_edge_irq, but using eoi and w/o the mask/unmask logic.

void **handle_percpu_irq**(struct irq_desc *desc)
Per CPU local irq handler

Parameters

struct irq_desc *desc
: the interrupt description structure for this irq

Per CPU interrupts on SMP machines without locking requirements

void **handle_percpu_devid_irq**(struct irq_desc *desc)
: Per CPU local irq handler with per cpu dev ids

Parameters

struct irq_desc *desc
: the interrupt description structure for this irq

Description

Per CPU interrupts on SMP machines without locking requirements. Same as *handle_percpu_irq()* above but with the following extras:

action->percpu_dev_id is a pointer to percpu variables which contain the real device id for the cpu on which this handler is called

void **handle_percpu_devid_fasteoi_ipi**(struct irq_desc *desc)
: Per CPU local IPI handler with per cpu dev ids

Parameters

struct irq_desc *desc
: the interrupt description structure for this irq

Description

The biggest difference with the IRQ version is that the interrupt is EOIed early, as the IPI could result in a context switch, and we need to make sure the IPI can fire again. We also assume that the arch code has registered an action. If not, we are positively doomed.

void **handle_percpu_devid_fasteoi_nmi**(struct irq_desc *desc)
: Per CPU local NMI handler with per cpu dev ids

Parameters

struct irq_desc *desc
: the interrupt description structure for this irq

Description

Similar to handle_fasteoi_nmi, but handling the dev_id cookie as a percpu pointer.

void **irq_cpu_online**(void)
: Invoke all irq_cpu_online functions.

Parameters

void
: no arguments

Description

Iterate through all irqs and invoke the chip.*irq_cpu_online()* for each.

void **irq_cpu_offline**(void)

Invoke all irq_cpu_offline functions.

Parameters

void
no arguments

Description

Iterate through all irqs and invoke the chip.*irq_cpu_offline()* for each.

int **irq_chip_compose_msi_msg**(struct *irq_data* *data, struct msi_msg *msg)

Componse msi message for a irq chip

Parameters

struct irq_data *data
Pointer to interrupt specific data

struct msi_msg *msg
Pointer to the MSI message

Description

For hierarchical domains we find the first chip in the hierarchy which implements the irq_compose_msi_msg callback. For non hierarchical we use the top level chip.

int **irq_chip_pm_get**(struct *irq_data* *data)

Enable power for an IRQ chip

Parameters

struct irq_data *data
Pointer to interrupt specific data

Description

Enable the power to the IRQ chip referenced by the interrupt data structure.

int **irq_chip_pm_put**(struct *irq_data* *data)

Disable power for an IRQ chip

Parameters

struct irq_data *data
Pointer to interrupt specific data

Description

Disable the power to the IRQ chip referenced by the interrupt data structure, belongs. Note that power will only be disabled, once this function has been called for all IRQs that have called *irq_chip_pm_get()*.

4.4.11 Credits

The following people have contributed to this document:

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4.5 Memory Protection Keys

Memory Protection Keys for Userspace (PKU aka PKEYs) is a feature which is found on Intel's Skylake (and later) "Scalable Processor" Server CPUs. It will be available in future non-server Intel parts and future AMD processors.

For anyone wishing to test or use this feature, it is available in Amazon's EC2 C5 instances and is known to work there using an Ubuntu 17.04 image.

Memory Protection Keys provides a mechanism for enforcing page-based protections, but without requiring modification of the page tables when an application changes protection domains. It works by dedicating 4 previously ignored bits in each page table entry to a "protection key", giving 16 possible keys.

There is also a new user-accessible register (PKRU) with two separate bits (Access Disable and Write Disable) for each key. Being a CPU register, PKRU is inherently thread-local, potentially giving each thread a different set of protections from every other thread.

There are two new instructions (RDPKRU/WRPKRU) for reading and writing to the new register. The feature is only available in 64-bit mode, even though there is theoretically space in the PAE PTEs. These permissions are enforced on data access only and have no effect on instruction fetches.

4.5.1 Syscalls

There are 3 system calls which directly interact with pkeys:

```
int pkey_alloc(unsigned long flags, unsigned long init_access_
↪rights)
int pkey_free(int pkey);
int pkey_mprotect(unsigned long start, size_t len,
                  unsigned long prot, int pkey);
```

Before a pkey can be used, it must first be allocated with pkey_alloc(). An application calls the WRPKRU instruction directly in order to change access permissions to memory covered with a key. In this example WRPKRU is wrapped by a C function called pkey_set().

```
int real_prot = PROT_READ|PROT_WRITE;
pkey = pkey_alloc(0, PKEY_DISABLE_WRITE);
ptr = mmap(NULL, PAGE_SIZE, PROT_NONE, MAP_ANONYMOUS|MAP_PRIVATE, -
↪1, 0);
```

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```
ret = pkey_mprotect(ptr, PAGE_SIZE, real_prot, pkey);
... application runs here
```

Now, if the application needs to update the data at 'ptr', it can gain access, do the update, then remove its write access:

```
pkey_set(pkey, 0); // clear PKEY_DISABLE_WRITE
*ptr = foo; // assign something
pkey_set(pkey, PKEY_DISABLE_WRITE); // set PKEY_DISABLE_WRITE again
```

Now when it frees the memory, it will also free the pkey since it is no longer in use:

```
munmap(ptr, PAGE_SIZE);
pkey_free(pkey);
```

Note: pkey_set() is a wrapper for the RDPKRU and WRPKRU instructions. An example implementation can be found in tools/testing/selftests/x86/protection_keys.c.

4.5.2 Behavior

The kernel attempts to make protection keys consistent with the behavior of a plain mprotect(). For instance if you do this:

```
mprotect(ptr, size, PROT_NONE);
something(ptr);
```

you can expect the same effects with protection keys when doing this:

```
pkey = pkey_alloc(0, PKEY_DISABLE_WRITE | PKEY_DISABLE_READ);
pkey_mprotect(ptr, size, PROT_READ|PROT_WRITE, pkey);
something(ptr);
```

That should be true whether something() is a direct access to 'ptr' like:

```
*ptr = foo;
```

or when the kernel does the access on the application's behalf like with a read():

```
read(fd, ptr, 1);
```

The kernel will send a SIGSEGV in both cases, but si_code will be set to SEGV_PKERR when violating protection keys versus SEGV_ACCERR when the plain mprotect() permissions are violated.

CHAPTER

FIVE

MEMORY MANAGEMENT

How to allocate and use memory in the kernel. Note that there is a lot more memory-management documentation in /vm/index.

5.1 Memory Allocation Guide

Linux provides a variety of APIs for memory allocation. You can allocate small chunks using *kmalloc* or *kmem_cache_alloc* families, large virtually contiguous areas using *vmalloc* and its derivatives, or you can directly request pages from the page allocator with *alloc_pages*. It is also possible to use more specialized allocators, for instance *cma_alloc* or *zs_malloc*.

Most of the memory allocation APIs use GFP flags to express how that memory should be allocated. The GFP acronym stands for "get free pages", the underlying memory allocation function.

Diversity of the allocation APIs combined with the numerous GFP flags makes the question "How should I allocate memory?" not that easy to answer, although very likely you should use

```
kzalloc(<size>, GFP_KERNEL);
```

Of course there are cases when other allocation APIs and different GFP flags must be used.

5.1.1 Get Free Page flags

The GFP flags control the allocators behavior. They tell what memory zones can be used, how hard the allocator should try to find free memory, whether the memory can be accessed by the userspace etc. The Memory Management APIs provides reference documentation for the GFP flags and their combinations and here we briefly outline their recommended usage:

- Most of the time `GFP_KERNEL` is what you need. Memory for the kernel data structures, DMAable memory, inode cache, all these and many other allocations types can use `GFP_KERNEL`. Note, that using `GFP_KERNEL` implies `GFP_RECLAIM`, which means that direct reclaim may be triggered under memory pressure; the calling context must be allowed to sleep.

- If the allocation is performed from an atomic context, e.g interrupt handler, use `GFP_NOWAIT`. This flag prevents direct reclaim and IO or filesystem operations. Consequently, under memory pressure `GFP_NOWAIT` allocation is likely to fail. Allocations which have a reasonable fallback should be using `GFP_NOWARN`.
- If you think that accessing memory reserves is justified and the kernel will be stressed unless allocation succeeds, you may use `GFP_ATOMIC`.
- Untrusted allocations triggered from userspace should be a subject of kmem accounting and must have `__GFP_ACCOUNT` bit set. There is the handy `GFP_KERNEL_ACCOUNT` shortcut for `GFP_KERNEL` allocations that should be accounted.
- Userspace allocations should use either of the `GFP_USER`, `GFP_HIGHUSER` or `GFP_HIGHUSER_MOVABLE` flags. The longer the flag name the less restrictive it is.

  `GFP_HIGHUSER_MOVABLE` does not require that allocated memory will be directly accessible by the kernel and implies that the data is movable.

  `GFP_HIGHUSER` means that the allocated memory is not movable, but it is not required to be directly accessible by the kernel. An example may be a hardware allocation that maps data directly into userspace but has no addressing limitations.

  `GFP_USER` means that the allocated memory is not movable and it must be directly accessible by the kernel.

You may notice that quite a few allocations in the existing code specify `GFP_NOIO` or `GFP_NOFS`. Historically, they were used to prevent recursion deadlocks caused by direct memory reclaim calling back into the FS or IO paths and blocking on already held resources. Since 4.12 the preferred way to address this issue is to use new scope APIs described in GFP masks used from FS/IO context.

Other legacy GFP flags are `GFP_DMA` and `GFP_DMA32`. They are used to ensure that the allocated memory is accessible by hardware with limited addressing capabilities. So unless you are writing a driver for a device with such restrictions, avoid using these flags. And even with hardware with restrictions it is preferable to use *dma_alloc** APIs.

GFP flags and reclaim behavior

Memory allocations may trigger direct or background reclaim and it is useful to understand how hard the page allocator will try to satisfy that or another request.

- `GFP_KERNEL & ~__GFP_RECLAIM` - optimistic allocation without _any_ attempt to free memory at all. The most light weight mode which even doesn't kick the background reclaim. Should be used carefully because it might deplete the memory and the next user might hit the more aggressive reclaim.
- `GFP_KERNEL & ~__GFP_DIRECT_RECLAIM` (or `GFP_NOWAIT`)- optimistic allocation without any attempt to free memory from the current context but can wake kswapd to reclaim memory if the zone is below the low watermark. Can be used from either atomic contexts or when the request is a performance optimization and there is another fallback for a slow path.

- `(GFP_KERNEL|__GFP_HIGH) & ~__GFP_DIRECT_RECLAIM` (aka `GFP_ATOMIC`) - non sleeping allocation with an expensive fallback so it can access some portion of memory reserves. Usually used from interrupt/bottom-half context with an expensive slow path fallback.
- `GFP_KERNEL` - both background and direct reclaim are allowed and the **default** page allocator behavior is used. That means that not costly allocation requests are basically no-fail but there is no guarantee of that behavior so failures have to be checked properly by callers (e.g. OOM killer victim is allowed to fail currently).
- `GFP_KERNEL | __GFP_NORETRY` - overrides the default allocator behavior and all allocation requests fail early rather than cause disruptive reclaim (one round of reclaim in this implementation). The OOM killer is not invoked.
- `GFP_KERNEL | __GFP_RETRY_MAYFAIL` - overrides the default allocator behavior and all allocation requests try really hard. The request will fail if the reclaim cannot make any progress. The OOM killer won't be triggered.
- `GFP_KERNEL | __GFP_NOFAIL` - overrides the default allocator behavior and all allocation requests will loop endlessly until they succeed. This might be really dangerous especially for larger orders.

5.1.2 Selecting memory allocator

The most straightforward way to allocate memory is to use a function from the *kmalloc()* family. And, to be on the safe side it's best to use routines that set memory to zero, like *kzalloc()*. If you need to allocate memory for an array, there are *kmalloc_array()* and *kcalloc()* helpers. The helpers struct_size(), array_size() and array3_size() can be used to safely calculate object sizes without overflowing.

The maximal size of a chunk that can be allocated with *kmalloc* is limited. The actual limit depends on the hardware and the kernel configuration, but it is a good practice to use *kmalloc* for objects smaller than page size.

The address of a chunk allocated with *kmalloc* is aligned to at least ARCH_KMALLOC_MINALIGN bytes. For sizes which are a power of two, the alignment is also guaranteed to be at least the respective size.

For large allocations you can use *vmalloc()* and *vzalloc()*, or directly request pages from the page allocator. The memory allocated by *vmalloc* and related functions is not physically contiguous.

If you are not sure whether the allocation size is too large for *kmalloc*, it is possible to use kvmalloc() and its derivatives. It will try to allocate memory with *kmalloc* and if the allocation fails it will be retried with *vmalloc*. There are restrictions on which GFP flags can be used with *kvmalloc*; please see *kvmalloc_node()* reference documentation. Note that *kvmalloc* may return memory that is not physically contiguous.

If you need to allocate many identical objects you can use the slab cache allocator. The cache should be set up with *kmem_cache_create()* or *kmem_cache_create_usercopy()* before it can be used. The second function should be used if a part of the cache might be copied to the userspace. After the cache is created *kmem_cache_alloc()* and its convenience wrappers can allocate memory from that cache.

When the allocated memory is no longer needed it must be freed. You can use *kvfree()* for the memory allocated with *kmalloc*, *vmalloc* and *kvmalloc*. The slab caches should be freed with *kmem_cache_free()*. And don't forget to destroy the cache with kmem_cache_destroy().

5.2 Unaligned Memory Accesses

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Linux runs on a wide variety of architectures which have varying behaviour when it comes to memory access. This document presents some details about unaligned accesses, why you need to write code that doesn't cause them, and how to write such code!

5.2.1 The definition of an unaligned access

Unaligned memory accesses occur when you try to read N bytes of data starting from an address that is not evenly divisible by N (i.e. addr % N != 0). For example, reading 4 bytes of data from address 0x10004 is fine, but reading 4 bytes of data from address 0x10005 would be an unaligned memory access.

The above may seem a little vague, as memory access can happen in different ways. The context here is at the machine code level: certain instructions read or write a number of bytes to or from memory (e.g. movb, movw, movl in x86 assembly). As will become clear, it is relatively easy to spot C statements which will compile to multiple-byte memory access instructions, namely when dealing with types such as u16, u32 and u64.

5.2.2 Natural alignment

The rule mentioned above forms what we refer to as natural alignment: When accessing N bytes of memory, the base memory address must be evenly divisible by N, i.e. addr % N == 0.

When writing code, assume the target architecture has natural alignment requirements.

In reality, only a few architectures require natural alignment on all sizes of memory access. However, we must consider ALL supported architectures; writing code that satisfies natural alignment requirements is the easiest way to achieve full portability.

5.2.3 Why unaligned access is bad

The effects of performing an unaligned memory access vary from architecture to architecture. It would be easy to write a whole document on the differences here; a summary of the common scenarios is presented below:

- Some architectures are able to perform unaligned memory accesses transparently, but there is usually a significant performance cost.
- Some architectures raise processor exceptions when unaligned accesses happen. The exception handler is able to correct the unaligned access, at significant cost to performance.
- Some architectures raise processor exceptions when unaligned accesses happen, but the exceptions do not contain enough information for the unaligned access to be corrected.
- Some architectures are not capable of unaligned memory access, but will silently perform a different memory access to the one that was requested, resulting in a subtle code bug that is hard to detect!

It should be obvious from the above that if your code causes unaligned memory accesses to happen, your code will not work correctly on certain platforms and will cause performance problems on others.

5.2.4 Code that does not cause unaligned access

At first, the concepts above may seem a little hard to relate to actual coding practice. After all, you don't have a great deal of control over memory addresses of certain variables, etc.

Fortunately things are not too complex, as in most cases, the compiler ensures that things will work for you. For example, take the following structure:

```
struct foo {
        u16 field1;
        u32 field2;
        u8 field3;
};
```

Let us assume that an instance of the above structure resides in memory starting at address 0x10000. With a basic level of understanding, it would not be unreasonable to expect that accessing field2 would cause an unaligned access. You'd be expecting field2 to be located at offset 2 bytes into the structure, i.e. address 0x10002, but that address is not evenly divisible by 4 (remember, we're reading a 4 byte value here).

Fortunately, the compiler understands the alignment constraints, so in the above case it would insert 2 bytes of padding in between field1 and field2. Therefore, for standard structure types you can always rely on the compiler to pad structures so that accesses to fields are suitably aligned (assuming you do not cast the field to a type of different length).

Similarly, you can also rely on the compiler to align variables and function parameters to a naturally aligned scheme, based on the size of the type of the variable.

At this point, it should be clear that accessing a single byte (u8 or char) will never cause an unaligned access, because all memory addresses are evenly divisible by one.

On a related topic, with the above considerations in mind you may observe that you could reorder the fields in the structure in order to place fields where padding would otherwise be inserted, and hence reduce the overall resident memory size of structure instances. The optimal layout of the above example is:

```
struct foo {
        u32 field2;
        u16 field1;
        u8 field3;
};
```

For a natural alignment scheme, the compiler would only have to add a single byte of padding at the end of the structure. This padding is added in order to satisfy alignment constraints for arrays of these structures.

Another point worth mentioning is the use of __attribute__((packed)) on a structure type. This GCC-specific attribute tells the compiler never to insert any padding within structures, useful when you want to use a C struct to represent some data that comes in a fixed arrangement 'off the wire'.

You might be inclined to believe that usage of this attribute can easily lead to unaligned accesses when accessing fields that do not satisfy architectural alignment requirements. However, again, the compiler is aware of the alignment constraints and will generate extra instructions to perform the memory access in a way that does not cause unaligned access. Of course, the extra instructions obviously cause a loss in performance compared to the non-packed case, so the packed attribute should only be used when avoiding structure padding is of importance.

5.2.5 Code that causes unaligned access

With the above in mind, let's move onto a real life example of a function that can cause an unaligned memory access. The following function taken from include/linux/etherdevice.h is an optimized routine to compare two ethernet MAC addresses for equality:

```
bool ether_addr_equal(const u8 *addr1, const u8 *addr2)
{
#ifdef CONFIG_HAVE_EFFICIENT_UNALIGNED_ACCESS
      u32 fold = ((*(const u32 *)addr1) ^ (*(const u32 *)addr2)) |
                 ((*(const u16 *)(addr1 + 4)) ^ (*(const u16␣
↪*)(addr2 + 4)));

      return fold == 0;
```

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```
#else
      const u16 *a = (const u16 *)addr1;
      const u16 *b = (const u16 *)addr2;
      return ((a[0] ^ b[0]) | (a[1] ^ b[1]) | (a[2] ^ b[2])) == 0;
#endif
}
```

In the above function, when the hardware has efficient unaligned access capability, there is no issue with this code. But when the hardware isn't able to access memory on arbitrary boundaries, the reference to a[0] causes 2 bytes (16 bits) to be read from memory starting at address addr1.

Think about what would happen if addr1 was an odd address such as 0x10003. (Hint: it' d be an unaligned access.)

Despite the potential unaligned access problems with the above function, it is included in the kernel anyway but is understood to only work normally on 16-bit-aligned addresses. It is up to the caller to ensure this alignment or not use this function at all. This alignment-unsafe function is still useful as it is a decent optimization for the cases when you can ensure alignment, which is true almost all of the time in ethernet networking context.

Here is another example of some code that could cause unaligned accesses:

```
void myfunc(u8 *data, u32 value)
{
        [...]
        *((u32 *) data) = cpu_to_le32(value);
        [...]
}
```

This code will cause unaligned accesses every time the data parameter points to an address that is not evenly divisible by 4.

In summary, the 2 main scenarios where you may run into unaligned access problems involve:

1. Casting variables to types of different lengths
2. Pointer arithmetic followed by access to at least 2 bytes of data

5.2.6 Avoiding unaligned accesses

The easiest way to avoid unaligned access is to use the get_unaligned() and put_unaligned() macros provided by the <asm/unaligned.h> header file.

Going back to an earlier example of code that potentially causes unaligned access:

```
void myfunc(u8 *data, u32 value)
{
        [...]
        *((u32 *) data) = cpu_to_le32(value);
```

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```
        [...]
}
```

To avoid the unaligned memory access, you would rewrite it as follows:

```
void myfunc(u8 *data, u32 value)
{
        [...]
        value = cpu_to_le32(value);
        put_unaligned(value, (u32 *) data);
        [...]
}
```

The get_unaligned() macro works similarly. Assuming 'data' is a pointer to memory and you wish to avoid unaligned access, its usage is as follows:

```
u32 value = get_unaligned((u32 *) data);
```

These macros work for memory accesses of any length (not just 32 bits as in the examples above). Be aware that when compared to standard access of aligned memory, using these macros to access unaligned memory can be costly in terms of performance.

If use of such macros is not convenient, another option is to use *memcpy()*, where the source or destination (or both) are of type u8* or unsigned char*. Due to the byte-wise nature of this operation, unaligned accesses are avoided.

5.2.7 Alignment vs. Networking

On architectures that require aligned loads, networking requires that the IP header is aligned on a four-byte boundary to optimise the IP stack. For regular ethernet hardware, the constant NET_IP_ALIGN is used. On most architectures this constant has the value 2 because the normal ethernet header is 14 bytes long, so in order to get proper alignment one needs to DMA to an address which can be expressed as 4*n + 2. One notable exception here is powerpc which defines NET_IP_ALIGN to 0 because DMA to unaligned addresses can be very expensive and dwarf the cost of unaligned loads.

For some ethernet hardware that cannot DMA to unaligned addresses like 4*n+2 or non-ethernet hardware, this can be a problem, and it is then required to copy the incoming frame into an aligned buffer. Because this is unnecessary on architectures that can do unaligned accesses, the code can be made dependent on CONFIG_HAVE_EFFICIENT_UNALIGNED_ACCESS like so:

```
#ifdef CONFIG_HAVE_EFFICIENT_UNALIGNED_ACCESS
        skb = original skb
#else
        skb = copy skb
#endif
```

5.3 Dynamic DMA mapping using the generic device

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This document describes the DMA API. For a more gentle introduction of the API (and actual examples), see *Dynamic DMA mapping Guide*.

This API is split into two pieces. Part I describes the basic API. Part II describes extensions for supporting non-consistent memory machines. Unless you know that your driver absolutely has to support non-consistent platforms (this is usually only legacy platforms) you should only use the API described in part I.

5.3.1 Part I - dma_API

To get the dma_API, you must #include <linux/dma-mapping.h>. This provides dma_addr_t and the interfaces described below.

A dma_addr_t can hold any valid DMA address for the platform. It can be given to a device to use as a DMA source or target. A CPU cannot reference a dma_addr_t directly because there may be translation between its physical address space and the DMA address space.

5.3.2 Part Ia - Using large DMA-coherent buffers

```
void *
dma_alloc_coherent(struct device *dev, size_t size,
                   dma_addr_t *dma_handle, gfp_t flag)
```

Consistent memory is memory for which a write by either the device or the processor can immediately be read by the processor or device without having to worry about caching effects. (You may however need to make sure to flush the processor's write buffers before telling devices to read that memory.)

This routine allocates a region of <size> bytes of consistent memory.

It returns a pointer to the allocated region (in the processor's virtual address space) or NULL if the allocation failed.

It also returns a <dma_handle> which may be cast to an unsigned integer the same width as the bus and given to the device as the DMA address base of the region.

Note: consistent memory can be expensive on some platforms, and the minimum allocation length may be as big as a page, so you should consolidate your requests for consistent memory as much as possible. The simplest way to do that is to use the dma_pool calls (see below).

The flag parameter (dma_alloc_coherent() only) allows the caller to specify the `GFP_` flags (see *kmalloc()*) for the allocation (the implementation may choose to ignore flags that affect the location of the returned memory, like GFP_DMA).

```
void
dma_free_coherent(struct device *dev, size_t size, void *cpu_addr,
                  dma_addr_t dma_handle)
```

Free a region of consistent memory you previously allocated. dev, size and dma_handle must all be the same as those passed into dma_alloc_coherent(). cpu_addr must be the virtual address returned by the dma_alloc_coherent().

Note that unlike their sibling allocation calls, these routines may only be called with IRQs enabled.

5.3.3 Part Ib - Using small DMA-coherent buffers

To get this part of the dma_API, you must #include <linux/dmapool.h>

Many drivers need lots of small DMA-coherent memory regions for DMA descriptors or I/O buffers. Rather than allocating in units of a page or more using dma_alloc_coherent(), you can use DMA pools. These work much like a struct kmem_cache, except that they use the DMA-coherent allocator, not __get_free_pages(). Also, they understand common hardware constraints for alignment, like queue heads needing to be aligned on N-byte boundaries.

```
struct dma_pool *
dma_pool_create(const char *name, struct device *dev,
                size_t size, size_t align, size_t alloc);
```

dma_pool_create() initializes a pool of DMA-coherent buffers for use with a given device. It must be called in a context which can sleep.

The "name" is for diagnostics (like a struct kmem_cache name); dev and size are like what you'd pass to dma_alloc_coherent(). The device's hardware alignment requirement for this type of data is "align" (which is expressed in bytes, and must be a power of two). If your device has no boundary crossing restrictions, pass 0 for alloc; passing 4096 says memory allocated from this pool must not cross 4KByte boundaries.

```
void *
dma_pool_zalloc(struct dma_pool *pool, gfp_t mem_flags,
                dma_addr_t *handle)
```

Wraps *dma_pool_alloc()* and also zeroes the returned memory if the allocation attempt succeeded.

```
void *
dma_pool_alloc(struct dma_pool *pool, gfp_t gfp_flags,
               dma_addr_t *dma_handle);
```

This allocates memory from the pool; the returned memory will meet the size and alignment requirements specified at creation time. Pass GFP_ATOMIC to prevent blocking, or if it's permitted (not in_interrupt, not holding SMP locks), pass GFP_KERNEL to allow blocking. Like dma_alloc_coherent(), this returns two values: an address usable by the CPU, and the DMA address usable by the pool's device.

```
void
dma_pool_free(struct dma_pool *pool, void *vaddr,
              dma_addr_t addr);
```

This puts memory back into the pool. The pool is what was passed to *dma_pool_alloc()*; the CPU (vaddr) and DMA addresses are what were returned when that routine allocated the memory being freed.

```
void
dma_pool_destroy(struct dma_pool *pool);
```

dma_pool_destroy() frees the resources of the pool. It must be called in a context which can sleep. Make sure you've freed all allocated memory back to the pool before you destroy it.

5.3.4 Part Ic - DMA addressing limitations

```
int
dma_set_mask_and_coherent(struct device *dev, u64 mask)
```

Checks to see if the mask is possible and updates the device streaming and coherent DMA mask parameters if it is.

Returns: 0 if successful and a negative error if not.

```
int
dma_set_mask(struct device *dev, u64 mask)
```

Checks to see if the mask is possible and updates the device parameters if it is.

Returns: 0 if successful and a negative error if not.

```
int
dma_set_coherent_mask(struct device *dev, u64 mask)
```

Checks to see if the mask is possible and updates the device parameters if it is.

Returns: 0 if successful and a negative error if not.

```
u64
dma_get_required_mask(struct device *dev)
```

This API returns the mask that the platform requires to operate efficiently. Usually this means the returned mask is the minimum required to cover all of memory. Examining the required mask gives drivers with variable descriptor sizes the opportunity to use smaller descriptors as necessary.

Requesting the required mask does not alter the current mask. If you wish to take advantage of it, you should issue a dma_set_mask() call to set the mask to the value returned.

```
size_t
dma_max_mapping_size(struct device *dev);
```

Returns the maximum size of a mapping for the device. The size parameter of the mapping functions like dma_map_single(), dma_map_page() and others should not be larger than the returned value.

```
bool
dma_need_sync(struct device *dev, dma_addr_t dma_addr);
```

Returns %true if dma_sync_single_for_{device,cpu} calls are required to transfer memory ownership. Returns %false if those calls can be skipped.

```
unsigned long
dma_get_merge_boundary(struct device *dev);
```

Returns the DMA merge boundary. If the device cannot merge any the DMA address segments, the function returns 0.

5.3.5 Part Id - Streaming DMA mappings

```
dma_addr_t
dma_map_single(struct device *dev, void *cpu_addr, size_t size,
               enum dma_data_direction direction)
```

Maps a piece of processor virtual memory so it can be accessed by the device and returns the DMA address of the memory.

The direction for both APIs may be converted freely by casting. However the dma_API uses a strongly typed enumerator for its direction:

DMA_NONE	no direction (used for debugging)
DMA_TO_DEVICE	data is going from the memory to the device
DMA_FROM_DEVICE	data is coming from the device to the memory
DMA_BIDIRECTIONAL	direction isn't known

Note: Not all memory regions in a machine can be mapped by this API. Further, contiguous kernel virtual space may not be contiguous as physical memory. Since this API does not provide any scatter/gather capability, it will fail if the user tries to map a non-physically contiguous piece of memory. For this reason, memory to be mapped by this API should be obtained from sources which guarantee it to be physically contiguous (like kmalloc).

Further, the DMA address of the memory must be within the dma_mask of the device (the dma_mask is a bit mask of the addressable region for the device, i.e., if the DMA address of the memory ANDed with the dma_mask is still equal to the DMA address, then the device can perform DMA to the memory). To ensure that the memory allocated by kmalloc is within the dma_mask, the driver may specify various platform-dependent flags to restrict the DMA address range of the allocation (e.g., on x86, GFP_DMA guarantees to be within the first 16MB of available DMA addresses, as required by ISA devices).

Note also that the above constraints on physical contiguity and dma_mask may not apply if the platform has an IOMMU (a device which maps an I/O DMA address to a physical memory address). However, to be portable, device driver writers may *not* assume that such an IOMMU exists.

Warning: Memory coherency operates at a granularity called the cache line width. In order for memory mapped by this API to operate correctly, the mapped region must begin exactly on a cache line boundary and end exactly on one (to prevent two separately mapped regions from sharing a single cache line). Since the cache line size may not be known at compile time, the API will not enforce this requirement. Therefore, it is recommended that driver writers who don't take special care to determine the cache line size at run time only map virtual regions that begin and end on page boundaries (which are guaranteed also to be cache line boundaries).

DMA_TO_DEVICE synchronisation must be done after the last modification of the memory region by the software and before it is handed off to the device. Once this primitive is used, memory covered by this primitive should be treated as read-only by the device. If the device may write to it at any point, it should be DMA_BIDIRECTIONAL (see below).

DMA_FROM_DEVICE synchronisation must be done before the driver accesses data that may be changed by the device. This memory should be treated as read-only by the driver. If the driver needs to write to it at any point, it should be DMA_BIDIRECTIONAL (see below).

DMA_BIDIRECTIONAL requires special handling: it means that the driver isn't sure if the memory was modified before being handed off to the device and also isn't sure if the device will also modify it. Thus, you must always sync bidirectional memory twice: once before the memory is handed off to the device (to make sure all memory changes are flushed from the processor) and once before the data may be accessed after being used by the device (to make sure any processor cache lines are updated with data that the device may have changed).

```
void
dma_unmap_single(struct device *dev, dma_addr_t dma_addr, size_t␣
↪size,
                 enum dma_data_direction direction)
```

Unmaps the region previously mapped. All the parameters passed in must be identical to those passed in (and returned) by the mapping API.

```
dma_addr_t
dma_map_page(struct device *dev, struct page *page,
             unsigned long offset, size_t size,
             enum dma_data_direction direction)
```

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```
void
dma_unmap_page(struct device *dev, dma_addr_t dma_address, size_t␣
↪size,
               enum dma_data_direction direction)
```

API for mapping and unmapping for pages. All the notes and warnings for the other mapping APIs apply here. Also, although the <offset> and <size> parameters are provided to do partial page mapping, it is recommended that you never use these unless you really know what the cache width is.

```
dma_addr_t
dma_map_resource(struct device *dev, phys_addr_t phys_addr, size_t␣
↪size,
                 enum dma_data_direction dir, unsigned long attrs)

void
dma_unmap_resource(struct device *dev, dma_addr_t addr, size_t size,
                   enum dma_data_direction dir, unsigned long attrs)
```

API for mapping and unmapping for MMIO resources. All the notes and warnings for the other mapping APIs apply here. The API should only be used to map device MMIO resources, mapping of RAM is not permitted.

```
int
dma_mapping_error(struct device *dev, dma_addr_t dma_addr)
```

In some circumstances dma_map_single(), dma_map_page() and dma_map_resource() will fail to create a mapping. A driver can check for these errors by testing the returned DMA address with dma_mapping_error(). A non-zero return value means the mapping could not be created and the driver should take appropriate action (e.g. reduce current DMA mapping usage or delay and try again later).

```
int
dma_map_sg(struct device *dev, struct scatterlist *sg,
           int nents, enum dma_data_direction direction)
```

Returns: the number of DMA address segments mapped (this may be shorter than <nents> passed in if some elements of the scatter/gather list are physically or virtually adjacent and an IOMMU maps them with a single entry).

Please note that the sg cannot be mapped again if it has been mapped once. The mapping process is allowed to destroy information in the sg.

As with the other mapping interfaces, dma_map_sg() can fail. When it does, 0 is returned and a driver must take appropriate action. It is critical that the driver do something, in the case of a block driver aborting the request or even oopsing is better than doing nothing and corrupting the filesystem.

With scatterlists, you use the resulting mapping like this:

```
int i, count = dma_map_sg(dev, sglist, nents, direction);
struct scatterlist *sg;

for_each_sg(sglist, sg, count, i) {
        hw_address[i] = sg_dma_address(sg);
        hw_len[i] = sg_dma_len(sg);
}
```

where nents is the number of entries in the sglist.

