Chapter 5: Synchronization and Scheduling

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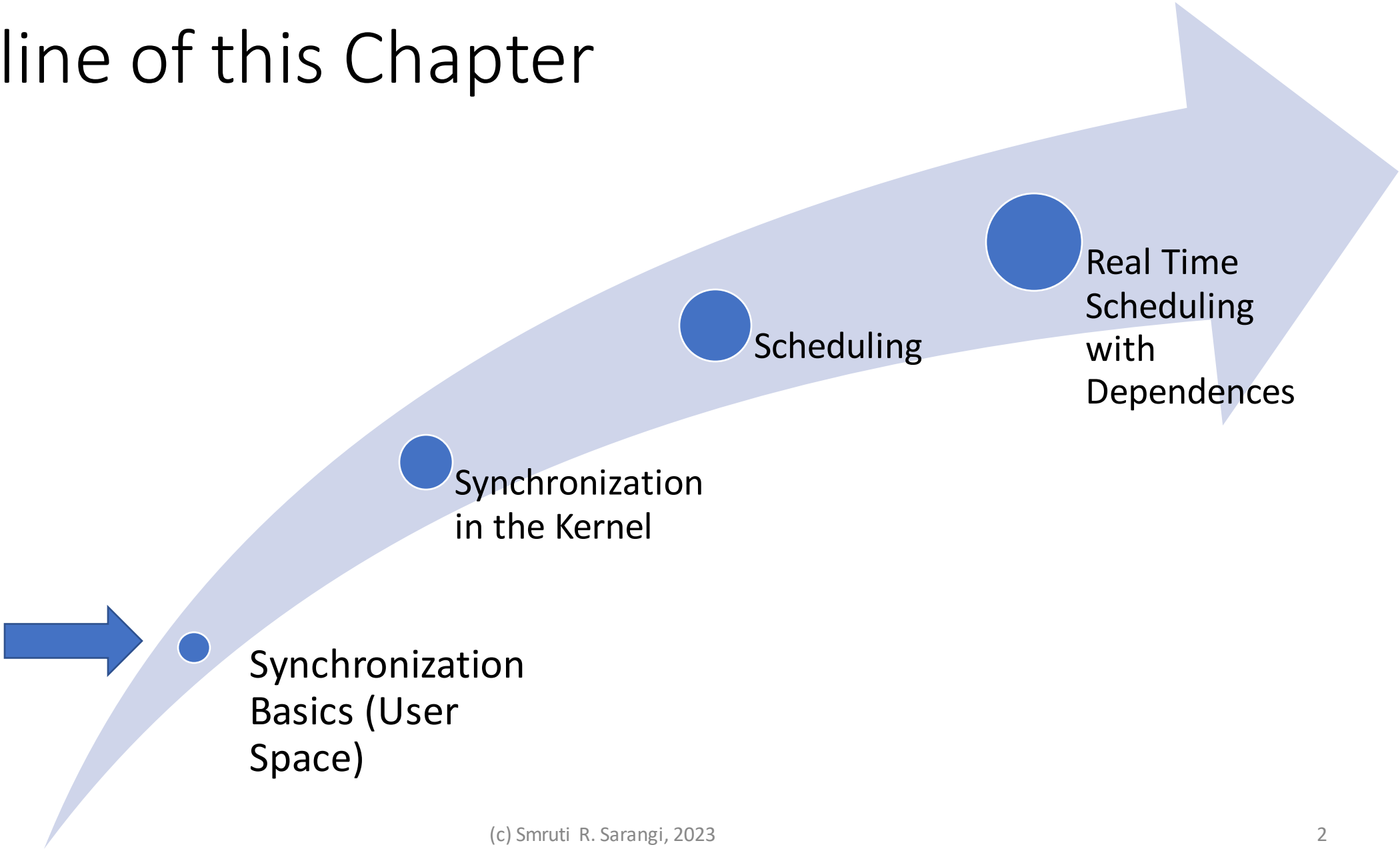
Outline of this Chapter



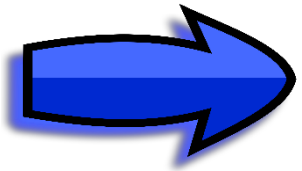
Consider a Multicore CPU

Do something as simple as

count++

Assume there are multiple threads.

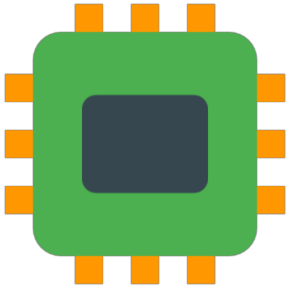
Will this work correctly?



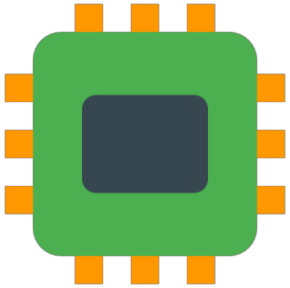
```
t1 = count
t1 = t1 + 1
count = t1
```

Each **line** corresponds to one line of assembly code. ***count*** is a global variable stored in memory and *t1* is a register.

Consider 2 Threads



count = 0



Thread 1

```
t1 = count
t1 = t1 + 1
count = t1
```

Thread 2

```
t1 = count
t1 = t1 + 1
count = t1
```

The delay between any two instructions can be indefinite

What can this cause?

Problematic Executions

count = 0

t1 = count

t1 = count

t1 = t1 + 1

t1 = t1 + 1

count = t1

count = t1

- There is no synchronization between threads here
- Arbitrary overlaps are possible

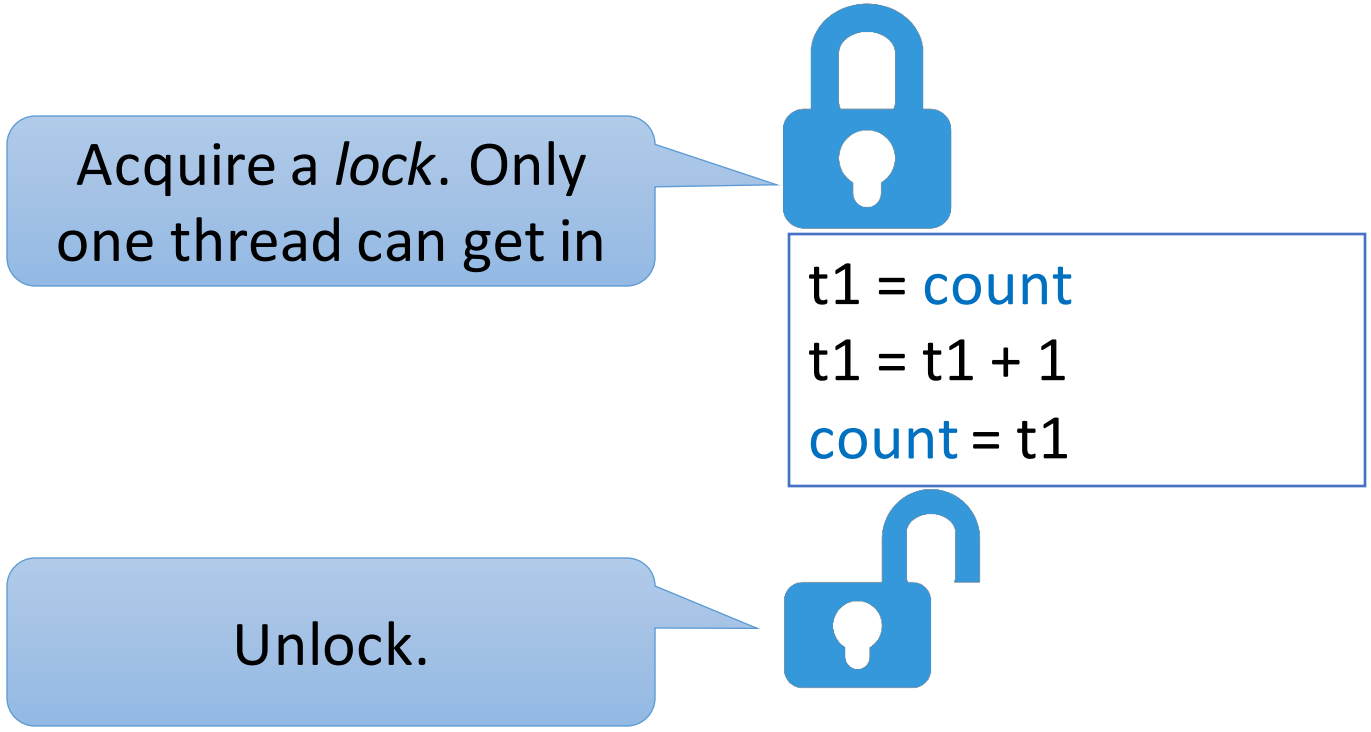
count = 1

count = 1

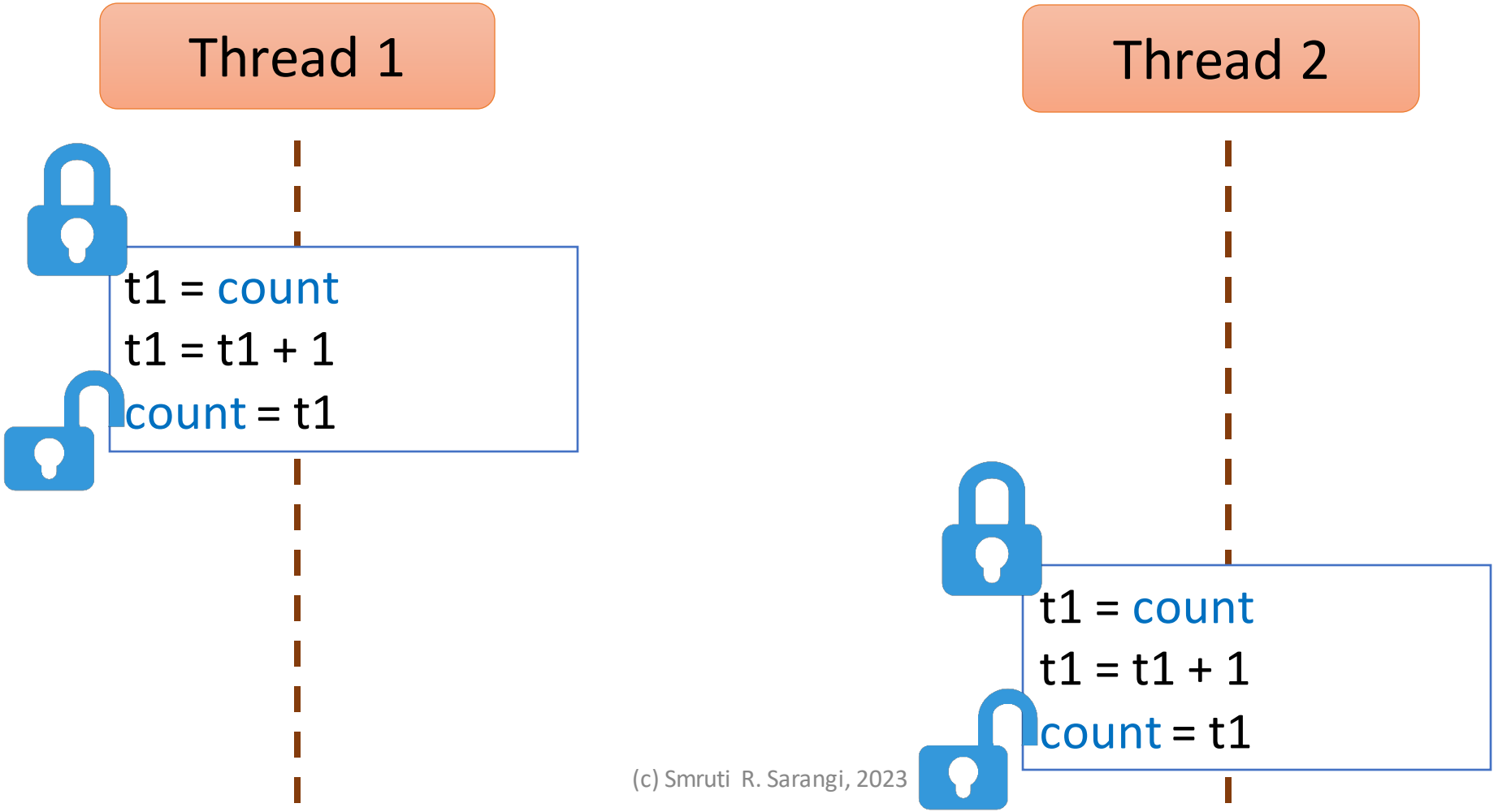
Should be 2

Concurrently incrementing *count* is hard

- What is the main issue?
- The instruction sequences are overlapping.
- We need synchronization.



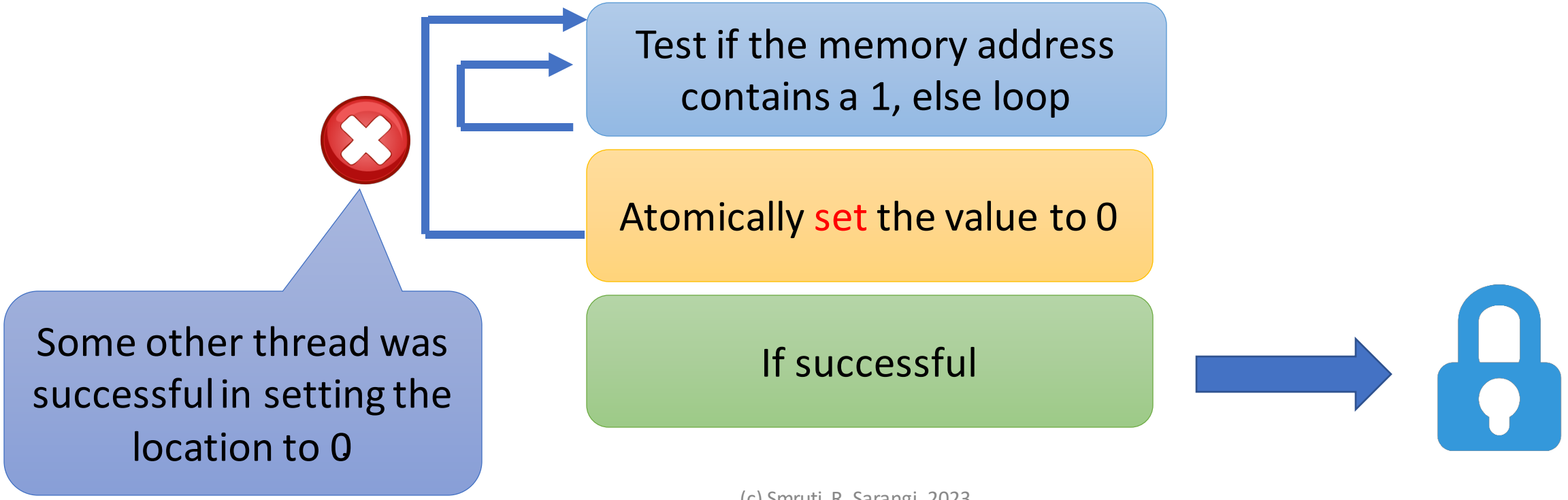
What will the code look with locks …



What is a lock anyway?

- Implementation of a lock

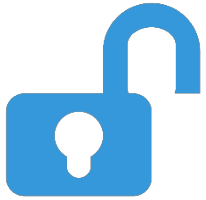
You lock a memory address *A*



Unlocking

Set the contents of the location to 1

Critical section



Notion of Data Races

- Why does this piece of code not work in the first place.
- We have a data race

Conflicting accesses by two threads

- At least one of the threads writes to the shared variable

Concurrent accesses

- Both the accesses are happening roughly at the same time. There is a more precise definition that uses the notion of happens-before relationships and lock-unlock relationships. Let *A* and *B* be memory access events. *A* happens before *B*, if *A* is a memory access in a critical section, then its lock is released and reacquired by the critical section that *B* is a part of.

Properly Labelled Programs

- Ensure that all your shared variables (shared across threads) are always accessed in the context of a critical section and there are no data races.

This program has a data race.

Lock (X)

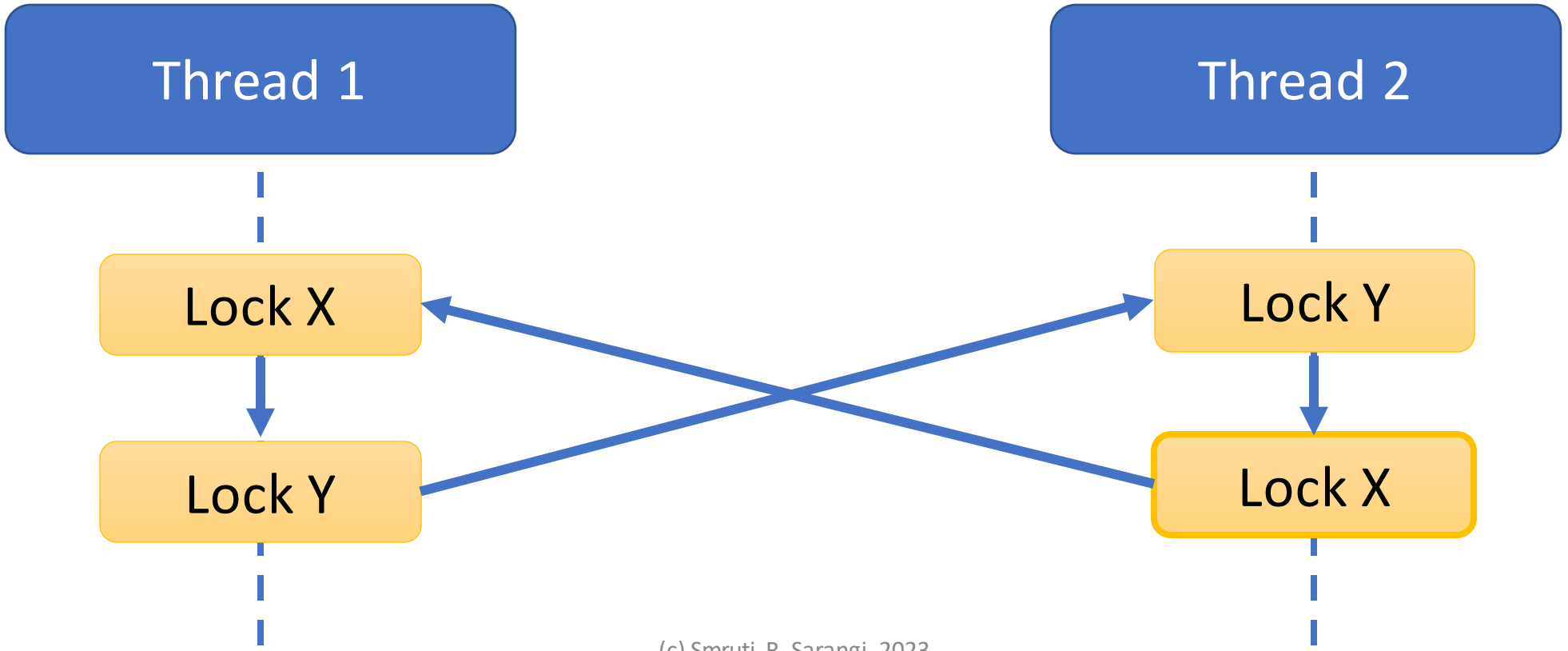
Access locations A, B, and C

Lock (Y)

Access locations D, E, and C

A shared variable always has to be protected by the same lock.

Locks can lead to deadlocks ....



Four Conditions for a Deadlock

Hold and Wait

- A thread is holding on to a **lock** and waiting for the other one.

No preemption

- The lock cannot be taken away from a thread.

Mutual exclusion

- A lock can be held by only a single thread.

Circular wait

Solutions for Preventing Deadlocks

Hold and Wait

- If a thread is waiting for a resources for too long, release the resources that it holds.

No preemption

- Resources can be taken away from threads by the OS.

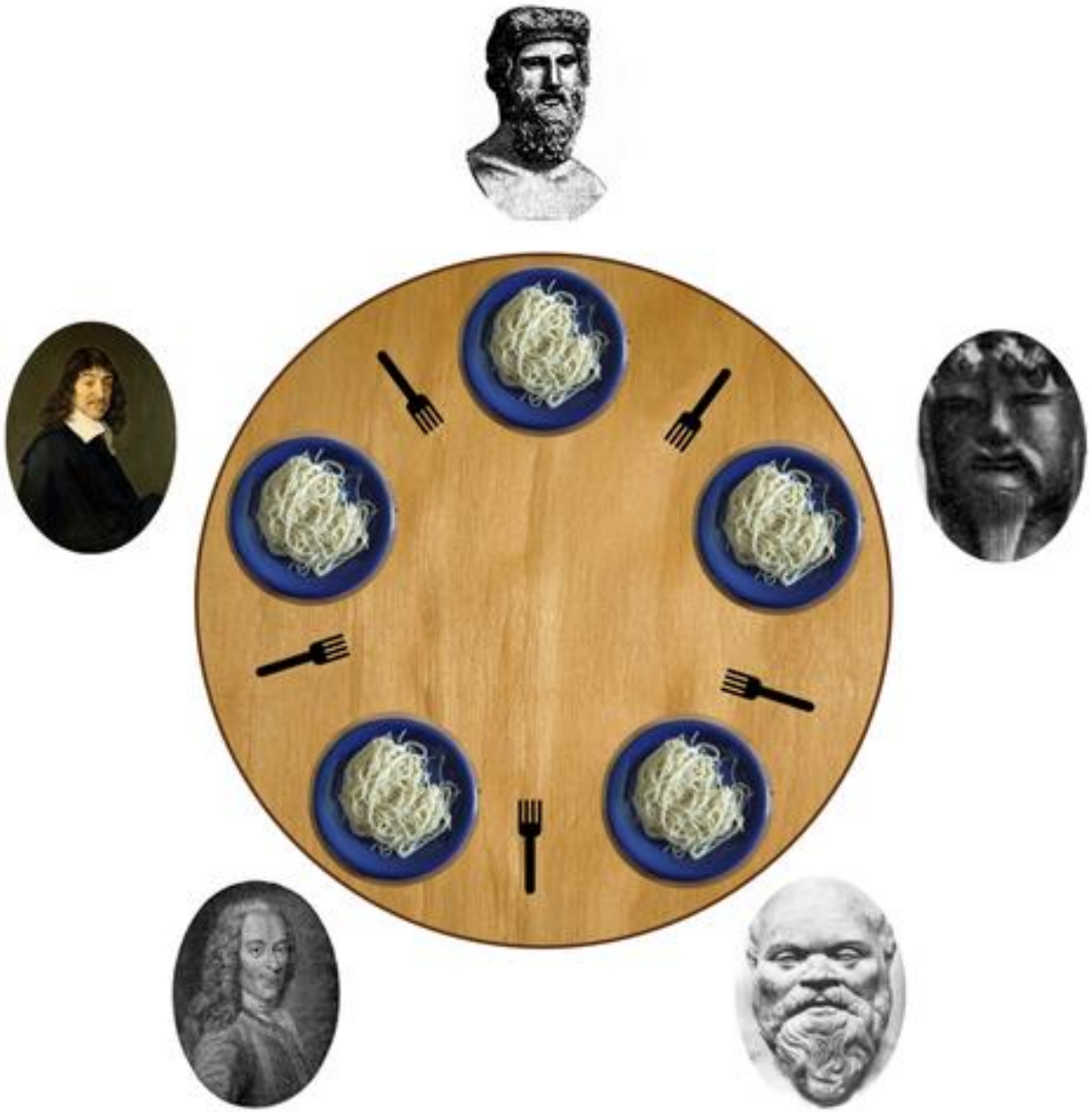
Mutual exclusion

- This is a basic property of a lock. This cannot be tampered with.