The implementation is free to merge several consecutive sglist entries into one (e.g. with an IOMMU, or if several pages just happen to be physically contiguous) and returns the actual number of sg entries it mapped them to. On failure 0, is returned.

Then you should loop count times (note: this can be less than nents times) and use sg_dma_address() and sg_dma_len() macros where you previously accessed sg->address and sg->length as shown above.

```
void
dma_unmap_sg(struct device *dev, struct scatterlist *sg,
             int nents, enum dma_data_direction direction)
```

Unmap the previously mapped scatter/gather list. All the parameters must be the same as those and passed in to the scatter/gather mapping API.

Note: <nents> must be the number you passed in, *not* the number of DMA address entries returned.

```
void
dma_sync_single_for_cpu(struct device *dev, dma_addr_t dma_handle,
                        size_t size,
                        enum dma_data_direction direction)

void
dma_sync_single_for_device(struct device *dev, dma_addr_t dma_
↪handle,
                           size_t size,
                           enum dma_data_direction direction)

void
dma_sync_sg_for_cpu(struct device *dev, struct scatterlist *sg,
                    int nents,
                    enum dma_data_direction direction)

void
dma_sync_sg_for_device(struct device *dev, struct scatterlist *sg,
                       int nents,
                       enum dma_data_direction direction)
```

Synchronise a single contiguous or scatter/gather mapping for the CPU and device. With the sync_sg API, all the parameters must be the same as those passed into the single mapping API. With the sync_single API, you can use dma_handle and size parameters that aren't identical to those passed into the single mapping API to do a partial sync.

Note: You must do this:

- Before reading values that have been written by DMA from the device (use the DMA_FROM_DEVICE direction)
- After writing values that will be written to the device using DMA (use the DMA_TO_DEVICE) direction
- before *and* after handing memory to the device if the memory is DMA_BIDIRECTIONAL

See also dma_map_single().

```
dma_addr_t
dma_map_single_attrs(struct device *dev, void *cpu_addr, size_t␣
↪size,
                     enum dma_data_direction dir,
                     unsigned long attrs)

void
dma_unmap_single_attrs(struct device *dev, dma_addr_t dma_addr,
                       size_t size, enum dma_data_direction dir,
                       unsigned long attrs)

int
dma_map_sg_attrs(struct device *dev, struct scatterlist *sgl,
                 int nents, enum dma_data_direction dir,
                 unsigned long attrs)

void
dma_unmap_sg_attrs(struct device *dev, struct scatterlist *sgl,
                   int nents, enum dma_data_direction dir,
                   unsigned long attrs)
```

The four functions above are just like the counterpart functions without the _attrs suffixes, except that they pass an optional dma_attrs.

The interpretation of DMA attributes is architecture-specific, and each attribute should be documented in *DMA attributes*.

If dma_attrs are 0, the semantics of each of these functions is identical to those of the corresponding function without the _attrs suffix. As a result dma_map_single_attrs() can generally replace dma_map_single(), etc.

As an example of the use of the `*_attrs` functions, here's how you could pass an attribute DMA_ATTR_FOO when mapping memory for DMA:

```
#include <linux/dma-mapping.h>
/* DMA_ATTR_FOO should be defined in linux/dma-mapping.h and
* documented in Documentation/core-api/dma-attributes.rst */
```

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```
...

        unsigned long attr;
        attr |= DMA_ATTR_FOO;
        ....
        n = dma_map_sg_attrs(dev, sg, nents, DMA_TO_DEVICE, attr);
        ....
```

Architectures that care about DMA_ATTR_FOO would check for its presence in their implementations of the mapping and unmapping routines, e.g.::

```
void whizco_dma_map_sg_attrs(struct device *dev, dma_addr_t dma_
→addr,
                             size_t size, enum dma_data_direction␣
→dir,
                             unsigned long attrs)
{
        ....
        if (attrs & DMA_ATTR_FOO)
                /* twizzle the frobnozzle */
        ....
}
```

5.3.6 Part II - Non-coherent DMA allocations

These APIs allow to allocate pages that are guaranteed to be DMA addressable by the passed in device, but which need explicit management of memory ownership for the kernel vs the device.

If you don't understand how cache line coherency works between a processor and an I/O device, you should not be using this part of the API.

```
void *
dma_alloc_noncoherent(struct device *dev, size_t size,
                dma_addr_t *dma_handle, enum dma_data_direction dir,
                gfp_t gfp)
```

This routine allocates a region of <size> bytes of consistent memory. It returns a pointer to the allocated region (in the processor's virtual address space) or NULL if the allocation failed. The returned memory may or may not be in the kernel direct mapping. Drivers must not call virt_to_page on the returned memory region.

It also returns a <dma_handle> which may be cast to an unsigned integer the same width as the bus and given to the device as the DMA address base of the region.

The dir parameter specified if data is read and/or written by the device, see dma_map_single() for details.

The gfp parameter allows the caller to specify the `GFP_` flags (see *kmalloc()*) for the allocation, but rejects flags used to specify a memory zone such as GFP_DMA or GFP_HIGHMEM.

Before giving the memory to the device, dma_sync_single_for_device() needs to be called, and before reading memory written by the device, dma_sync_single_for_cpu(), just like for streaming DMA mappings that are reused.

```
void
dma_free_noncoherent(struct device *dev, size_t size, void *cpu_
↪addr,
                dma_addr_t dma_handle, enum dma_data_direction dir)
```

Free a region of memory previously allocated using dma_alloc_noncoherent(). dev, size and dma_handle and dir must all be the same as those passed into dma_alloc_noncoherent(). cpu_addr must be the virtual address returned by dma_alloc_noncoherent().

```
struct page *
dma_alloc_pages(struct device *dev, size_t size, dma_addr_t *dma_
↪handle,
                enum dma_data_direction dir, gfp_t gfp)
```

This routine allocates a region of <size> bytes of non-coherent memory. It returns a pointer to first struct page for the region, or NULL if the allocation failed. The resulting struct page can be used for everything a struct page is suitable for.

It also returns a <dma_handle> which may be cast to an unsigned integer the same width as the bus and given to the device as the DMA address base of the region.

The dir parameter specified if data is read and/or written by the device, see dma_map_single() for details.

The gfp parameter allows the caller to specify the `GFP_` flags (see *kmalloc()*) for the allocation, but rejects flags used to specify a memory zone such as GFP_DMA or GFP_HIGHMEM.

Before giving the memory to the device, dma_sync_single_for_device() needs to be called, and before reading memory written by the device, dma_sync_single_for_cpu(), just like for streaming DMA mappings that are reused.

```
void
dma_free_pages(struct device *dev, size_t size, struct page *page,
                dma_addr_t dma_handle, enum dma_data_direction dir)
```

Free a region of memory previously allocated using dma_alloc_pages(). dev, size and dma_handle and dir must all be the same as those passed into dma_alloc_noncoherent(). page must be the pointer returned by dma_alloc_pages().

```
int
dma_get_cache_alignment(void)
```

Returns the processor cache alignment. This is the absolute minimum alignment *and* width that you must observe when either mapping memory or doing partial flushes.

Note: This API may return a number *larger* than the actual cache line, but it will guarantee that one or more cache lines fit exactly into the width returned by this call. It will also always be a power of two for easy alignment.

5.3.7 Part III - Debug drivers use of the DMA-API

The DMA-API as described above has some constraints. DMA addresses must be released with the corresponding function with the same size for example. With the advent of hardware IOMMUs it becomes more and more important that drivers do not violate those constraints. In the worst case such a violation can result in data corruption up to destroyed filesystems.

To debug drivers and find bugs in the usage of the DMA-API checking code can be compiled into the kernel which will tell the developer about those violations. If your architecture supports it you can select the "Enable debugging of DMA-API usage" option in your kernel configuration. Enabling this option has a performance impact. Do not enable it in production kernels.

If you boot the resulting kernel will contain code which does some bookkeeping about what DMA memory was allocated for which device. If this code detects an error it prints a warning message with some details into your kernel log. An example warning message may look like this:

```
WARNING: at /data2/repos/linux-2.6-iommu/lib/dma-debug.c:448
        check_unmap+0x203/0x490()
Hardware name:
forcedeth 0000:00:08.0: DMA-API: device driver frees DMA memory␣
↪with wrong
        function [device address=0x00000000640444be] [size=66␣
↪bytes] [mapped as
single] [unmapped as page]
Modules linked in: nfsd exportfs bridge stp llc r8169
Pid: 0, comm: swapper Tainted: G        W  2.6.28-dmatest-09289-
↪g8bb99c0 #1
Call Trace:
<IRQ>  [<ffffffff80240b22>] warn_slowpath+0xf2/0x130
[<ffffffff80647b70>] _spin_unlock+0x10/0x30
[<ffffffff80537e75>] usb_hcd_link_urb_to_ep+0x75/0xc0
[<ffffffff80647c22>] _spin_unlock_irqrestore+0x12/0x40
[<ffffffff8055347f>] ohci_urb_enqueue+0x19f/0x7c0
[<ffffffff80252f96>] queue_work+0x56/0x60
[<ffffffff80237e10>] enqueue_task_fair+0x20/0x50
[<ffffffff80539279>] usb_hcd_submit_urb+0x379/0xbc0
[<ffffffff803b78c3>] cpumask_next_and+0x23/0x40
[<ffffffff80235177>] find_busiest_group+0x207/0x8a0
[<ffffffff8064784f>] _spin_lock_irqsave+0x1f/0x50
```

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```
[<ffffffff803c7ea3>] check_unmap+0x203/0x490
[<ffffffff803c8259>] debug_dma_unmap_page+0x49/0x50
[<ffffffff80485f26>] nv_tx_done_optimized+0xc6/0x2c0
[<ffffffff80486c13>] nv_nic_irq_optimized+0x73/0x2b0
[<ffffffff8026df84>] handle_IRQ_event+0x34/0x70
[<ffffffff8026ffe9>] handle_edge_irq+0xc9/0x150
[<ffffffff8020e3ab>] do_IRQ+0xcb/0x1c0
[<ffffffff8020c093>] ret_from_intr+0x0/0xa
<EOI> <4>---[ end trace f6435a98e2a38c0e ]---
```

The driver developer can find the driver and the device including a stacktrace of the DMA-API call which caused this warning.

Per default only the first error will result in a warning message. All other errors will only silently counted. This limitation exist to prevent the code from flooding your kernel log. To support debugging a device driver this can be disabled via debugfs. See the debugfs interface documentation below for details.

The debugfs directory for the DMA-API debugging code is called dma-api/. In this directory the following files can currently be found:

dma-api/all_er	This file contains a numeric value. If this value is not equal to zero the debugging code will print a warning for every error it finds into the kernel log. Be careful with this option, as it can easily flood your logs.
dma-api/disabl	This read-only file contains the character 'Y' if the debugging code is disabled. This can happen when it runs out of memory or if it was disabled at boot time
dma-api/dump	This read-only file contains current DMA mappings.
dma-api/error_	This file is read-only and shows the total numbers of errors found.
dma-api/num_	The number in this file shows how many warnings will be printed to the kernel log before it stops. This number is initialized to one at system boot and be set by writing into this file
dma-api/min_f	This read-only file can be read to get the minimum number of free dma_debug_entries the allocator has ever seen. If this value goes down to zero the code will attempt to increase nr_total_entries to compensate.
dma-api/num_f	The current number of free dma_debug_entries in the allocator.
dma-api/nr_tot	The total number of dma_debug_entries in the allocator, both free and used.
dma-api/driver	You can write a name of a driver into this file to limit the debug output to requests from that particular driver. Write an empty string to that file to disable the filter and see all errors again.

If you have this code compiled into your kernel it will be enabled by default. If you want to boot without the bookkeeping anyway you can provide 'dma_debug=off' as a boot parameter. This will disable DMA-API debugging. Notice that you can not enable it again at runtime. You have to reboot to do so.

If you want to see debug messages only for a special device driver you can specify the dma_debug_driver=<drivername> parameter. This will enable the driver filter at boot time. The debug code will only print errors for that driver afterwards. This filter can be disabled or changed later using debugfs.

When the code disables itself at runtime this is most likely because it ran out of dma_debug_entries and was unable to allocate more on-demand. 65536 entries are preallocated at boot - if this is too low for you boot with 'dma_debug_entries=<your_desired_number>' to overwrite the default. Note that the code allocates entries in batches, so the exact number of preallocated entries may be greater than the actual number requested. The code will print to the kernel log each time it has dynamically allocated as many entries as were initially preallocated. This is to indicate that a larger preallocation size may be appropriate, or if it happens continually that a driver may be leaking mappings.

```
void
debug_dma_mapping_error(struct device *dev, dma_addr_t dma_addr);
```

dma-debug interface debug_dma_mapping_error() to debug drivers that fail to check DMA mapping errors on addresses returned by dma_map_single() and dma_map_page() interfaces. This interface clears a flag set by debug_dma_map_page() to indicate that dma_mapping_error() has been called by the driver. When driver does unmap, debug_dma_unmap() checks the flag and if this flag is still set, prints warning message that includes call trace that leads up to the unmap. This interface can be called from dma_mapping_error() routines to enable DMA mapping error check debugging.

5.4 Dynamic DMA mapping Guide

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This is a guide to device driver writers on how to use the DMA API with example pseudo-code. For a concise description of the API, see DMA-API.txt.

5.4.1 CPU and DMA addresses

There are several kinds of addresses involved in the DMA API, and it's important to understand the differences.

The kernel normally uses virtual addresses. Any address returned by *kmalloc()*, *vmalloc()*, and similar interfaces is a virtual address and can be stored in a `void *`.

The virtual memory system (TLB, page tables, etc.) translates virtual addresses to CPU physical addresses, which are stored as "phys_addr_t" or "resource_size_t". The kernel manages device resources like registers as physical addresses. These are the addresses in /proc/iomem. The physical address is not directly useful to a driver; it must use ioremap() to map the space and produce a virtual address.

I/O devices use a third kind of address: a "bus address". If a device has registers at an MMIO address, or if it performs DMA to read or write system memory, the addresses used by the device are bus addresses. In some systems, bus addresses are identical to CPU physical addresses, but in general they are not. IOMMUs and host bridges can produce arbitrary mappings between physical and bus addresses.

From a device's point of view, DMA uses the bus address space, but it may be restricted to a subset of that space. For example, even if a system supports 64-bit addresses for main memory and PCI BARs, it may use an IOMMU so devices only need to use 32-bit DMA addresses.

Here's a picture and some examples:

```
             CPU                  CPU                  Bus
           Virtual              Physical             Address
           Address              Address               Space
            Space                Space

          +-------+             +------+             +------+
          |       |             |MMIO  |   Offset    |      |
          |       |  Virtual    |Space |   applied   |      |
        C +-------+ --------> B +------+ ----------> +------+ A
          |       |  mapping    |      |   by host   |      |
+-----+   |       |             |      |   bridge    |      |   +--------+
|     |   |       |             +------+             |      |   |        |
| CPU |   |       |             | RAM  |             |      |   | Device |
|     |   |       |             |      |             |      |   |        |
+-----+   +-------+             +------+             +------+   +--------+
          |       |  Virtual    |Buffer|   Mapping   |      |
        X +-------+ --------> Y +------+ <---------- +------+ Z
          |       |  mapping    | RAM  |   by IOMMU
          |       |             |      |
          |       |             |      |
```

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```
          +-------+             +------+
```

During the enumeration process, the kernel learns about I/O devices and their MMIO space and the host bridges that connect them to the system. For example, if a PCI device has a BAR, the kernel reads the bus address (A) from the BAR and converts it to a CPU physical address (B). The address B is stored in a struct resource and usually exposed via /proc/iomem. When a driver claims a device, it typically uses ioremap() to map physical address B at a virtual address (C). It can then use, e.g., ioread32(C), to access the device registers at bus address A.

If the device supports DMA, the driver sets up a buffer using *kmalloc()* or a similar interface, which returns a virtual address (X). The virtual memory system maps X to a physical address (Y) in system RAM. The driver can use virtual address X to access the buffer, but the device itself cannot because DMA doesn't go through the CPU virtual memory system.

In some simple systems, the device can do DMA directly to physical address Y. But in many others, there is IOMMU hardware that translates DMA addresses to physical addresses, e.g., it translates Z to Y. This is part of the reason for the DMA API: the driver can give a virtual address X to an interface like dma_map_single(), which sets up any required IOMMU mapping and returns the DMA address Z. The driver then tells the device to do DMA to Z, and the IOMMU maps it to the buffer at address Y in system RAM.

So that Linux can use the dynamic DMA mapping, it needs some help from the drivers, namely it has to take into account that DMA addresses should be mapped only for the time they are actually used and unmapped after the DMA transfer.

The following API will work of course even on platforms where no such hardware exists.

Note that the DMA API works with any bus independent of the underlying microprocessor architecture. You should use the DMA API rather than the bus-specific DMA API, i.e., use the dma_map_*() interfaces rather than the pci_map_*() interfaces.

First of all, you should make sure:

```
#include <linux/dma-mapping.h>
```

is in your driver, which provides the definition of dma_addr_t. This type can hold any valid DMA address for the platform and should be used everywhere you hold a DMA address returned from the DMA mapping functions.

5.4.2 What memory is DMA' able?

The first piece of information you must know is what kernel memory can be used with the DMA mapping facilities. There has been an unwritten set of rules regarding this, and this text is an attempt to finally write them down.

If you acquired your memory via the page allocator (i.e. __get_free_page*()) or the generic memory allocators (i.e. `kmalloc()` or `kmem_cache_alloc()`) then you may DMA to/from that memory using the addresses returned from those routines.

This means specifically that you may _not_ use the memory/addresses returned from `vmalloc()` for DMA. It is possible to DMA to the _underlying_ memory mapped into a `vmalloc()` area, but this requires walking page tables to get the physical addresses, and then translating each of those pages back to a kernel address using something like __va(). [EDIT: Update this when we integrate Gerd Knorr' s generic code which does this.]

This rule also means that you may use neither kernel image addresses (items in data/text/bss segments), nor module image addresses, nor stack addresses for DMA. These could all be mapped somewhere entirely different than the rest of physical memory. Even if those classes of memory could physically work with DMA, you' d need to ensure the I/O buffers were cacheline-aligned. Without that, you' d see cacheline sharing problems (data corruption) on CPUs with DMA-incoherent caches. (The CPU could write to one word, DMA would write to a different one in the same cache line, and one of them could be overwritten.)

Also, this means that you cannot take the return of a kmap() call and DMA to/from that. This is similar to `vmalloc()`.

What about block I/O and networking buffers? The block I/O and networking subsystems make sure that the buffers they use are valid for you to DMA from/to.

5.4.3 DMA addressing capabilities

By default, the kernel assumes that your device can address 32-bits of DMA addressing. For a 64-bit capable device, this needs to be increased, and for a device with limitations, it needs to be decreased.

Special note about PCI: PCI-X specification requires PCI-X devices to support 64-bit addressing (DAC) for all transactions. And at least one platform (SGI SN2) requires 64-bit consistent allocations to operate correctly when the IO bus is in PCI-X mode.

For correct operation, you must set the DMA mask to inform the kernel about your devices DMA addressing capabilities.

This is performed via a call to dma_set_mask_and_coherent():

```
int dma_set_mask_and_coherent(struct device *dev, u64 mask);
```

which will set the mask for both streaming and coherent APIs together. If you have some special requirements, then the following two separate calls can be used instead:

The setup for streaming mappings is performed via a call to dma_set_mask():

```
int dma_set_mask(struct device *dev, u64 mask);
```

The setup for consistent allocations is performed via a call to dma_set_coherent_mask():

```
int dma_set_coherent_mask(struct device *dev, u64 mask);
```

Here, dev is a pointer to the device struct of your device, and mask is a bit mask describing which bits of an address your device supports. Often the device struct of your device is embedded in the bus-specific device struct of your device. For example, &pdev->dev is a pointer to the device struct of a PCI device (pdev is a pointer to the PCI device struct of your device).

These calls usually return zero to indicated your device can perform DMA properly on the machine given the address mask you provided, but they might return an error if the mask is too small to be supportable on the given system. If it returns non-zero, your device cannot perform DMA properly on this platform, and attempting to do so will result in undefined behavior. You must not use DMA on this device unless the dma_set_mask family of functions has returned success.

This means that in the failure case, you have two options:

1) Use some non-DMA mode for data transfer, if possible.
2) Ignore this device and do not initialize it.

It is recommended that your driver print a kernel KERN_WARNING message when setting the DMA mask fails. In this manner, if a user of your driver reports that performance is bad or that the device is not even detected, you can ask them for the kernel messages to find out exactly why.

The standard 64-bit addressing device would do something like this:

```
if (dma_set_mask_and_coherent(dev, DMA_BIT_MASK(64))) {
        dev_warn(dev, "mydev: No suitable DMA available\n");
        goto ignore_this_device;
}
```

If the device only supports 32-bit addressing for descriptors in the coherent allocations, but supports full 64-bits for streaming mappings it would look like this:

```
if (dma_set_mask(dev, DMA_BIT_MASK(64))) {
        dev_warn(dev, "mydev: No suitable DMA available\n");
        goto ignore_this_device;
}
```

The coherent mask will always be able to set the same or a smaller mask as the streaming mask. However for the rare case that a device driver only uses consistent allocations, one would have to check the return value from dma_set_coherent_mask().

Finally, if your device can only drive the low 24-bits of address you might do something like:

```
if (dma_set_mask(dev, DMA_BIT_MASK(24))) {
        dev_warn(dev, "mydev: 24-bit DMA addressing not available\n
↪");
        goto ignore_this_device;
}
```

When dma_set_mask() or dma_set_mask_and_coherent() is successful, and returns zero, the kernel saves away this mask you have provided. The kernel will use this information later when you make DMA mappings.

There is a case which we are aware of at this time, which is worth mentioning in this documentation. If your device supports multiple functions (for example a sound card provides playback and record functions) and the various different functions have _different_ DMA addressing limitations, you may wish to probe each mask and only provide the functionality which the machine can handle. It is important that the last call to dma_set_mask() be for the most specific mask.

Here is pseudo-code showing how this might be done:

```
#define PLAYBACK_ADDRESS_BITS   DMA_BIT_MASK(32)
#define RECORD_ADDRESS_BITS     DMA_BIT_MASK(24)

struct my_sound_card *card;
struct device *dev;

...
if (!dma_set_mask(dev, PLAYBACK_ADDRESS_BITS)) {
        card->playback_enabled = 1;
} else {
        card->playback_enabled = 0;
        dev_warn(dev, "%s: Playback disabled due to DMA limitations\
↪n",
               card->name);
}
if (!dma_set_mask(dev, RECORD_ADDRESS_BITS)) {
        card->record_enabled = 1;
} else {
        card->record_enabled = 0;
        dev_warn(dev, "%s: Record disabled due to DMA limitations\n
↪",
               card->name);
}
```

A sound card was used as an example here because this genre of PCI devices seems to be littered with ISA chips given a PCI front end, and thus retaining the 16MB DMA addressing limitations of ISA.

5.4.4 Types of DMA mappings

There are two types of DMA mappings:

- Consistent DMA mappings which are usually mapped at driver initialization, unmapped at the end and for which the hardware should guarantee that the device and the CPU can access the data in parallel and will see updates made by each other without any explicit software flushing.

  Think of "consistent" as "synchronous" or "coherent".

  The current default is to return consistent memory in the low 32 bits of the DMA space. However, for future compatibility you should set the consistent mask even if this default is fine for your driver.

  Good examples of what to use consistent mappings for are:

  - Network card DMA ring descriptors.
  - SCSI adapter mailbox command data structures.
  - Device firmware microcode executed out of main memory.

  The invariant these examples all require is that any CPU store to memory is immediately visible to the device, and vice versa. Consistent mappings guarantee this.

  Important: Consistent DMA memory does not preclude the usage of proper memory barriers. The CPU may reorder stores to consistent memory just as it may normal memory. Example: if it is important for the device to see the first word of a descriptor updated before the second, you must do something like:

  ```
  desc->word0 = address;
  wmb();
  desc->word1 = DESC_VALID;
  ```

  in order to get correct behavior on all platforms.

  Also, on some platforms your driver may need to flush CPU write buffers in much the same way as it needs to flush write buffers found in PCI bridges (such as by reading a register's value after writing it).

- Streaming DMA mappings which are usually mapped for one DMA transfer, unmapped right after it (unless you use dma_sync_* below) and for which hardware can optimize for sequential accesses.

  Think of "streaming" as "asynchronous" or "outside the coherency domain".

  Good examples of what to use streaming mappings for are:

  - Networking buffers transmitted/received by a device.
  - Filesystem buffers written/read by a SCSI device.

> The interfaces for using this type of mapping were designed in such a way that an implementation can make whatever performance optimizations the hardware allows. To this end, when using such mappings you must be explicit about what you want to happen.

Neither type of DMA mapping has alignment restrictions that come from the underlying bus, although some devices may have such restrictions. Also, systems with caches that aren't DMA-coherent will work better when the underlying buffers don' t share cache lines with other data.

5.4.5 Using Consistent DMA mappings

To allocate and map large (PAGE_SIZE or so) consistent DMA regions, you should do:

```
dma_addr_t dma_handle;

cpu_addr = dma_alloc_coherent(dev, size, &dma_handle, gfp);
```

where device is a `struct device *`. This may be called in interrupt context with the GFP_ATOMIC flag.

Size is the length of the region you want to allocate, in bytes.

This routine will allocate RAM for that region, so it acts similarly to __get_free_pages() (but takes size instead of a page order). If your driver needs regions sized smaller than a page, you may prefer using the dma_pool interface, described below.

The consistent DMA mapping interfaces, will by default return a DMA address which is 32-bit addressable. Even if the device indicates (via the DMA mask) that it may address the upper 32-bits, consistent allocation will only return > 32-bit addresses for DMA if the consistent DMA mask has been explicitly changed via dma_set_coherent_mask(). This is true of the dma_pool interface as well.

dma_alloc_coherent() returns two values: the virtual address which you can use to access it from the CPU and dma_handle which you pass to the card.

The CPU virtual address and the DMA address are both guaranteed to be aligned to the smallest PAGE_SIZE order which is greater than or equal to the requested size. This invariant exists (for example) to guarantee that if you allocate a chunk which is smaller than or equal to 64 kilobytes, the extent of the buffer you receive will not cross a 64K boundary.

To unmap and free such a DMA region, you call:

```
dma_free_coherent(dev, size, cpu_addr, dma_handle);
```

where dev, size are the same as in the above call and cpu_addr and dma_handle are the values dma_alloc_coherent() returned to you. This function may not be called in interrupt context.

If your driver needs lots of smaller memory regions, you can write custom code to subdivide pages returned by dma_alloc_coherent(), or you can use the dma_pool API to do that. A dma_pool is like a kmem_cache, but it uses dma_alloc_coherent(), not __get_free_pages(). Also, it understands common hardware constraints for alignment, like queue heads needing to be aligned on N byte boundaries.

Create a dma_pool like this:

```
struct dma_pool *pool;

pool = dma_pool_create(name, dev, size, align, boundary);
```

The "name" is for diagnostics (like a kmem_cache name); dev and size are as above. The device's hardware alignment requirement for this type of data is "align" (which is expressed in bytes, and must be a power of two). If your device has no boundary crossing restrictions, pass 0 for boundary; passing 4096 says memory allocated from this pool must not cross 4KByte boundaries (but at that time it may be better to use dma_alloc_coherent() directly instead).

Allocate memory from a DMA pool like this:

```
cpu_addr = dma_pool_alloc(pool, flags, &dma_handle);
```

flags are GFP_KERNEL if blocking is permitted (not in_interrupt nor holding SMP locks), GFP_ATOMIC otherwise. Like dma_alloc_coherent(), this returns two values, cpu_addr and dma_handle.

Free memory that was allocated from a dma_pool like this:

```
dma_pool_free(pool, cpu_addr, dma_handle);
```

where pool is what you passed to *dma_pool_alloc()*, and cpu_addr and dma_handle are the values *dma_pool_alloc()* returned. This function may be called in interrupt context.

Destroy a dma_pool by calling:

```
dma_pool_destroy(pool);
```

Make sure you've called *dma_pool_free()* for all memory allocated from a pool before you destroy the pool. This function may not be called in interrupt context.

5.4.6 DMA Direction

The interfaces described in subsequent portions of this document take a DMA direction argument, which is an integer and takes on one of the following values:

```
DMA_BIDIRECTIONAL
DMA_TO_DEVICE
DMA_FROM_DEVICE
DMA_NONE
```

You should provide the exact DMA direction if you know it.

DMA_TO_DEVICE means "from main memory to the device" DMA_FROM_DEVICE means "from the device to main memory" It is the direction in which the data moves during the DMA transfer.

You are _strongly_ encouraged to specify this as precisely as you possibly can.

If you absolutely cannot know the direction of the DMA transfer, specify DMA_BIDIRECTIONAL. It means that the DMA can go in either direction. The platform guarantees that you may legally specify this, and that it will work, but this may be at the cost of performance for example.

The value DMA_NONE is to be used for debugging. One can hold this in a data structure before you come to know the precise direction, and this will help catch cases where your direction tracking logic has failed to set things up properly.

Another advantage of specifying this value precisely (outside of potential platform-specific optimizations of such) is for debugging. Some platforms actually have a write permission boolean which DMA mappings can be marked with, much like page protections in the user program address space. Such platforms can and do report errors in the kernel logs when the DMA controller hardware detects violation of the permission setting.

Only streaming mappings specify a direction, consistent mappings implicitly have a direction attribute setting of DMA_BIDIRECTIONAL.

The SCSI subsystem tells you the direction to use in the 'sc_data_direction'member of the SCSI command your driver is working on.

For Networking drivers, it' s a rather simple affair. For transmit packets, map/unmap them with the DMA_TO_DEVICE direction specifier. For receive packets, just the opposite, map/unmap them with the DMA_FROM_DEVICE direction specifier.

5.4.7 Using Streaming DMA mappings

The streaming DMA mapping routines can be called from interrupt context. There are two versions of each map/unmap, one which will map/unmap a single memory region, and one which will map/unmap a scatterlist.

To map a single region, you do:

```
struct device *dev = &my_dev->dev;
dma_addr_t dma_handle;
void *addr = buffer->ptr;
size_t size = buffer->len;

dma_handle = dma_map_single(dev, addr, size, direction);
if (dma_mapping_error(dev, dma_handle)) {
        /*
         * reduce current DMA mapping usage,
         * delay and try again later or
         * reset driver.
         */
        goto map_error_handling;
}
```

and to unmap it:

```
dma_unmap_single(dev, dma_handle, size, direction);
```

You should call dma_mapping_error() as dma_map_single() could fail and return error. Doing so will ensure that the mapping code will work correctly on all DMA implementations without any dependency on the specifics of the underlying implementation. Using the returned address without checking for errors could result in failures ranging from panics to silent data corruption. The same applies to dma_map_page() as well.

You should call dma_unmap_single() when the DMA activity is finished, e.g., from the interrupt which told you that the DMA transfer is done.

Using CPU pointers like this for single mappings has a disadvantage: you cannot reference HIGHMEM memory in this way. Thus, there is a map/unmap interface pair akin to dma_{map,unmap}_single(). These interfaces deal with page/offset pairs instead of CPU pointers. Specifically:

```
struct device *dev = &my_dev->dev;
dma_addr_t dma_handle;
struct page *page = buffer->page;
unsigned long offset = buffer->offset;
size_t size = buffer->len;

dma_handle = dma_map_page(dev, page, offset, size, direction);
if (dma_mapping_error(dev, dma_handle)) {
        /*
         * reduce current DMA mapping usage,
         * delay and try again later or
         * reset driver.
         */
        goto map_error_handling;
}

...

dma_unmap_page(dev, dma_handle, size, direction);
```

Here, "offset" means byte offset within the given page.

You should call dma_mapping_error() as dma_map_page() could fail and return error as outlined under the dma_map_single() discussion.

You should call dma_unmap_page() when the DMA activity is finished, e.g., from the interrupt which told you that the DMA transfer is done.

With scatterlists, you map a region gathered from several regions by:

```
int i, count = dma_map_sg(dev, sglist, nents, direction);
struct scatterlist *sg;

for_each_sg(sglist, sg, count, i) {
        hw_address[i] = sg_dma_address(sg);
```

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```
        hw_len[i] = sg_dma_len(sg);
}
```

where nents is the number of entries in the sglist.

The implementation is free to merge several consecutive sglist entries into one (e.g. if DMA mapping is done with PAGE_SIZE granularity, any consecutive sglist entries can be merged into one provided the first one ends and the second one starts on a page boundary - in fact this is a huge advantage for cards which either cannot do scatter-gather or have very limited number of scatter-gather entries) and returns the actual number of sg entries it mapped them to. On failure 0 is returned.

Then you should loop count times (note: this can be less than nents times) and use sg_dma_address() and sg_dma_len() macros where you previously accessed sg->address and sg->length as shown above.

To unmap a scatterlist, just call:

```
dma_unmap_sg(dev, sglist, nents, direction);
```

Again, make sure DMA activity has already finished.

Note: The 'nents' argument to the dma_unmap_sg call must be the _same_ one you passed into the dma_map_sg call, it should _NOT_ be the 'count' value _returned_ from the dma_map_sg call.

Every dma_map_{single,sg}() call should have its dma_unmap_{single,sg}() counterpart, because the DMA address space is a shared resource and you could render the machine unusable by consuming all DMA addresses.