Circular wait

- Acquire locks in a given order

Dining Philosopher's Problem



A philosopher needs to pick up both the forks to eat. He can pick up only one fork at a time.

Avoid deadlocks.

Livelocks, Deadlocks, and Starvation

Deadlocks

- All the threads are waiting on each other.

Starvation

- A thread waits indefinitely to get access to the resource. Starvation freedom implies deadlock freedom (not the other way).

Livelocks

- Threads keep executing instructions but nothing productive gets done.

```c
#include<stdio.h>
#include<pthread.h>
#include<stdlib.h>
#include<unistd.h>

pthread_t tid[2];
int counter;

void* func(void *arg)
{
    int *ptr = (int *) arg;
    printf("Thread %d \n", *ptr);
}
```

```c
int main(void)
{
    int errcode, i = 0; int *ptr;
    for (i=0; i < 2; i++)
    {
        ptr = (int *) malloc (sizeof(int));
        *ptr = i;
        errcode = pthread_create(&(tid[i]), NULL,
                                 &func, ptr);
        if (errcode)
         printf("Error in creating pthreads \n");
    }

    pthread_join(tid[0], NULL);
    pthread_join(tid[1], NULL);
}
```

gcc <prog_name> -lpthread

The same code with locks for incrementing a *counter*

```
int counter = 0;
pthread_mutex_t cntlock;

void* func(void *arg)
{
    pthread_mutex_lock(&cntlock);
    counter++;
    pthread_mutex_unlock(&cntlock);
}

int main () {
    ...
    ...
    printf ("The final value of counter is %d \n", counter);
}
```

Code without locks (lock-free programming)

```
#include <stdatomic.h>

atomic_int counter = 0;

void * fetch_and_increment (void *arg) {
    atomic_fetch_add (&counter, 1);
}
```

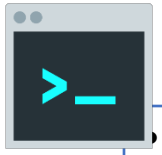
Also known as non-blocking algorithms

Same Example with Compare_and_Exchange

Increment using the compare_and_swap primitive

```
atomic_int counter = 0;
#define CAS atomic_compare_exchange_strong

void* fetch_and_increment (void *arg){
    int oldval, newval;
    do {
        oldval = atomic_load (&counter);
        newval = oldval + 1;
        printf ("old = %d, new = %d \n", oldval, newval);
    while (! CAS (&counter, &oldval, newval)) {}
}
```

Output



```
• old = 0, new = 1
• old = 0, new = 1
• old = 1, new = 2
• The final value of counter is 2
```

In this case, there is the possibility of many failed attempts at performing the CAS.

If threads are allowed to call this function repeatedly, then it is possible that a few threads may starve forever.

Obstruction-free vs Lock-free vs Wait-free

- Assuming a thread that is holding a lock goes off to sleep or is swapped out
- Then this means that the rest of the threads will not be able to make any progress
- This is unfair.
- We thus need algorithms with better progress guarantees

Obstruction-free	• If *n-1* threads stop, then the n^{th} thread can finish in a bounded number of steps
Lock-free	• At any point of time, there is at least one thread that is going to complete in a bounded number of steps.
Wait-free	• All threads complete within a bounded number of steps.

What does all of this mean?

- In an obstruction-free algorithm, no thread can hold a lock and go off to sleep
  - It should be possible to finish one thread's operation by putting the rest of the threads to sleep all the time
  - Using locks is thus precluded unless locks can be released on a context switch
- Lock-free algorithms are more difficult to write
  - They are fast in practice
  - They guarantee system wide progress, but individual threads can starve
- Use wait-free algorithms
  - They are slower than lock-free algorithms in practice but have much stronger progress guarantees.

Case of Bounded Queues

- The bounded queue is an important data structure
- It is used in a large number of kernel subsystems
- Device drivers use such structures a lot for communicating with other processes and devices
- There are multiple producer threads and multiple consumer threads
- This needs to be a concurrent queue.

Codes

E.g. 1 — Bounded wait-free queue – single producer and single consumer

wfq.c

E.g. 2 — Bounded queue with locks – pthread mutexes

wfbusylock.c

E.g. 3 — Bounded queue with semaphores

wfsem.c

E.g. 4 — Bounded queue with semaphores – no busy waiting

wfsem-ii.c

E.g. 5 — Bounded queue with semaphores and reader-writer locks

rwlock.c

Atomics

Example 1

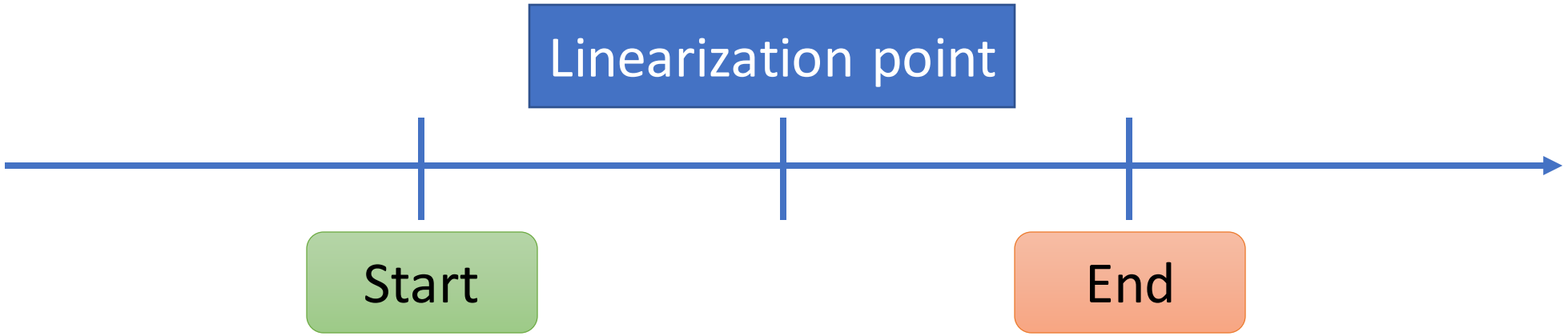
- <stdatomic.h> contains a library of atomic integers and characters
- *atomic_load* and *atomic_store* operations are used to read and write these atomic variables
- A few atomic operations are supported:
  - *atomic_fetch_add*
  - *atomic_flag_test_and_set*
  - *atomic_compare_exchange_strong*
- For the sake of simplicity, let us assume that atomic operations are globally (sequentially) ordered.
  - We cannot say the same about regular memory accesses
- This is the crux of lock-free programming

How do you prove the correctness of lock-free programs?

Linearizability

- The operation needs to be atomic
  - It needs to "appear" to execute instantaneously (single instant of time)
  - Either the entire operation executes or it appears to not have execute at all
- Atomicity vs Linearizability
  - Atomicity basically says that the entire operation (like enqueue/dequeue) appears to execute at any one instant of time
  - However, it does not say that this execution point needs to lie between the start and end of the operation
  - This is where we have linearizability – a stronger criterion
  - It says that if the end time of an operation is before the start time of another operation, then their execution (linearization) points follow the same order
  - With regards to concurrent operations (they can be ordered in any way)

More about the Correctness of such Algorithms



- The linearization point needs to lie between the start and end
- It corresponds to a specific instruction within the function
- Proving that a certain instruction is a linearization point is a very well established area of research, and it is often quite difficult to do so
- This makes it quite difficult to write such programs

Example 2

Wait-free Queue → Queue with Locks

- Wait-free queue → It is easy to construct one for a single enqueuer and dequeuer. One thread enqueues and the other dequeues.
- However, it is quite hard to design a wait-free algorithm with multiple enqueuers and dequeuers
- Easier to use locks

Mutex

Spin-lock of busy-wait loop: Keep looping on the lock variable until it is locked

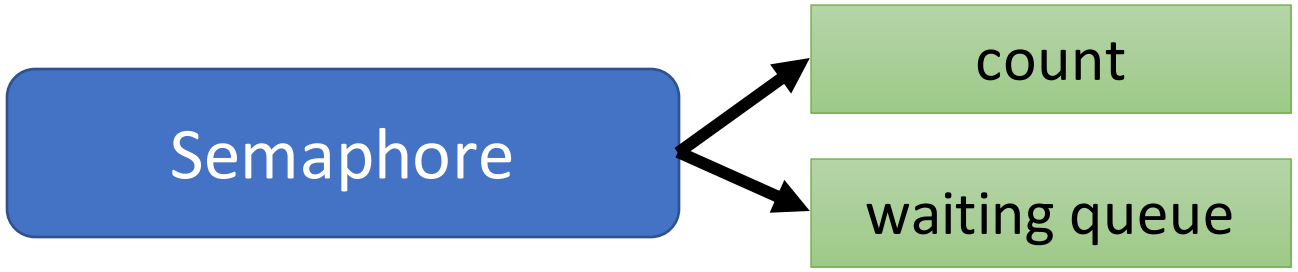
Futex

Do busy waiting for some time. Then, request the kernel to put the process into sleep and put it in a wait queue.

Release the CPU to do useful work

Semaphores

Example 3



- A semaphore maintains a count
- + a kernel-level wait queue

sem_wait

```
if (count == 0)
    insert_into_wait_queue();
else
    count --;
```

Semaphores – II

Example 4

sem_post

```
if ( (count == 0)  && process_waiting())
    wake_from_wait_queue();
else
    count ++;
```

- A binary semaphore (Boolean count) is equivalent to a lock
- A non-binary semaphore uses a count larger than 1
- Quite useful while implementing a bounded queue

Reader-Writer Lock

Example 5

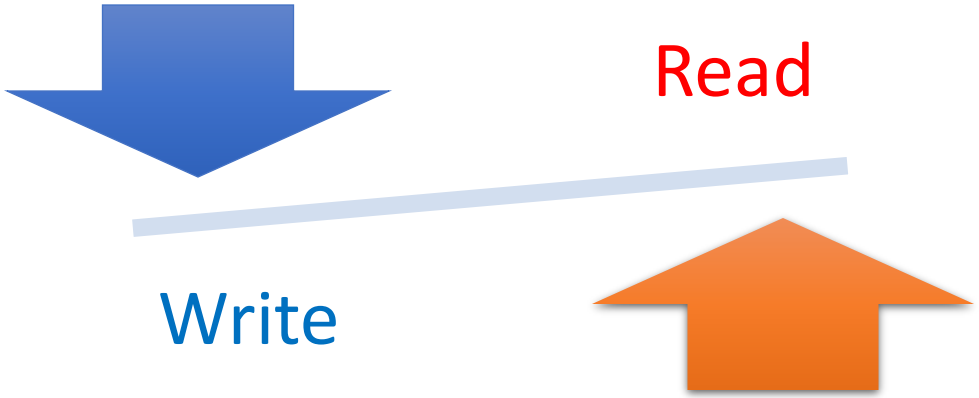
- Let us now add a new function.

```
int peak() {
    /* This is the read function */
    int val = (head == tail)? -1 : queue[head];
    printf ("Queue head = %d\n",val);
    return val;
}
```

Just read the head of the queue

If you have multiple readers at a time, they can be allowed to read the head of the queue concurrently.

Key Idea: Either one thread writes or multiple threads read



Read-write lock

Read lock

Have two modes:

1. A write mode that allows a single writer
2. A read mode that allows multiple readers but no writer

Switch between them

Read and Write Locks

Basic Idea:

1. The enqueue and dequeue function need the read_write lock: *rwlock*
   Writing always involves reading

2. For acquiring the read lock, we need to ensure that there are no current writers. Hence, acquire *rwlock* if there are no other readers

3. Update the number of readers, by locking the read lock

```
void get_write_lock(){
    WAIT(rwlock);
}
void
release_write_lock(){
    POST(rwlock);
}
void get_read_lock(){
    WAIT(read_lock);
    if (readers == 0)
        WAIT(rwlock);
    readers++;
    POST(read_lock);
}
```

```
void release_read_lock(){
    WAIT(read_lock);
    readers--;
    if (readers == 0)
        POST (rwlock);
    POST(read_lock);
}
```

Fairness is an issue

Other kinds of synchronization

Condition Variables

- Semaphores are a generic OS mechanism
- *pthreads* have a lightweight version – condition variables

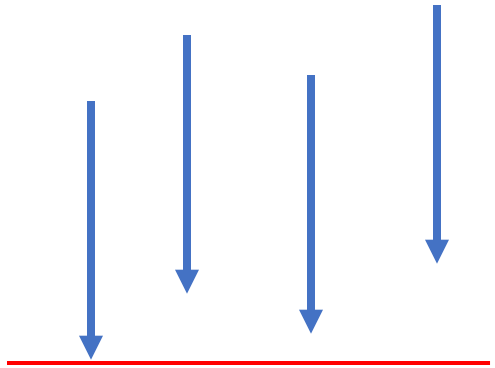
```
pthread_mutex_t mlock;
pthread_cond_t count;
pthread_cond_init (&count, NULL);

/* wait on the condition variable*/
pthread_mutex_lock (&mlock);
pthread_cond_wait (&count, &mlock);
pthread_mutex_unlock (&mlock);

pthread_mutex_lock (&mlock);
pthread_cond_signal (&count);
pthread_mutex_unlock (&mlock);
```

A conditional variable is always associated with a mutex

The *wait* call releases the mutex while waiting and reacquires it once woken up

The pthread_cond_signal and pthread_cond_broadcast functions wake up waiting threads

Barriers

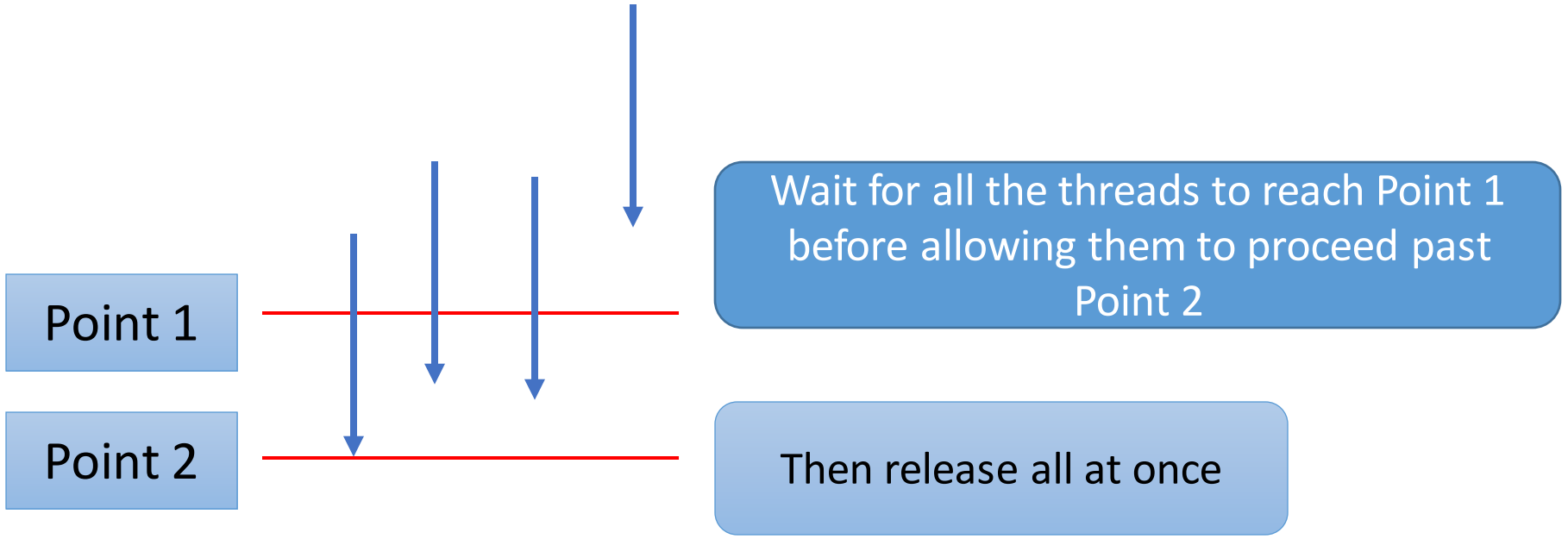


Wait for all the threads to reach the barrier

Then release all at once

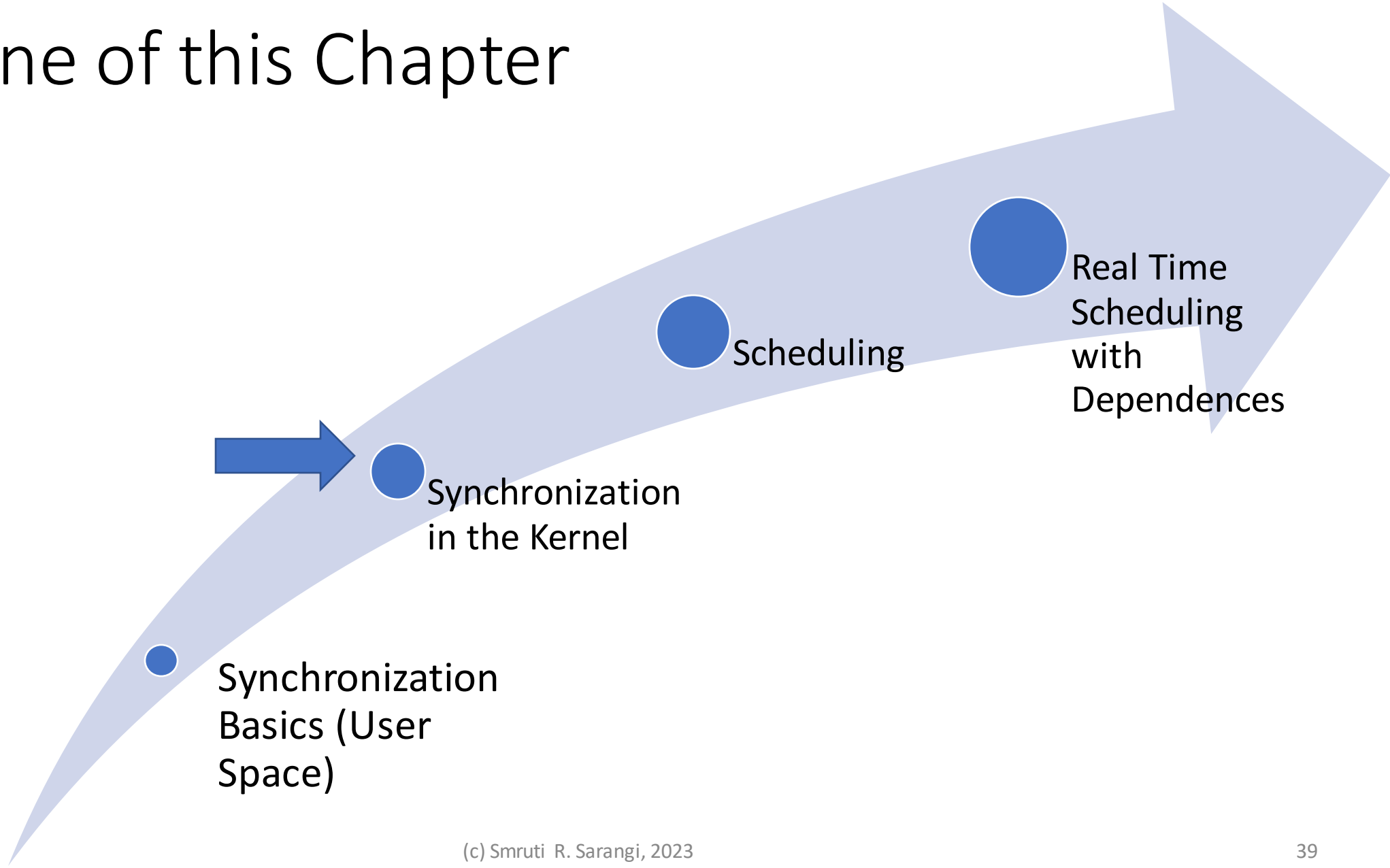
- A *barrier* acts as a synchronization point
- All the threads wait at the barrier for the slowest thread to arrive
- Then all of them are released and begin to execute

Phasers



- A *phaser* is a more complex synchronization point
- All the threads wait at Point 2 till the slowest thread reaches Point 1
- Then all of them are released and can proceed past Point 2

Outline of this Chapter



Questions regarding Concurrency in the Kernel

- If we have multiple threads in the kernel (as is normally the case), then a data structure can be accessed in parallel
- We need to support concurrency
  - Either use locks
  - Some variant of lock-free programming

- The other source of concurrency is the interrupt and scheduling process
- Kernel code can be interrupted in the middle. Then, the scheduler can schedule other threads, which can modify the state of the data structure.

Spinlocks

- It is the most basic type of lock
- They run a “busy wait” lock. Unlike other locks, the thread does not go off to sleep.
- They can be used in the interrupt context where blocking is not permitted
- After acquiring a spinlock, the kernel turns off pre-emption
- Otherwise, a new thread can run and that can try to acquire the lock. It will block yet the system will not make progress.
- The spinlock can also be visualized as a lock on the CPU. We don’t want to migrate the thread to a different CPU.

How to enable/disable pre-emption?

- The kernel maintains a per CPU variable that indicates whether pre-emption is allowed or not
  - If it is 0, pre-emption is allowed
  - Else, it is disallowed

```
#define preempt_disable() \
do { \
    preempt_count_inc(); \
    barrier(); \
} while (0)
```

Stop memory reordering

Not the same barrier we studied before. A different one

/include/linux/preempt.h

Enable Preemption

```
#define preempt_enable() \
do { \
    barrier(); \
    if (unlikely(preempt_count_dec_and_test())) \
        __preempt_schedule(); \
} while (0)
```

- If the count reaches 0
  - Run the *schedule* function

Some Memory Consistency Concepts

Thread 1	Thread 2
x = 1	y = 1
t1 = y	t2 = x

- Consider two threads that access two global variables: *x* and *y*
- They are initialized to 0
- t1 and t2 are temporary variables stored in registers

Is the outcome <t1,t2> = <0,0> possible?