If you need to use the same streaming DMA region multiple times and touch the data in between the DMA transfers, the buffer needs to be synced properly in order for the CPU and device to see the most up-to-date and correct copy of the DMA buffer.

So, firstly, just map it with dma_map_{single,sg}(), and after each DMA transfer call either:

```
dma_sync_single_for_cpu(dev, dma_handle, size, direction);
```

or:

```
dma_sync_sg_for_cpu(dev, sglist, nents, direction);
```

as appropriate.

Then, if you wish to let the device get at the DMA area again, finish accessing the data with the CPU, and then before actually giving the buffer to the hardware call either:

```
dma_sync_single_for_device(dev, dma_handle, size, direction);
```

or:

```
dma_sync_sg_for_device(dev, sglist, nents, direction);
```

as appropriate.

Note: The 'nents' argument to dma_sync_sg_for_cpu() and dma_sync_sg_for_device() must be the same passed to dma_map_sg(). It is _NOT_ the count returned by dma_map_sg().

After the last DMA transfer call one of the DMA unmap routines dma_unmap_{single,sg}(). If you don't touch the data from the first dma_map_*() call till dma_unmap_*(), then you don't have to call the dma_sync_*() routines at all.

Here is pseudo code which shows a situation in which you would need to use the dma_sync_*() interfaces:

```
my_card_setup_receive_buffer(struct my_card *cp, char *buffer, int␣
↪len)
{
        dma_addr_t mapping;

        mapping = dma_map_single(cp->dev, buffer, len, DMA_FROM_
↪DEVICE);
        if (dma_mapping_error(cp->dev, mapping)) {
                /*
                 * reduce current DMA mapping usage,
                 * delay and try again later or
                 * reset driver.
                 */
                goto map_error_handling;
        }

        cp->rx_buf = buffer;
        cp->rx_len = len;
        cp->rx_dma = mapping;

        give_rx_buf_to_card(cp);
}

...

my_card_interrupt_handler(int irq, void *devid, struct pt_regs␣
↪*regs)
{
        struct my_card *cp = devid;

        ...
        if (read_card_status(cp) == RX_BUF_TRANSFERRED) {
```

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```
                struct my_card_header *hp;

                /* Examine the header to see if we wish
                 * to accept the data.  But synchronize
                 * the DMA transfer with the CPU first
                 * so that we see updated contents.
                 */
                dma_sync_single_for_cpu(&cp->dev, cp->rx_dma,
                                        cp->rx_len,
                                        DMA_FROM_DEVICE);

                /* Now it is safe to examine the buffer. */
                hp = (struct my_card_header *) cp->rx_buf;
                if (header_is_ok(hp)) {
                        dma_unmap_single(&cp->dev, cp->rx_dma, cp->
↪rx_len,
                                         DMA_FROM_DEVICE);
                        pass_to_upper_layers(cp->rx_buf);
                        make_and_setup_new_rx_buf(cp);
                } else {
                        /* CPU should not write to
                         * DMA_FROM_DEVICE-mapped area,
                         * so dma_sync_single_for_device() is
                         * not needed here. It would be required
                         * for DMA_BIDIRECTIONAL mapping if
                         * the memory was modified.
                         */
                        give_rx_buf_to_card(cp);
                }
        }
}
```

Drivers converted fully to this interface should not use virt_to_bus() any longer, nor should they use bus_to_virt(). Some drivers have to be changed a little bit, because there is no longer an equivalent to bus_to_virt() in the dynamic DMA mapping scheme - you have to always store the DMA addresses returned by the dma_alloc_coherent(), *dma_pool_alloc()*, and dma_map_single() calls (dma_map_sg() stores them in the scatterlist itself if the platform supports dynamic DMA mapping in hardware) in your driver structures and/or in the card registers.

All drivers should be using these interfaces with no exceptions. It is planned to completely remove virt_to_bus() and bus_to_virt() as they are entirely deprecated. Some ports already do not provide these as it is impossible to correctly support them.

5.4.8 Handling Errors

DMA address space is limited on some architectures and an allocation failure can be determined by:

- checking if dma_alloc_coherent() returns NULL or dma_map_sg returns 0
- checking the dma_addr_t returned from dma_map_single() and dma_map_page() by using dma_mapping_error():

```
dma_addr_t dma_handle;

dma_handle = dma_map_single(dev, addr, size, direction);
if (dma_mapping_error(dev, dma_handle)) {
        /*
         * reduce current DMA mapping usage,
         * delay and try again later or
         * reset driver.
         */
        goto map_error_handling;
}
```

- unmap pages that are already mapped, when mapping error occurs in the middle of a multiple page mapping attempt. These example are applicable to dma_map_page() as well.

Example 1:

```
dma_addr_t dma_handle1;
dma_addr_t dma_handle2;

dma_handle1 = dma_map_single(dev, addr, size, direction);
if (dma_mapping_error(dev, dma_handle1)) {
        /*
         * reduce current DMA mapping usage,
         * delay and try again later or
         * reset driver.
         */
        goto map_error_handling1;
}
dma_handle2 = dma_map_single(dev, addr, size, direction);
if (dma_mapping_error(dev, dma_handle2)) {
        /*
         * reduce current DMA mapping usage,
         * delay and try again later or
         * reset driver.
         */
        goto map_error_handling2;
}

...
```

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```
map_error_handling2:
        dma_unmap_single(dma_handle1);
map_error_handling1:
```

Example 2:

```
/*
 * if buffers are allocated in a loop, unmap all mapped buffers when
 * mapping error is detected in the middle
 */

dma_addr_t dma_addr;
dma_addr_t array[DMA_BUFFERS];
int save_index = 0;

for (i = 0; i < DMA_BUFFERS; i++) {

        ...

        dma_addr = dma_map_single(dev, addr, size, direction);
        if (dma_mapping_error(dev, dma_addr)) {
                /*
                 * reduce current DMA mapping usage,
                 * delay and try again later or
                 * reset driver.
                 */
                goto map_error_handling;
        }
        array[i].dma_addr = dma_addr;
        save_index++;
}

...

map_error_handling:

for (i = 0; i < save_index; i++) {

        ...

        dma_unmap_single(array[i].dma_addr);
}
```

Networking drivers must call dev_kfree_skb() to free the socket buffer and return NETDEV_TX_OK if the DMA mapping fails on the transmit hook (ndo_start_xmit). This means that the socket buffer is just dropped in the failure case.

SCSI drivers must return SCSI_MLQUEUE_HOST_BUSY if the DMA mapping fails in the queuecommand hook. This means that the SCSI subsystem passes the command to the driver again later.

5.4.9 Optimizing Unmap State Space Consumption

On many platforms, dma_unmap_{single,page}() is simply a nop. Therefore, keeping track of the mapping address and length is a waste of space. Instead of filling your drivers up with ifdefs and the like to "work around" this (which would defeat the whole purpose of a portable API) the following facilities are provided.

Actually, instead of describing the macros one by one, we'll transform some example code.

1) Use DEFINE_DMA_UNMAP_{ADDR,LEN} in state saving structures. Example, before:

```
struct ring_state {
        struct sk_buff *skb;
        dma_addr_t mapping;
        __u32 len;
};
```

after:

```
struct ring_state {
        struct sk_buff *skb;
        DEFINE_DMA_UNMAP_ADDR(mapping);
        DEFINE_DMA_UNMAP_LEN(len);
};
```

2) Use dma_unmap_{addr,len}_set() to set these values. Example, before:

```
ringp->mapping = FOO;
ringp->len = BAR;
```

after:

```
dma_unmap_addr_set(ringp, mapping, FOO);
dma_unmap_len_set(ringp, len, BAR);
```

3) Use dma_unmap_{addr,len}() to access these values. Example, before:

```
dma_unmap_single(dev, ringp->mapping, ringp->len,
                 DMA_FROM_DEVICE);
```

after:

```
dma_unmap_single(dev,
                 dma_unmap_addr(ringp, mapping),
                 dma_unmap_len(ringp, len),
                 DMA_FROM_DEVICE);
```

It really should be self-explanatory. We treat the ADDR and LEN separately, because it is possible for an implementation to only need the address in order to perform the unmap operation.

5.4.10 Platform Issues

If you are just writing drivers for Linux and do not maintain an architecture port for the kernel, you can safely skip down to "Closing".

1) Struct scatterlist requirements.

   You need to enable CONFIG_NEED_SG_DMA_LENGTH if the architecture supports IOMMUs (including software IOMMU).

2) ARCH_DMA_MINALIGN

   Architectures must ensure that kmalloc'ed buffer is DMA-safe. Drivers and subsystems depend on it. If an architecture isn't fully DMA-coherent (i.e. hardware doesn't ensure that data in the CPU cache is identical to data in main memory), ARCH_DMA_MINALIGN must be set so that the memory allocator makes sure that kmalloc'ed buffer doesn't share a cache line with the others. See arch/arm/include/asm/cache.h as an example.

   Note that ARCH_DMA_MINALIGN is about DMA memory alignment constraints. You don't need to worry about the architecture data alignment constraints (e.g. the alignment constraints about 64-bit objects).

5.4.11 Closing

This document, and the API itself, would not be in its current form without the feedback and suggestions from numerous individuals. We would like to specifically mention, in no particular order, the following people:

```
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```

5.5 DMA attributes

This document describes the semantics of the DMA attributes that are defined in linux/dma-mapping.h.

5.5.1 DMA_ATTR_WEAK_ORDERING

DMA_ATTR_WEAK_ORDERING specifies that reads and writes to the mapping may be weakly ordered, that is that reads and writes may pass each other.

Since it is optional for platforms to implement DMA_ATTR_WEAK_ORDERING, those that do not will simply ignore the attribute and exhibit default behavior.

5.5.2 DMA_ATTR_WRITE_COMBINE

DMA_ATTR_WRITE_COMBINE specifies that writes to the mapping may be buffered to improve performance.

Since it is optional for platforms to implement DMA_ATTR_WRITE_COMBINE, those that do not will simply ignore the attribute and exhibit default behavior.

5.5.3 DMA_ATTR_NO_KERNEL_MAPPING

DMA_ATTR_NO_KERNEL_MAPPING lets the platform to avoid creating a kernel virtual mapping for the allocated buffer. On some architectures creating such mapping is non-trivial task and consumes very limited resources (like kernel virtual address space or dma consistent address space). Buffers allocated with this attribute can be only passed to user space by calling dma_mmap_attrs(). By using this API, you are guaranteeing that you won't dereference the pointer returned by dma_alloc_attr(). You can treat it as a cookie that must be passed to dma_mmap_attrs() and dma_free_attrs(). Make sure that both of these also get this attribute set on each call.

Since it is optional for platforms to implement DMA_ATTR_NO_KERNEL_MAPPING, those that do not will simply ignore the attribute and exhibit default behavior.

5.5.4 DMA_ATTR_SKIP_CPU_SYNC

By default dma_map_{single,page,sg} functions family transfer a given buffer from CPU domain to device domain. Some advanced use cases might require sharing a buffer between more than one device. This requires having a mapping created separately for each device and is usually performed by calling dma_map_{single,page,sg} function more than once for the given buffer with device pointer to each device taking part in the buffer sharing. The first call transfers a buffer from 'CPU' domain to 'device' domain, what synchronizes CPU caches for the given region (usually it means that the cache has been flushed or invalidated depending on the dma direction). However, next calls to dma_map_{single,page,sg}() for other devices will perform exactly the same synchronization operation on the CPU cache. CPU cache synchronization might be a time consuming operation, especially if the buffers are large, so it is highly recommended to avoid it if possible. DMA_ATTR_SKIP_CPU_SYNC allows platform code to skip synchronization of the CPU cache for the given buffer assuming that it has been already transferred to 'device' domain. This attribute can be also used for dma_unmap_{single,page,sg} functions family to force buffer to stay in device domain after releasing a mapping for it. Use this attribute with care!

5.5.5 DMA_ATTR_FORCE_CONTIGUOUS

By default DMA-mapping subsystem is allowed to assemble the buffer allocated by dma_alloc_attrs() function from individual pages if it can be mapped as contiguous chunk into device dma address space. By specifying this attribute the allocated buffer is forced to be contiguous also in physical memory.

5.5.6 DMA_ATTR_ALLOC_SINGLE_PAGES

This is a hint to the DMA-mapping subsystem that it's probably not worth the time to try to allocate memory to in a way that gives better TLB efficiency (AKA it's not worth trying to build the mapping out of larger pages). You might want to specify this if:

- You know that the accesses to this memory won't thrash the TLB. You might know that the accesses are likely to be sequential or that they aren't sequential but it's unlikely you'll ping-pong between many addresses that are likely to be in different physical pages.
- You know that the penalty of TLB misses while accessing the memory will be small enough to be inconsequential. If you are doing a heavy operation like decryption or decompression this might be the case.
- You know that the DMA mapping is fairly transitory. If you expect the mapping to have a short lifetime then it may be worth it to optimize allocation (avoid coming up with large pages) instead of getting the slight performance win of larger pages.

Setting this hint doesn't guarantee that you won't get huge pages, but it means that we won't try quite as hard to get them.

Note: At the moment DMA_ATTR_ALLOC_SINGLE_PAGES is only implemented on ARM, though ARM64 patches will likely be posted soon.

5.5.7 DMA_ATTR_NO_WARN

This tells the DMA-mapping subsystem to suppress allocation failure reports (similarly to __GFP_NOWARN).

On some architectures allocation failures are reported with error messages to the system logs. Although this can help to identify and debug problems, drivers which handle failures (eg, retry later) have no problems with them, and can actually flood the system logs with error messages that aren't any problem at all, depending on the implementation of the retry mechanism.

So, this provides a way for drivers to avoid those error messages on calls where allocation failures are not a problem, and shouldn't bother the logs.

Note: At the moment DMA_ATTR_NO_WARN is only implemented on PowerPC.

5.5.8 DMA_ATTR_PRIVILEGED

Some advanced peripherals such as remote processors and GPUs perform accesses to DMA buffers in both privileged "supervisor" and unprivileged "user" modes. This attribute is used to indicate to the DMA-mapping subsystem that the buffer is fully accessible at the elevated privilege level (and ideally inaccessible or at least read-only at the lesser-privileged levels).

5.6 DMA with ISA and LPC devices

Author
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This document describes how to do DMA transfers using the old ISA DMA controller. Even though ISA is more or less dead today the LPC bus uses the same DMA system so it will be around for quite some time.

5.6.1 Headers and dependencies

To do ISA style DMA you need to include two headers:

```
#include <linux/dma-mapping.h>
#include <asm/dma.h>
```

The first is the generic DMA API used to convert virtual addresses to bus addresses (see *Dynamic DMA mapping using the generic device* for details).

The second contains the routines specific to ISA DMA transfers. Since this is not present on all platforms make sure you construct your Kconfig to be dependent on ISA_DMA_API (not ISA) so that nobody tries to build your driver on unsupported platforms.

5.6.2 Buffer allocation

The ISA DMA controller has some very strict requirements on which memory it can access so extra care must be taken when allocating buffers.

(You usually need a special buffer for DMA transfers instead of transferring directly to and from your normal data structures.)

The DMA-able address space is the lowest 16 MB of _physical_ memory. Also the transfer block may not cross page boundaries (which are 64 or 128 KiB depending on which channel you use).

In order to allocate a piece of memory that satisfies all these requirements you pass the flag GFP_DMA to kmalloc.

Unfortunately the memory available for ISA DMA is scarce so unless you allocate the memory during boot-up it's a good idea to also pass __GFP_RETRY_MAYFAIL and __GFP_NOWARN to make the allocator try a bit harder.

(This scarcity also means that you should allocate the buffer as early as possible and not release it until the driver is unloaded.)

5.6.3 Address translation

To translate the virtual address to a bus address, use the normal DMA API. Do _not_ use isa_virt_to_bus() even though it does the same thing. The reason for this is that the function isa_virt_to_bus() will require a Kconfig dependency to ISA, not just ISA_DMA_API which is really all you need. Remember that even though the DMA controller has its origins in ISA it is used elsewhere.

Note: x86_64 had a broken DMA API when it came to ISA but has since been fixed. If your arch has problems then fix the DMA API instead of reverting to the ISA functions.

5.6.4 Channels

A normal ISA DMA controller has 8 channels. The lower four are for 8-bit transfers and the upper four are for 16-bit transfers.

(Actually the DMA controller is really two separate controllers where channel 4 is used to give DMA access for the second controller (0-3). This means that of the four 16-bits channels only three are usable.)

You allocate these in a similar fashion as all basic resources:

extern int request_dma(unsigned int dmanr, const char * device_id); extern void free_dma(unsigned int dmanr);

The ability to use 16-bit or 8-bit transfers is _not_ up to you as a driver author but depends on what the hardware supports. Check your specs or test different channels.

5.6.5 Transfer data

Now for the good stuff, the actual DMA transfer. :)

Before you use any ISA DMA routines you need to claim the DMA lock using claim_dma_lock(). The reason is that some DMA operations are not atomic so only one driver may fiddle with the registers at a time.

The first time you use the DMA controller you should call clear_dma_ff(). This clears an internal register in the DMA controller that is used for the non-atomic operations. As long as you (and everyone else) uses the locking functions then you only need to reset this once.

Next, you tell the controller in which direction you intend to do the transfer using set_dma_mode(). Currently you have the options DMA_MODE_READ and DMA_MODE_WRITE.

Set the address from where the transfer should start (this needs to be 16-bit aligned for 16-bit transfers) and how many bytes to transfer. Note that it's _bytes_. The DMA routines will do all the required translation to values that the DMA controller understands.

The final step is enabling the DMA channel and releasing the DMA lock.

Once the DMA transfer is finished (or timed out) you should disable the channel again. You should also check get_dma_residue() to make sure that all data has been transferred.

Example:

```
int flags, residue;

flags = claim_dma_lock();

clear_dma_ff();

set_dma_mode(channel, DMA_MODE_WRITE);
set_dma_addr(channel, phys_addr);
set_dma_count(channel, num_bytes);

dma_enable(channel);

release_dma_lock(flags);

while (!device_done());

flags = claim_dma_lock();

dma_disable(channel);

residue = dma_get_residue(channel);
if (residue != 0)
        printk(KERN_ERR "driver: Incomplete DMA transfer!"
                " %d bytes left!\n", residue);