If you assume sequential consistency: statements execute one by one.

Non-Sequentially Consistent Machines

Owing to performance reasons, all modern machines will allow this behavior. Their memory models not sequentially consistent.

How do you write parallel code then?

Take a computer architecture class.

- Accesses to global atomic variables can have data races → concurrent and conflicting accesses
- A *fence* or a *memory barrier* instruction forces sequentiality
  - All instructions before it need to complete before an instruction after it can begin.
- For all accesses to regular (non-atomic) variables, just wrap them in critical sections

Spinlocks

/include/linux/spinlock.h

/include/linux/spinlock_types_raw.h

```
typedef struct raw_spinlock {
    arch_spinlock_t raw_lock;
#ifdef CONFIG_DEBUG_LOCK_ALLOC
    struct lockdep_map dep_map;
#endif
} raw_spinlock_t;
```

- The *raw_spinlock_t* type is just a wrapper on the architecture defined spin lock → This structure wraps an atomic/volatile integer
- It also has a *lockdep_map* structure to find deadlocks

Inner Workings of the Spinlock

Ticket lock

/include/asm-generic/spin-lock.h

Ticket id | To be served

```
void arch_spin_lock(arch_spinlock_t *lock)
{
    u32 val = atomic_fetch_add (1<<16, lock);
    u16 ticket = val >> 16;   /* upper 16 bits of lock */

    if (ticket == (u16) val)  /* Ticket id == ticket next in line */
        return;

    atomic_cond_read_acquire(lock, ticket == (u16)VAL);
    smp_mb();    /* barrier instruction*/
}
```

The spin lock function

The actual spin loop (keeping the memory model into account)

```
#define smp_cond_load_relaxed(ptr, cond_expr) ({          \
    typeof(ptr) __PTR = (ptr);                            \
    __unqual_scalar_typeof(*ptr) VAL;                     \
    for (;;) {                                            \
        VAL = READ_ONCE(*__PTR);                          \
        if (cond_expr)                                    \
            break;                                        \
        cpu_relax();     /* insert a delay*/              \
    }                                                     \
    (typeof(*ptr)) VAL;                                   \
})
```

The *unlock* Function

Ticket id	To be served

```
void arch_spin_unlock(arch_spinlock_t *lock)
{
    u16 *ptr = (u16 *)lock + IS_ENABLED(CONFIG_CPU_BIG_ENDIAN);
    u32 val = atomic_read(lock);

    smp_store_release(ptr, (u16)val + 1);  /* store following release semantics */
}
```

- Increment the "to be served" part
- The *acquire* and *release* keywords are the same as the ones used in the Release Consistency (RC) literature
  - All memory operations after the acquire can complete only **after** it completes
  - The release needs to complete only after all the memory operations **before** it have completed

A Fast Path: Trylock function

```
static __always_inline bool arch_spin_trylock(arch_spinlock_t
*lock)
{
    u32 old = atomic_read(lock);

    if ((old >> 16) != (old & 0xffff))
        return false;

    return atomic_try_cmpxchg(lock, &old, old + (1<<16));
}
```

The lock is held

Attempt to get the lock quickly

The fast path/ slow path approach is a standard technique. If the lock is unlikely to be held, attempt the fast path, otherwise fall back to the slow(er) path.

Spin locks and Interrupts

- Interrupts can still be processed on the CPU that is waiting on a spin lock
- What if the interrupt handler tries to acquire the same spinlock
  - We have a deadlock
- Hence, we use the "_irq" variant of the function. It enables and disables interrupts in the critical section.
  - *raw_spin_lock_irq* and *raw_spin_unlock_irq*
- Sadly *raw_spin_unlock_irq* will enable all interrupts (not in your best interest)
- Hence, use the *_irqsave* and *_irqrestore* versions that save and restore the interrupt state.

Kernel Mutexes

/include/linux/mutex.h

mutex_lock(struct mutex *lock)
mutex_unlock(struct mutex *lock)
mutex_trylock(struct mutex *lock)

- A spinlock is held by a CPU, a mutex is held by a task
- The task can go off to sleep

```
struct mutex {
    atomic_long_t       owner;
    raw_spinlock_t      wait_lock;
    struct list_head    wait_list;

#ifdef CONFIG_DEBUG_LOCK_ALLOC
    struct lockdep_map  dep_map;
#endif
};
```

struct task_struct*

The spin lock protecting the wait_list

Contending processes

Mutex Locking

/kernel/locking/mutex.c

```
void mutex_lock(struct mutex *lock)
{
    might_sleep();  /* prints a stacktrace if called in
an atomic context (sleeping not allowed */

    if (!__mutex_trylock_fast(lock))   /* cmpxchg on owner */
        __mutex_lock_slowpath(lock);
}
```

- Supports the slow path/ fast path concept
- Fast path: Compare and exchange (acquire) as we have seen earlier
- Slow path: We need to try to acquire the spinlock. However, if that does not seem to be possible, make the process sleep. Lock the task in the UNINTERRUPTIBLE state.

Slow Path

- First, attempt a fast path lock
  - *cmpxchg* on the *owner* field
  - If that works, well and good
- Acquire a lock on the wait_list
  - Lock wait_lock using a spinlock
  - Insert the current task to the wait_list
  - Set the state of the current task to a sleeping state: UNINTERRUPTIBLE or INTERRUPTIBLE (in some cases)
- Call the scheduler to schedule ready processes

/kernel/locking/…

Different Kinds of Locks in the Kernel

- Queued Spinlock or MCS lock (qspinlock.c)
  - Create a linked list of nodes
  - Insert the given node (consisting of the current task) atomically to the end of this list
  - Uses complex lock-free programming
  - It is far more scalable than a regular spinlock.
  - It eliminates cache line bouncing: When we try to read/write the lock a copy of it needs to be brought into the local cache. When another core needs it, the entire cache line's contents needs to be transferred to it.
- osq_lock.c → A variant of the MCS lock (useful with mutexes)
- qrwlock.c → A reader writer lock that gives priority to readers

/kernel/locking/semaphore.c

Semaphores in the Kernel

```
struct semaphore {
    raw_spinlock_t      lock;
    unsigned int        count;
    struct list_head    wait_list;
};
```

/include/linux/semaphore.h

Waiting list of processes

- There are two key functions: *up* and *down*
- Very similar to user-level semaphores
- For *down*, set the current state to UNINTERRUPTIBLE and call the scheduler
- For *up*, set the current state to RUNNING and call the scheduler

The Lockdep Mechanism

The *lockdep* mechanism

/kernel/locking/lockdep.c

- It is the kernel lock validator
- There could be different issues with locks
- We might have circular waiting that leads to deadlocks
- The base function that is called whenever a lock is acquired is *lock_acquire* in lockdep.c
- This makes a call to __lock_acquire that does the bulk of the processing
  - It verifies that the lock depth (number of locks that the current task has acquired) is below a maximum number.
  - Next, it needs to validate the chain of locks that have been acquired including the lock that is about to be acquired. Makes a call to *validate_chain*

Validate spin locks

Validate mutexes

Validate reader writer locks

validate_chain

https://www.kernel.org/doc/Documentation/locking/lockdep-design.rst

- We define four types of states: softirq-safe, softirq-unsafe, hardirq-safe, hardirq-unsafe
- A softirq-safe lock means it was acquired in a softirq context. At that point, irqs would have been disabled.
- On the other hand, a softirq-unsafe lock would have been acquired with irq interrupts turned on. This potentially allows the interrupt handler to try to reacquire the lock.
- A softirq-unsafe is also hardirq-unsafe
- First, check for deadlocks. Cannot have the A → B, and B → A problem (trivial deadlock). *A* and *B* are locks. → is a path
- No path can contain a hardirq-unsafe and then a hardirq-safe lock. The latter may have interrupted the former. May lead to lock inversion. Same for softirq locks.

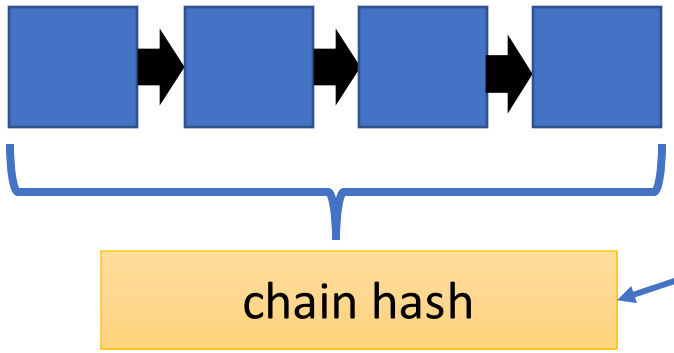
Lock inversion problem

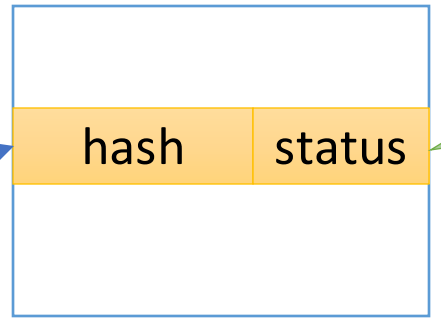
Why validate_chain not validate_graph?

- Find the cycle in a graph using breadth first search (algorithm used in lockdep.c) requires $O(N^2)$ steps
- This is very slow.

Consider a chain of locks

A long sequence of lock operations possibly acquired by different threads.





Acts as a cache for chains of locks. No need to compute again and again

The RCU Mechanism

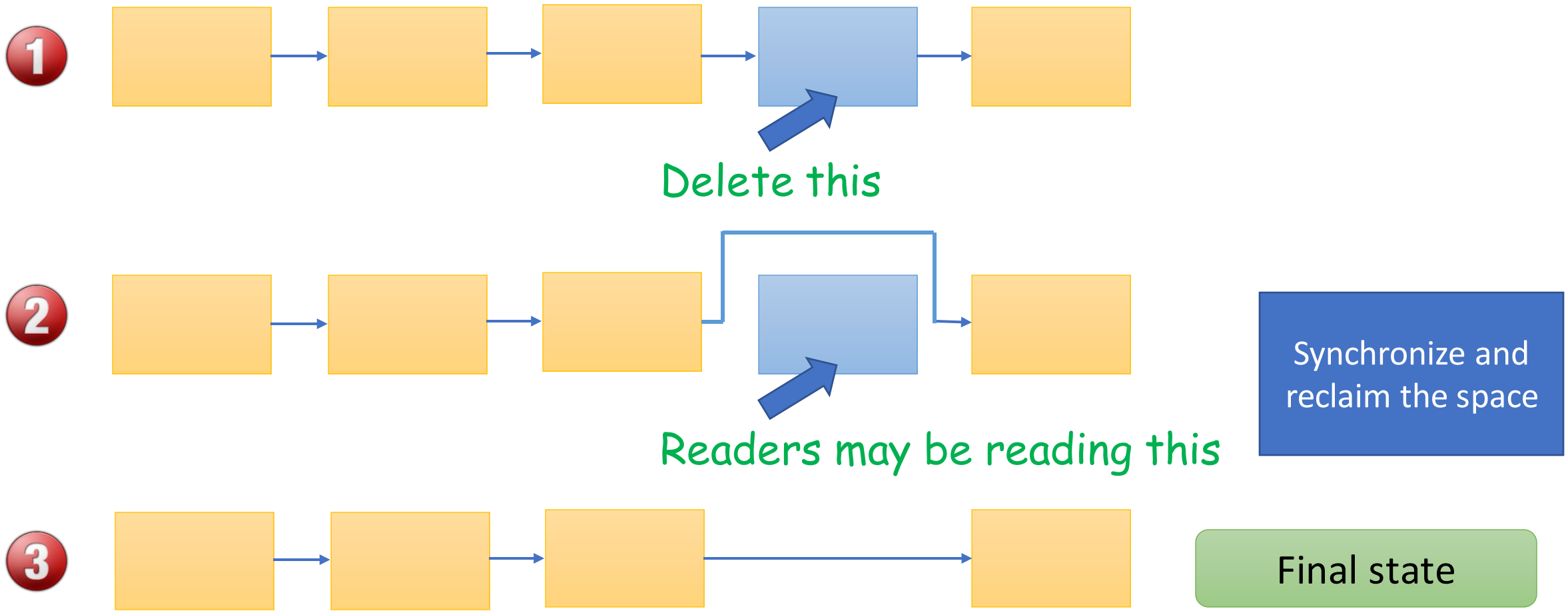
The RCU Mechanism

A smart reader-writer lock

- Allocating and freeing data structures in the kernel is a tricky issue
- Especially, when multiple threads are involved.
- This is where the read-copy-update (RCU) mechanism is handy

1. Deactivate pointers to a data structure. Cannot be accessed subsequently
2. Wait for all the readers to complete their reads.
3. Reclaim the space using the *kfree* function call.

Example of a Linked List



The Key Idea

/include/linux/rcupdate.h

Decouple the write(update), read, and memory reclamation steps.

Call	Explanation	Action
rcu_read_lock()	Enter a read-side critical section	Disable preemptions
rcu_read_unlock()	Exit a read-side critical section	Enable preemptions
synchronize_rcu()	Marks the end of the reading phase	Wait until all readers finish
rcu_assign_pointer()	Assign a value to an RCU-protected pointer	Assignment + checks + memory barrier
rcu_dereference()	Read the value of an RCU-protected pointer	Read → memory barrier

Using an RCU

https://lwn.net/Articles/262464/

```
rcu_read_lock();
list_for_each_entry_rcu(p, head, list) {
    t1 = p->a;
    t2 = p->b;
}
rcu_read_unlock();
```

Reads the list between RCU calls

```
list_replace_rcu(&p->list, &q->list);
synchronize_rcu();
kfree(p);
```

Write to the list, synchronize, and then free

Blocking and non-blocking versions (with callbacks) are available for the *synchronize_rcu* operation

Assign an RCU-protected pointer

/include/linux/rcupdate.h

```
#define rcu_assign_pointer(p, v)
do {                                                    \
    uintptr_t _r_a_p__v = (uintptr_t)(v);               \
          /* do some checking */                        \
    if (__builtin_constant_p(v) && (_r_a_p__v) == (uintptr_t)NULL)   \
        WRITE_ONCE((p), (typeof(p))(_r_a_p__v));        \
    else                                                \
        smp_store_release(&p, RCU_INITIALIZER((typeof(p))_r_a_p__v));  \
} while (0)
```

- This is a regular assignment to a pointer + some checks + memory barrier

Get the value of an RCU-protected Pointer

```
#define __rcu_dereference_check(p, local, c, space) \
({ \
    /* Dependency order vs. p above. */ \
    typeof(*p) *local = (typeof(*p) *__force) READ_ONCE(p); \
    rcu_check_sparse(p, space); \
    ((typeof(*p) __force __kernel *)(local)); \
})
```

- Do some checks, read the value of the pointer, typecast and return
- Read → memory barrier

Example of *rcu_assign_pointer*

/include/linux/rculist.h

```
static inline void list_replace_rcu(struct list_head *old,
                struct list_head *new)
{
    new->next = old->next;
    new->prev = old->prev;
    rcu_assign_pointer(list_next_rcu(new->prev), new); /* new->prev->next = new */
    new->next->prev = new;
    old->prev = LIST_POISON2;
}
```

Example of *rcu_dereference*

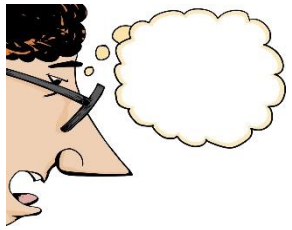
```
#define __hlist_for_each_rcu(pos, head)                    \
    for (pos = rcu_dereference(hlist_first_rcu(head));  \
         pos;                                          \
         pos = rcu_dereference(hlist_next_rcu(pos)))
```

An *hlist* is a non-circular doubly-linked list

Mystery behind synchronize_rcu

- rcu_read_lock and rcu_read_unlock pretty much do nothing other than disabling and enabling pre-emption

How does synchronize_rcu know that all readers are done?



Insight: If you are able to run a thread on a CPU, then it means that it is in a preemptable state. This means that it has exited the "read critical section" → The reader is not active anymore → The pointer can be reclaimed

```
foreach_cpu (cpu)
        run_curr_task_on_cpu (cpu);
```

Too simple and too slow

RCU in all its glory …

https://docs.kernel.org/RCU/index.html

RCU has two implementations

- Tree RCU (/kernel/rcu/tree.c)
- Tiny RCU (/kernel/rcu/tiny.c)

Tree RCU is the default implementation for kernels in servers

Grace periods in RCUs

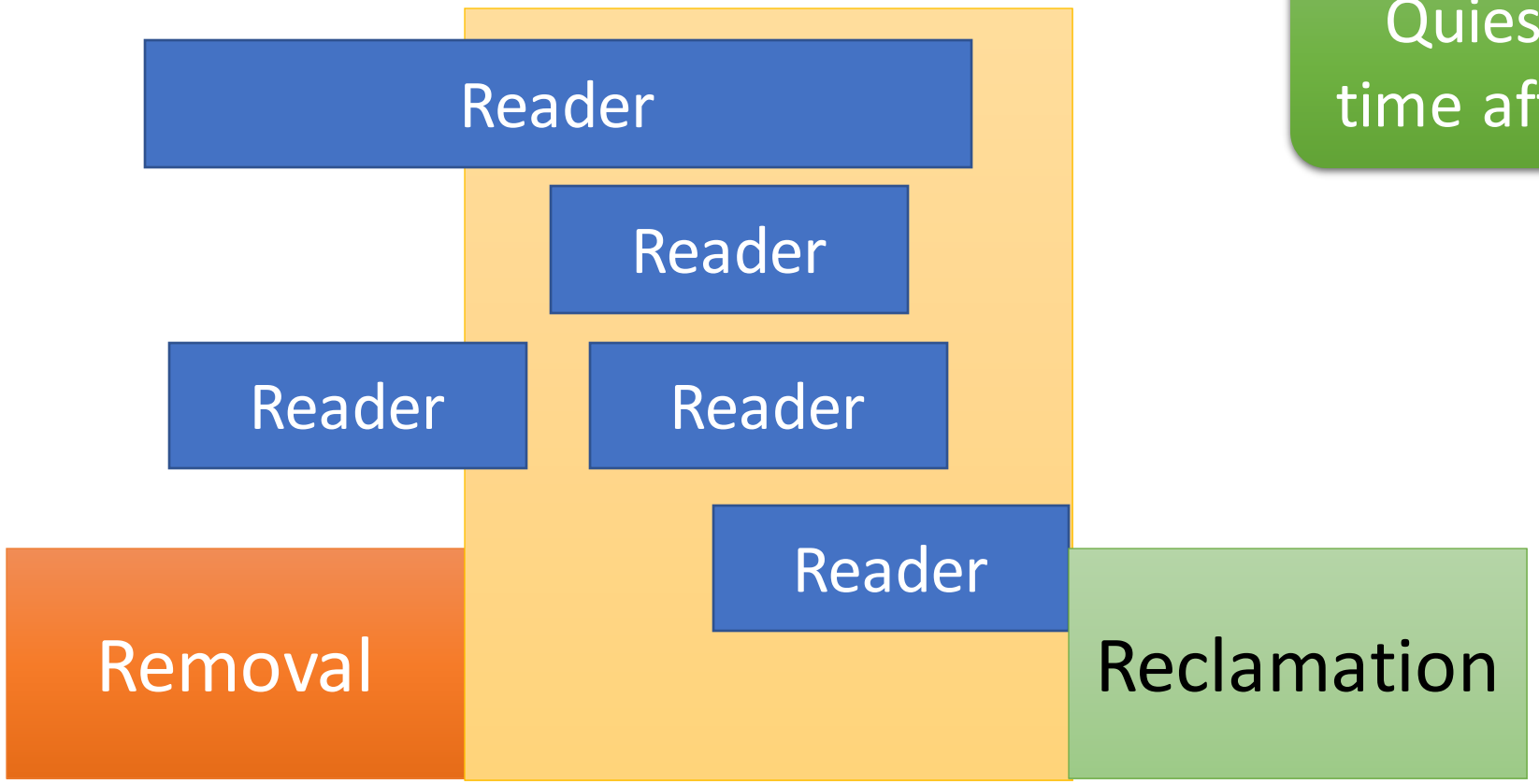
It is the time between the read+update and the reclamation. It must be long enough for all the readers to have dropped the references to the object.

When does the “Grace Period” end?

- Four conditions
  - When a thread blocks (you know it is out of the read lock-unlock phase)
  - Switches to user-mode execution
  - Enters an idle loop
  - Switch the context to run a kernel thread
- There are preemptible variants of RCU
  - However, they do not rely on indirect mechanisms
  - They require read_lock operations to increment per-CPU counters
- *synchronize_rcu* provides a strict ordering between threads. Acts like a barrier (waits for all readers to finish) and a barrier (a memory barrier where all the writes that happen in the read block are visible later)