release_dma_lock(flags);
```

5.6.6 Suspend/resume

It is the driver’s responsibility to make sure that the machine isn’t suspended while a DMA transfer is in progress. Also, all DMA settings are lost when the system suspends so if your driver relies on the DMA controller being in a certain state then you have to restore these registers upon resume.

5.7 Memory Management APIs

5.7.1 User Space Memory Access

access_ok

`access_ok (addr, size)`

Checks if a user space pointer is valid

Parameters

addr
User space pointer to start of block to check

size
Size of block to check

Context

User context only. This function may sleep if pagefaults are enabled.

Description

Checks if a pointer to a block of memory in user space is valid.

Note that, depending on architecture, this function probably just checks that the pointer is in the user space range - after calling this function, memory access functions may still return -EFAULT.

Return

true (nonzero) if the memory block may be valid, false (zero) if it is definitely invalid.

get_user

`get_user (x, ptr)`

Get a simple variable from user space.

Parameters

x
Variable to store result.

ptr
Source address, in user space.

Context

User context only. This function may sleep if pagefaults are enabled.

Description

This macro copies a single simple variable from user space to kernel space. It supports simple types like char and int, but not larger data types like structures or arrays.

ptr must have pointer-to-simple-variable type, and the result of dereferencing **ptr** must be assignable to **x** without a cast.

Return

zero on success, or -EFAULT on error. On error, the variable **x** is set to zero.

__get_user

`__get_user (x, ptr)`

Get a simple variable from user space, with less checking.

Parameters

x
Variable to store result.

ptr
Source address, in user space.

Context

User context only. This function may sleep if pagefaults are enabled.

Description

This macro copies a single simple variable from user space to kernel space. It supports simple types like char and int, but not larger data types like structures or arrays.

ptr must have pointer-to-simple-variable type, and the result of dereferencing **ptr** must be assignable to **x** without a cast.

Caller must check the pointer with *access_ok()* before calling this function.

Return

zero on success, or -EFAULT on error. On error, the variable **x** is set to zero.

put_user

`put_user (x, ptr)`

Write a simple value into user space.

Parameters

x
Value to copy to user space.

ptr
Destination address, in user space.

Context

User context only. This function may sleep if pagefaults are enabled.

Description

This macro copies a single simple value from kernel space to user space. It supports simple types like char and int, but not larger data types like structures or arrays.

ptr must have pointer-to-simple-variable type, and **x** must be assignable to the result of dereferencing **ptr**.

Return

zero on success, or -EFAULT on error.

__put_user

`__put_user (x, ptr)`

Write a simple value into user space, with less checking.

Parameters

x
Value to copy to user space.

ptr
Destination address, in user space.

Context

User context only. This function may sleep if pagefaults are enabled.

Description

This macro copies a single simple value from kernel space to user space. It supports simple types like char and int, but not larger data types like structures or arrays.

ptr must have pointer-to-simple-variable type, and **x** must be assignable to the result of dereferencing **ptr**.

Caller must check the pointer with *access_ok()* before calling this function.

Return

zero on success, or -EFAULT on error.

unsigned long **clear_user**(void __user *to, unsigned long n)

Zero a block of memory in user space.

Parameters

void __user *to
Destination address, in user space.

unsigned long n
Number of bytes to zero.

Description

Zero a block of memory in user space.

Return

number of bytes that could not be cleared. On success, this will be zero.

unsigned long **__clear_user**(void __user *to, unsigned long n)

Zero a block of memory in user space, with less checking.

Parameters

void __user *to
Destination address, in user space.

unsigned long n
Number of bytes to zero.

Description

Zero a block of memory in user space. Caller must check the specified block with *access_ok()* before calling this function.

Return

number of bytes that could not be cleared. On success, this will be zero.

int **get_user_pages_fast**(unsigned long start, int nr_pages, unsigned int gup_flags, struct page **pages)

pin user pages in memory

Parameters

unsigned long start
starting user address

int nr_pages
number of pages from start to pin

unsigned int gup_flags
flags modifying pin behaviour

struct page **pages
array that receives pointers to the pages pinned. Should be at least nr_pages long.

Description

Attempt to pin user pages in memory without taking mm->mmap_lock. If not successful, it will fall back to taking the lock and calling get_user_pages().

Returns number of pages pinned. This may be fewer than the number requested. If nr_pages is 0 or negative, returns 0. If no pages were pinned, returns -errno.

5.7.2 Memory Allocation Controls

Functions which need to allocate memory often use GFP flags to express how that memory should be allocated. The GFP acronym stands for "get free pages", the underlying memory allocation function. Not every GFP flag is allowed to every function which may allocate memory. Most users will want to use a plain `GFP_KERNEL`.

Page mobility and placement hints

These flags provide hints about how mobile the page is. Pages with similar mobility are placed within the same pageblocks to minimise problems due to external fragmentation.

`__GFP_MOVABLE` (also a zone modifier) indicates that the page can be moved by page migration during memory compaction or can be reclaimed.

`__GFP_RECLAIMABLE` is used for slab allocations that specify SLAB_RECLAIM_ACCOUNT and whose pages can be freed via shrinkers.

`__GFP_WRITE` indicates the caller intends to dirty the page. Where possible, these pages will be spread between local zones to avoid all the dirty pages being in one zone (fair zone allocation policy).

`__GFP_HARDWALL` enforces the cpuset memory allocation policy.

`__GFP_THISNODE` forces the allocation to be satisfied from the requested node with no fallbacks or placement policy enforcements.

`__GFP_ACCOUNT` causes the allocation to be accounted to kmemcg.

Watermark modifiers – controls access to emergency reserves

`__GFP_HIGH` indicates that the caller is high-priority and that granting the request is necessary before the system can make forward progress. For example, creating an IO context to clean pages.

`__GFP_ATOMIC` indicates that the caller cannot reclaim or sleep and is high priority. Users are typically interrupt handlers. This may be used in conjunction with `__GFP_HIGH`

`__GFP_MEMALLOC` allows access to all memory. This should only be used when the caller guarantees the allocation will allow more memory to be freed very shortly e.g. process exiting or swapping. Users either should be the MM or co-ordinating closely with the VM (e.g. swap over NFS). Users of this flag have to be extremely careful to not deplete the reserve completely and implement a throttling mechanism which controls the consumption of the reserve based on the amount of freed memory. Usage of a pre-allocated pool (e.g. mempool) should be always considered before using this flag.

`__GFP_NOMEMALLOC` is used to explicitly forbid access to emergency reserves. This takes precedence over the `__GFP_MEMALLOC` flag if both are set.

Reclaim modifiers

Please note that all the following flags are only applicable to sleepable allocations (e.g. `GFP_NOWAIT` and `GFP_ATOMIC` will ignore them).

`__GFP_IO` can start physical IO.

`__GFP_FS` can call down to the low-level FS. Clearing the flag avoids the allocator recursing into the filesystem which might already be holding locks.

`__GFP_DIRECT_RECLAIM` indicates that the caller may enter direct reclaim. This flag can be cleared to avoid unnecessary delays when a fallback option is available.

`__GFP_KSWAPD_RECLAIM` indicates that the caller wants to wake kswapd when the low watermark is reached and have it reclaim pages until the high watermark is reached. A caller may wish to clear this flag when fallback options are available and the reclaim is likely to disrupt the system. The canonical example is THP allocation where a fallback is cheap but reclaim/compaction may cause indirect stalls.

`__GFP_RECLAIM` is shorthand to allow/forbid both direct and kswapd reclaim.

The default allocator behavior depends on the request size. We have a concept of so called costly allocations (with order > `PAGE_ALLOC_COSTLY_ORDER`). !costly allocations are too essential to fail so they are implicitly non-failing by default (with some exceptions like OOM victims might fail so the caller still has to check for failures) while costly requests try to be not disruptive and back off even without invoking the OOM killer. The following three modifiers might be used to override some of these implicit rules

`__GFP_NORETRY`: The VM implementation will try only very lightweight memory direct reclaim to get some memory under memory pressure (thus it can sleep). It will avoid disruptive actions like OOM killer. The caller must handle the failure which is quite likely to happen under heavy memory pressure. The flag is suitable when failure can easily be handled at small cost, such as reduced throughput

`__GFP_RETRY_MAYFAIL`: The VM implementation will retry memory reclaim procedures that have previously failed if there is some indication that progress has been made else where. It can wait for other tasks to attempt high level approaches to freeing memory such as compaction (which removes fragmentation) and page-out. There is still a definite limit to the number of retries, but it is a larger limit than with `__GFP_NORETRY`. Allocations with this flag may fail, but only when there is genuinely little unused memory. While these allocations do not directly trigger the OOM killer, their failure indicates that the system is likely to need to use the OOM killer soon. The caller must handle failure, but can reasonably do so by failing a higher-level request, or completing it only in a much less efficient manner. If the allocation does fail, and the caller is in a position to free some non-essential memory, doing so could benefit the system as a whole.

`__GFP_NOFAIL`: The VM implementation _must_ retry infinitely: the caller cannot handle allocation failures. The allocation could block indefinitely but will never return with failure. Testing for failure is pointless. New users should be evaluated carefully (and the flag should be used only when there is no reasonable failure policy) but it is definitely preferable to use the flag rather than opencode endless loop around allocator. Using this flag for costly allocations is _highly_ discouraged.

Useful GFP flag combinations

Useful GFP flag combinations that are commonly used. It is recommended that subsystems start with one of these combinations and then set/clear `__GFP_FOO` flags as necessary.

`GFP_ATOMIC` users can not sleep and need the allocation to succeed. A lower watermark is applied to allow access to "atomic reserves". The current implementation doesn't support NMI and few other strict non-preemptive contexts (e.g. raw_spin_lock). The same applies to `GFP_NOWAIT`.

`GFP_KERNEL` is typical for kernel-internal allocations. The caller requires `ZONE_NORMAL` or a lower zone for direct access but can direct reclaim.

`GFP_KERNEL_ACCOUNT` is the same as GFP_KERNEL, except the allocation is accounted to kmemcg.

`GFP_NOWAIT` is for kernel allocations that should not stall for direct reclaim, start physical IO or use any filesystem callback.

`GFP_NOIO` will use direct reclaim to discard clean pages or slab pages that do not require the starting of any physical IO. Please try to avoid using this flag directly and instead use memalloc_noio_{save,restore} to mark the whole scope which cannot perform any IO with a short explanation why. All allocation requests will inherit GFP_NOIO implicitly.

`GFP_NOFS` will use direct reclaim but will not use any filesystem interfaces. Please try to avoid using this flag directly and instead use memalloc_nofs_{save,restore} to mark the whole scope which cannot/shouldn't recurse into the FS layer with a short explanation why. All allocation requests will inherit GFP_NOFS implicitly.

`GFP_USER` is for userspace allocations that also need to be directly accessibly by the kernel or hardware. It is typically used by hardware for buffers that are mapped to userspace (e.g. graphics) that hardware still must DMA to. cpuset limits are enforced for these allocations.

`GFP_DMA` exists for historical reasons and should be avoided where possible. The flags indicates that the caller requires that the lowest zone be used (`ZONE_DMA` or 16M on x86-64). Ideally, this would be removed but it would require careful auditing as some users really require it and others use the flag to avoid lowmem reserves in `ZONE_DMA` and treat the lowest zone as a type of emergency reserve.

`GFP_DMA32` is similar to `GFP_DMA` except that the caller requires a 32-bit address.

`GFP_HIGHUSER` is for userspace allocations that may be mapped to userspace, do not need to be directly accessible by the kernel but that cannot move once in use. An example may be a hardware allocation that maps data directly into userspace but has no addressing limitations.

`GFP_HIGHUSER_MOVABLE` is for userspace allocations that the kernel does not need direct access to but can use kmap() when access is required. They are expected to be movable via page reclaim or page migration. Typically, pages on the LRU would also be allocated with `GFP_HIGHUSER_MOVABLE`.

`GFP_TRANSHUGE` and `GFP_TRANSHUGE_LIGHT` are used for THP allocations. They are compound allocations that will generally fail quickly if memory is not available and will not wake kswapd/kcompactd on failure. The _LIGHT version does not attempt reclaim/compaction at all and is by default used in page fault path, while the non-light is used by khugepaged.

5.7.3 The Slab Cache

void *`kmalloc`(size_t size, gfp_t flags)

allocate memory

Parameters

`size_t size`
how many bytes of memory are required.

`gfp_t flags`
the type of memory to allocate.

Description

kmalloc is the normal method of allocating memory for objects smaller than page size in the kernel.

The allocated object address is aligned to at least ARCH_KMALLOC_MINALIGN bytes. For **size** of power of two bytes, the alignment is also guaranteed to be at least to the size.

The **flags** argument may be one of the GFP flags defined at include/linux/gfp.h and described at Memory Management APIs

The recommended usage of the **flags** is described at Memory Allocation Guide

Below is a brief outline of the most useful GFP flags

`GFP_KERNEL`
Allocate normal kernel ram. May sleep.

`GFP_NOWAIT`
Allocation will not sleep.

`GFP_ATOMIC`
Allocation will not sleep. May use emergency pools.

`GFP_HIGHUSER`
Allocate memory from high memory on behalf of user.

Also it is possible to set different flags by OR' ing in one or more of the following additional **flags**:

`__GFP_HIGH`
This allocation has high priority and may use emergency pools.

`__GFP_NOFAIL`
Indicate that this allocation is in no way allowed to fail (think twice before using).

`__GFP_NORETRY`
If memory is not immediately available, then give up at once.

`__GFP_NOWARN`
If allocation fails, don' t issue any warnings.

__GFP_RETRY_MAYFAIL
Try really hard to succeed the allocation but fail eventually.

void ***kmalloc_array**(size_t n, size_t size, gfp_t flags)
allocate memory for an array.

Parameters

size_t n
number of elements.

size_t size
element size.

gfp_t flags
the type of memory to allocate (see kmalloc).

void ***kcalloc**(size_t n, size_t size, gfp_t flags)
allocate memory for an array. The memory is set to zero.

Parameters

size_t n
number of elements.

size_t size
element size.

gfp_t flags
the type of memory to allocate (see kmalloc).

void ***kzalloc**(size_t size, gfp_t flags)
allocate memory. The memory is set to zero.

Parameters

size_t size
how many bytes of memory are required.

gfp_t flags
the type of memory to allocate (see kmalloc).

void ***kzalloc_node**(size_t size, gfp_t flags, int node)
allocate zeroed memory from a particular memory node.

Parameters

size_t size
how many bytes of memory are required.

gfp_t flags
the type of memory to allocate (see kmalloc).

int node
memory node from which to allocate

void ***kmem_cache_alloc**(struct kmem_cache *cachep, gfp_t flags)
Allocate an object

Parameters

struct kmem_cache *cachep
The cache to allocate from.

gfp_t flags
See *kmalloc()*.

Description

Allocate an object from this cache. The flags are only relevant if the cache has no available objects.

Return

pointer to the new object or NULL in case of error

void ***kmem_cache_alloc_node**(struct kmem_cache *cachep, gfp_t flags, int nodeid)
Allocate an object on the specified node

Parameters

struct kmem_cache *cachep
The cache to allocate from.

gfp_t flags
See *kmalloc()*.

int nodeid
node number of the target node.

Description

Identical to kmem_cache_alloc but it will allocate memory on the given node, which can improve the performance for cpu bound structures.

Fallback to other node is possible if __GFP_THISNODE is not set.

Return

pointer to the new object or NULL in case of error

void **kmem_cache_free**(struct kmem_cache *cachep, void *objp)
Deallocate an object

Parameters

struct kmem_cache *cachep
The cache the allocation was from.

void *objp
The previously allocated object.

Description

Free an object which was previously allocated from this cache.

void **kfree**(const void *objp)
free previously allocated memory

Parameters

const void *objp
pointer returned by kmalloc.

Description

If **objp** is NULL, no operation is performed.

Don't free memory not originally allocated by *kmalloc()* or you will run into trouble.

size_t **__ksize**(const void *objp)

- Uninstrumented ksize.

Parameters

const void *objp
pointer to the object

Description

Unlike *ksize()*, *__ksize()* is uninstrumented, and does not provide the same safety checks as *ksize()* with KASAN instrumentation enabled.

Return

size of the actual memory used by **objp** in bytes

struct kmem_cache ***kmem_cache_create_usercopy**(const char *name, unsigned int size, unsigned int align, slab_flags_t flags, unsigned int useroffset, unsigned int usersize, void (*ctor)(void*))

Create a cache with a region suitable for copying to userspace

Parameters

const char *name
A string which is used in /proc/slabinfo to identify this cache.

unsigned int size
The size of objects to be created in this cache.

unsigned int align
The required alignment for the objects.

slab_flags_t flags
SLAB flags

unsigned int useroffset
Usercopy region offset

unsigned int usersize
Usercopy region size

void (*ctor)(void *)
A constructor for the objects.

Description

Cannot be called within a interrupt, but can be interrupted. The **ctor** is run when new pages are allocated by the cache.

The flags are

`SLAB_POISON` - Poison the slab with a known test pattern (a5a5a5a5) to catch references to uninitialised memory.

`SLAB_RED_ZONE` - Insert *Red* zones around the allocated memory to check for buffer overruns.

`SLAB_HWCACHE_ALIGN` - Align the objects in this cache to a hardware cacheline. This can be beneficial if you're counting cycles as closely as davem.

Return

a pointer to the cache on success, NULL on failure.

struct kmem_cache ***kmem_cache_create**(const char *name, unsigned int size, unsigned int align, slab_flags_t flags, void (*ctor)(void*))

Create a cache.

Parameters

const char *name
A string which is used in /proc/slabinfo to identify this cache.

unsigned int size
The size of objects to be created in this cache.

unsigned int align
The required alignment for the objects.

slab_flags_t flags
SLAB flags

void (*ctor)(void *)
A constructor for the objects.

Description

Cannot be called within a interrupt, but can be interrupted. The **ctor** is run when new pages are allocated by the cache.

The flags are

`SLAB_POISON` - Poison the slab with a known test pattern (a5a5a5a5) to catch references to uninitialised memory.

`SLAB_RED_ZONE` - Insert *Red* zones around the allocated memory to check for buffer overruns.

`SLAB_HWCACHE_ALIGN` - Align the objects in this cache to a hardware cacheline. This can be beneficial if you're counting cycles as closely as davem.

Return

a pointer to the cache on success, NULL on failure.

int **kmem_cache_shrink**(struct kmem_cache *cachep)

Shrink a cache.

Parameters

struct kmem_cache *cachep
The cache to shrink.

Description

Releases as many slabs as possible for a cache. To help debugging, a zero exit status indicates all slabs were released.

Return

`0` if all slabs were released, non-zero otherwise

void *`krealloc`(const void *p, size_t new_size, gfp_t flags)

reallocate memory. The contents will remain unchanged.

Parameters

`const void *p`
object to reallocate memory for.

`size_t new_size`
how many bytes of memory are required.

`gfp_t flags`
the type of memory to allocate.

Description

The contents of the object pointed to are preserved up to the lesser of the new and old sizes. If **p** is `NULL`, *`krealloc()`* behaves exactly like *`kmalloc()`*. If **new_size** is 0 and **p** is not a `NULL` pointer, the object pointed to is freed.

Return

pointer to the allocated memory or `NULL` in case of error

void `kfree_sensitive`(const void *p)

Clear sensitive information in memory before freeing

Parameters

`const void *p`
object to free memory of

Description

The memory of the object **p** points to is zeroed before freed. If **p** is `NULL`, *`kfree_sensitive()`* does nothing.

Note

this function zeroes the whole allocated buffer which can be a good deal bigger than the requested buffer size passed to *`kmalloc()`*. So be careful when using this function in performance sensitive code.

size_t `ksize`(const void *objp)

get the actual amount of memory allocated for a given object

Parameters

`const void *objp`
Pointer to the object

Description

kmalloc may internally round up allocations and return more memory than requested. *ksize()* can be used to determine the actual amount of memory allocated. The caller may use this additional memory, even though a smaller amount of memory was initially specified with the kmalloc call. The caller must guarantee that objp points to a valid object previously allocated with either *kmalloc()* or *kmem_cache_alloc()*. The object must not be freed during the duration of the call.

Return

size of the actual memory used by **objp** in bytes

void **kfree_const**(const void *x)

conditionally free memory

Parameters

const void *x
pointer to the memory

Description

Function calls kfree only if **x** is not in .rodata section.

void ***kvmalloc_node**(size_t size, gfp_t flags, int node)

attempt to allocate physically contiguous memory, but upon failure, fall back to non-contiguous (vmalloc) allocation.

Parameters

size_t size
size of the request.

gfp_t flags
gfp mask for the allocation - must be compatible (superset) with GFP_KERNEL.

int node
numa node to allocate from

Description

Uses kmalloc to get the memory but if the allocation fails then falls back to the vmalloc allocator. Use kvfree for freeing the memory.

Reclaim modifiers - __GFP_NORETRY and __GFP_NOFAIL are not supported. __GFP_RETRY_MAYFAIL is supported, and it should be used only if kmalloc is preferable to the vmalloc fallback, due to visible performance drawbacks.

Please note that any use of gfp flags outside of GFP_KERNEL is careful to not fall back to vmalloc.

Return

pointer to the allocated memory of `NULL` in case of failure

void **kvfree**(const void *addr)

Free memory.

Parameters

const void *addr
: Pointer to allocated memory.

Description

kvfree frees memory allocated by any of *vmalloc()*, *kmalloc()* or kvmalloc(). It is slightly more efficient to use *kfree()* or *vfree()* if you are certain that you know which one to use.

Context

Either preemptible task context or not-NMI interrupt.

5.7.4 Virtually Contiguous Mappings

void **vm_unmap_aliases**(void)
: unmap outstanding lazy aliases in the vmap layer

Parameters

void
: no arguments

Description

The vmap/vmalloc layer lazily flushes kernel virtual mappings primarily to amortize TLB flushing overheads. What this means is that any page you have now, may, in a former life, have been mapped into kernel virtual address by the vmap layer and so there might be some CPUs with TLB entries still referencing that page (additional to the regular 1:1 kernel mapping).

vm_unmap_aliases flushes all such lazy mappings. After it returns, we can be sure that none of the pages we have control over will have any aliases from the vmap layer.

void **vm_unmap_ram**(const void *mem, unsigned int count)
: unmap linear kernel address space set up by vm_map_ram

Parameters

const void *mem
: the pointer returned by vm_map_ram

unsigned int count
: the count passed to that vm_map_ram call (cannot unmap partial)

void ***vm_map_ram**(struct page **pages, unsigned int count, int node)
: map pages linearly into kernel virtual address (vmalloc space)

Parameters

struct page **pages
: an array of pointers to the pages to be mapped

unsigned int count
: number of pages

int node
: prefer to allocate data structures on this node

Description

If you use this function for less than VMAP_MAX_ALLOC pages, it could be faster than vmap so it’ s good. But if you mix long-life and short-life objects with *vm_map_ram()*, it could consume lots of address space through fragmentation (especially on a 32bit machine). You could see failures in the end. Please use this function for short-lived objects.

Return

a pointer to the address that has been mapped, or NULL on failure

void **vfree**(const void *addr)

Release memory allocated by *vmalloc()*

Parameters

const void *addr
Memory base address

Description

Free the virtually continuous memory area starting at **addr**, as obtained from one of the *vmalloc()* family of APIs. This will usually also free the physical memory underlying the virtual allocation, but that memory is reference counted, so it will not be freed until the last user goes away.

If **addr** is NULL, no operation is performed.

Context

May sleep if called *not* from interrupt context. Must not be called in NMI context (strictly speaking, it could be if we have CONFIG_ARCH_HAVE_NMI_SAFE_CMPXCHG, but making the calling conventions for *vfree()* arch-depenedent would be a really bad idea).

void **vunmap**(const void *addr)

release virtual mapping obtained by *vmap()*

Parameters

const void *addr
memory base address

Description

Free the virtually contiguous memory area starting at **addr**, which was created from the page array passed to *vmap()*.

Must not be called in interrupt context.

void ***vmap**(struct page **pages, unsigned int count, unsigned long flags, pgprot_t prot)

map an array of pages into virtually contiguous space

Parameters

struct page **pages
array of page pointers

unsigned int count
number of pages to map

unsigned long flags
vm_area->flags

pgprot_t prot
page protection for the mapping

Description

Maps **count** pages from **pages** into contiguous kernel virtual space. If **flags** contains `VM_MAP_PUT_PAGES` the ownership of the pages array itself (which must be kmalloc or vmalloc memory) and one reference per pages in it are transferred from the caller to *vmap()*, and will be freed / dropped when *vfree()* is called on the return value.

Return

the address of the area or `NULL` on failure

void ***vmap_pfn**(unsigned long *pfns, unsigned int count, pgprot_t prot)
map an array of PFNs into virtually contiguous space

Parameters

unsigned long *pfns
array of PFNs

unsigned int count
number of pages to map

pgprot_t prot
page protection for the mapping

Description

Maps **count** PFNs from **pfns** into contiguous kernel virtual space and returns the start address of the mapping.

void ***__vmalloc_node**(unsigned long size, unsigned long align, gfp_t gfp_mask, int node, const void *caller)
allocate virtually contiguous memory

Parameters

unsigned long size
allocation size

unsigned long align
desired alignment

gfp_t gfp_mask
flags for the page level allocator

int node
node to use for allocation or NUMA_NO_NODE

const void *caller
caller's return address

Description

Allocate enough pages to cover **size** from the page level allocator with **gfp_mask** flags. Map them into contiguous kernel virtual space.

Reclaim modifiers in **gfp_mask** - __GFP_NORETRY, __GFP_RETRY_MAYFAIL and __GFP_NOFAIL are not supported

Any use of gfp flags outside of GFP_KERNEL should be consulted with mm people.

Return

pointer to the allocated memory or `NULL` on error

void *`vmalloc`(unsigned long size)

allocate virtually contiguous memory

Parameters

`unsigned long size`
allocation size

Description

Allocate enough pages to cover **size** from the page level allocator and map them into contiguous kernel virtual space.

For tight control over page level allocator and protection flags use __vmalloc() instead.

Return

pointer to the allocated memory or `NULL` on error

void *`vzalloc`(unsigned long size)

allocate virtually contiguous memory with zero fill

Parameters

`unsigned long size`
allocation size

Description

Allocate enough pages to cover **size** from the page level allocator and map them into contiguous kernel virtual space. The memory allocated is set to zero.

For tight control over page level allocator and protection flags use __vmalloc() instead.

Return

pointer to the allocated memory or `NULL` on error

void *`vmalloc_user`(unsigned long size)

allocate zeroed virtually contiguous memory for userspace

Parameters

`unsigned long size`
allocation size

Description

The resulting memory area is zeroed so it can be mapped to userspace without leaking data.

Return

pointer to the allocated memory or `NULL` on error

void ***vmalloc_node**(unsigned long size, int node)
allocate memory on a specific node

Parameters

unsigned long size
allocation size

int node
numa node

Description

Allocate enough pages to cover **size** from the page level allocator and map them into contiguous kernel virtual space.

For tight control over page level allocator and protection flags use __vmalloc() instead.

Return

pointer to the allocated memory or `NULL` on error

void ***vzalloc_node**(unsigned long size, int node)
allocate memory on a specific node with zero fill

Parameters

unsigned long size
allocation size

int node
numa node

Description

Allocate enough pages to cover **size** from the page level allocator and map them into contiguous kernel virtual space. The memory allocated is set to zero.

Return

pointer to the allocated memory or `NULL` on error

void ***vmalloc_32**(unsigned long size)
allocate virtually contiguous memory (32bit addressable)

Parameters

unsigned long size
allocation size

Description

Allocate enough 32bit PA addressable pages to cover **size** from the page level allocator and map them into contiguous kernel virtual space.

Return

pointer to the allocated memory or `NULL` on error

void ***vmalloc_32_user**(unsigned long size)

allocate zeroed virtually contiguous 32bit memory

Parameters

unsigned long size
allocation size

Description

The resulting memory area is 32bit addressable and zeroed so it can be mapped to userspace without leaking data.

Return

pointer to the allocated memory or `NULL` on error

int **remap_vmalloc_range_partial**(struct vm_area_struct *vma, unsigned long uaddr, void *kaddr, unsigned long pgoff, unsigned long size)

map vmalloc pages to userspace

Parameters

struct vm_area_struct *vma
vma to cover

unsigned long uaddr
target user address to start at

void *kaddr
virtual address of vmalloc kernel memory

unsigned long pgoff
offset from **kaddr** to start at

unsigned long size
size of map area

Return

0 for success, -Exxx on failure

Description

This function checks that **kaddr** is a valid vmalloc'ed area, and that it is big enough to cover the range starting at **uaddr** in **vma**. Will return failure if that criteria isn't met.

Similar to *remap_pfn_range()* (see mm/memory.c)

int **remap_vmalloc_range**(struct vm_area_struct *vma, void *addr, unsigned long pgoff)

map vmalloc pages to userspace

Parameters

struct vm_area_struct *vma
vma to cover (map full range of vma)

void *addr
vmalloc memory

unsigned long pgoff
number of pages into addr before first page to map

Return

0 for success, -Exxx on failure

Description

This function checks that addr is a valid vmalloc'ed area, and that it is big enough to cover the vma. Will return failure if that criteria isn't met.

Similar to *remap_pfn_range()* (see mm/memory.c)

5.7.5 File Mapping and Page Cache

int **read_cache_pages**(struct address_space *mapping, struct list_head *pages, int (*filler)(void*, struct page*), void *data)

populate an address space with some pages & start reads against them

Parameters

struct address_space *mapping
the address_space

struct list_head *pages
The address of a list_head which contains the target pages. These pages have their ->index populated and are otherwise uninitialised.

int (*filler)(void *, struct page *)
callback routine for filling a single page.

void *data
private data for the callback routine.

Description

Hides the details of the LRU cache etc from the filesystems.

Return

0 on success, error return by **filler** otherwise

void **page_cache_ra_unbounded**(struct *readahead_control* *ractl, unsigned long nr_to_read, unsigned long lookahead_size)

Start unchecked readahead.

Parameters

struct readahead_control *ractl
Readahead control.

unsigned long nr_to_read
The number of pages to read.

unsigned long lookahead_size
Where to start the next readahead.

Description

This function is for filesystems to call when they want to start readahead beyond a file's stated i_size. This is almost certainly not the function you want to call. Use *page_cache_async_readahead()* or *page_cache_sync_readahead()* instead.

Context

File is referenced by caller. Mutexes may be held by caller. May sleep, but will not reenter filesystem to reclaim memory.

void **delete_from_page_cache**(struct *page* *page)
delete page from page cache

Parameters

struct page *page
the page which the kernel is trying to remove from page cache

Description

This must be called only on pages that have been verified to be in the page cache and locked. It will never put the page into the free list, the caller has a reference on the page.

int **filemap_flush**(struct address_space *mapping)
mostly a non-blocking flush

Parameters

struct address_space *mapping
target address_space

Description

This is a mostly non-blocking flush. Not suitable for data-integrity purposes - I/O may not be started against all dirty pages.

Return

0 on success, negative error code otherwise.

bool **filemap_range_has_page**(struct address_space *mapping, loff_t start_byte, loff_t end_byte)
check if a page exists in range.

Parameters

struct address_space *mapping
address space within which to check

loff_t start_byte
offset in bytes where the range starts

loff_t end_byte
offset in bytes where the range ends (inclusive)

Description

Find at least one page in the range supplied, usually used to check if direct writing in this range will trigger a writeback.

Return

`true` if at least one page exists in the specified range, `false` otherwise.

int **filemap_fdatawait_range**(struct address_space *mapping, loff_t start_byte, loff_t end_byte)

wait for writeback to complete

Parameters

struct address_space *mapping
address space structure to wait for

loff_t start_byte
offset in bytes where the range starts

loff_t end_byte
offset in bytes where the range ends (inclusive)

Description

Walk the list of under-writeback pages of the given address space in the given range and wait for all of them. Check error status of the address space and return it.

Since the error status of the address space is cleared by this function, callers are responsible for checking the return value and handling and/or reporting the error.

Return

error status of the address space.

int **filemap_fdatawait_range_keep_errors**(struct address_space *mapping, loff_t start_byte, loff_t end_byte)

wait for writeback to complete

Parameters

struct address_space *mapping
address space structure to wait for

loff_t start_byte
offset in bytes where the range starts

loff_t end_byte
offset in bytes where the range ends (inclusive)

Description

Walk the list of under-writeback pages of the given address space in the given range and wait for all of them. Unlike *filemap_fdatawait_range()*, this function does not clear error status of the address space.

Use this function if callers don't handle errors themselves. Expected call sites are system-wide / filesystem-wide data flushers: e.g. sync(2), fsfreeze(8)

int **file_fdatawait_range**(struct *file* *file, loff_t start_byte, loff_t end_byte)
wait for writeback to complete

Parameters

struct file *file
file pointing to address space structure to wait for

loff_t start_byte
offset in bytes where the range starts

loff_t end_byte
offset in bytes where the range ends (inclusive)

Description

Walk the list of under-writeback pages of the address space that file refers to, in the given range and wait for all of them. Check error status of the address space vs. the file->f_wb_err cursor and return it.

Since the error status of the file is advanced by this function, callers are responsible for checking the return value and handling and/or reporting the error.

Return

error status of the address space vs. the file->f_wb_err cursor.

int **filemap_fdatawait_keep_errors**(struct address_space *mapping)
wait for writeback without clearing errors

Parameters

struct address_space *mapping
address space structure to wait for

Description

Walk the list of under-writeback pages of the given address space and wait for all of them. Unlike filemap_fdatawait(), this function does not clear error status of the address space.

Use this function if callers don't handle errors themselves. Expected call sites are system-wide / filesystem-wide data flushers: e.g. sync(2), fsfreeze(8)

Return

error status of the address space.

int **filemap_write_and_wait_range**(struct address_space *mapping, loff_t lstart, loff_t lend)
write out & wait on a file range

Parameters

struct address_space *mapping
the address_space for the pages

loff_t lstart
offset in bytes where the range starts

loff_t lend
offset in bytes where the range ends (inclusive)

Description

Write out and wait upon file offsets lstart->lend, inclusive.

Note that **lend** is inclusive (describes the last byte to be written) so that this function can be used to write to the very end-of-file (end = -1).

Return

error status of the address space.

int **file_check_and_advance_wb_err**(struct *file* *file)

report wb error (if any) that was previously and advance wb_err to current one

Parameters

struct file *file

struct file on which the error is being reported

Description

When userland calls fsync (or something like nfsd does the equivalent), we want to report any writeback errors that occurred since the last fsync (or since the file was opened if there haven't been any).

Grab the wb_err from the mapping. If it matches what we have in the file, then just quickly return 0. The file is all caught up.

If it doesn't match, then take the mapping value, set the "seen" flag in it and try to swap it into place. If it works, or another task beat us to it with the new value, then update the f_wb_err and return the error portion. The error at this point must be reported via proper channels (a'la fsync, or NFS COMMIT operation, etc.).

While we handle mapping->wb_err with atomic operations, the f_wb_err value is protected by the f_lock since we must ensure that it reflects the latest value swapped in for this file descriptor.

Return

`0` on success, negative error code otherwise.

int **file_write_and_wait_range**(struct *file* *file, loff_t lstart, loff_t lend)

write out & wait on a file range

Parameters

struct file *file

file pointing to address_space with pages

loff_t lstart

offset in bytes where the range starts

loff_t lend

offset in bytes where the range ends (inclusive)

Description

Write out and wait upon file offsets lstart->lend, inclusive.

Note that **lend** is inclusive (describes the last byte to be written) so that this function can be used to write to the very end-of-file (end = -1).

After writing out and waiting on the data, we check and advance the f_wb_err cursor to the latest value, and return any errors detected there.

Return

`0` on success, negative error code otherwise.

int **replace_page_cache_page**(struct page *old, struct page *new, gfp_t gfp_mask)

replace a pagecache page with a new one

Parameters

struct page *old
page to be replaced

struct page *new
page to replace with

gfp_t gfp_mask
allocation mode

Description

This function replaces a page in the pagecache with a new one. On success it acquires the pagecache reference for the new page and drops it for the old page. Both the old and new pages must be locked. This function does not add the new page to the LRU, the caller must do that.

The remove + add is atomic. This function cannot fail.

Return

`0`

int **add_to_page_cache_locked**(struct *page* *page, struct address_space *mapping, pgoff_t offset, gfp_t gfp_mask)

add a locked page to the pagecache

Parameters

struct page *page
page to add

struct address_space *mapping
the page's address_space

pgoff_t offset
page index

gfp_t gfp_mask
page allocation mode

Description

This function is used to add a page to the pagecache. It must be locked. This function does not add the page to the LRU. The caller must do that.

Return

`0` on success, negative error code otherwise.

void **add_page_wait_queue**(struct *page* *page, wait_queue_entry_t *waiter)
Add an arbitrary waiter to a page's wait queue

Parameters

struct page *page
Page defining the wait queue of interest

wait_queue_entry_t *waiter
Waiter to add to the queue

Description

Add an arbitrary **waiter** to the wait queue for the nominated **page**.

void **unlock_page**(struct *page* *page)
unlock a locked page

Parameters

struct page *page
the page

Description

Unlocks the page and wakes up sleepers in wait_on_page_locked(). Also wakes sleepers in wait_on_page_writeback() because the wakeup mechanism between PageLocked pages and PageWriteback pages is shared. But that's OK - sleepers in wait_on_page_writeback() just go back to sleep.

Note that this depends on PG_waiters being the sign bit in the byte that contains PG_locked - thus the BUILD_BUG_ON(). That allows us to clear the PG_locked bit and test PG_waiters at the same time fairly portably (architectures that do LL/SC can test any bit, while x86 can test the sign bit).

void **end_page_writeback**(struct *page* *page)
end writeback against a page

Parameters

struct page *page
the page

void **__lock_page**(struct page *__page)
get a lock on the page, assuming we need to sleep to get it

Parameters

struct page *__page
the page to lock

pgoff_t **page_cache_next_miss**(struct address_space *mapping, pgoff_t index, unsigned long max_scan)
Find the next gap in the page cache.

Parameters

struct address_space *mapping
Mapping.

pgoff_t index
Index.

unsigned long max_scan
Maximum range to search.

Description

Search the range [index, min(index + max_scan - 1, ULONG_MAX)] for the gap with the lowest index.

This function may be called under the rcu_read_lock. However, this will not atomically search a snapshot of the cache at a single point in time. For example, if a gap is created at index 5, then subsequently a gap is created at index 10, page_cache_next_miss covering both indices may return 10 if called under the rcu_read_lock.

Return

The index of the gap if found, otherwise an index outside the range specified (in which case 'return - index >= max_scan' will be true). In the rare case of index wrap-around, 0 will be returned.

pgoff_t **page_cache_prev_miss**(struct address_space *mapping, pgoff_t index, unsigned long max_scan)

Find the previous gap in the page cache.

Parameters

struct address_space *mapping
Mapping.

pgoff_t index
Index.

unsigned long max_scan
Maximum range to search.

Description

Search the range [max(index - max_scan + 1, 0), index] for the gap with the highest index.

This function may be called under the rcu_read_lock. However, this will not atomically search a snapshot of the cache at a single point in time. For example, if a gap is created at index 10, then subsequently a gap is created at index 5, *page_cache_prev_miss()* covering both indices may return 5 if called under the rcu_read_lock.

Return

The index of the gap if found, otherwise an index outside the range specified (in which case 'index - return >= max_scan' will be true). In the rare case of wrap-around, ULONG_MAX will be returned.

struct page ***pagecache_get_page**(struct address_space *mapping, pgoff_t index, int fgp_flags, gfp_t gfp_mask)

Find and get a reference to a page.

Parameters

struct address_space *mapping
The address_space to search.

pgoff_t index
The page index.

int fgp_flags
FGP flags modify how the page is returned.

gfp_t gfp_mask
Memory allocation flags to use if FGP_CREAT is specified.

Description

Looks up the page cache entry at **mapping** & **index**.

fgp_flags can be zero or more of these flags:

- FGP_ACCESSED - The page will be marked accessed.
- FGP_LOCK - The page is returned locked.
- FGP_HEAD - If the page is present and a THP, return the head page rather than the exact page specified by the index.
- FGP_CREAT - If no page is present then a new page is allocated using **gfp_mask** and added to the page cache and the VM's LRU list. The page is returned locked and with an increased refcount.
- FGP_FOR_MMAP - The caller wants to do its own locking dance if the page is already in cache. If the page was allocated, unlock it before returning so the caller can do the same dance.
- FGP_WRITE - The page will be written
- FGP_NOFS - __GFP_FS will get cleared in gfp mask
- FGP_NOWAIT - Don't get blocked by page lock

If FGP_LOCK or FGP_CREAT are specified then the function may sleep even if the GFP flags specified for FGP_CREAT are atomic.

If there is a page cache page, it is returned with an increased refcount.

Return

The found page or NULL otherwise.

unsigned **find_get_pages_contig**(struct address_space *mapping, pgoff_t index, unsigned int nr_pages, struct page **pages)

gang contiguous pagecache lookup

Parameters

struct address_space *mapping
The address_space to search

pgoff_t index
The starting page index

unsigned int nr_pages
The maximum number of pages

struct page **pages
Where the resulting pages are placed

Description

find_get_pages_contig() works exactly like find_get_pages(), except that the returned number of pages are guaranteed to be contiguous.

Return

the number of pages which were found.

unsigned **find_get_pages_range_tag**(struct address_space *mapping, pgoff_t *index, pgoff_t end, xa_mark_t tag, unsigned int nr_pages, struct page **pages)

find and return pages in given range matching **tag**

Parameters

struct address_space *mapping
the address_space to search

pgoff_t *index
the starting page index

pgoff_t end
The final page index (inclusive)

xa_mark_t tag
the tag index

unsigned int nr_pages
the maximum number of pages

struct page **pages
where the resulting pages are placed

Description

Like find_get_pages, except we only return pages which are tagged with **tag**. We update **index** to index the next page for the traversal.

Return

the number of pages which were found.

ssize_t **generic_file_buffered_read**(struct kiocb *iocb, struct iov_iter *iter, ssize_t written)

generic file read routine

Parameters

struct kiocb *iocb
the iocb to read

struct iov_iter *iter
data destination

ssize_t written
already copied

Description

This is a generic file read routine, and uses the mapping->a_ops->readpage() function for the actual low-level stuff.

This is really ugly. But the goto's actually try to clarify some of the logic when it comes to error handling etc.

Return

- total number of bytes copied, including those the were already **written**
- negative error code if nothing was copied

ssize_t **generic_file_read_iter**(struct kiocb *iocb, struct iov_iter *iter)
generic filesystem read routine

Parameters

struct kiocb *iocb
kernel I/O control block

struct iov_iter *iter
destination for the data read

Description

This is the "read_iter()" routine for all filesystems that can use the page cache directly.

The IOCB_NOWAIT flag in iocb->ki_flags indicates that -EAGAIN shall be returned when no data can be read without waiting for I/O requests to complete; it doesn't prevent readahead.

The IOCB_NOIO flag in iocb->ki_flags indicates that no new I/O requests shall be made for the read or for readahead. When no data can be read, -EAGAIN shall be returned. When readahead would be triggered, a partial, possibly empty read shall be returned.

Return

- number of bytes copied, even for partial reads
- negative error code (or 0 if IOCB_NOIO) if nothing was read

vm_fault_t **filemap_fault**(struct vm_fault *vmf)
read in file data for page fault handling

Parameters

struct vm_fault *vmf
struct vm_fault containing details of the fault

Description

filemap_fault() is invoked via the vma operations vector for a mapped memory region to read in file data during a page fault.

The goto's are kind of ugly, but this streamlines the normal case of having it in the page cache, and handles the special cases reasonably without having a lot of duplicated code.

vma->vm_mm->mmap_lock must be held on entry.

If our return value has VM_FAULT_RETRY set, it's because the mmap_lock may be dropped before doing I/O or by lock_page_maybe_drop_mmap().

If our return value does not have VM_FAULT_RETRY set, the mmap_lock has not been released.

We never return with VM_FAULT_RETRY and a bit from VM_FAULT_ERROR set.

Return

bitwise-OR of `VM_FAULT_` codes.

struct page ***read_cache_page**(struct address_space *mapping, pgoff_t index, int (*filler)(void*, struct page*), void *data)

read into page cache, fill it if needed

Parameters

struct address_space *mapping
the page's address_space

pgoff_t index
the page index

int (*filler)(void *, struct page *)
function to perform the read

void *data
first arg to filler(data, page) function, often left as NULL

Description

Read into the page cache. If a page already exists, and PageUptodate() is not set, try to fill the page and wait for it to become unlocked.

If the page does not get brought uptodate, return -EIO.

Return

up to date page on success, ERR_PTR() on failure.

struct page ***read_cache_page_gfp**(struct address_space *mapping, pgoff_t index, gfp_t gfp)

read into page cache, using specified page allocation flags.

Parameters

struct address_space *mapping
the page's address_space

pgoff_t index
the page index

gfp_t gfp
the page allocator flags to use if allocating

Description

This is the same as "read_mapping_page(mapping, index, NULL)", but with any new page allocations done using the specified allocation flags.

If the page does not get brought uptodate, return -EIO.

Return

up to date page on success, ERR_PTR() on failure.

ssize_t **__generic_file_write_iter**(struct kiocb *iocb, struct iov_iter *from)

write data to a file

Parameters

struct kiocb *iocb
IO state structure (file, offset, etc.)

struct iov_iter *from
iov_iter with data to write

Description

This function does all the work needed for actually writing data to a file. It does all basic checks, removes SUID from the file, updates modification times and calls proper subroutines depending on whether we do direct IO or a standard buffered write.

It expects i_mutex to be grabbed unless we work on a block device or similar object which does not need locking at all.

This function does *not* take care of syncing data in case of O_SYNC write. A caller has to handle it. This is mainly due to the fact that we want to avoid syncing under i_mutex.

Return

- number of bytes written, even for truncated writes
- negative error code if no data has been written at all

ssize_t **generic_file_write_iter**(struct kiocb *iocb, struct iov_iter *from)

write data to a file

Parameters

struct kiocb *iocb
IO state structure

struct iov_iter *from
iov_iter with data to write

Description

This is a wrapper around *__generic_file_write_iter()* to be used by most filesystems. It takes care of syncing the file in case of O_SYNC file and acquires i_mutex as needed.

Return

- negative error code if no data has been written at all of vfs_fsync_range() failed for a synchronous write
- number of bytes written, even for truncated writes

int **try_to_release_page**(struct *page* *page, gfp_t gfp_mask)

release old fs-specific metadata on a page

Parameters

struct page *page
the page which the kernel is trying to free

gfp_t gfp_mask
memory allocation flags (and I/O mode)

Description

The address_space is to try to release any data against the page (presumably at page->private).

This may also be called if PG_fscache is set on a page, indicating that the page is known to the local caching routines.

The **gfp_mask** argument specifies whether I/O may be performed to release this page (__GFP_IO), and whether the call may block (__GFP_RECLAIM & __GFP_FS).

Return

1 if the release was successful, otherwise return zero.

void **balance_dirty_pages_ratelimited**(struct address_space *mapping)

balance dirty memory state

Parameters

struct address_space *mapping
address_space which was dirtied

Description

Processes which are dirtying memory should call in here once for each page which was newly dirtied. The function will periodically check the system's dirty state and will initiate writeback if needed.

On really big machines, get_writeback_state is expensive, so try to avoid calling it too often (ratelimiting). But once we're over the dirty memory limit we decrease the ratelimiting by a lot, to prevent individual processes from overshooting the limit by (ratelimit_pages) each.

void **tag_pages_for_writeback**(struct address_space *mapping, pgoff_t start, pgoff_t end)

tag pages to be written by write_cache_pages

Parameters

struct address_space *mapping
address space structure to write

pgoff_t start
starting page index

pgoff_t end
    ending page index (inclusive)

Description

This function scans the page range from **start** to **end** (inclusive) and tags all pages that have DIRTY tag set with a special TOWRITE tag. The idea is that write_cache_pages (or whoever calls this function) will then use TOWRITE tag to identify pages eligible for writeback. This mechanism is used to avoid livelocking of writeback by a process steadily creating new dirty pages in the file (thus it is important for this function to be quick so that it can tag pages faster than a dirtying process can create them).

int **write_cache_pages**(struct address_space *mapping, struct writeback_control *wbc, writepage_t writepage, void *data)
    walk the list of dirty pages of the given address space and write all of them.

Parameters

struct address_space *mapping
    address space structure to write

struct writeback_control *wbc
    subtract the number of written pages from ***wbc->nr_to_write**

writepage_t writepage
    function called for each page

void *data
    data passed to writepage function

Description

If a page is already under I/O, *write_cache_pages()* skips it, even if it's dirty. This is desirable behaviour for memory-cleaning writeback, but it is INCORRECT for data-integrity system calls such as fsync(). fsync() and msync() need to guarantee that all the data which was dirty at the time the call was made get new I/O started against them. If wbc->sync_mode is WB_SYNC_ALL then we were called for data integrity and we must wait for existing IO to complete.

To avoid livelocks (when other process dirties new pages), we first tag pages which should be written back with TOWRITE tag and only then start writing them. For data-integrity sync we have to be careful so that we do not miss some pages (e.g., because some other process has cleared TOWRITE tag we set). The rule we follow is that TOWRITE tag can be cleared only by the process clearing the DIRTY tag (and submitting the page for IO).

To avoid deadlocks between range_cyclic writeback and callers that hold pages in PageWriteback to aggregate IO until *write_cache_pages()* returns, we do not loop back to the start of the file. Doing so causes a page lock/page writeback access order inversion - we should only ever lock multiple pages in ascending page->index order, and looping back to the start of the file violates that rule and causes deadlocks.

Return

`0` on success, negative error code otherwise int **generic_writepages**(struct address_space *mapping, struct writeback_control *wbc)

walk the list of dirty pages of the given address space and writepage() all of them.

Parameters

struct address_space *mapping
address space structure to write

struct writeback_control *wbc
subtract the number of written pages from ***wbc->nr_to_write**

Description

This is a library function, which implements the writepages() address_space_operation.

Return

`0` on success, negative error code otherwise

int **write_one_page**(struct *page* *page)

write out a single page and wait on I/O

Parameters

struct page *page
the page to write

Description

The page must be locked by the caller and will be unlocked upon return.

Note that the mapping's AS_EIO/AS_ENOSPC flags will be cleared when this function returns.

Return

`0` on success, negative error code otherwise

void **wait_for_stable_page**(struct *page* *page)

wait for writeback to finish, if necessary.

Parameters

struct page *page
The page to wait on.

Description

This function determines if the given page is related to a backing device that requires page contents to be held stable during writeback. If so, then it will wait for any pending writeback to complete.

void **truncate_inode_pages_range**(struct address_space *mapping, loff_t lstart, loff_t lend)

truncate range of pages specified by start & end byte offsets

Parameters

struct address_space *mapping
mapping to truncate

loff_t lstart
offset from which to truncate

loff_t lend
offset to which to truncate (inclusive)

Description

Truncate the page cache, removing the pages that are between specified offsets (and zeroing out partial pages if lstart or lend + 1 is not page aligned).

Truncate takes two passes - the first pass is nonblocking. It will not block on page locks and it will not block on writeback. The second pass will wait. This is to prevent as much IO as possible in the affected region. The first pass will remove most pages, so the search cost of the second pass is low.

We pass down the cache-hot hint to the page freeing code. Even if the mapping is large, it is probably the case that the final pages are the most recently touched, and freeing happens in ascending file offset order.

Note that since ->invalidatepage() accepts range to invalidate truncate_inode_pages_range is able to handle cases where lend + 1 is not page aligned properly.

void **truncate_inode_pages**(struct address_space *mapping, loff_t lstart)
truncate *all* the pages from an offset

Parameters

struct address_space *mapping
mapping to truncate

loff_t lstart
offset from which to truncate

Description

Called under (and serialised by) inode->i_mutex.

Note

When this function returns, there can be a page in the process of deletion (inside __delete_from_page_cache()) in the specified range. Thus mapping->nrpages can be non-zero when this function returns even after truncation of the whole mapping.

void **truncate_inode_pages_final**(struct address_space *mapping)
truncate *all* pages before inode dies

Parameters

struct address_space *mapping
mapping to truncate

Description

Called under (and serialized by) inode->i_mutex.

Filesystems have to use this in the .evict_inode path to inform the VM that this is the final truncate and the inode is going away.

unsigned long **invalidate_mapping_pages**(struct address_space *mapping, pgoff_t start, pgoff_t end)

Invalidate all the unlocked pages of one inode

Parameters

struct address_space *mapping
the address_space which holds the pages to invalidate

pgoff_t start
the offset 'from' which to invalidate

pgoff_t end
the offset 'to' which to invalidate (inclusive)

Description

This function only removes the unlocked pages, if you want to remove all the pages of one inode, you must call truncate_inode_pages.

invalidate_mapping_pages() will not block on IO activity. It will not invalidate pages which are dirty, locked, under writeback or mapped into pagetables.

Return

the number of the pages that were invalidated

int **invalidate_inode_pages2_range**(struct address_space *mapping, pgoff_t start, pgoff_t end)

remove range of pages from an address_space

Parameters

struct address_space *mapping
the address_space

pgoff_t start
the page offset 'from' which to invalidate

pgoff_t end
the page offset 'to' which to invalidate (inclusive)

Description

Any pages which are found to be mapped into pagetables are unmapped prior to invalidation.

Return

-EBUSY if any pages could not be invalidated.

int **invalidate_inode_pages2**(struct address_space *mapping)

remove all pages from an address_space

Parameters

struct address_space *mapping
the address_space

Description

Any pages which are found to be mapped into pagetables are unmapped prior to invalidation.

Return

-EBUSY if any pages could not be invalidated.

void **truncate_pagecache**(struct *inode* *inode, loff_t newsize)
unmap and remove pagecache that has been truncated

Parameters

struct inode *inode
inode

loff_t newsize
new file size

Description

inode's new i_size must already be written before truncate_pagecache is called.

This function should typically be called before the filesystem releases resources associated with the freed range (eg. deallocates blocks). This way, pagecache will always stay logically coherent with on-disk format, and the filesystem would not have to deal with situations such as writepage being called for a page that has already had its underlying blocks deallocated.

void **truncate_setsize**(struct *inode* *inode, loff_t newsize)
update inode and pagecache for a new file size

Parameters

struct inode *inode
inode

loff_t newsize
new file size

Description

truncate_setsize updates i_size and performs pagecache truncation (if necessary) to **newsize**. It will be typically be called from the filesystem's setattr function when ATTR_SIZE is passed in.

Must be called with a lock serializing truncates and writes (generally i_mutex but e.g. xfs uses a different lock) and before all filesystem specific block truncation has been performed.

void **pagecache_isize_extended**(struct *inode* *inode, loff_t from, loff_t to)
update pagecache after extension of i_size

Parameters

struct inode *inode
inode for which i_size was extended

loff_t from
original inode size

loff_t to
new inode size

Description

Handle extension of inode size either caused by extending truncate or by write starting after current i_size. We mark the page straddling current i_size RO so that page_mkwrite() is called on the nearest write access to the page. This way filesystem can be sure that page_mkwrite() is called on the page before user writes to the page via mmap after the i_size has been changed.

The function must be called after i_size is updated so that page fault coming after we unlock the page will already see the new i_size. The function must be called while we still hold i_mutex - this not only makes sure i_size is stable but also that userspace cannot observe new i_size value before we are prepared to store mmap writes at new inode size.

void **truncate_pagecache_range**(struct *inode* *inode, loff_t lstart, loff_t lend)
unmap and remove pagecache that is hole-punched

Parameters

struct inode *inode
inode

loff_t lstart
offset of beginning of hole

loff_t lend
offset of last byte of hole

Description

This function should typically be called before the filesystem releases resources associated with the freed range (eg. deallocates blocks). This way, pagecache will always stay logically coherent with on-disk format, and the filesystem would not have to deal with situations such as writepage being called for a page that has already had its underlying blocks deallocated.

void **mapping_set_error**(struct address_space *mapping, int error)
record a writeback error in the address_space

Parameters

struct address_space *mapping
the mapping in which an error should be set

int error
the error to set in the mapping

Description

When writeback fails in some way, we must record that error so that userspace can be informed when fsync and the like are called. We endeavor to report errors on any file that was open at the time of the error. Some internal callers also need to know when writeback errors have occurred.

When a writeback error occurs, most filesystems will want to call mapping_set_error to record the error in the mapping so that it can be reported when the application calls fsync(2).

void **attach_page_private**(struct *page* *page, void *data)
Attach private data to a page.

Parameters

struct page *page
Page to attach data to.

void *data
Data to attach to page.

Description

Attaching private data to a page increments the page' s reference count. The data must be detached before the page will be freed.

void ***detach_page_private**(struct *page* *page)
Detach private data from a page.

Parameters

struct page *page
Page to detach data from.

Description

Removes the data that was previously attached to the page and decrements the refcount on the page.

Return

Data that was attached to the page.

struct page ***find_get_page**(struct address_space *mapping, pgoff_t offset)
find and get a page reference

Parameters

struct address_space *mapping
the address_space to search

pgoff_t offset
the page index

Description

Looks up the page cache slot at **mapping** & **offset**. If there is a page cache page, it is returned with an increased refcount.

Otherwise, `NULL` is returned.

struct page ***find_lock_page**(struct address_space *mapping, pgoff_t index)
locate, pin and lock a pagecache page

Parameters

struct address_space *mapping
the address_space to search

pgoff_t index
the page index

Description

Looks up the page cache entry at **mapping** & **index**. If there is a page cache page, it is returned locked and with an increased refcount.

Context

May sleep.

Return

A struct page or `NULL` if there is no page in the cache for this index.

struct page ***find_lock_head**(struct address_space *mapping, pgoff_t index)

Locate, pin and lock a pagecache page.

Parameters

struct address_space *mapping
The address_space to search.

pgoff_t index
The page index.

Description

Looks up the page cache entry at **mapping** & **index**. If there is a page cache page, its head page is returned locked and with an increased refcount.

Context

May sleep.

Return

A struct page which is !PageTail, or `NULL` if there is no page in the cache for this index.

struct page ***find_or_create_page**(struct address_space *mapping, pgoff_t index, gfp_t gfp_mask)

locate or add a pagecache page

Parameters

struct address_space *mapping
the page's address_space

pgoff_t index
the page's index into the mapping

gfp_t gfp_mask
page allocation mode

Description

Looks up the page cache slot at **mapping** & **offset**. If there is a page cache page, it is returned locked and with an increased refcount.

If the page is not present, a new page is allocated using **gfp_mask** and added to the page cache and the VM's LRU list. The page is returned locked and with an increased refcount.

On memory exhaustion, `NULL` is returned.

find_or_create_page() may sleep, even if **gfp_flags** specifies an atomic allocation!

struct page ***grab_cache_page_nowait**(struct address_space *mapping, pgoff_t index)

returns locked page at given index in given cache

Parameters

struct address_space *mapping
target address_space

pgoff_t index
the page index

Description

Same as grab_cache_page(), but do not wait if the page is unavailable. This is intended for speculative data generators, where the data can be regenerated if the page couldn't be grabbed. This routine should be safe to call while holding the lock for another page.

Clear __GFP_FS when allocating the page to avoid recursion into the fs and deadlock against the caller's locked page.

struct **readahead_control**

Describes a readahead request.

Definition