Removal and Reclamation

https://lwn.net/Articles/305782/

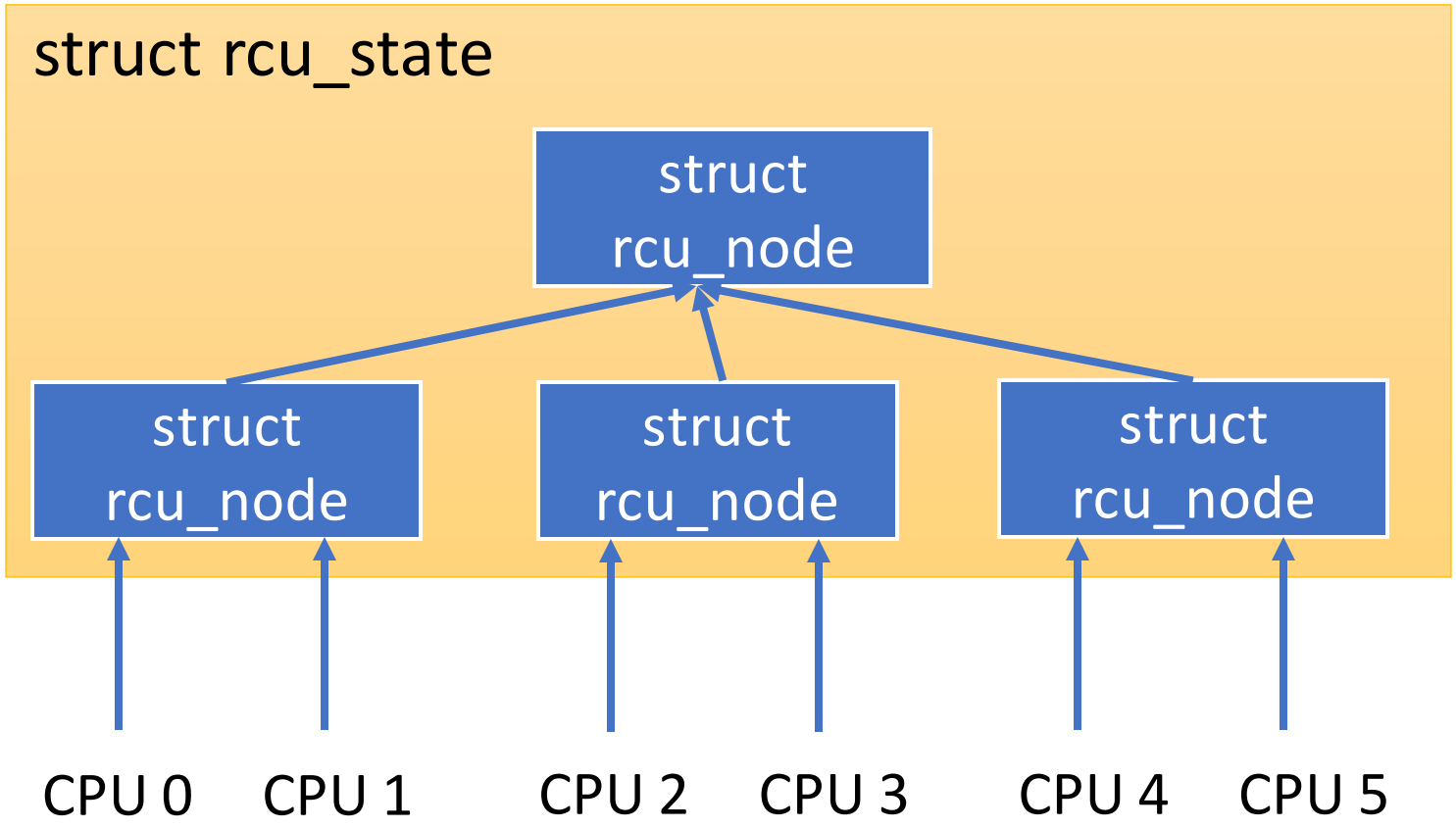


Quiescent state: A point of time after the read block ends

Let's say that a CPU sets/resets a bit at the end of a grace period

Tree RCU

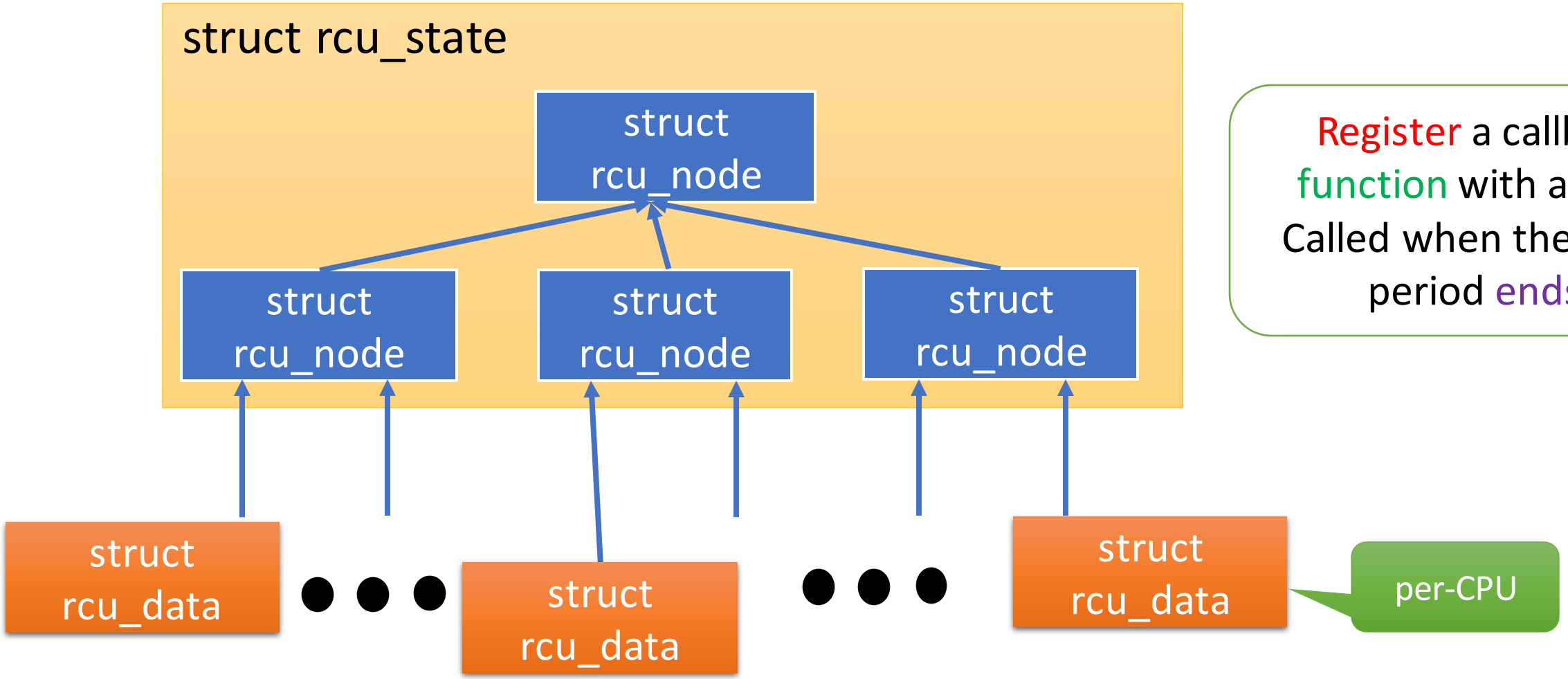
Manage these bits as an Emde Boas tree



Underlying storage structure is an array in the *rcu_state* structure. Allows efficient storage and traversal.v

RCUs and callbacks

- When all the CPUs pass through a quiescent state, the grace period ends

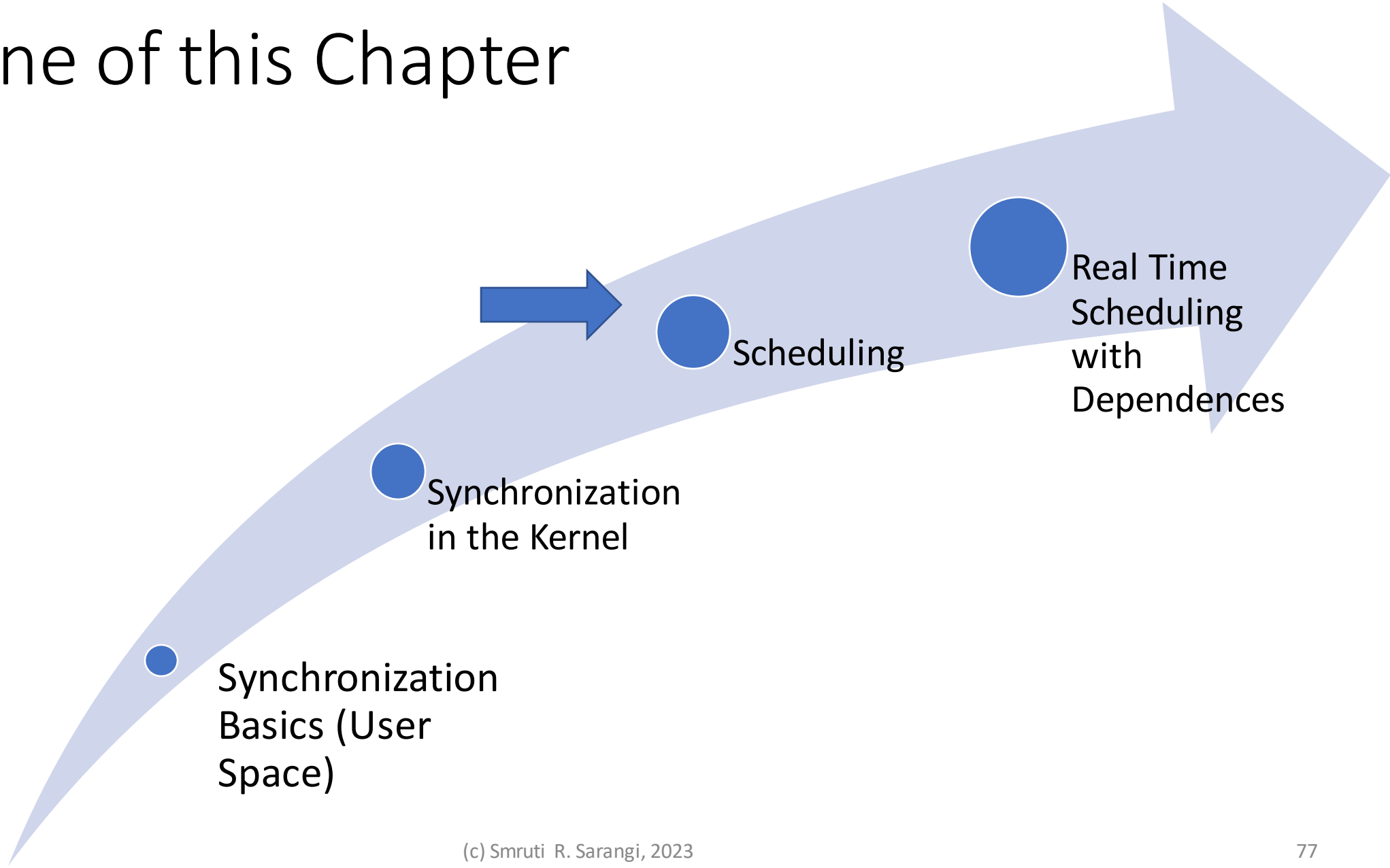


Register a callback function with a CPU. Called when the grace period ends.

Expedited Grace Periods

- Assume that a CPU is not entering a quiescent state
  - A quiescent state can be forced by sending an IPI to it
- Non-preemptable read block
  - The IPI will be serviced after the read block has finished. Its interrupt handler runs in the quiescent state.
- If the read block is preemptable (real-time kernel), then register a callback function that is called once the target CPU reaches a quiescent state
- Preemptible RCU-protected regions cause problems
  - We need to add reference counters and state variables to the *rcu_read_lock* and *rcu_read_unlock* functions. They don't remain ZERO overhead anymore.