```
struct readahead_control {
  struct file *file;
  struct address_space *mapping;
};
```

Members

file
The file, used primarily by network filesystems for authentication. May be NULL if invoked internally by the filesystem.

mapping
Readahead this filesystem object.

Description

A readahead request is for consecutive pages. Filesystems which implement the ->readahead method should call *readahead_page()* or *readahead_page_batch()* in a loop and attempt to start I/O against each page in the request.

Most of the fields in this struct are private and should be accessed by the functions below.

void **page_cache_sync_readahead**(struct address_space *mapping, struct file_ra_state *ra, struct *file* *file, pgoff_t index, unsigned long req_count)

generic file readahead

Parameters

struct address_space *mapping
address_space which holds the pagecache and I/O vectors

struct file_ra_state *ra
file_ra_state which holds the readahead state

struct file *file
Used by the filesystem for authentication.

pgoff_t index
Index of first page to be read.

unsigned long req_count
Total number of pages being read by the caller.

Description

page_cache_sync_readahead() should be called when a cache miss happened: it will submit the read. The readahead logic may decide to piggyback more pages onto the read request if access patterns suggest it will improve performance.

void **page_cache_async_readahead**(struct address_space *mapping, struct file_ra_state *ra, struct *file* *file, struct *page* *page, pgoff_t index, unsigned long req_count)

file readahead for marked pages

Parameters

struct address_space *mapping
address_space which holds the pagecache and I/O vectors

struct file_ra_state *ra
file_ra_state which holds the readahead state

struct file *file
Used by the filesystem for authentication.

struct page *page
The page at **index** which triggered the readahead call.

pgoff_t index
Index of first page to be read.

unsigned long req_count
Total number of pages being read by the caller.

Description

page_cache_async_readahead() should be called when a page is used which is marked as PageReadahead; this is a marker to suggest that the application has used up enough of the readahead window that we should start pulling in more pages.

struct page ***readahead_page**(struct *readahead_control* *rac)

Get the next page to read.

Parameters

struct readahead_control *rac
: The current readahead request.

Context

The page is locked and has an elevated refcount. The caller should decreases the refcount once the page has been submitted for I/O and unlock the page once all I/O to that page has completed.

Return

A pointer to the next page, or `NULL` if we are done.

readahead_page_batch

`readahead_page_batch (rac, array)`

Get a batch of pages to read.

Parameters

rac
: The current readahead request.

array
: An array of pointers to struct page.

Context

The pages are locked and have an elevated refcount. The caller should decreases the refcount once the page has been submitted for I/O and unlock the page once all I/O to that page has completed.

Return

The number of pages placed in the array. 0 indicates the request is complete.

loff_t **readahead_pos**(struct *readahead_control* *rac)

The byte offset into the file of this readahead request.

Parameters

struct readahead_control *rac
: The readahead request.

loff_t **readahead_length**(struct *readahead_control* *rac)

The number of bytes in this readahead request.

Parameters

struct readahead_control *rac
: The readahead request.

pgoff_t **readahead_index**(struct *readahead_control* *rac)

The index of the first page in this readahead request.

Parameters

struct readahead_control *rac
: The readahead request.

unsigned int **readahead_count**(struct *readahead_control* *rac)
The number of pages in this readahead request.

Parameters

struct readahead_control *rac
The readahead request.

int **page_mkwrite_check_truncate**(struct *page* *page, struct *inode* *inode)
check if page was truncated

Parameters

struct page *page
the page to check

struct inode *inode
the inode to check the page against

Description

Returns the number of bytes in the page up to EOF, or -EFAULT if the page was truncated.

unsigned int **i_blocks_per_page**(struct *inode* *inode, struct *page* *page)
How many blocks fit in this page.

Parameters

struct inode *inode
The inode which contains the blocks.

struct page *page
The page (head page if the page is a THP).

Description

If the block size is larger than the size of this page, return zero.

Context

The caller should hold a refcount on the page to prevent it from being split.

Return

The number of filesystem blocks covered by this page.

5.7.6 Memory pools

void **mempool_exit**(mempool_t *pool)
exit a mempool initialized with *mempool_init()*

Parameters

mempool_t *pool
pointer to the memory pool which was initialized with *mempool_init()*.

Description

Free all reserved elements in **pool** and **pool** itself. This function only sleeps if the free_fn() function sleeps.

May be called on a zeroed but uninitialized mempool (i.e. allocated with *kzalloc()*).

void **mempool_destroy**(mempool_t *pool)

deallocate a memory pool

Parameters

mempool_t *pool
pointer to the memory pool which was allocated via *mempool_create()*.

Description

Free all reserved elements in **pool** and **pool** itself. This function only sleeps if the free_fn() function sleeps.

int **mempool_init**(mempool_t *pool, int min_nr, mempool_alloc_t *alloc_fn, mempool_free_t *free_fn, void *pool_data)

initialize a memory pool

Parameters

mempool_t *pool
pointer to the memory pool that should be initialized

int min_nr
the minimum number of elements guaranteed to be allocated for this pool.

mempool_alloc_t *alloc_fn
user-defined element-allocation function.

mempool_free_t *free_fn
user-defined element-freeing function.

void *pool_data
optional private data available to the user-defined functions.

Description

Like *mempool_create()*, but initializes the pool in (i.e. embedded in another structure).

Return

`0` on success, negative error code otherwise.

mempool_t ***mempool_create**(int min_nr, mempool_alloc_t *alloc_fn, mempool_free_t *free_fn, void *pool_data)

create a memory pool

Parameters

int min_nr
the minimum number of elements guaranteed to be allocated for this pool.

mempool_alloc_t *alloc_fn
user-defined element-allocation function.

mempool_free_t *free_fn
user-defined element-freeing function.

void *pool_data
: optional private data available to the user-defined functions.

Description

this function creates and allocates a guaranteed size, preallocated memory pool. The pool can be used from the *mempool_alloc()* and *mempool_free()* functions. This function might sleep. Both the alloc_fn() and the free_fn() functions might sleep - as long as the *mempool_alloc()* function is not called from IRQ contexts.

Return

pointer to the created memory pool object or NULL on error.

int **mempool_resize**(mempool_t *pool, int new_min_nr)
: resize an existing memory pool

Parameters

mempool_t *pool
: pointer to the memory pool which was allocated via *mempool_create()*.

int new_min_nr
: the new minimum number of elements guaranteed to be allocated for this pool.

Description

This function shrinks/grows the pool. In the case of growing, it cannot be guaranteed that the pool will be grown to the new size immediately, but new *mempool_free()* calls will refill it. This function may sleep.

Note, the caller must guarantee that no mempool_destroy is called while this function is running. *mempool_alloc()* & *mempool_free()* might be called (eg. from IRQ contexts) while this function executes.

Return

0 on success, negative error code otherwise.

void ***mempool_alloc**(mempool_t *pool, gfp_t gfp_mask)
: allocate an element from a specific memory pool

Parameters

mempool_t *pool
: pointer to the memory pool which was allocated via *mempool_create()*.

gfp_t gfp_mask
: the usual allocation bitmask.

Description

this function only sleeps if the alloc_fn() function sleeps or returns NULL. Note that due to preallocation, this function *never* fails when called from process contexts. (it might fail if called from an IRQ context.)

Note

using __GFP_ZERO is not supported.

Return

pointer to the allocated element or NULL on error.

void **mempool_free**(void *element, mempool_t *pool)

return an element to the pool.

Parameters

void *element
pool element pointer.

mempool_t *pool
pointer to the memory pool which was allocated via *mempool_create()*.

Description

this function only sleeps if the free_fn() function sleeps.

5.7.7 DMA pools

struct dma_pool ***dma_pool_create**(const char *name, struct device *dev, size_t size, size_t align, size_t boundary)

Creates a pool of consistent memory blocks, for dma.

Parameters

const char *name
name of pool, for diagnostics

struct device *dev
device that will be doing the DMA

size_t size
size of the blocks in this pool.

size_t align
alignment requirement for blocks; must be a power of two

size_t boundary
returned blocks won't cross this power of two boundary

Context

not in_interrupt()

Description

Given one of these pools, *dma_pool_alloc()* may be used to allocate memory. Such memory will all have "consistent" DMA mappings, accessible by the device and its driver without using cache flushing primitives. The actual size of blocks allocated may be larger than requested because of alignment.

If **boundary** is nonzero, objects returned from *dma_pool_alloc()* won't cross that size boundary. This is useful for devices which have addressing restrictions on individual DMA transfers, such as not crossing boundaries of 4KBytes.

Return

a dma allocation pool with the requested characteristics, or NULL if one can't be created.

void **dma_pool_destroy**(struct dma_pool *pool)
destroys a pool of dma memory blocks.

Parameters

struct dma_pool *pool
dma pool that will be destroyed

Context

!in_interrupt()

Description

Caller guarantees that no more memory from the pool is in use, and that nothing will try to use the pool after this call.

void ***dma_pool_alloc**(struct dma_pool *pool, gfp_t mem_flags, dma_addr_t *handle)
get a block of consistent memory

Parameters

struct dma_pool *pool
dma pool that will produce the block

gfp_t mem_flags
GFP_* bitmask

dma_addr_t *handle
pointer to dma address of block

Return

the kernel virtual address of a currently unused block, and reports its dma address through the handle. If such a memory block can't be allocated, `NULL` is returned.

void **dma_pool_free**(struct dma_pool *pool, void *vaddr, dma_addr_t dma)
put block back into dma pool

Parameters

struct dma_pool *pool
the dma pool holding the block

void *vaddr
virtual address of block

dma_addr_t dma
dma address of block

Description

Caller promises neither device nor driver will again touch this block unless it is first re-allocated.

struct dma_pool ***dmam_pool_create**(const char *name, struct device *dev, size_t size, size_t align, size_t allocation)
Managed *dma_pool_create()*

Parameters

const char *name
name of pool, for diagnostics

struct device *dev
device that will be doing the DMA

size_t size
size of the blocks in this pool.

size_t align
alignment requirement for blocks; must be a power of two

size_t allocation
returned blocks won't cross this boundary (or zero)

Description

Managed *dma_pool_create()*. DMA pool created with this function is automatically destroyed on driver detach.

Return

a managed dma allocation pool with the requested characteristics, or `NULL` if one can't be created.

void **dmam_pool_destroy**(struct dma_pool *pool)

Managed *dma_pool_destroy()*

Parameters

struct dma_pool *pool
dma pool that will be destroyed

Description

Managed *dma_pool_destroy()*.

5.7.8 More Memory Management Functions

void **zap_vma_ptes**(struct vm_area_struct *vma, unsigned long address, unsigned long size)

remove ptes mapping the vma

Parameters

struct vm_area_struct *vma
vm_area_struct holding ptes to be zapped

unsigned long address
starting address of pages to zap

unsigned long size
number of bytes to zap

Description

This function only unmaps ptes assigned to VM_PFNMAP vmas.

The entire address range must be fully contained within the vma.

int **vm_insert_pages**(struct vm_area_struct *vma, unsigned long addr, struct page **pages, unsigned long *num)

insert multiple pages into user vma, batching the pmd lock.

Parameters

struct vm_area_struct *vma
user vma to map to

unsigned long addr
target start user address of these pages

struct page **pages
source kernel pages

unsigned long *num
in: number of pages to map. out: number of pages that were *not* mapped. (0 means all pages were successfully mapped).

Description

Preferred over *vm_insert_page()* when inserting multiple pages.

In case of error, we may have mapped a subset of the provided pages. It is the caller's responsibility to account for this case.

The same restrictions apply as in *vm_insert_page()*.

int **vm_insert_page**(struct vm_area_struct *vma, unsigned long addr, struct *page* *page)

insert single page into user vma

Parameters

struct vm_area_struct *vma
user vma to map to

unsigned long addr
target user address of this page

struct page *page
source kernel page

Description

This allows drivers to insert individual pages they've allocated into a user vma.

The page has to be a nice clean _individual_ kernel allocation. If you allocate a compound page, you need to have marked it as such (__GFP_COMP), or manually just split the page up yourself (see split_page()).

NOTE! Traditionally this was done with "*remap_pfn_range()*" which took an arbitrary page protection parameter. This doesn't allow that. Your vma protection will have to be set up correctly, which means that if you want a shared writable mapping, you'd better ask for a shared writable mapping!

The page does not need to be reserved.

Usually this function is called from f_op->mmap() handler under mm->mmap_lock write-lock, so it can change vma->vm_flags. Caller must set VM_MIXEDMAP on vma if it wants to call this function from other places, for example from page-fault handler.

Return

`0` on success, negative error code otherwise.

int **vm_map_pages**(struct vm_area_struct *vma, struct page **pages, unsigned long num)

maps range of kernel pages starts with non zero offset

Parameters

struct vm_area_struct *vma
user vma to map to

struct page **pages
pointer to array of source kernel pages

unsigned long num
number of pages in page array

Description

Maps an object consisting of **num** pages, catering for the user' s requested vm_pgoff

If we fail to insert any page into the vma, the function will return immediately leaving any previously inserted pages present. Callers from the mmap handler may immediately return the error as their caller will destroy the vma, removing any successfully inserted pages. Other callers should make their own arrangements for calling unmap_region().

Context

Process context. Called by mmap handlers.

Return

0 on success and error code otherwise.

int **vm_map_pages_zero**(struct vm_area_struct *vma, struct page **pages, unsigned long num)

map range of kernel pages starts with zero offset

Parameters

struct vm_area_struct *vma
user vma to map to

struct page **pages
pointer to array of source kernel pages

unsigned long num
number of pages in page array

Description

Similar to *vm_map_pages()*, except that it explicitly sets the offset to 0. This function is intended for the drivers that did not consider vm_pgoff.

Context

Process context. Called by mmap handlers.

Return

0 on success and error code otherwise.

vm_fault_t **vmf_insert_pfn_prot**(struct vm_area_struct *vma, unsigned long addr, unsigned long pfn, pgprot_t pgprot)

insert single pfn into user vma with specified pgprot

Parameters

struct vm_area_struct *vma
user vma to map to

unsigned long addr
target user address of this page

unsigned long pfn
source kernel pfn

pgprot_t pgprot
pgprot flags for the inserted page

Description

This is exactly like *vmf_insert_pfn()*, except that it allows drivers to override pgprot on a per-page basis.

This only makes sense for IO mappings, and it makes no sense for COW mappings. In general, using multiple vmas is preferable; vmf_insert_pfn_prot should only be used if using multiple VMAs is impractical.

See *vmf_insert_mixed_prot()* for a discussion of the implication of using a value of **pgprot** different from that of **vma->vm_page_prot**.

Context

Process context. May allocate using `GFP_KERNEL`.

Return

vm_fault_t value.

vm_fault_t **vmf_insert_pfn**(struct vm_area_struct *vma, unsigned long addr, unsigned long pfn)

insert single pfn into user vma

Parameters

struct vm_area_struct *vma
user vma to map to

unsigned long addr
target user address of this page

unsigned long pfn
source kernel pfn

Description

Similar to vm_insert_page, this allows drivers to insert individual pages they've allocated into a user vma. Same comments apply.

This function should only be called from a vm_ops->fault handler, and in that case the handler should return the result of this function.

vma cannot be a COW mapping.

As this is called only for pages that do not currently exist, we do not need to flush old virtual caches or the TLB.

Context

Process context. May allocate using `GFP_KERNEL`.

Return

vm_fault_t value.

vm_fault_t **vmf_insert_mixed_prot**(struct vm_area_struct *vma, unsigned long addr, pfn_t pfn, pgprot_t pgprot)

insert single pfn into user vma with specified pgprot

Parameters

struct vm_area_struct *vma
user vma to map to

unsigned long addr
target user address of this page

pfn_t pfn
source kernel pfn

pgprot_t pgprot
pgprot flags for the inserted page

Description

This is exactly like vmf_insert_mixed(), except that it allows drivers to override pgprot on a per-page basis.

Typically this function should be used by drivers to set caching- and encryption bits different than those of **vma->vm_page_prot**, because the caching- or encryption mode may not be known at mmap() time. This is ok as long as **vma->vm_page_prot** is not used by the core vm to set caching and encryption bits for those vmas (except for COW pages). This is ensured by core vm only modifying these page table entries using functions that don't touch caching- or encryption bits, using pte_modify() if needed. (See for example mprotect()). Also when new page-table entries are created, this is only done using the fault() callback, and never using the value of vma->vm_page_prot, except for page-table entries that point to anonymous pages as the result of COW.

Context

Process context. May allocate using `GFP_KERNEL`.

Return

vm_fault_t value.

int **remap_pfn_range**(struct vm_area_struct *vma, unsigned long addr, unsigned long pfn, unsigned long size, pgprot_t prot)

remap kernel memory to userspace

Parameters

struct vm_area_struct *vma
user vma to map to

unsigned long addr
target page aligned user address to start at

unsigned long pfn
page frame number of kernel physical memory address

unsigned long size
size of mapping area

pgprot_t prot
page protection flags for this mapping

Note

this is only safe if the mm semaphore is held when called.

Return

`0` on success, negative error code otherwise.

int **vm_iomap_memory**(struct vm_area_struct *vma, phys_addr_t start, unsigned long len)

remap memory to userspace

Parameters

struct vm_area_struct *vma
user vma to map to

phys_addr_t start
start of the physical memory to be mapped

unsigned long len
size of area

Description

This is a simplified io_remap_pfn_range() for common driver use. The driver just needs to give us the physical memory range to be mapped, we'll figure out the rest from the vma information.

NOTE! Some drivers might want to tweak vma->vm_page_prot first to get whatever write-combining details or similar.

Return

`0` on success, negative error code otherwise.

void **unmap_mapping_range**(struct address_space *mapping, loff_t const holebegin, loff_t const holelen, int even_cows)

unmap the portion of all mmaps in the specified address_space corresponding to the specified byte range in the underlying file.

Parameters

struct address_space *mapping
the address space containing mmaps to be unmapped.

loff_t const holebegin
byte in first page to unmap, relative to the start of the underlying file. This will be rounded down to a PAGE_SIZE boundary. Note that this is different from *truncate_pagecache()*, which must keep the partial page. In contrast, we must get rid of partial pages.

loff_t const holelen
size of prospective hole in bytes. This will be rounded up to a PAGE_SIZE boundary. A holelen of zero truncates to the end of the file.

int even_cows
1 when truncating a file, unmap even private COWed pages; but 0 when invalidating pagecache, don't throw away private data.

int **follow_pte**(struct mm_struct *mm, unsigned long address, pte_t **ptepp, spinlock_t **ptlp)

look up PTE at a user virtual address

Parameters

struct mm_struct *mm
the mm_struct of the target address space

unsigned long address
user virtual address

pte_t **ptepp
location to store found PTE

spinlock_t **ptlp
location to store the lock for the PTE

Description

On a successful return, the pointer to the PTE is stored in **ptepp**; the corresponding lock is taken and its location is stored in **ptlp**. The contents of the PTE are only stable until **ptlp** is released; any further use, if any, must be protected against invalidation with MMU notifiers.

Only IO mappings and raw PFN mappings are allowed. The mmap semaphore should be taken for read.

KVM uses this function. While it is arguably less bad than `follow_pfn`, it is not a good general-purpose API.

Return

zero on success, -ve otherwise.

int **follow_pfn**(struct vm_area_struct *vma, unsigned long address, unsigned long *pfn)

look up PFN at a user virtual address

Parameters

struct vm_area_struct *vma
memory mapping

unsigned long address
user virtual address

unsigned long *pfn
location to store found PFN

Description

Only IO mappings and raw PFN mappings are allowed.

This function does not allow the caller to read the permissions of the PTE. Do not use it.

Return

zero and the pfn at **pfn** on success, -ve otherwise.

unsigned long **__get_pfnblock_flags_mask**(struct *page* *page, unsigned long pfn, unsigned long mask)

Return the requested group of flags for the pageblock_nr_pages block of pages

Parameters

struct page *page
The page within the block of interest

unsigned long pfn
The target page frame number

unsigned long mask
mask of bits that the caller is interested in

Return

pageblock_bits flags

void **set_pfnblock_flags_mask**(struct *page* *page, unsigned long flags, unsigned long pfn, unsigned long mask)

Set the requested group of flags for a pageblock_nr_pages block of pages

Parameters

struct page *page
The page within the block of interest

unsigned long flags
The flags to set

unsigned long pfn
The target page frame number

unsigned long mask
mask of bits that the caller is interested in

void **__putback_isolated_page**(struct *page* *page, unsigned int order, int mt)

Return a now-isolated page back where we got it

Parameters

struct page *page
Page that was isolated

unsigned int order
Order of the isolated page

int mt
The page’ s pageblock’ s migratetype

Description

This function is meant to return a page pulled from the free lists via __isolate_free_page back to the free lists they were pulled from.

void ***alloc_pages_exact**(size_t size, gfp_t gfp_mask)
allocate an exact number physically-contiguous pages.

Parameters

size_t size
the number of bytes to allocate

gfp_t gfp_mask
GFP flags for the allocation, must not contain __GFP_COMP

Description

This function is similar to alloc_pages(), except that it allocates the minimum number of pages to satisfy the request. alloc_pages() can only allocate memory in power-of-two pages.

This function is also limited by MAX_ORDER.

Memory allocated by this function must be released by *free_pages_exact()*.

Return

pointer to the allocated area or `NULL` in case of error.

void ***alloc_pages_exact_nid**(int nid, size_t size, gfp_t gfp_mask)
allocate an exact number of physically-contiguous pages on a node.

Parameters

int nid
the preferred node ID where memory should be allocated

size_t size
the number of bytes to allocate

gfp_t gfp_mask
GFP flags for the allocation, must not contain __GFP_COMP

Description

Like *alloc_pages_exact()*, but try to allocate on node nid first before falling back.

Return

pointer to the allocated area or `NULL` in case of error.

void **free_pages_exact**(void *virt, size_t size)
release memory allocated via *alloc_pages_exact()*

Parameters

void *virt
the value returned by alloc_pages_exact.

size_t size
size of allocation, same value as passed to *alloc_pages_exact()*.

Description

Release the memory allocated by a previous call to alloc_pages_exact.

unsigned long **nr_free_zone_pages**(int offset)
count number of pages beyond high watermark

Parameters

int offset
The zone index of the highest zone

Description

nr_free_zone_pages() counts the number of pages which are beyond the high watermark within all zones at or below a given zone index. For each zone, the number of pages is calculated as:

nr_free_zone_pages = managed_pages - high_pages

Return

number of pages beyond high watermark.

unsigned long **nr_free_buffer_pages**(void)
count number of pages beyond high watermark

Parameters

void
no arguments

Description

nr_free_buffer_pages() counts the number of pages which are beyond the high watermark within ZONE_DMA and ZONE_NORMAL.

Return

number of pages beyond high watermark within ZONE_DMA and ZONE_NORMAL.

int **find_next_best_node**(int node, nodemask_t *used_node_mask)
find the next node that should appear in a given node's fallback list

Parameters

int node
node whose fallback list we're appending

nodemask_t *used_node_mask
nodemask_t of already used nodes

Description

We use a number of factors to determine which is the next node that should appear on a given node's fallback list. The node should not have appeared already in **node**' s fallback list, and it should be the next closest node according to the distance array (which contains arbitrary distance values from each node to each node in the system), and should also prefer nodes with no CPUs, since presumably they' ll have very little allocation pressure on them otherwise.

Return

node id of the found node or `NUMA_NO_NODE` if no node is found.

void **get_pfn_range_for_nid**(unsigned int nid, unsigned long *start_pfn, unsigned long *end_pfn)

Return the start and end page frames for a node

Parameters

unsigned int nid
The nid to return the range for. If MAX_NUMNODES, the min and max PFN are returned.

unsigned long *start_pfn
Passed by reference. On return, it will have the node start_pfn.

unsigned long *end_pfn
Passed by reference. On return, it will have the node end_pfn.

Description

It returns the start and end page frame of a node based on information provided by *memblock_set_node()*. If called for a node with no available memory, a warning is printed and the start and end PFNs will be 0.

unsigned long **absent_pages_in_range**(unsigned long start_pfn, unsigned long end_pfn)

Return number of page frames in holes within a range

Parameters

unsigned long start_pfn
The start PFN to start searching for holes

unsigned long end_pfn
The end PFN to stop searching for holes

Return

the number of pages frames in memory holes within a range.

unsigned long **node_map_pfn_alignment**(void)

determine the maximum internode alignment

Parameters

void
no arguments

Description

This function should be called after node map is populated and sorted. It calculates the maximum power of two alignment which can distinguish all the nodes.

For example, if all nodes are 1GiB and aligned to 1GiB, the return value would indicate 1GiB alignment with (1 << (30 - PAGE_SHIFT)). If the nodes are shifted by 256MiB, 256MiB. Note that if only the last node is shifted, 1GiB is enough and this function will indicate so.

This is used to test whether pfn -> nid mapping of the chosen memory model has fine enough granularity to avoid incorrect mapping for the populated node map.

Return

the determined alignment in pfn' s. 0 if there is no alignment requirement (single node).

unsigned long **find_min_pfn_with_active_regions**(void)

Find the minimum PFN registered

Parameters

void
no arguments

Return

the minimum PFN based on information provided via *memblock_set_node()*.

void **free_area_init**(unsigned long *max_zone_pfn)

Initialise all pg_data_t and zone data

Parameters

unsigned long *max_zone_pfn
an array of max PFNs for each zone

Description

This will call free_area_init_node() for each active node in the system. Using the page ranges provided by *memblock_set_node()*, the size of each zone in each node and their holes is calculated. If the maximum PFN between two adjacent zones match, it is assumed that the zone is empty. For example, if arch_max_dma_pfn == arch_max_dma32_pfn, it is assumed that arch_max_dma32_pfn has no pages. It is also assumed that a zone starts where the previous one ended. For example, ZONE_DMA32 starts at arch_max_dma_pfn.

void **set_dma_reserve**(unsigned long new_dma_reserve)

set the specified number of pages reserved in the first zone

Parameters

unsigned long new_dma_reserve
The number of pages to mark reserved

Description

The per-cpu batchsize and zone watermarks are determined by managed_pages. In the DMA zone, a significant percentage may be consumed by kernel image and other unfreeable allocations which can skew the watermarks badly. This function may optionally be used to account for unfreeable pages in the first zone (e.g., ZONE_DMA). The effect will be lower watermarks and smaller per-cpu batchsize.

void **setup_per_zone_wmarks**(void)

called when min_free_kbytes changes or when memory is hot-{added|removed}

Parameters

void
no arguments

Description

Ensures that the watermark[min,low,high] values for each zone are set correctly with respect to min_free_kbytes.

int **alloc_contig_range**(unsigned long start, unsigned long end, unsigned migratetype, gfp_t gfp_mask)

- tries to allocate given range of pages

Parameters

unsigned long start
start PFN to allocate

unsigned long end
one-past-the-last PFN to allocate

unsigned migratetype
migratetype of the underlaying pageblocks (either #MIGRATE_MOVABLE or #MIGRATE_CMA). All pageblocks in range must have the same migratetype and it must be either of the two.

gfp_t gfp_mask
GFP mask to use during compaction

Description

The PFN range does not have to be pageblock or MAX_ORDER_NR_PAGES aligned. The PFN range must belong to a single zone.

The first thing this routine does is attempt to MIGRATE_ISOLATE all pageblocks in the range. Once isolated, the pageblocks should not be modified by others.

Return

zero on success or negative error code. On success all pages which PFN is in [start, end) are allocated for the caller and need to be freed with free_contig_range().

struct page ***alloc_contig_pages**(unsigned long nr_pages, gfp_t gfp_mask, int nid, nodemask_t *nodemask)

- tries to find and allocate contiguous range of pages

Parameters

unsigned long nr_pages
Number of contiguous pages to allocate

gfp_t gfp_mask
GFP mask to limit search and used during compaction

int nid
Target node

nodemask_t *nodemask
Mask for other possible nodes

Description

This routine is a wrapper around *alloc_contig_range()*. It scans over zones on an applicable zonelist to find a contiguous pfn range which can then be tried for allocation with *alloc_contig_range()*. This routine is intended for allocation requests which can not be fulfilled with the buddy allocator.

The allocated memory is always aligned to a page boundary. If nr_pages is a power of two then the alignment is guaranteed to be to the given nr_pages (e.g. 1GB request would be aligned to 1GB).

Allocated pages can be freed with free_contig_range() or by manually calling __free_page() on each allocated page.

Return

pointer to contiguous pages on success, or NULL if not successful.

5.8 The genalloc/genpool subsystem

There are a number of memory-allocation subsystems in the kernel, each aimed at a specific need. Sometimes, however, a kernel developer needs to implement a new allocator for a specific range of special-purpose memory; often that memory is located on a device somewhere. The author of the driver for that device can certainly write a little allocator to get the job done, but that is the way to fill the kernel with dozens of poorly tested allocators. Back in 2005, Jes Sorensen lifted one of those allocators from the sym53c8xx_2 driver and posted it as a generic module for the creation of ad hoc memory allocators. This code was merged for the 2.6.13 release; it has been modified considerably since then.

Code using this allocator should include <linux/genalloc.h>. The action begins with the creation of a pool using one of:

struct gen_pool ***gen_pool_create**(int min_alloc_order, int nid)
create a new special memory pool

Parameters

int min_alloc_order
log base 2 of number of bytes each bitmap bit represents

int nid
node id of the node the pool structure should be allocated on, or -1

Description

Create a new special memory pool that can be used to manage special purpose memory not managed by the regular kmalloc/kfree interface.

struct gen_pool ***devm_gen_pool_create**(struct device *dev, int min_alloc_order, int nid, const char *name)

managed gen_pool_create

Parameters

struct device *dev
device that provides the gen_pool

int min_alloc_order
log base 2 of number of bytes each bitmap bit represents

int nid
node selector for allocated gen_pool, `NUMA_NO_NODE` for all nodes

const char *name
name of a gen_pool or NULL, identifies a particular gen_pool on device

Description

Create a new special memory pool that can be used to manage special purpose memory not managed by the regular kmalloc/kfree interface. The pool will be automatically destroyed by the device management code.

A call to *gen_pool_create()* will create a pool. The granularity of allocations is set with min_alloc_order; it is a log-base-2 number like those used by the page allocator, but it refers to bytes rather than pages. So, if min_alloc_order is passed as 3, then all allocations will be a multiple of eight bytes. Increasing min_alloc_order decreases the memory required to track the memory in the pool. The nid parameter specifies which NUMA node should be used for the allocation of the housekeeping structures; it can be -1 if the caller doesn't care.

The "managed" interface *devm_gen_pool_create()* ties the pool to a specific device. Among other things, it will automatically clean up the pool when the given device is destroyed.

A pool is shut down with:

void **gen_pool_destroy**(struct gen_pool *pool)

destroy a special memory pool

Parameters

struct gen_pool *pool
pool to destroy

Description

Destroy the specified special memory pool. Verifies that there are no outstanding allocations.

It's worth noting that, if there are still allocations outstanding from the given pool, this function will take the rather extreme step of invoking BUG(), crashing the entire system. You have been warned.

A freshly created pool has no memory to allocate. It is fairly useless in that state, so one of the first orders of business is usually to add memory to the pool. That can be done with one of:

int **gen_pool_add**(struct gen_pool *pool, unsigned long addr, size_t size, int nid)

add a new chunk of special memory to the pool

Parameters

struct gen_pool *pool
pool to add new memory chunk to

unsigned long addr
starting address of memory chunk to add to pool

size_t size
size in bytes of the memory chunk to add to pool

int nid
node id of the node the chunk structure and bitmap should be allocated on, or -1

Description

Add a new chunk of special memory to the specified pool.

Returns 0 on success or a -ve errno on failure.

int **gen_pool_add_owner**(struct gen_pool *pool, unsigned long virt, phys_addr_t phys, size_t size, int nid, void *owner)

add a new chunk of special memory to the pool

Parameters

struct gen_pool *pool
pool to add new memory chunk to

unsigned long virt
virtual starting address of memory chunk to add to pool

phys_addr_t phys
physical starting address of memory chunk to add to pool

size_t size
size in bytes of the memory chunk to add to pool

int nid
node id of the node the chunk structure and bitmap should be allocated on, or -1

void *owner
private data the publisher would like to recall at alloc time

Description

Add a new chunk of special memory to the specified pool.

Returns 0 on success or a -ve errno on failure.

A call to *gen_pool_add()* will place the size bytes of memory starting at addr (in the kernel's virtual address space) into the given pool, once again using nid as the node ID for ancillary memory allocations. The gen_pool_add_virt() variant associates an explicit physical address with the memory; this is only necessary if the pool will be used for DMA allocations.

The functions for allocating memory from the pool (and putting it back) are:

unsigned long **gen_pool_alloc**(struct gen_pool *pool, size_t size)

allocate special memory from the pool

Parameters

struct gen_pool *pool
pool to allocate from

size_t size
number of bytes to allocate from the pool

Description

Allocate the requested number of bytes from the specified pool. Uses the pool allocation function (with first-fit algorithm by default). Can not be used in NMI handler on architectures without NMI-safe cmpxchg implementation.

void ***gen_pool_dma_alloc**(struct gen_pool *pool, size_t size, dma_addr_t *dma)

allocate special memory from the pool for DMA usage

Parameters

struct gen_pool *pool
pool to allocate from

size_t size
number of bytes to allocate from the pool

dma_addr_t *dma
dma-view physical address return value. Use `NULL` if unneeded.

Description

Allocate the requested number of bytes from the specified pool. Uses the pool allocation function (with first-fit algorithm by default). Can not be used in NMI handler on architectures without NMI-safe cmpxchg implementation.

Return

virtual address of the allocated memory, or `NULL` on failure

void **gen_pool_free_owner**(struct gen_pool *pool, unsigned long addr, size_t size, void **owner)

free allocated special memory back to the pool

Parameters

struct gen_pool *pool
pool to free to

unsigned long addr
starting address of memory to free back to pool

size_t size
size in bytes of memory to free

void **owner
private data stashed at *gen_pool_add()* time

Description

Free previously allocated special memory back to the specified pool. Can not be used in NMI handler on architectures without NMI-safe cmpxchg implementation.

As one would expect, *gen_pool_alloc()* will allocate size< bytes from the given pool. The *gen_pool_dma_alloc()* variant allocates memory for use with DMA operations, returning the associated physical address in the space pointed to by dma. This will only work if the memory was added with gen_pool_add_virt(). Note that this function departs from the usual genpool pattern of using unsigned long values to represent kernel addresses; it returns a void * instead.

That all seems relatively simple; indeed, some developers clearly found it to be too simple. After all, the interface above provides no control over how the allocation functions choose which specific piece of memory to return. If that sort of control is needed, the following functions will be of interest:

unsigned long **gen_pool_alloc_algo_owner**(struct gen_pool *pool, size_t size, genpool_algo_t algo, void *data, void **owner)

allocate special memory from the pool

Parameters

struct gen_pool *pool
pool to allocate from

size_t size
number of bytes to allocate from the pool

genpool_algo_t algo
algorithm passed from caller

void *data
data passed to algorithm

void **owner
optionally retrieve the chunk owner

Description

Allocate the requested number of bytes from the specified pool. Uses the pool allocation function (with first-fit algorithm by default). Can not be used in NMI handler on architectures without NMI-safe cmpxchg implementation.

void **gen_pool_set_algo**(struct gen_pool *pool, genpool_algo_t algo, void *data)

set the allocation algorithm

Parameters

struct gen_pool *pool
pool to change allocation algorithm

genpool_algo_t algo
custom algorithm function

void *data
additional data used by **algo**

Description

Call **algo** for each memory allocation in the pool. If **algo** is NULL use gen_pool_first_fit as default memory allocation function.

Allocations with gen_pool_alloc_algo() specify an algorithm to be used to choose the memory to be allocated; the default algorithm can be set with *gen_pool_set_algo()*. The data value is passed to the algorithm; most ignore it, but it is occasionally needed. One can, naturally, write a special-purpose algorithm, but there is a fair set already available:

- gen_pool_first_fit is a simple first-fit allocator; this is the default algorithm if none other has been specified.
- gen_pool_first_fit_align forces the allocation to have a specific alignment (passed via data in a genpool_data_align structure).
- gen_pool_first_fit_order_align aligns the allocation to the order of the size. A 60-byte allocation will thus be 64-byte aligned, for example.
- gen_pool_best_fit, as one would expect, is a simple best-fit allocator.
- gen_pool_fixed_alloc allocates at a specific offset (passed in a genpool_data_fixed structure via the data parameter) within the pool. If the indicated memory is not available the allocation fails.

There is a handful of other functions, mostly for purposes like querying the space available in the pool or iterating through chunks of memory. Most users, however, should not need much beyond what has been described above. With luck, wider awareness of this module will help to prevent the writing of special-purpose memory allocators in the future.

phys_addr_t **gen_pool_virt_to_phys**(struct gen_pool *pool, unsigned long addr)

return the physical address of memory

Parameters

struct gen_pool *pool
pool to allocate from

unsigned long addr
starting address of memory

Description

Returns the physical address on success, or -1 on error.

void **gen_pool_for_each_chunk**(struct gen_pool *pool, void (*func)(struct gen_pool *pool, struct gen_pool_chunk *chunk, void *data), void *data)

call func for every chunk of generic memory pool

Parameters

struct gen_pool *pool
the generic memory pool

void (*func)(struct gen_pool *pool, struct gen_pool_chunk *chunk, void *data)
func to call

void *data
additional data used by **func**

Description

Call **func** for every chunk of generic memory pool. The **func** is called with rcu_read_lock held.

bool **gen_pool_has_addr**(struct gen_pool *pool, unsigned long start, size_t size)
checks if an address falls within the range of a pool

Parameters

struct gen_pool *pool
the generic memory pool

unsigned long start
start address

size_t size
size of the region

Description

Check if the range of addresses falls within the specified pool. Returns true if the entire range is contained in the pool and false otherwise.

size_t **gen_pool_avail**(struct gen_pool *pool)
get available free space of the pool

Parameters

struct gen_pool *pool
pool to get available free space

Description

Return available free space of the specified pool.

size_t **gen_pool_size**(struct gen_pool *pool)
get size in bytes of memory managed by the pool

Parameters

struct gen_pool *pool
pool to get size

Description

Return size in bytes of memory managed by the pool.

struct gen_pool ***gen_pool_get**(struct device *dev, const char *name)
Obtain the gen_pool (if any) for a device

Parameters

struct device *dev
device to retrieve the gen_pool from

const char *name
name of a gen_pool or NULL, identifies a particular gen_pool on device

Description

Returns the gen_pool for the device if one is present, or NULL.

struct gen_pool ***of_gen_pool_get**(struct device_node *np, const char *propname, int index)

find a pool by phandle property

Parameters

struct device_node *np
device node

const char *propname
property name containing phandle(s)

int index
index into the phandle array

Description

Returns the pool that contains the chunk starting at the physical address of the device tree node pointed at by the phandle property, or NULL if not found.

5.9 pin_user_pages() and related calls

- *References*

5.9.1 Overview

This document describes the following functions:

```
pin_user_pages()
pin_user_pages_fast()
pin_user_pages_remote()
```

5.9.2 Basic description of FOLL_PIN

FOLL_PIN and FOLL_LONGTERM are flags that can be passed to the get_user_pages*() ("gup") family of functions. FOLL_PIN has significant interactions and interdependencies with FOLL_LONGTERM, so both are covered here.

FOLL_PIN is internal to gup, meaning that it should not appear at the gup call sites. This allows the associated wrapper functions (pin_user_pages*() and others) to set the correct combination of these flags, and to check for problems as well.

FOLL_LONGTERM, on the other hand, *is* allowed to be set at the gup call sites. This is in order to avoid creating a large number of wrapper functions to cover all combinations of get*(), pin*(), FOLL_LONGTERM, and more. Also, the pin_user_pages*() APIs are clearly distinct from the get_user_pages*() APIs, so that' s a natural dividing line, and a good point to make separate wrapper calls. In other words, use pin_user_pages*() for DMA-pinned pages, and get_user_pages*() for other cases. There are five cases described later on in this document, to further clarify that concept.

FOLL_PIN and FOLL_GET are mutually exclusive for a given gup call. However, multiple threads and call sites are free to pin the same struct pages, via both FOLL_PIN and FOLL_GET. It' s just the call site that needs to choose one or the other, not the struct page(s).

The FOLL_PIN implementation is nearly the same as FOLL_GET, except that FOLL_PIN uses a different reference counting technique.

FOLL_PIN is a prerequisite to FOLL_LONGTERM. Another way of saying that is, FOLL_LONGTERM is a specific case, more restrictive case of FOLL_PIN.

5.9.3 Which flags are set by each wrapper

For these pin_user_pages*() functions, FOLL_PIN is OR' d in with whatever gup flags the caller provides. The caller is required to pass in a non-null struct pages* array, and the function then pins pages by incrementing each by a special value: GUP_PIN_COUNTING_BIAS.

For huge pages (and in fact, any compound page of more than 2 pages), the GUP_PIN_COUNTING_BIAS scheme is not used. Instead, an exact form of pin counting is achieved, by using the 3rd struct page in the compound page. A new struct page field, hpage_pinned_refcount, has been added in order to support this.

This approach for compound pages avoids the counting upper limit problems that are discussed below. Those limitations would have been aggravated severely by huge pages, because each tail page adds a refcount to the head page. And in fact, testing revealed that, without a separate hpage_pinned_refcount field, page overflows were seen in some huge page stress tests.

This also means that huge pages and compound pages (of order > 1) do not suffer from the false positives problem that is mentioned below.:

```
Function
--------
pin_user_pages          FOLL_PIN is always set internally by this␣
↪function.
pin_user_pages_fast     FOLL_PIN is always set internally by this␣
↪function.
pin_user_pages_remote   FOLL_PIN is always set internally by this␣
↪function.
```

For these get_user_pages*() functions, FOLL_GET might not even be specified. Behavior is a little more complex than above. If FOLL_GET was *not* specified, but the caller passed in a non-null struct pages* array, then the function sets FOLL_GET for you, and proceeds to pin pages by incrementing the refcount of each page by +1.:

```
Function
--------
get_user_pages           FOLL_GET is sometimes set internally by␣
↪this function.
get_user_pages_fast      FOLL_GET is sometimes set internally by␣
↪this function.
get_user_pages_remote    FOLL_GET is sometimes set internally by␣
↪this function.
```

5.9.4 Tracking dma-pinned pages

Some of the key design constraints, and solutions, for tracking dma-pinned pages:

- An actual reference count, per struct page, is required. This is because multiple processes may pin and unpin a page.
- False positives (reporting that a page is dma-pinned, when in fact it is not) are acceptable, but false negatives are not.
- struct page may not be increased in size for this, and all fields are already used.
- Given the above, we can overload the page->_refcount field by using, sort of, the upper bits in that field for a dma-pinned count. "Sort of", means that, rather than dividing page->_refcount into bit fields, we simple add a medium-large value (GUP_PIN_COUNTING_BIAS, initially chosen to be 1024: 10 bits) to page->_refcount. This provides fuzzy behavior: if a page has get_page() called on it 1024 times, then it will appear to have a single dma-pinned count. And again, that's acceptable.

This also leads to limitations: there are only 31-10==21 bits available for a counter that increments 10 bits at a time.

- Callers must specifically request "dma-pinned tracking of pages". In other words, just calling get_user_pages() will not suffice; a new set of functions, pin_user_page() and related, must be used.

5.9.5 FOLL_PIN, FOLL_GET, FOLL_LONGTERM: when to use which flags

Thanks to Jan Kara, Vlastimil Babka and several other -mm people, for describing these categories:

CASE 1: Direct IO (DIO)

There are GUP references to pages that are serving as DIO buffers. These buffers are needed for a relatively short time (so they are not "long term"). No special synchronization with page_mkclean() or munmap() is provided. Therefore, flags to set at the call site are:

```
FOLL_PIN
```

…but rather than setting FOLL_PIN directly, call sites should use one of the pin_user_pages*() routines that set FOLL_PIN.

CASE 2: RDMA

There are GUP references to pages that are serving as DMA buffers. These buffers are needed for a long time ("long term"). No special synchronization with page_mkclean() or munmap() is provided. Therefore, flags to set at the call site are:

```
FOLL_PIN | FOLL_LONGTERM
```

NOTE: Some pages, such as DAX pages, cannot be pinned with longterm pins. That's because DAX pages do not have a separate page cache, and so "pinning" implies locking down file system blocks, which is not (yet) supported in that way.

CASE 3: MMU notifier registration, with or without page faulting hardware

Device drivers can pin pages via get_user_pages*(), and register for mmu notifier callbacks for the memory range. Then, upon receiving a notifier "invalidate range" callback , stop the device from using the range, and unpin the pages. There may be other possible schemes, such as for example explicitly synchronizing against pending IO, that accomplish approximately the same thing.

Or, if the hardware supports replayable page faults, then the device driver can avoid pinning entirely (this is ideal), as follows: register for mmu notifier callbacks as above, but instead of stopping the device and unpinning in the callback, simply remove the range from the device's page tables.

Either way, as long as the driver unpins the pages upon mmu notifier callback, then there is proper synchronization with both filesystem and mm (page_mkclean(), munmap(), etc). Therefore, neither flag needs to be set.

CASE 4: Pinning for struct page manipulation only

If only struct page data (as opposed to the actual memory contents that a page is tracking) is affected, then normal GUP calls are sufficient, and neither flag needs to be set.

CASE 5: Pinning in order to write to the data within the page

Even though neither DMA nor Direct IO is involved, just a simple case of "pin, write to a page's data, unpin" can cause a problem. Case 5 may be considered a superset of Case 1, plus Case 2, plus anything that invokes that pattern. In other words, if the code is neither Case 1 nor Case 2, it may still require FOLL_PIN, for patterns like this:

Correct (uses FOLL_PIN calls):
pin_user_pages() write to the data within the pages unpin_user_pages()

INCORRECT (uses FOLL_GET calls):
get_user_pages() write to the data within the pages put_page()

5.9.6 page_maybe_dma_pinned(): the whole point of pinning

The whole point of marking pages as "DMA-pinned" or "gup-pinned" is to be able to query, "is this page DMA-pinned?" That allows code such as page_mkclean() (and file system writeback code in general) to make informed decisions about what to do when a page cannot be unmapped due to such pins.

What to do in those cases is the subject of a years-long series of discussions and debates (see the References at the end of this document). It's a TODO item here: fill in the details once that's worked out. Meanwhile, it's safe to say that having this available:

```
static inline bool page_maybe_dma_pinned(struct page *page)
```

…is a prerequisite to solving the long-running gup+DMA problem.

5.9.7 Another way of thinking about FOLL_GET, FOLL_PIN, and FOLL_LONGTERM

Another way of thinking about these flags is as a progression of restrictions: FOLL_GET is for struct page manipulation, without affecting the data that the struct page refers to. FOLL_PIN is a *replacement* for FOLL_GET, and is for short term pins on pages whose data *will* get accessed. As such, FOLL_PIN is a "more severe" form of pinning. And finally, FOLL_LONGTERM is an even more restrictive case that has FOLL_PIN as a prerequisite: this is for pages that will be pinned longterm, and whose data will be accessed.

5.9.8 Unit testing

This file:

```
tools/testing/selftests/vm/gup_benchmark.c
```

has the following new calls to exercise the new pin*() wrapper functions:

- PIN_FAST_BENCHMARK (./gup_benchmark -a)
- PIN_BENCHMARK (./gup_benchmark -b)

You can monitor how many total dma-pinned pages have been acquired and released since the system was booted, via two new /proc/vmstat entries:

```
/proc/vmstat/nr_foll_pin_acquired
/proc/vmstat/nr_foll_pin_released
```

Under normal conditions, these two values will be equal unless there are any long-term [R]DMA pins in place, or during pin/unpin transitions.

- nr_foll_pin_acquired: This is the number of logical pins that have been acquired since the system was powered on. For huge pages, the head page is pinned once for each page (head page and each tail page) within the huge page. This follows the same sort of behavior that get_user_pages() uses for huge pages: the head page is refcounted once for each tail or head page in the huge page, when get_user_pages() is applied to a huge page.
- nr_foll_pin_released: The number of logical pins that have been released since the system was powered on. Note that pages are released (unpinned) on a PAGE_SIZE granularity, even if the original pin was applied to a huge page. Becaused of the pin count behavior described above in "nr_foll_pin_acquired" , the accounting balances out, so that after doing this:

  ```
  pin_user_pages(huge_page);
  for (each page in huge_page)
      unpin_user_page(page);
  ```

…the following is expected:

```
nr_foll_pin_released == nr_foll_pin_acquired
```

(…unless it was already out of balance due to a long-term RDMA pin being in place.)

5.9.9 Other diagnostics

dump_page() has been enhanced slightly, to handle these new counting fields, and to better report on compound pages in general. Specifically, for compound pages with order > 1, the exact (hpage_pinned_refcount) pincount is reported.

5.9.10 References

- Some slow progress on get_user_pages() (Apr 2, 2019)
- DMA and get_user_pages() (LPC: Dec 12, 2018)
- The trouble with get_user_pages() (Apr 30, 2018)
- LWN kernel index: get_user_pages()

John Hubbard, October, 2019

5.10 Boot time memory management

Early system initialization cannot use "normal" memory management simply because it is not set up yet. But there is still need to allocate memory for various data structures, for instance for the physical page allocator.

A specialized allocator called `memblock` performs the boot time memory management. The architecture specific initialization must set it up in `setup_arch()` and tear it down in `mem_init()` functions.

Once the early memory management is available it offers a variety of functions and macros for memory allocations. The allocation request may be directed to the first (and probably the only) node or to a particular node in a NUMA system. There are API variants that panic when an allocation fails and those that don't.

Memblock also offers a variety of APIs that control its own behaviour.

5.10.1 Memblock Overview

Memblock is a method of managing memory regions during the early boot period when the usual kernel memory allocators are not up and running.

Memblock views the system memory as collections of contiguous regions. There are several types of these collections:

- `memory` - describes the physical memory available to the kernel; this may differ from the actual physical memory installed in the system, for instance when the memory is restricted with `mem=` command line parameter
- `reserved` - describes the regions that were allocated
- `physmem` - describes the actual physical memory available during boot regardless of the possible restrictions and memory hot(un)plug; the `physmem` type is only available on some architectures.

Each region is represented by *struct memblock_region* that defines the region extents, its attributes and NUMA node id on NUMA systems. Every memory type is described by the *struct memblock_type* which contains an array of memory regions along with the allocator metadata. The "memory" and "reserved" types are nicely wrapped with *struct memblock*. This structure is statically initialized at build time. The region arrays are initially sized to `INIT_MEMBLOCK_REGIONS` for "memory" and `INIT_MEMBLOCK_RESERVED_REGIONS` for "reserved". The region array for "physmem" is initially sized to `INIT_PHYSMEM_REGIONS`. The memblock_allow_resize() enables automatic resizing of the region arrays during addition of new regions. This feature should be used with care so that memory allocated for the region array will not overlap with areas that should be reserved, for example initrd.

The early architecture setup should tell memblock what the physical memory layout is by using *memblock_add()* or *memblock_add_node()* functions. The first function does not assign the region to a NUMA node and it is appropriate for UMA systems. Yet, it is possible to use it on NUMA systems as well and assign the region to a NUMA node later in the setup process using *memblock_set_node()*. The *memblock_add_node()* performs such an assignment directly.

Once memblock is setup the memory can be allocated using one of the API variants:

- memblock_phys_alloc*() - these functions return the **physical** address of the allocated memory
- memblock_alloc*() - these functions return the **virtual** address of the allocated memory.

Note, that both API variants use implicit assumptions about allowed memory ranges and the fallback methods. Consult the documentation of *memblock_alloc_internal()* and *memblock_alloc_range_nid()* functions for more elaborate description.

As the system boot progresses, the architecture specific mem_init() function frees all the memory to the buddy page allocator.

Unless an architecture enables `CONFIG_ARCH_KEEP_MEMBLOCK`, the memblock data structures (except "physmem") will be discarded after the system initialization completes.

5.10.2 Functions and structures

Here is the description of memblock data structures, functions and macros. Some of them are actually internal, but since they are documented it would be silly to omit them. Besides, reading the descriptions for the internal functions can help to understand what really happens under the hood.

enum **memblock_flags**

definition of memory region attributes

Constants

MEMBLOCK_NONE

no special request

MEMBLOCK_HOTPLUG
hotpluggable region

MEMBLOCK_MIRROR
mirrored region

MEMBLOCK_NOMAP
don't add to kernel direct mapping

struct **memblock_region**
represents a memory region

Definition

```
struct memblock_region {
  phys_addr_t base;
  phys_addr_t size;
  enum memblock_flags flags;
#ifdef CONFIG_NEED_MULTIPLE_NODES;
  int nid;
#endif;
};
```

Members

base
base address of the region

size
size of the region

flags
memory region attributes

nid
NUMA node id

struct **memblock_type**
collection of memory regions of certain type

Definition

```
struct memblock_type {
  unsigned long cnt;
  unsigned long max;
  phys_addr_t total_size;
  struct memblock_region *regions;
  char *name;
};
```

Members

cnt
number of regions

max
size of the allocated array

total_size
size of all regions

regions
array of regions

name
the memory type symbolic name

struct **memblock**
memblock allocator metadata

Definition

```
struct memblock {
  bool bottom_up;
  phys_addr_t current_limit;
  struct memblock_type memory;
  struct memblock_type reserved;
};
```

Members

bottom_up
is bottom up direction?

current_limit
physical address of the current allocation limit

memory
usable memory regions

reserved
reserved memory regions

for_each_physmem_range

`for_each_physmem_range (i, type, p_start, p_end)`

iterate through physmem areas not included in type.

Parameters

i
u64 used as loop variable

type
ptr to memblock_type which excludes from the iteration, can be `NULL`

p_start
ptr to phys_addr_t for start address of the range, can be `NULL`

p_end
ptr to phys_addr_t for end address of the range, can be `NULL`

__for_each_mem_range

`__for_each_mem_range (i, type_a, type_b, nid, flags, p_start, p_end, p_nid)` iterate through memblock areas from type_a and not included in type_b. Or just type_a if type_b is NULL.

Parameters

i
u64 used as loop variable

type_a
ptr to memblock_type to iterate

type_b
ptr to memblock_type which excludes from the iteration

nid
node selector, `NUMA_NO_NODE` for all nodes

flags
pick from blocks based on memory attributes

p_start
ptr to phys_addr_t for start address of the range, can be `NULL`

p_end
ptr to phys_addr_t for end address of the range, can be `NULL`

p_nid
ptr to int for nid of the range, can be `NULL`

__for_each_mem_range_rev

`__for_each_mem_range_rev (i, type_a, type_b, nid, flags, p_start, p_end, p_nid)`

reverse iterate through memblock areas from type_a and not included in type_b. Or just type_a if type_b is NULL.

Parameters

i
u64 used as loop variable

type_a
ptr to memblock_type to iterate

type_b
ptr to memblock_type which excludes from the iteration

nid
node selector, `NUMA_NO_NODE` for all nodes

flags
pick from blocks based on memory attributes

p_start
ptr to phys_addr_t for start address of the range, can be `NULL`

p_end
ptr to phys_addr_t for end address of the range, can be `NULL`

p_nid
ptr to int for nid of the range, can be `NULL`

for_each_mem_range

`for_each_mem_range (i, p_start, p_end)`

iterate through memory areas.

Parameters

i
u64 used as loop variable

p_start
ptr to phys_addr_t for start address of the range, can be `NULL`

p_end
ptr to phys_addr_t for end address of the range, can be `NULL`

for_each_mem_range_rev

`for_each_mem_range_rev (i, p_start, p_end)`

reverse iterate through memblock areas from type_a and not included in type_b. Or just type_a if type_b is NULL.

Parameters

i
u64 used as loop variable

p_start
ptr to phys_addr_t for start address of the range, can be `NULL`

p_end
ptr to phys_addr_t for end address of the range, can be `NULL`

for_each_reserved_mem_range

`for_each_reserved_mem_range (i, p_start, p_end)`

iterate over all reserved memblock areas

Parameters

i
u64 used as loop variable

p_start
ptr to phys_addr_t for start address of the range, can be `NULL`

p_end
ptr to phys_addr_t for end address of the range, can be `NULL`

Description

Walks over reserved areas of memblock. Available as soon as memblock is initialized.

for_each_mem_pfn_range

`for_each_mem_pfn_range (i, nid, p_start, p_end, p_nid)`

early memory pfn range iterator

Parameters

i
an integer used as loop variable

nid
node selector, `MAX_NUMNODES` for all nodes

p_start
ptr to ulong for start pfn of the range, can be `NULL`

p_end
ptr to ulong for end pfn of the range, can be `NULL`

p_nid
ptr to int for nid of the range, can be `NULL`

Description

Walks over configured memory ranges.

for_each_free_mem_pfn_range_in_zone

`for_each_free_mem_pfn_range_in_zone (i, zone, p_start, p_end)`

iterate through zone specific free memblock areas

Parameters

i
u64 used as loop variable

zone
zone in which all of the memory blocks reside

p_start
ptr to phys_addr_t for start address of the range, can be `NULL`

p_end
ptr to phys_addr_t for end address of the range, can be `NULL`

Description

Walks over free (memory && !reserved) areas of memblock in a specific zone. Available once memblock and an empty zone is initialized. The main assumption is that the zone start, end, and pgdat have been associated. This way we can use the zone to determine NUMA node, and if a given part of the memblock is valid for the zone.

for_each_free_mem_pfn_range_in_zone_from

`for_each_free_mem_pfn_range_in_zone_from (i, zone, p_start, p_end)`

iterate through zone specific free memblock areas from a given point

Parameters

i
u64 used as loop variable

zone
zone in which all of the memory blocks reside

p_start
: ptr to phys_addr_t for start address of the range, can be NULL

p_end
: ptr to phys_addr_t for end address of the range, can be NULL

Description

Walks over free (memory && !reserved) areas of memblock in a specific zone, continuing from current position. Available as soon as memblock is initialized.

for_each_free_mem_range

`for_each_free_mem_range (i, nid, flags, p_start, p_end, p_nid)`

iterate through free memblock areas

Parameters

i
: u64 used as loop variable

nid
: node selector, NUMA_NO_NODE for all nodes

flags
: pick from blocks based on memory attributes

p_start
: ptr to phys_addr_t for start address of the range, can be NULL

p_end
: ptr to phys_addr_t for end address of the range, can be NULL

p_nid
: ptr to int for nid of the range, can be NULL

Description

Walks over free (memory && !reserved) areas of memblock. Available as soon as memblock is initialized.

for_each_free_mem_range_reverse

`for_each_free_mem_range_reverse (i, nid, flags, p_start, p_end, p_nid)`

rev-iterate through free memblock areas

Parameters

i
: u64 used as loop variable

nid
: node selector, NUMA_NO_NODE for all nodes

flags
: pick from blocks based on memory attributes

p_start
: ptr to phys_addr_t for start address of the range, can be NULL

p_end
ptr to phys_addr_t for end address of the range, can be NULL

p_nid
ptr to int for nid of the range, can be NULL

Description

Walks over free (memory && !reserved) areas of memblock in reverse order. Available as soon as memblock is initialized.

void **memblock_set_current_limit**(phys_addr_t limit)
Set the current allocation limit to allow limiting allocations to what is currently accessible during boot

Parameters

phys_addr_t limit
New limit value (physical address)

unsigned long **memblock_region_memory_base_pfn**(const struct *memblock_region* *reg)
get the lowest pfn of the memory region

Parameters

const struct memblock_region *reg
memblock_region structure

Return

the lowest pfn intersecting with the memory region

unsigned long **memblock_region_memory_end_pfn**(const struct *memblock_region* *reg)
get the end pfn of the memory region

Parameters

const struct memblock_region *reg
memblock_region structure

Return

the end_pfn of the reserved region

unsigned long **memblock_region_reserved_base_pfn**(const struct *memblock_region* *reg)
get the lowest pfn of the reserved region

Parameters

const struct memblock_region *reg
memblock_region structure

Return

the lowest pfn intersecting with the reserved region unsigned long **memblock_region_reserved_end_pfn**(const struct *memblock_region* *reg)

get the end pfn of the reserved region

Parameters

const struct memblock_region *reg
memblock_region structure

Return

the end_pfn of the reserved region

for_each_mem_region

`for_each_mem_region (region)`

itereate over memory regions

Parameters

region
loop variable

for_each_reserved_mem_region

`for_each_reserved_mem_region (region)`

itereate over reserved memory regions

Parameters

region
loop variable

phys_addr_t __init_memblock **__memblock_find_range_bottom_up**(phys_addr_t start, phys_addr_t end, phys_addr_t size, phys_addr_t align, int nid, enum *memblock_flags* flags)

find free area utility in bottom-up

Parameters

phys_addr_t start
start of candidate range

phys_addr_t end
end of candidate range, can be `MEMBLOCK_ALLOC_ANYWHERE` or `MEMBLOCK_ALLOC_ACCESSIBLE`

phys_addr_t size
size of free area to find

phys_addr_t align
    alignment of free area to find

int nid
    nid of the free area to find, NUMA_NO_NODE for any node

enum memblock_flags flags
    pick from blocks based on memory attributes

Description

Utility called from *memblock_find_in_range_node()*, find free area bottom-up.

Return

Found address on success, 0 on failure.

phys_addr_t __init_memblock **__memblock_find_range_top_down**(phys_addr_t start, phys_addr_t end, phys_addr_t size, phys_addr_t align, int nid, enum *memblock_flags* flags)

    find free area utility, in top-down

Parameters

phys_addr_t start
    start of candidate range

phys_addr_t end
    end of candidate range, can be MEMBLOCK_ALLOC_ANYWHERE or MEMBLOCK_ALLOC_ACCESSIBLE

phys_addr_t size
    size of free area to find

phys_addr_t align
    alignment of free area to find

int nid
    nid of the free area to find, NUMA_NO_NODE for any node

enum memblock_flags flags
    pick from blocks based on memory attributes

Description

Utility called from *memblock_find_in_range_node()*, find free area top-down.

Return

Found address on success, 0 on failure.

phys_addr_t __init_memblock **memblock_find_in_range_node**(phys_addr_t size, phys_addr_t align, phys_addr_t start, phys_addr_t end, int nid, enum *memblock_flags* flags)

find free area in given range and node

Parameters

phys_addr_t size
size of free area to find

phys_addr_t align
alignment of free area to find

phys_addr_t start
start of candidate range

phys_addr_t end
end of candidate range, can be MEMBLOCK_ALLOC_ANYWHERE or MEMBLOCK_ALLOC_ACCESSIBLE

int nid
nid of the free area to find, NUMA_NO_NODE for any node

enum memblock_flags flags
pick from blocks based on memory attributes

Description

Find **size** free area aligned to **align** in the specified range and node.

Return

Found address on success, 0 on failure.

phys_addr_t __init_memblock **memblock_find_in_range**(phys_addr_t start, phys_addr_t end, phys_addr_t size, phys_addr_t align)

find free area in given range

Parameters

phys_addr_t start
start of candidate range

phys_addr_t end
end of candidate range, can be MEMBLOCK_ALLOC_ANYWHERE or MEMBLOCK_ALLOC_ACCESSIBLE

phys_addr_t size
size of free area to find

phys_addr_t align
alignment of free area to find

Description

Find **size** free area aligned to **align** in the specified range.

Return

Found address on success, 0 on failure.

void **memblock_discard**(void)

discard memory and reserved arrays if they were allocated

Parameters

void
no arguments

int __init_memblock **memblock_double_array**(struct *memblock_type* *type, phys_addr_t new_area_start, phys_addr_t new_area_size)

double the size of the memblock regions array

Parameters

struct memblock_type *type
memblock type of the regions array being doubled

phys_addr_t new_area_start
starting address of memory range to avoid overlap with

phys_addr_t new_area_size
size of memory range to avoid overlap with

Description

Double the size of the **type** regions array. If memblock is being used to allocate memory for a new reserved regions array and there is a previously allocated memory range [**new_area_start**, **new_area_start** + **new_area_size**] waiting to be reserved, ensure the memory used by the new array does not overlap.

Return

0 on success, -1 on failure.

void __init_memblock **memblock_merge_regions**(struct *memblock_type* *type)

merge neighboring compatible regions

Parameters

struct memblock_type *type
memblock type to scan

Description

Scan **type** and merge neighboring compatible regions.

void __init_memblock **memblock_insert_region**(struct *memblock_type* *type, int idx, phys_addr_t base, phys_addr_t size, int nid, enum *memblock_flags* flags)

insert new memblock region

Parameters

struct memblock_type *type
: memblock type to insert into

int idx
: index for the insertion point

phys_addr_t base
: base address of the new region

phys_addr_t size
: size of the new region

int nid
: node id of the new region

enum memblock_flags flags
: flags of the new region

Description

Insert new memblock region [**base**, **base** + **size**) into **type** at **idx**. **type** must already have extra room to accommodate the new region.

int __init_memblock **memblock_add_range**(struct *memblock_type* *type, phys_addr_t base, phys_addr_t size, int nid, enum *memblock_flags* flags)

add new memblock region

Parameters

struct memblock_type *type
: memblock type to add new region into

phys_addr_t base
: base address of the new region

phys_addr_t size
: size of the new region

int nid
: nid of the new region

enum memblock_flags flags
: flags of the new region

Description

Add new memblock region [**base**, **base** + **size**) into **type**. The new region is allowed to overlap with existing ones - overlaps don't affect already existing regions. **type** is guaranteed to be minimal (all neighbouring compatible regions are merged) after the addition.

Return

0 on success, -errno on failure.

int __init_memblock **memblock_add_node**(phys_addr_t base, phys_addr_t size, int nid)

add new memblock region within a NUMA node

Parameters

phys_addr_t base
base address of the new region

phys_addr_t size
size of the new region

int nid
nid of the new region

Description

Add new memblock region [**base**, **base** + **size**) to the "memory" type. See *memblock_add_range()* description for mode details

Return

0 on success, -errno on failure.

int __init_memblock **memblock_add**(phys_addr_t base, phys_addr_t size)
add new memblock region

Parameters

phys_addr_t base
base address of the new region

phys_addr_t size
size of the new region

Description

Add new memblock region [**base**, **base** + **size**) to the "memory" type. See *memblock_add_range()* description for mode details

Return

0 on success, -errno on failure.

int __init_memblock **memblock_isolate_range**(struct *memblock_type* *type, phys_addr_t base, phys_addr_t size, int *start_rgn, int *end_rgn)
isolate given range into disjoint memblocks

Parameters

struct memblock_type *type
memblock type to isolate range for

phys_addr_t base
base of range to isolate

phys_addr_t size
size of range to isolate

int *start_rgn
out parameter for the start of isolated region

int *end_rgn
out parameter for the end of isolated region

Description

Walk **type** and ensure that regions don't cross the boundaries defined by [**base**, **base** + **size**). Crossing regions are split at the boundaries, which may create at most two more regions. The index of the first region inside the range is returned in ***start_rgn** and end in ***end_rgn**.

Return

0 on success, -errno on failure.

int __init_memblock **memblock_free**(phys_addr_t base, phys_addr_t size)

free boot memory block

Parameters

phys_addr_t base
phys starting address of the boot memory block

phys_addr_t size
size of the boot memory block in bytes

Description

Free boot memory block previously allocated by memblock_alloc_xx() API. The freeing memory will not be released to the buddy allocator.

int __init_memblock **memblock_setclr_flag**(phys_addr_t base, phys_addr_t size, int set, int flag)

set or clear flag for a memory region

Parameters

phys_addr_t base
base address of the region

phys_addr_t size
size of the region

int set
set or clear the flag

int flag
the flag to udpate

Description

This function isolates region [**base**, **base** + **size**), and sets/clears flag

Return

0 on success, -errno on failure.

int __init_memblock **memblock_mark_hotplug**(phys_addr_t base, phys_addr_t size)

Mark hotpluggable memory with flag MEMBLOCK_HOTPLUG.

Parameters

phys_addr_t base
the base phys addr of the region

phys_addr_t size
the size of the region

Return

0 on success, -errno on failure.

int __init_memblock **memblock_clear_hotplug**(phys_addr_t base, phys_addr_t size)

Clear flag MEMBLOCK_HOTPLUG for a specified region.

Parameters

phys_addr_t base
the base phys addr of the region

phys_addr_t size
the size of the region

Return

0 on success, -errno on failure.

int __init_memblock **memblock_mark_mirror**(phys_addr_t base, phys_addr_t size)

Mark mirrored memory with flag MEMBLOCK_MIRROR.

Parameters

phys_addr_t base
the base phys addr of the region

phys_addr_t size
the size of the region

Return

0 on success, -errno on failure.

int __init_memblock **memblock_mark_nomap**(phys_addr_t base, phys_addr_t size)

Mark a memory region with flag MEMBLOCK_NOMAP.

Parameters

phys_addr_t base
the base phys addr of the region

phys_addr_t size
the size of the region

Return

0 on success, -errno on failure.

int __init_memblock **memblock_clear_nomap**(phys_addr_t base, phys_addr_t size)

Clear flag MEMBLOCK_NOMAP for a specified region.

Parameters

phys_addr_t base
the base phys addr of the region

phys_addr_t size
the size of the region

Return

0 on success, -errno on failure.

void **__next_mem_range**(u64 *idx, int nid, enum *memblock_flags* flags, struct *memblock_type* *type_a, struct *memblock_type* *type_b, phys_addr_t *out_start, phys_addr_t *out_end, int *out_nid)

next function for *for_each_free_mem_range()* etc.

Parameters

u64 *idx
pointer to u64 loop variable

int nid
node selector, `NUMA_NO_NODE` for all nodes

enum memblock_flags flags
pick from blocks based on memory attributes

struct memblock_type *type_a
pointer to memblock_type from where the range is taken

struct memblock_type *type_b
pointer to memblock_type which excludes memory from being taken

phys_addr_t *out_start
ptr to phys_addr_t for start address of the range, can be `NULL`

phys_addr_t *out_end
ptr to phys_addr_t for end address of the range, can be `NULL`

int *out_nid
ptr to int for nid of the range, can be `NULL`

Description

Find the first area from ***idx** which matches **nid**, fill the out parameters, and update ***idx** for the next iteration. The lower 32bit of ***idx** contains index into type_a and the upper 32bit indexes the areas before each region in type_b. For example, if type_b regions look like the following,

0:[0-16), 1:[32-48), 2:[128-130)

The upper 32bit indexes the following regions.

0:[0-0), 1:[16-32), 2:[48-128), 3:[130-MAX)

As both region arrays are sorted, the function advances the two indices in lockstep and returns each intersection.

void __init_memblock **__next_mem_range_rev**(u64 *idx, int nid, enum *memblock_flags* flags, struct *memblock_type* *type_a, struct *memblock_type* *type_b, phys_addr_t *out_start, phys_addr_t *out_end, int *out_nid)

generic next function for for_each_*_range_rev()

Parameters

u64 *idx
pointer to u64 loop variable

int nid
node selector, `NUMA_NO_NODE` for all nodes

enum memblock_flags flags
pick from blocks based on memory attributes

struct memblock_type *type_a
pointer to memblock_type from where the range is taken

struct memblock_type *type_b
pointer to memblock_type which excludes memory from being taken

phys_addr_t *out_start
ptr to phys_addr_t for start address of the range, can be `NULL`

phys_addr_t *out_end
ptr to phys_addr_t for end address of the range, can be `NULL`

int *out_nid
ptr to int for nid of the range, can be `NULL`

Description

Finds the next range from type_a which is not marked as unsuitable in type_b.

Reverse of *__next_mem_range()*.

int __init_memblock **memblock_set_node**(phys_addr_t base, phys_addr_t size, struct *memblock_type* *type, int nid)

set node ID on memblock regions

Parameters

phys_addr_t base
base of area to set node ID for

phys_addr_t size
size of area to set node ID for

struct memblock_type *type
memblock type to set node ID for

int nid
node ID to set

Description

Set the nid of memblock **type** regions in [**base**, **base** + **size**) to **nid**. Regions which cross the area boundaries are split as necessary.

Return

0 on success, -errno on failure.

void __init_memblock **`__next_mem_pfn_range_in_zone`**(u64 *idx, struct *zone* *zone, unsigned long *out_spfn, unsigned long *out_epfn)

iterator for for_each_*_range_in_zone()

Parameters

`u64 *idx`
pointer to u64 loop variable

`struct zone *zone`
zone in which all of the memory blocks reside

`unsigned long *out_spfn`
ptr to ulong for start pfn of the range, can be `NULL`

`unsigned long *out_epfn`
ptr to ulong for end pfn of the range, can be `NULL`

Description

This function is meant to be a zone/pfn specific wrapper for the for_each_mem_range type iterators. Specifically they are used in the deferred memory init routines and as such we were duplicating much of this logic throughout the code. So instead of having it in multiple locations it seemed like it would make more sense to centralize this to one new iterator that does everything they need.

phys_addr_t **`memblock_alloc_range_nid`**(phys_addr_t size, phys_addr_t align, phys_addr_t start, phys_addr_t end, int nid, bool exact_nid)

allocate boot memory block

Parameters

`phys_addr_t size`
size of memory block to be allocated in bytes

`phys_addr_t align`
alignment of the region and block's size

`phys_addr_t start`
the lower bound of the memory region to allocate (phys address)

`phys_addr_t end`
the upper bound of the memory region to allocate (phys address)

`int nid`
nid of the free area to find, `NUMA_NO_NODE` for any node

bool exact_nid
control the allocation fall back to other nodes

Description

The allocation is performed from memory region limited by memblock.current_limit if **end** == `MEMBLOCK_ALLOC_ACCESSIBLE`.

If the specified node can not hold the requested memory and **exact_nid** is false, the allocation falls back to any node in the system.

For systems with memory mirroring, the allocation is attempted first from the regions with mirroring enabled and then retried from any memory region.

In addition, function sets the min_count to 0 using kmemleak_alloc_phys for allocated boot memory block, so that it is never reported as leaks.

Return

Physical address of allocated memory block on success, `0` on failure.

phys_addr_t **memblock_phys_alloc_range**(phys_addr_t size, phys_addr_t align, phys_addr_t start, phys_addr_t end)
allocate a memory block inside specified range

Parameters

phys_addr_t size
size of memory block to be allocated in bytes

phys_addr_t align
alignment of the region and block's size

phys_addr_t start
the lower bound of the memory region to allocate (physical address)

phys_addr_t end
the upper bound of the memory region to allocate (physical address)

Description

Allocate **size** bytes in the between **start** and **end**.

Return

physical address of the allocated memory block on success, `0` on failure.

phys_addr_t **memblock_phys_alloc_try_nid**(phys_addr_t size, phys_addr_t align, int nid)
allocate a memory block from specified MUMA node

Parameters

phys_addr_t size
size of memory block to be allocated in bytes

phys_addr_t align
alignment of the region and block's size

int nid
nid of the free area to find, `NUMA_NO_NODE` for any node

Description

Allocates memory block from the specified NUMA node. If the node has no available memory, attempts to allocated from any node in the system.

Return

physical address of the allocated memory block on success, `0` on failure.

void ***memblock_alloc_internal**(phys_addr_t size, phys_addr_t align, phys_addr_t min_addr, phys_addr_t max_addr, int nid, bool exact_nid)

allocate boot memory block

Parameters

phys_addr_t size
size of memory block to be allocated in bytes

phys_addr_t align
alignment of the region and block's size

phys_addr_t min_addr
the lower bound of the memory region to allocate (phys address)

phys_addr_t max_addr
the upper bound of the memory region to allocate (phys address)

int nid
nid of the free area to find, `NUMA_NO_NODE` for any node

bool exact_nid
control the allocation fall back to other nodes

Description

Allocates memory block using *memblock_alloc_range_nid()* and converts the returned physical address to virtual.

The **min_addr** limit is dropped if it can not be satisfied and the allocation will fall back to memory below **min_addr**. Other constraints, such as node and mirrored memory will be handled again in *memblock_alloc_range_nid()*.

Return

Virtual address of allocated memory block on success, NULL on failure.

void ***memblock_alloc_exact_nid_raw**(phys_addr_t size, phys_addr_t align, phys_addr_t min_addr, phys_addr_t max_addr, int nid)

allocate boot memory block on the exact node without zeroing memory

Parameters

phys_addr_t size
size of memory block to be allocated in bytes

phys_addr_t align
alignment of the region and block's size

phys_addr_t min_addr
the lower bound of the memory region from where the allocation is preferred (phys address)

phys_addr_t max_addr
the upper bound of the memory region from where the allocation is preferred (phys address), or MEMBLOCK_ALLOC_ACCESSIBLE to allocate only from memory limited by memblock.current_limit value

int nid
nid of the free area to find, NUMA_NO_NODE for any node

Description

Public function, provides additional debug information (including caller info), if enabled. Does not zero allocated memory.

Return

Virtual address of allocated memory block on success, NULL on failure.

void ***memblock_alloc_try_nid_raw**(phys_addr_t size, phys_addr_t align, phys_addr_t min_addr, phys_addr_t max_addr, int nid)

allocate boot memory block without zeroing memory and without panicking

Parameters

phys_addr_t size
size of memory block to be allocated in bytes

phys_addr_t align
alignment of the region and block's size

phys_addr_t min_addr
the lower bound of the memory region from where the allocation is preferred (phys address)

phys_addr_t max_addr
the upper bound of the memory region from where the allocation is preferred (phys address), or MEMBLOCK_ALLOC_ACCESSIBLE to allocate only from memory limited by memblock.current_limit value

int nid
nid of the free area to find, NUMA_NO_NODE for any node

Description

Public function, provides additional debug information (including caller info), if enabled. Does not zero allocated memory, does not panic if request cannot be satisfied.

Return

Virtual address of allocated memory block on success, NULL on failure.

void ***memblock_alloc_try_nid**(phys_addr_t size, phys_addr_t align, phys_addr_t min_addr, phys_addr_t max_addr, int nid)

allocate boot memory block

Parameters

phys_addr_t size
size of memory block to be allocated in bytes

phys_addr_t align
alignment of the region and block's size

phys_addr_t min_addr
the lower bound of the memory region from where the allocation is preferred (phys address)

phys_addr_t max_addr
the upper bound of the memory region from where the allocation is preferred (phys address), or MEMBLOCK_ALLOC_ACCESSIBLE to allocate only from memory limited by memblock.current_limit value

int nid
nid of the free area to find, NUMA_NO_NODE for any node

Description

Public function, provides additional debug information (including caller info), if enabled. This function zeroes the allocated memory.

Return

Virtual address of allocated memory block on success, NULL on failure.

void **__memblock_free_late**(phys_addr_t base, phys_addr_t size)
free pages directly to buddy allocator

Parameters

phys_addr_t base
phys starting address of the boot memory block

phys_addr_t size
size of the boot memory block in bytes

Description

This is only useful when the memblock allocator has already been torn down, but we are still initializing the system. Pages are released directly to the buddy allocator.

bool __init_memblock **memblock_is_region_memory**(phys_addr_t base, phys_addr_t size)
check if a region is a subset of memory

Parameters

phys_addr_t base
base of region to check

phys_addr_t size
size of region to check

Description

Check if the region [**base**, **base** + **size**) is a subset of a memory block.

Return

0 if false, non-zero if true

bool __init_memblock **memblock_is_region_reserved**(phys_addr_t base, phys_addr_t size)

check if a region intersects reserved memory

Parameters

phys_addr_t base
base of region to check

phys_addr_t size
size of region to check

Description

Check if the region [**base**, **base** + **size**) intersects a reserved memory block.

Return

True if they intersect, false if not.

unsigned long **memblock_free_all**(void)

release free pages to the buddy allocator

Parameters

void
no arguments

Return

the number of pages actually released.

5.11 GFP masks used from FS/IO context

Date
May, 2018

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5.11.1 Introduction

Code paths in the filesystem and IO stacks must be careful when allocating memory to prevent recursion deadlocks caused by direct memory reclaim calling back into the FS or IO paths and blocking on already held resources (e.g. locks - most commonly those used for the transaction context).

The traditional way to avoid this deadlock problem is to clear __GFP_FS respectively __GFP_IO (note the latter implies clearing the first as well) in the gfp mask when calling an allocator. GFP_NOFS respectively GFP_NOIO can be used as shortcut. It turned out though that above approach has led to abuses when the restricted gfp mask is used "just in case" without a deeper consideration which leads to problems because an excessive use of GFP_NOFS/GFP_NOIO can lead to memory over-reclaim or other memory reclaim issues.

5.11.2 New API

Since 4.12 we do have a generic scope API for both NOFS and NOIO context `memalloc_nofs_save`, `memalloc_nofs_restore` respectively `memalloc_noio_save`, `memalloc_noio_restore` which allow to mark a scope to be a critical section from a filesystem or I/O point of view. Any allocation from that scope will inherently drop __GFP_FS respectively __GFP_IO from the given mask so no memory allocation can recurse back in the FS/IO.

unsigned int **memalloc_nofs_save**(void)

Marks implicit GFP_NOFS allocation scope.

Parameters

void

no arguments

Description

This functions marks the beginning of the GFP_NOFS allocation scope. All further allocations will implicitly drop __GFP_FS flag and so they are safe for the FS critical section from the allocation recursion point of view. Use memalloc_nofs_restore to end the scope with flags returned by this function.

This function is safe to be used from any context.

void **memalloc_nofs_restore**(unsigned int flags)

Ends the implicit GFP_NOFS scope.

Parameters

unsigned int flags

Flags to restore.

Description

Ends the implicit GFP_NOFS scope started by memalloc_nofs_save function. Always make sure that the given flags is the return value from the pairing memalloc_nofs_save call.

unsigned int **memalloc_noio_save**(void)

Marks implicit GFP_NOIO allocation scope.

Parameters

void

no arguments

Description

This functions marks the beginning of the GFP_NOIO allocation scope. All further allocations will implicitly drop __GFP_IO flag and so they are safe for the IO critical section from the allocation recursion point of view. Use memalloc_noio_restore to end the scope with flags returned by this function.

This function is safe to be used from any context.

void **memalloc_noio_restore**(unsigned int flags)

Ends the implicit GFP_NOIO scope.

Parameters

unsigned int flags
Flags to restore.

Description

Ends the implicit GFP_NOIO scope started by memalloc_noio_save function. Always make sure that the given flags is the return value from the pairing memalloc_noio_save call.

FS/IO code then simply calls the appropriate save function before any critical section with respect to the reclaim is started - e.g. lock shared with the reclaim context or when a transaction context nesting would be possible via reclaim. The restore function should be called when the critical section ends. All that ideally along with an explanation what is the reclaim context for easier maintenance.

Please note that the proper pairing of save/restore functions allows nesting so it is safe to call `memalloc_noio_save` or `memalloc_noio_restore` respectively from an existing NOIO or NOFS scope.

5.11.3 What about __vmalloc(GFP_NOFS)

vmalloc doesn't support GFP_NOFS semantic because there are hardcoded GFP_KERNEL allocations deep inside the allocator which are quite non-trivial to fix up. That means that calling `vmalloc` with GFP_NOFS/GFP_NOIO is almost always a bug. The good news is that the NOFS/NOIO semantic can be achieved by the scope API.

In the ideal world, upper layers should already mark dangerous contexts and so no special care is required and vmalloc should be called without any problems. Sometimes if the context is not really clear or there are layering violations then the recommended way around that is to wrap `vmalloc` by the scope API with a comment explaining the problem.

CHAPTER

SIX

INTERFACES FOR KERNEL DEBUGGING

6.1 The object-lifetime debugging infrastructure

Author
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6.1.1 Introduction

debugobjects is a generic infrastructure to track the life time of kernel objects and validate the operations on those.

debugobjects is useful to check for the following error patterns:

- Activation of uninitialized objects
- Initialization of active objects
- Usage of freed/destroyed objects

debugobjects is not changing the data structure of the real object so it can be compiled in with a minimal runtime impact and enabled on demand with a kernel command line option.

6.1.2 Howto use debugobjects

A kernel subsystem needs to provide a data structure which describes the object type and add calls into the debug code at appropriate places. The data structure to describe the object type needs at minimum the name of the object type. Optional functions can and should be provided to fixup detected problems so the kernel can continue to work and the debug information can be retrieved from a live system instead of hard core debugging with serial consoles and stack trace transcripts from the monitor.

The debug calls provided by debugobjects are:

- debug_object_init
- debug_object_init_on_stack
- debug_object_activate
- debug_object_deactivate
- debug_object_destroy

- debug_object_free
- debug_object_assert_init

Each of these functions takes the address of the real object and a pointer to the object type specific debug description structure.

Each detected error is reported in the statistics and a limited number of errors are printk'ed including a full stack trace.

The statistics are available via /sys/kernel/debug/debug_objects/stats. They provide information about the number of warnings and the number of successful fixups along with information about the usage of the internal tracking objects and the state of the internal tracking objects pool.

6.1.3 Debug functions

void **debug_object_init**(void *addr, const struct *debug_obj_descr* *descr)

debug checks when an object is initialized

Parameters

void *addr
address of the object

const struct debug_obj_descr *descr
pointer to an object specific debug description structure

This function is called whenever the initialization function of a real object is called.

When the real object is already tracked by debugobjects it is checked, whether the object can be initialized. Initializing is not allowed for active and destroyed objects. When debugobjects detects an error, then it calls the fixup_init function of the object type description structure if provided by the caller. The fixup function can correct the problem before the real initialization of the object happens. E.g. it can deactivate an active object in order to prevent damage to the subsystem.

When the real object is not yet tracked by debugobjects, debugobjects allocates a tracker object for the real object and sets the tracker object state to ODEBUG_STATE_INIT. It verifies that the object is not on the callers stack. If it is on the callers stack then a limited number of warnings including a full stack trace is printk'ed. The calling code must use *debug_object_init_on_stack()* and remove the object before leaving the function which allocated it. See next section.

void **debug_object_init_on_stack**(void *addr, const struct *debug_obj_descr* *descr)

debug checks when an object on stack is initialized

Parameters

void *addr
address of the object

const struct debug_obj_descr *descr
pointer to an object specific debug description structure

This function is called whenever the initialization function of a real object which resides on the stack is called.

When the real object is already tracked by debugobjects it is checked, whether the object can be initialized. Initializing is not allowed for active and destroyed objects. When debugobjects detects an error, then it calls the fixup_init function of the object type description structure if provided by the caller. The fixup function can correct the problem before the real initialization of the object happens. E.g. it can deactivate an active object in order to prevent damage to the subsystem.

When the real object is not yet tracked by debugobjects debugobjects allocates a tracker object for the real object and sets the tracker object state to ODEBUG_STATE_INIT. It verifies that the object is on the callers stack.

An object which is on the stack must be removed from the tracker by calling *debug_object_free()* before the function which allocates the object returns. Otherwise we keep track of stale objects.

int **debug_object_activate**(void *addr, const struct *debug_obj_descr* *descr)

debug checks when an object is activated

Parameters

void *addr
address of the object

const struct debug_obj_descr *descr
pointer to an object specific debug description structure Returns 0 for success, -EINVAL for check failed.

This function is called whenever the activation function of a real object is called.

When the real object is already tracked by debugobjects it is checked, whether the object can be activated. Activating is not allowed for active and destroyed objects. When debugobjects detects an error, then it calls the fixup_activate function of the object type description structure if provided by the caller. The fixup function can correct the problem before the real activation of the object happens. E.g. it can deactivate an active object in order to prevent damage to the subsystem.

When the real object is not yet tracked by debugobjects then the fixup_activate function is called if available. This is necessary to allow the legitimate activation of statically allocated and initialized objects. The fixup function checks whether the object is valid and calls the debug_objects_init() function to initialize the tracking of this object.

When the activation is legitimate, then the state of the associated tracker object is set to ODEBUG_STATE_ACTIVE.

void **debug_object_deactivate**(void *addr, const struct *debug_obj_descr* *descr)

debug checks when an object is deactivated

Parameters

void *addr
address of the object

const struct debug_obj_descr *descr
pointer to an object specific debug description structure

This function is called whenever the deactivation function of a real object is called.

When the real object is tracked by debugobjects it is checked, whether the object can be deactivated. Deactivating is not allowed for untracked or destroyed objects.

When the deactivation is legitimate, then the state of the associated tracker object is set to ODEBUG_STATE_INACTIVE.

void **debug_object_destroy**(void *addr, const struct *debug_obj_descr* *descr)
debug checks when an object is destroyed

Parameters

void *addr
address of the object

const struct debug_obj_descr *descr
pointer to an object specific debug description structure

This function is called to mark an object destroyed. This is useful to prevent the usage of invalid objects, which are still available in memory: either statically allocated objects or objects which are freed later.

When the real object is tracked by debugobjects it is checked, whether the object can be destroyed. Destruction is not allowed for active and destroyed objects. When debugobjects detects an error, then it calls the fixup_destroy function of the object type description structure if provided by the caller. The fixup function can correct the problem before the real destruction of the object happens. E.g. it can deactivate an active object in order to prevent damage to the subsystem.

When the destruction is legitimate, then the state of the associated tracker object is set to ODEBUG_STATE_DESTROYED.

void **debug_object_free**(void *addr, const struct *debug_obj_descr* *descr)
debug checks when an object is freed

Parameters

void *addr
address of the object

const struct debug_obj_descr *descr
pointer to an object specific debug description structure

This function is called before an object is freed.

When the real object is tracked by debugobjects it is checked, whether the object can be freed. Free is not allowed for active objects. When debugobjects detects an error, then it calls the fixup_free function of the object type description structure if provided by the caller. The fixup function can correct the problem before the real free of the object happens. E.g. it can deactivate an active object in order to prevent damage to the subsystem.

Note that debug_object_free removes the object from the tracker. Later usage of the object is detected by the other debug checks.

void **debug_object_assert_init**(void *addr, const struct *debug_obj_descr* *descr)

debug checks when object should be init-ed

Parameters

void *addr
address of the object

const struct debug_obj_descr *descr
pointer to an object specific debug description structure

This function is called to assert that an object has been initialized.

When the real object is not tracked by debugobjects, it calls fixup_assert_init of the object type description structure provided by the caller, with the hardcoded object state ODEBUG_NOT_AVAILABLE. The fixup function can correct the problem by calling debug_object_init and other specific initializing functions.

When the real object is already tracked by debugobjects it is ignored.

6.1.4 Fixup functions

Debug object type description structure

struct **debug_obj**

representaion of an tracked object

Definition

```
struct debug_obj {
  struct hlist_node       node;
  enum debug_obj_state    state;
  unsigned int            astate;
  void *object;
  const struct debug_obj_descr *descr;
};
```

Members

node
hlist node to link the object into the tracker list

state
tracked object state

astate
current active state

object
pointer to the real object

descr
pointer to an object type specific debug description structure

struct **debug_obj_descr**
object type specific debug description structure

Definition

```
struct debug_obj_descr {
  const char              *name;
  void *(*debug_hint)(void *addr);
  bool (*is_static_object)(void *addr);
  bool (*fixup_init)(void *addr, enum debug_obj_state state);
  bool (*fixup_activate)(void *addr, enum debug_obj_state state);
  bool (*fixup_destroy)(void *addr, enum debug_obj_state state);
  bool (*fixup_free)(void *addr, enum debug_obj_state state);
  bool (*fixup_assert_init)(void *addr, enum debug_obj_state state);
};
```

Members

name
name of the object typee

debug_hint
function returning address, which have associated kernel symbol, to allow identify the object

is_static_object
return true if the obj is static, otherwise return false

fixup_init
fixup function, which is called when the init check fails. All fixup functions must return true if fixup was successful, otherwise return false

fixup_activate
fixup function, which is called when the activate check fails

fixup_destroy
fixup function, which is called when the destroy check fails

fixup_free
fixup function, which is called when the free check fails

fixup_assert_init
fixup function, which is called when the assert_init check fails

fixup_init

This function is called from the debug code whenever a problem in debug_object_init is detected. The function takes the address of the object and the state which is currently recorded in the tracker.

Called from debug_object_init when the object state is:

- ODEBUG_STATE_ACTIVE

The function returns true when the fixup was successful, otherwise false. The return value is used to update the statistics.

Note, that the function needs to call the *debug_object_init()* function again, after the damage has been repaired in order to keep the state consistent.

fixup_activate

This function is called from the debug code whenever a problem in debug_object_activate is detected.

Called from debug_object_activate when the object state is:

- ODEBUG_STATE_NOTAVAILABLE
- ODEBUG_STATE_ACTIVE

The function returns true when the fixup was successful, otherwise false. The return value is used to update the statistics.

Note that the function needs to call the *debug_object_activate()* function again after the damage has been repaired in order to keep the state consistent.

The activation of statically initialized objects is a special case. When *debug_object_activate()* has no tracked object for this object address then fixup_activate() is called with object state ODEBUG_STATE_NOTAVAILABLE. The fixup function needs to check whether this is a legitimate case of a statically initialized object or not. In case it is it calls *debug_object_init()* and *debug_object_activate()* to make the object known to the tracker and marked active. In this case the function should return false because this is not a real fixup.

fixup_destroy

This function is called from the debug code whenever a problem in debug_object_destroy is detected.

Called from debug_object_destroy when the object state is:

- ODEBUG_STATE_ACTIVE

The function returns true when the fixup was successful, otherwise false. The return value is used to update the statistics.

fixup_free

This function is called from the debug code whenever a problem in debug_object_free is detected. Further it can be called from the debug checks in kfree/vfree, when an active object is detected from the debug_check_no_obj_freed() sanity checks.

Called from *debug_object_free()* or debug_check_no_obj_freed() when the object state is:

- ODEBUG_STATE_ACTIVE

The function returns true when the fixup was successful, otherwise false. The return value is used to update the statistics.

fixup_assert_init

This function is called from the debug code whenever a problem in debug_object_assert_init is detected.

Called from *debug_object_assert_init()* with a hardcoded state ODEBUG_STATE_NOTAVAILABLE when the object is not found in the debug bucket.

The function returns true when the fixup was successful, otherwise false. The return value is used to update the statistics.

Note, this function should make sure *debug_object_init()* is called before returning.

The handling of statically initialized objects is a special case. The fixup function should check if this is a legitimate case of a statically initialized object or not. In this case only *debug_object_init()* should be called to make the object known to the tracker. Then the function should return false because this is not a real fixup.

6.1.5 Known Bugs And Assumptions

None (knock on wood).

6.2 The Linux Kernel Tracepoint API

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6.2.1 Introduction

Tracepoints are static probe points that are located in strategic points throughout the kernel. 'Probes' register/unregister with tracepoints via a callback mechanism. The 'probes' are strictly typed functions that are passed a unique set of parameters defined by each tracepoint.

From this simple callback mechanism, 'probes' can be used to profile, debug, and understand kernel behavior. There are a number of tools that provide a framework for using 'probes'. These tools include Systemtap, ftrace, and LTTng.

Tracepoints are defined in a number of header files via various macros. Thus, the purpose of this document is to provide a clear accounting of the available tracepoints. The intention is to understand not only what tracepoints are available but also to understand where future tracepoints might be added.

The API presented has functions of the form: `trace_tracepointname(function parameters)`. These are the tracepoints callbacks that are found throughout the code. Registering and unregistering probes with these callback sites is covered in the `Documentation/trace/*` directory.

6.2.2 IRQ

void **trace_irq_handler_entry**(int irq, struct *irqaction* *action)

called immediately before the irq action handler

Parameters

int irq
irq number

struct irqaction *action
pointer to *struct irqaction*

Description

The *struct irqaction* pointed to by **action** contains various information about the handler, including the device name, **action->name**, and the device id, **action->dev_id**. When used in conjunction with the irq_handler_exit tracepoint, we can figure out irq handler latencies.

void **trace_irq_handler_exit**(int irq, struct *irqaction* *action, int ret)

called immediately after the irq action handler returns

Parameters

int irq
irq number

struct irqaction *action
pointer to *struct irqaction*

int ret
return value

Description

If the **ret** value is set to IRQ_HANDLED, then we know that the corresponding **action->handler** successfully handled this irq. Otherwise, the irq might be a shared irq line, or the irq was not handled successfully. Can be used in conjunction with the irq_handler_entry to understand irq handler latencies.

void **trace_softirq_entry**(unsigned int vec_nr)

called immediately before the softirq handler

Parameters

unsigned int vec_nr
softirq vector number

Description

When used in combination with the softirq_exit tracepoint we can determine the softirq handler routine.

void **trace_softirq_exit**(unsigned int vec_nr)

called immediately after the softirq handler returns

Parameters

unsigned int vec_nr
softirq vector number

Description

When used in combination with the softirq_entry tracepoint we can determine the softirq handler routine.

void **trace_softirq_raise**(unsigned int vec_nr)
called immediately when a softirq is raised

Parameters

unsigned int vec_nr
softirq vector number

Description

When used in combination with the softirq_entry tracepoint we can determine the softirq raise to run latency.

6.2.3 SIGNAL

void **trace_signal_generate**(int sig, struct kernel_siginfo *info, struct task_struct *task, int group, int result)
called when a signal is generated

Parameters

int sig
signal number

struct kernel_siginfo *info
pointer to struct siginfo

struct task_struct *task
pointer to struct task_struct

int group
shared or private

int result
TRACE_SIGNAL_*

Description

Current process sends a 'sig' signal to 'task' process with 'info' siginfo. If 'info' is SEND_SIG_NOINFO or SEND_SIG_PRIV, 'info' is not a pointer and you can't access its field. Instead, SEND_SIG_NOINFO means that si_code is SI_USER, and SEND_SIG_PRIV means that si_code is SI_KERNEL.

void **trace_signal_deliver**(int sig, struct kernel_siginfo *info, struct k_sigaction *ka)
called when a signal is delivered

Parameters

int sig
signal number

struct kernel_siginfo *info
pointer to struct siginfo

struct k_sigaction *ka
pointer to struct k_sigaction

Description

A 'sig' signal is delivered to current process with 'info' siginfo, and it will be handled by 'ka'. ka->sa.sa_handler can be SIG_IGN or SIG_DFL. Note that some signals reported by signal_generate tracepoint can be lost, ignored or modified (by debugger) before hitting this tracepoint. This means, this can show which signals are actually delivered, but matching generated signals and delivered signals may not be correct.

6.2.4 Block IO

void **trace_block_touch_buffer**(struct buffer_head *bh)
mark a buffer accessed

Parameters

struct buffer_head *bh
buffer_head being touched

Description

Called from touch_buffer().

void **trace_block_dirty_buffer**(struct buffer_head *bh)
mark a buffer dirty

Parameters

struct buffer_head *bh
buffer_head being dirtied

Description

Called from mark_buffer_dirty().

void **trace_block_rq_requeue**(struct request *rq)
place block IO request back on a queue

Parameters

struct request *rq
block IO operation request

Description

The block operation request **rq** is being placed back into queue **q**. For some reason the request was not completed and needs to be put back in the queue.

void **trace_block_rq_complete**(struct request *rq, int error, unsigned int nr_bytes)
block IO operation completed by device driver

Parameters

struct request *rq
block operations request

int error
status code

unsigned int nr_bytes
number of completed bytes

Description

The block_rq_complete tracepoint event indicates that some portion of operation request has been completed by the device driver. If the **rq->bio** is `NULL`, then there is absolutely no additional work to do for the request. If **rq->bio** is non-NULL then there is additional work required to complete the request.

void **trace_block_rq_insert**(struct request *rq)
insert block operation request into queue

Parameters

struct request *rq
block IO operation request

Description

Called immediately before block operation request **rq** is inserted into queue **q**. The fields in the operation request **rq** struct can be examined to determine which device and sectors the pending operation would access.

void **trace_block_rq_issue**(struct request *rq)
issue pending block IO request operation to device driver

Parameters

struct request *rq
block IO operation operation request

Description

Called when block operation request **rq** from queue **q** is sent to a device driver for processing.

void **trace_block_rq_merge**(struct request *rq)
merge request with another one in the elevator

Parameters

struct request *rq
block IO operation operation request

Description

Called when block operation request **rq** from queue **q** is merged to another request queued in the elevator.

void **trace_block_bio_bounce**(struct request_queue *q, struct *bio* *bio)
used bounce buffer when processing block operation

Parameters

struct request_queue *q
queue holding the block operation

struct bio *bio
block operation

Description

A bounce buffer was used to handle the block operation **bio** in **q**. This occurs when hardware limitations prevent a direct transfer of data between the **bio** data memory area and the IO device. Use of a bounce buffer requires extra copying of data and decreases performance.

void **trace_block_bio_complete**(struct request_queue *q, struct *bio* *bio)
completed all work on the block operation

Parameters

struct request_queue *q
queue holding the block operation

struct bio *bio
block operation completed

Description

This tracepoint indicates there is no further work to do on this block IO operation **bio**.

void **trace_block_bio_backmerge**(struct request_queue *q, struct request *rq, struct *bio* *bio)
merging block operation to the end of an existing operation

Parameters

struct request_queue *q
queue holding operation

struct request *rq
request bio is being merged into

struct bio *bio
new block operation to merge

Description

Merging block request **bio** to the end of an existing block request in queue **q**.

void **trace_block_bio_frontmerge**(struct request_queue *q, struct request *rq, struct *bio* *bio)
merging block operation to the beginning of an existing operation

Parameters

struct request_queue *q
queue holding operation

struct request *rq
request bio is being merged into

struct bio *bio
new block operation to merge

Description

Merging block IO operation **bio** to the beginning of an existing block operation in queue **q**.

void **trace_block_bio_queue**(struct request_queue *q, struct *bio* *bio)
putting new block IO operation in queue

Parameters

struct request_queue *q
queue holding operation

struct bio *bio
new block operation

Description

About to place the block IO operation **bio** into queue **q**.

void **trace_block_getrq**(struct request_queue *q, struct *bio* *bio, int rw)
get a free request entry in queue for block IO operations

Parameters

struct request_queue *q
queue for operations

struct bio *bio
pending block IO operation (can be NULL)

int rw
low bit indicates a read (0) or a write (1)

Description

A request struct for queue **q** has been allocated to handle the block IO operation **bio**.

void **trace_block_sleeprq**(struct request_queue *q, struct *bio* *bio, int rw)
waiting to get a free request entry in queue for block IO operation

Parameters

struct request_queue *q
queue for operation

struct bio *bio
pending block IO operation (can be NULL)

int rw
low bit indicates a read (0) or a write (1)

Description

In the case where a request struct cannot be provided for queue **q** the process needs to wait for an request struct to become available. This tracepoint event is generated each time the process goes to sleep waiting for request struct become available.

void **trace_block_plug**(struct request_queue *q)
    keep operations requests in request queue

Parameters

struct request_queue *q
    request queue to plug

Description

Plug the request queue **q**. Do not allow block operation requests to be sent to the device driver. Instead, accumulate requests in the queue to improve throughput performance of the block device.

void **trace_block_unplug**(struct request_queue *q, unsigned int depth, bool explicit)
    release of operations requests in request queue

Parameters

struct request_queue *q
    request queue to unplug

unsigned int depth
    number of requests just added to the queue

bool explicit
    whether this was an explicit unplug, or one from schedule()

Description

Unplug request queue **q** because device driver is scheduled to work on elements in the request queue.

void **trace_block_split**(struct request_queue *q, struct *bio* *bio, unsigned int new_sector)
    split a single bio struct into two bio structs

Parameters

struct request_queue *q
    queue containing the bio

struct bio *bio
    block operation being split

unsigned int new_sector
    The starting sector for the new bio

Description

The bio request **bio** in request queue **q** needs to be split into two bio requests. The newly created **bio** request starts at **new_sector**. This split may be required due to hardware limitation such as operation crossing device boundaries in a RAID system.

void **trace_block_bio_remap**(struct request_queue *q, struct *bio* *bio, dev_t dev, sector_t from)
    map request for a logical device to the raw device

Parameters

struct request_queue *q
queue holding the operation

struct bio *bio
revised operation

dev_t dev
device for the operation

sector_t from
original sector for the operation

Description

An operation for a logical device has been mapped to the raw block device.

void **trace_block_rq_remap**(struct request *rq, dev_t dev, sector_t from)
map request for a block operation request

Parameters

struct request *rq
block IO operation request

dev_t dev
device for the operation

sector_t from
original sector for the operation

Description

The block operation request **rq** in **q** has been remapped. The block operation request **rq** holds the current information and **from** hold the original sector.

6.2.5 Workqueue

void **trace_workqueue_queue_work**(unsigned int req_cpu, struct pool_workqueue *pwq, struct work_struct *work)
called when a work gets queued

Parameters

unsigned int req_cpu
the requested cpu

struct pool_workqueue *pwq
pointer to struct pool_workqueue

struct work_struct *work
pointer to struct work_struct

Description

This event occurs when a work is queued immediately or once a delayed work is actually queued on a workqueue (ie: once the delay has been reached).

void **trace_workqueue_activate_work**(struct work_struct *work)
called when a work gets activated

Parameters

struct work_struct *work
pointer to struct work_struct

Description

This event occurs when a queued work is put on the active queue, which happens immediately after queueing unless **max_active** limit is reached.

void **trace_workqueue_execute_start**(struct work_struct *work)
called immediately before the workqueue callback

Parameters

struct work_struct *work
pointer to struct work_struct

Description

Allows to track workqueue execution.

void **trace_workqueue_execute_end**(struct work_struct *work, work_func_t function)
called immediately after the workqueue callback

Parameters

struct work_struct *work
pointer to struct work_struct

work_func_t function
pointer to worker function

Description

Allows to track workqueue execution.

6.3 Using physical DMA provided by OHCI-1394 FireWire controllers for debugging

6.3.1 Introduction

Basically all FireWire controllers which are in use today are compliant to the OHCI-1394 specification which defines the controller to be a PCI bus master which uses DMA to offload data transfers from the CPU and has a "Physical Response Unit" which executes specific requests by employing PCI-Bus master DMA after applying filters defined by the OHCI-1394 driver.

Once properly configured, remote machines can send these requests to ask the OHCI-1394 controller to perform read and write requests on physical system memory and, for read requests, send the result of the physical memory read back to the requester.

With that, it is possible to debug issues by reading interesting memory locations such as buffers like the printk buffer or the process table.

Retrieving a full system memory dump is also possible over the FireWire, using data transfer rates in the order of 10MB/s or more.

With most FireWire controllers, memory access is limited to the low 4 GB of physical address space. This can be a problem on IA64 machines where memory is located mostly above that limit, but it is rarely a problem on more common hardware such as x86, x86-64 and PowerPC.

At least LSI FW643e and FW643e2 controllers are known to support access to physical addresses above 4 GB, but this feature is currently not enabled by Linux.

Together with a early initialization of the OHCI-1394 controller for debugging, this facility proved most useful for examining long debugs logs in the printk buffer on to debug early boot problems in areas like ACPI where the system fails to boot and other means for debugging (serial port) are either not available (notebooks) or too slow for extensive debug information (like ACPI).

6.3.2 Drivers

The firewire-ohci driver in drivers/firewire uses filtered physical DMA by default, which is more secure but not suitable for remote debugging. Pass the remote_dma=1 parameter to the driver to get unfiltered physical DMA.

Because the firewire-ohci driver depends on the PCI enumeration to be completed, an initialization routine which runs pretty early has been implemented for x86. This routine runs long before console_init() can be called, i.e. before the printk buffer appears on the console.

To activate it, enable CONFIG_PROVIDE_OHCI1394_DMA_INIT (Kernel hacking menu: Remote debugging over FireWire early on boot) and pass the parameter "ohci1394_dma=early" to the recompiled kernel on boot.

6.3.3 Tools

firescope - Originally developed by Benjamin Herrenschmidt, Andi Kleen ported it from PowerPC to x86 and x86_64 and added functionality, firescope can now be used to view the printk buffer of a remote machine, even with live update.

Bernhard Kaindl enhanced firescope to support accessing 64-bit machines from 32-bit firescope and vice versa: - http://v3.sk/~lkundrak/firescope/

and he implemented fast system dump (alpha version - read README.txt): - http://halobates.de/firewire/firedump-0.1.tar.bz2

There is also a gdb proxy for firewire which allows to use gdb to access data which can be referenced from symbols found by gdb in vmlinux: - http://halobates.de/firewire/fireproxy-0.33.tar.bz2

The latest version of this gdb proxy (fireproxy-0.34) can communicate (not yet stable) with kgdb over an memory-based communication module (kgdbom).

6.3.4 Getting Started

The OHCI-1394 specification regulates that the OHCI-1394 controller must disable all physical DMA on each bus reset.

This means that if you want to debug an issue in a system state where interrupts are disabled and where no polling of the OHCI-1394 controller for bus resets takes place, you have to establish any FireWire cable connections and fully initialize all FireWire hardware __before__ the system enters such state.

Step-by-step instructions for using firescope with early OHCI initialization:

1) Verify that your hardware is supported:

   Load the firewire-ohci module and check your kernel logs. You should see a line similar to:

   ```
   firewire_ohci 0000:15:00.1: added OHCI v1.0 device as card 2, 4␣
   ↪IR + 4 IT
   ... contexts, quirks 0x11
   ```

   when loading the driver. If you have no supported controller, many PCI, CardBus and even some Express cards which are fully compliant to OHCI-1394 specification are available. If it requires no driver for Windows operating systems, it most likely is. Only specialized shops have cards which are not compliant, they are based on TI PCILynx chips and require drivers for Windows operating systems.

   The mentioned kernel log message contains the string "physUB" if the controller implements a writable Physical Upper Bound register. This is required for physical DMA above 4 GB (but not utilized by Linux yet).

2) Establish a working FireWire cable connection:

   Any FireWire cable, as long at it provides electrically and mechanically stable connection and has matching connectors (there are small 4-pin and large 6-pin FireWire ports) will do.

   If an driver is running on both machines you should see a line like:

   ```
   firewire_core 0000:15:00.1: created device fw1: GUID␣
   ↪00061b0020105917, S400
   ```

   on both machines in the kernel log when the cable is plugged in and connects the two machines.

3) Test physical DMA using firescope:

   On the debug host, make sure that /dev/fw* is accessible, then start firescope:

   ```
       $ firescope
       Port 0 (/dev/fw1) opened, 2 nodes detected

       FireScope
       ---------
       Target : <unspecified>
   ```

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```
    Gen    : 1
    [Ctrl-T] choose target
    [Ctrl-H] this menu
    [Ctrl-Q] quit

------> Press Ctrl-T now, the output should be similar to:

    2 nodes available, local node is: 0
     0: ffc0, uuid: 00000000 00000000 [LOCAL]
     1: ffc1, uuid: 00279000 ba4bb801
```

Besides the [LOCAL] node, it must show another node without error message.

4) Prepare for debugging with early OHCI-1394 initialization:

   4.1) Kernel compilation and installation on debug target

   Compile the kernel to be debugged with CONFIG_PROVIDE_OHCI1394_DMA_INIT (Kernel hacking: Provide code for enabling DMA over FireWire early on boot) enabled and install it on the machine to be debugged (debug target).

   4.2) Transfer the System.map of the debugged kernel to the debug host

   Copy the System.map of the kernel be debugged to the debug host (the host which is connected to the debugged machine over the FireWire cable).

5) Retrieving the printk buffer contents:

   With the FireWire cable connected, the OHCI-1394 driver on the debugging host loaded, reboot the debugged machine, booting the kernel which has CONFIG_PROVIDE_OHCI1394_DMA_INIT enabled, with the option ohci1394_dma=early.

   Then, on the debugging host, run firescope, for example by using -A:

```
firescope -A System.map-of-debug-target-kernel
```

   Note: -A automatically attaches to the first non-local node. It only works reliably if only connected two machines are connected using FireWire.

   After having attached to the debug target, press Ctrl-D to view the complete printk buffer or Ctrl-U to enter auto update mode and get an updated live view of recent kernel messages logged on the debug target.

   Call "firescope -h" to get more information on firescope's options.

6.3.5 Notes

Documentation and specifications: http://halobates.de/firewire/

FireWire is a trademark of Apple Inc. - for more information please refer to: https://en.wikipedia.org/wiki/FireWire

CHAPTER

SEVEN

EVERYTHING ELSE

Documents that don't fit elsewhere or which have yet to be categorized.

7.1 Reed-Solomon Library Programming Interface

Author
Thomas Gleixner

7.1.1 Introduction

The generic Reed-Solomon Library provides encoding, decoding and error correction functions.

Reed-Solomon codes are used in communication and storage applications to ensure data integrity.

This documentation is provided for developers who want to utilize the functions provided by the library.

7.1.2 Known Bugs And Assumptions

None.

7.1.3 Usage

This chapter provides examples of how to use the library.

Initializing

The init function init_rs returns a pointer to an rs decoder structure, which holds the necessary information for encoding, decoding and error correction with the given polynomial. It either uses an existing matching decoder or creates a new one. On creation all the lookup tables for fast en/decoding are created. The function may take a while, so make sure not to call it in critical code paths.

```
/* the Reed Solomon control structure */
static struct rs_control *rs_decoder;

/* Symbolsize is 10 (bits)
 * Primitive polynomial is x^10+x^3+1
 * first consecutive root is 0
 * primitive element to generate roots = 1
 * generator polynomial degree (number of roots) = 6
 */
rs_decoder = init_rs (10, 0x409, 0, 1, 6);
```

Encoding

The encoder calculates the Reed-Solomon code over the given data length and stores the result in the parity buffer. Note that the parity buffer must be initialized before calling the encoder.

The expanded data can be inverted on the fly by providing a non-zero inversion mask. The expanded data is XOR' ed with the mask. This is used e.g. for FLASH ECC, where the all 0xFF is inverted to an all 0x00. The Reed-Solomon code for all 0x00 is all 0x00. The code is inverted before storing to FLASH so it is 0xFF too. This prevents that reading from an erased FLASH results in ECC errors.

The databytes are expanded to the given symbol size on the fly. There is no support for encoding continuous bitstreams with a symbol size != 8 at the moment. If it is necessary it should be not a big deal to implement such functionality.

```
/* Parity buffer. Size = number of roots */
uint16_t par[6];
/* Initialize the parity buffer */
memset(par, 0, sizeof(par));
/* Encode 512 byte in data8. Store parity in buffer par */
encode_rs8 (rs_decoder, data8, 512, par, 0);
```

Decoding

The decoder calculates the syndrome over the given data length and the received parity symbols and corrects errors in the data.

If a syndrome is available from a hardware decoder then the syndrome calculation is skipped.

The correction of the data buffer can be suppressed by providing a correction pattern buffer and an error location buffer to the decoder. The decoder stores the calculated error location and the correction bitmask in the given buffers. This is useful for hardware decoders which use a weird bit ordering scheme.

The databytes are expanded to the given symbol size on the fly. There is no support for decoding continuous bitstreams with a symbolsize != 8 at the moment. If it is necessary it should be not a big deal to implement such functionality.

Decoding with syndrome calculation, direct data correction

```
/* Parity buffer. Size = number of roots */
uint16_t par[6];
uint8_t  data[512];
int numerr;
/* Receive data */
.....
/* Receive parity */
.....
/* Decode 512 byte in data8.*/
numerr = decode_rs8 (rs_decoder, data8, par, 512, NULL, 0, NULL, 0,␣
↪NULL);
```

Decoding with syndrome given by hardware decoder, direct data correction

```
/* Parity buffer. Size = number of roots */
uint16_t par[6], syn[6];
uint8_t  data[512];
int numerr;
/* Receive data */
.....
/* Receive parity */
.....
/* Get syndrome from hardware decoder */
.....
/* Decode 512 byte in data8.*/
numerr = decode_rs8 (rs_decoder, data8, par, 512, syn, 0, NULL, 0,␣
↪NULL);
```

Decoding with syndrome given by hardware decoder, no direct data correction.

Note: It's not necessary to give data and received parity to the decoder.

```
/* Parity buffer. Size = number of roots */
uint16_t par[6], syn[6], corr[8];
uint8_t  data[512];
int numerr, errpos[8];
/* Receive data */
.....
/* Receive parity */
.....
/* Get syndrome from hardware decoder */
.....
/* Decode 512 byte in data8.*/
```

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```
numerr = decode_rs8 (rs_decoder, NULL, NULL, 512, syn, 0, errpos, 0,
↪ corr);
for (i = 0; i < numerr; i++) {
    do_error_correction_in_your_buffer(errpos[i], corr[i]);
}
```

Cleanup

The function free_rs frees the allocated resources, if the caller is the last user of the decoder.

```
/* Release resources */
free_rs(rs_decoder);
```

7.1.4 Structures

This chapter contains the autogenerated documentation of the structures which are used in the Reed-Solomon Library and are relevant for a developer.

struct **rs_codec**

rs codec data

Definition

```
struct rs_codec {
  int mm;
  int nn;
  uint16_t *alpha_to;
  uint16_t *index_of;
  uint16_t *genpoly;
  int nroots;
  int fcr;
  int prim;
  int iprim;
  int gfpoly;
  int (*gffunc)(int);
  int users;
  struct list_head list;
};
```

Members

mm
Bits per symbol

nn
Symbols per block (= (1<<mm)-1)

alpha_to
log lookup table

index_of
: Antilog lookup table

genpoly
: Generator polynomial

nroots
: Number of generator roots = number of parity symbols

fcr
: First consecutive root, index form

prim
: Primitive element, index form

iprim
: prim-th root of 1, index form

gfpoly
: The primitive generator polynominal

gffunc
: Function to generate the field, if non-canonical representation

users
: Users of this structure

list
: List entry for the rs codec list

struct **rs_control**
: rs control structure per instance

Definition

```
struct rs_control {
  struct rs_codec *codec;
  uint16_t buffers[];
};
```

Members

codec
: The codec used for this instance

buffers
: Internal scratch buffers used in calls to decode_rs()

struct *rs_control* ***init_rs**(int symsize, int gfpoly, int fcr, int prim, int nroots)
: Create a RS control struct and initialize it

Parameters

int symsize
: the symbol size (number of bits)

int gfpoly
: the extended Galois field generator polynomial coefficients, with the 0th coefficient in the low order bit. The polynomial must be primitive;

int fcr
the first consecutive root of the rs code generator polynomial in index form

int prim
primitive element to generate polynomial roots

int nroots
RS code generator polynomial degree (number of roots)

Description

Allocations use GFP_KERNEL.

7.1.5 Public Functions Provided

This chapter contains the autogenerated documentation of the Reed-Solomon functions which are exported.

void **free_rs**(struct *rs_control* *rs)
Free the rs control structure

Parameters

struct rs_control *rs
The control structure which is not longer used by the caller

Description

Free the control structure. If **rs** is the last user of the associated codec, free the codec as well.

struct *rs_control* ***init_rs_gfp**(int symsize, int gfpoly, int fcr, int prim, int nroots, gfp_t gfp)
Create a RS control struct and initialize it

Parameters

int symsize
the symbol size (number of bits)

int gfpoly
the extended Galois field generator polynomial coefficients, with the 0th coefficient in the low order bit. The polynomial must be primitive;

int fcr
the first consecutive root of the rs code generator polynomial in index form

int prim
primitive element to generate polynomial roots

int nroots
RS code generator polynomial degree (number of roots)

gfp_t gfp
Memory allocation flags.

struct *rs_control* ***init_rs_non_canonical**(int symsize, int (*gffunc)(int), int fcr, int prim, int nroots)
Allocate rs control struct for fields with non-canonical representation

Parameters

int symsize
: the symbol size (number of bits)

int (*gffunc)(int)
: pointer to function to generate the next field element, or the multiplicative identity element if given 0. Used instead of gfpoly if gfpoly is 0

int fcr
: the first consecutive root of the rs code generator polynomial in index form

int prim
: primitive element to generate polynomial roots

int nroots
: RS code generator polynomial degree (number of roots)

int **encode_rs8**(struct *rs_control* *rsc, uint8_t *data, int len, uint16_t *par, uint16_t invmsk)

Calculate the parity for data values (8bit data width)

Parameters

struct rs_control *rsc
: the rs control structure

uint8_t *data
: data field of a given type

int len
: data length

uint16_t *par
: parity data, must be initialized by caller (usually all 0)

uint16_t invmsk
: invert data mask (will be xored on data)

The parity uses a uint16_t data type to enable symbol size > 8. The calling code must take care of encoding of the syndrome result for storage itself.

int **decode_rs8**(struct *rs_control* *rsc, uint8_t *data, uint16_t *par, int len, uint16_t *s, int no_eras, int *eras_pos, uint16_t invmsk, uint16_t *corr)

Decode codeword (8bit data width)

Parameters

struct rs_control *rsc
: the rs control structure

uint8_t *data
: data field of a given type

uint16_t *par
: received parity data field

int len
: data length

uint16_t *s
syndrome data field, must be in index form (if NULL, syndrome is calculated)

int no_eras
number of erasures

int *eras_pos
position of erasures, can be NULL

uint16_t invmsk
invert data mask (will be xored on data, not on parity!)

uint16_t *corr
buffer to store correction bitmask on eras_pos

The syndrome and parity uses a uint16_t data type to enable symbol size > 8. The calling code must take care of decoding of the syndrome result and the received parity before calling this code.

Note

The rs_control struct rsc contains buffers which are used for
decoding, so the caller has to ensure that decoder invocations are serialized.

Returns the number of corrected symbols or -EBADMSG for uncorrectable errors. The count includes errors in the parity.

int **encode_rs16**(struct *rs_control* *rsc, uint16_t *data, int len, uint16_t *par, uint16_t invmsk)

Calculate the parity for data values (16bit data width)

Parameters

struct rs_control *rsc
the rs control structure

uint16_t *data
data field of a given type

int len
data length

uint16_t *par
parity data, must be initialized by caller (usually all 0)

uint16_t invmsk
invert data mask (will be xored on data, not on parity!)

Each field in the data array contains up to symbol size bits of valid data.

int **decode_rs16**(struct *rs_control* *rsc, uint16_t *data, uint16_t *par, int len, uint16_t *s, int no_eras, int *eras_pos, uint16_t invmsk, uint16_t *corr)

Decode codeword (16bit data width)

Parameters

struct rs_control *rsc
the rs control structure

uint16_t *data
data field of a given type

uint16_t *par
received parity data field

int len
data length

uint16_t *s
syndrome data field, must be in index form (if NULL, syndrome is calculated)

int no_eras
number of erasures

int *eras_pos
position of erasures, can be NULL

uint16_t invmsk
invert data mask (will be xored on data, not on parity!)

uint16_t *corr
buffer to store correction bitmask on eras_pos

Each field in the data array contains up to symbol size bits of valid data.

Note

The rc_control struct rsc contains buffers which are used for
decoding, so the caller has to ensure that decoder invocations are serialized.

Returns the number of corrected symbols or -EBADMSG for uncorrectable errors. The count includes errors in the parity.

7.1.6 Credits

The library code for encoding and decoding was written by Phil Karn.

```
Copyright 2002, Phil Karn, KA9Q
May be used under the terms of the GNU General Public License (GPL)
```

The wrapper functions and interfaces are written by Thomas Gleixner.

Many users have provided bugfixes, improvements and helping hands for testing. Thanks a lot.

The following people have contributed to this document:

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