Outline of this Chapter



The Problem of Scheduling

Simple variant

Assume that there is no preemption

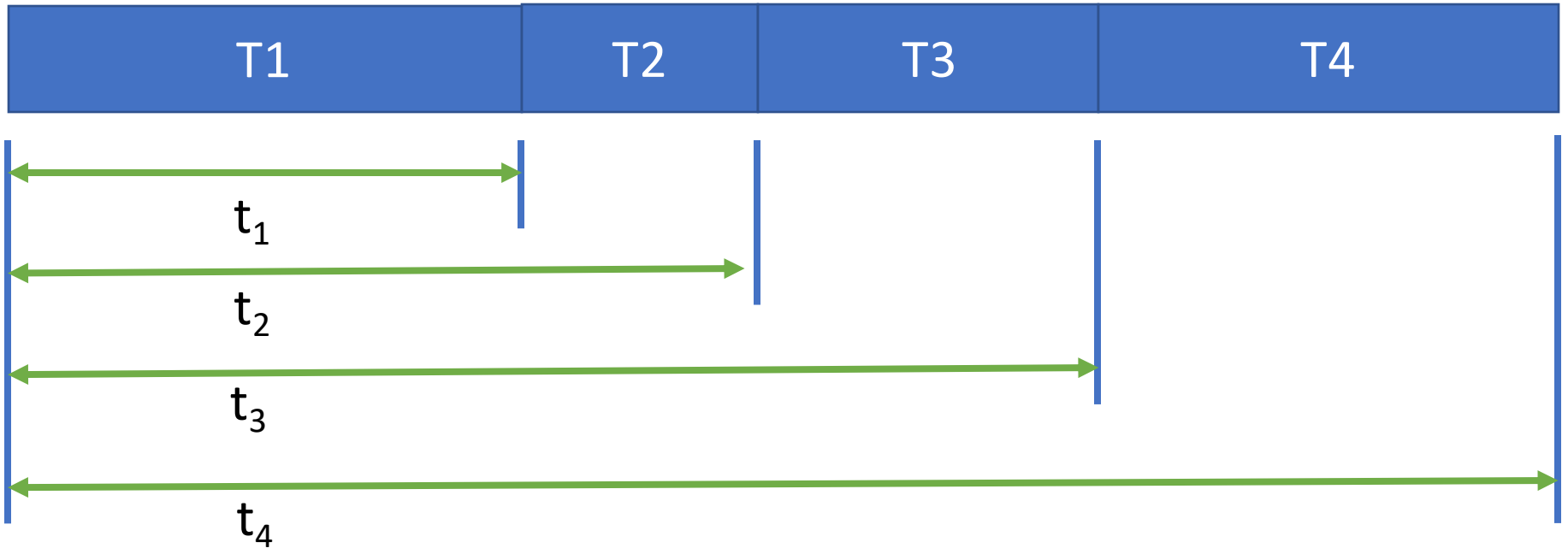
Single CPU

Set of tasks/jobs model

A bunch of tasks that arrive at the beginning. Each one has a fixed duration, which is known in advance (somewhat impractical assumption).

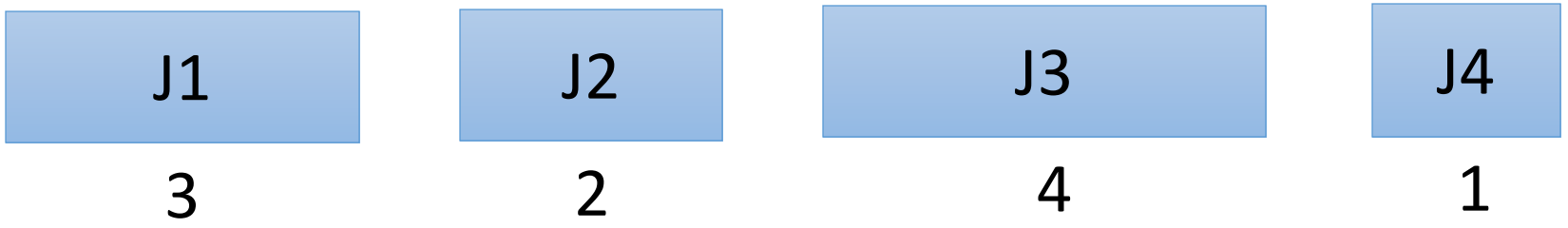
Find different ways of sequencing them.

Metric: Minimize the Mean Completion Time

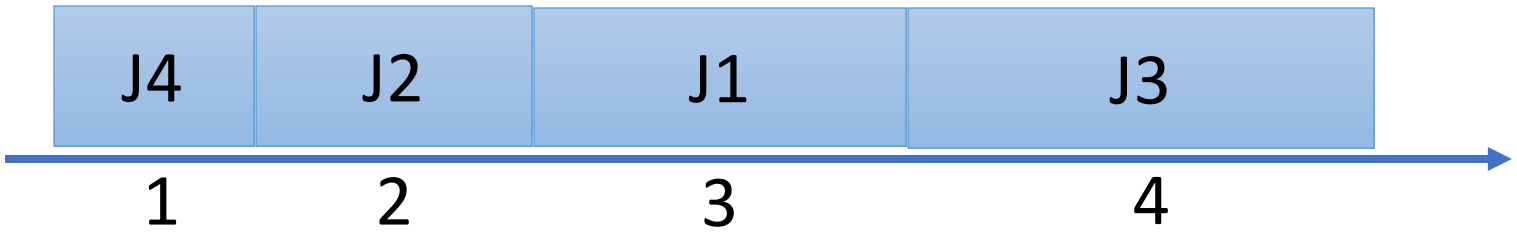


- In this case the completion times are t_1, t_2, t_3, and t_4
- It is a more convenient tool to create a formal model

Example



- Shortest job first (SJF) algorithm



A More Formal Way of Thinking

The Karger-Stein-Wein Model (KSW model) [1]

KSW Model

$\boldsymbol{\alpha}|\boldsymbol{\beta}|\boldsymbol{\gamma}$

$\boldsymbol{\alpha}$: There are *n* jobs, 1 ... n. The processing time of the j^{th} job is p_j. This parameter characterizes the machine: #cores.
$\boldsymbol{\beta}$: Constraints: pre-emption, arrival (release) times of jobs, dependence between jobs, deadlines
$\boldsymbol{\gamma}$:Optimality criteria: Mean completion time, Max. completion time, weighted completion time

Class of Scheduling Problems

- For different values of $\alpha|\beta|\gamma$, we need to have different scheduling algorithms
- Some of them are optimal with respect to different optimality criteria
- In general in scheduling problems:
  - We either have an optimal algorithm. The metric of interest is minimized.
  - OR the setting is **NP-complete**
- For NP-complete scheduling problems
  - Need effective heuristics.

Mostly either very easy or NP-Complete

How do you prove that a scheduling algorithm *A* is optimal?

Set up the problem	Assume it is not 
	Then there must be another optimal algorithm A’
	Let it take the same decisions till a certain point
Prove by contradiction	Find the first point of divergence 
	Prove that an algorithm A’’ is better than A’ because of the decision that it took.
	Hence, A’ cannot be optimal.

Proof that SJF is Optimal for $1||\Sigma C_j$

- For the Algorithm A' (supposedly optimal) there must be a pair of jobs
  - *j* and *k* such that
  - *j* immediately precedes *k*
  - $p_j > p_k$ (this will not happen in the optimal algorithm)
  - p_j started at time *t*
  - Now exchange them (result of algorithm A'')
    - Contribution to the completion time of *j* and *k* in *A'*: $(t+p_j) + (t+p_j+p_k)$
    - Contribution to the completion time of *j* and *k* in *A''*: $(t+p_k) + (t+p_j+p_k)$
    - Given that $p_k < p_j$, *A''* has a lower completion time
    - Thus A' cannot be optimal.

Contradiction

Weighted Jobs

- Every job has a weight w_j
- Let us schedule it in a non-increasing order of w_j/p_j
- If $\forall j, w_j = 1$, this is the SJF algorithm
- Then for the following this algorithm is optimal.

$$1||\Sigma w_j C_j$$

Same exchange-based argument

Lateness and the Earliest Due Date (EDD) Algorithm/ Earliest Deadline First (EDF) Algorithm

- Assume that jobs are associated with deadlines
- Let us define lateness as <completion time> - <deadline>
- Let us now solve the problem:

$$1||L_{max}$$

- EDF algorithm: Order jobs by non-decreasing deadlines
- Schedule in that order; break ties arbitrarily.
- It is an exact algorithm for this problem

Same exchange-based argument

Preemption and Release Dates

$$1|r_i, pmtn|\Sigma C_i$$

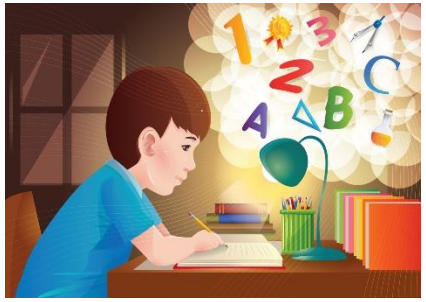
- Jobs arrive at different times. Job *i* arrives at time r_i.
- Preemption is allowed
- The most optimal algorithm is SRTF → Shortest Remaining Time First algorithm
- Same exchange-based argument

EDF is an exact algorithm for ➡ $1|r_i, pmtn|L_{max}$

Some NP-Complete and Impossibility Results

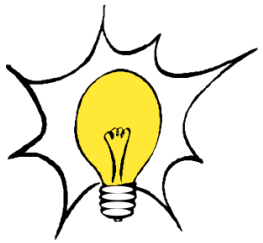
- The ability to pre-empt jobs when all the jobs are released at t=0 does not lead to better schedules (ΣC_i or L_{max}).
- NP-Hard Problems
  - $1|r_i|\Sigma C_i$
  - $1|r_i|L_{max}$
  - $1|r_i, pmtn|\Sigma w_i C_i$

Look up other variants



What about the fact that it is impractical?

You normally don't know how long a job will take to execute.



However, you can approximate.

- You just need to predict CPU bursts. Let t_n be the size of the n^{th} burst. Predict it using a time-series model.

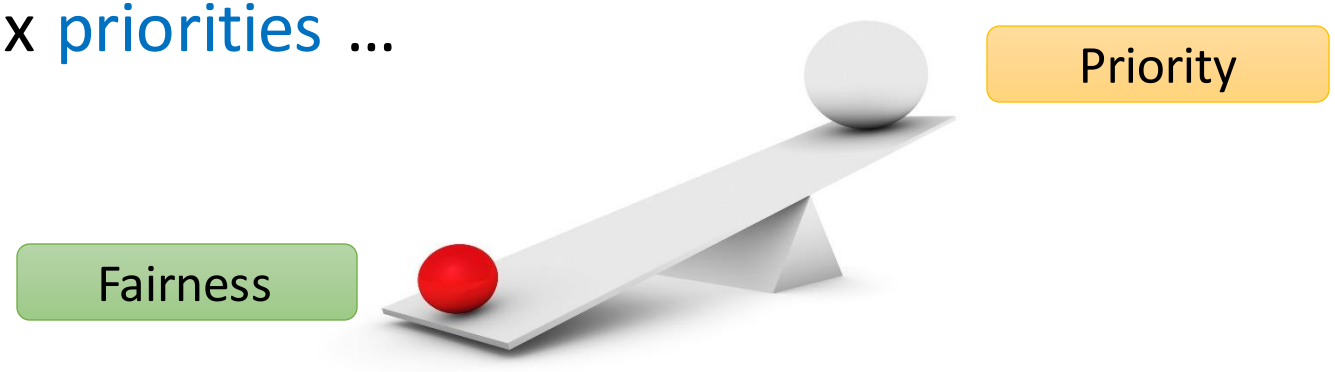
$$t_n = \alpha t_{n-1} + \beta t_{n-2} + \gamma t_{n-3}$$

Other Algorithms

FIFO	Maintain a queue of all processes
	At every point, choose the process at the head of the queue
Problems with FIFO	A long job might delay a lot of small jobs: convoy effect
	Fairness is an issue
Round robin	Run each job for one time quanta
	Then preempt the task and run a new job in round robin order

Priority-based Scheduling

- At any point of time, the highest-priority task should be running
- If a task with a higher priority arrives, then swap out the currently running task
- We can think of SRTF and FIFO as subsets of this class
  - For SRTF, the priority is the reciprocal of the remaining time
  - For FIFO, the priority is the reciprocal of the job arrival time
- Recall Linux priorities …



Priority Classes

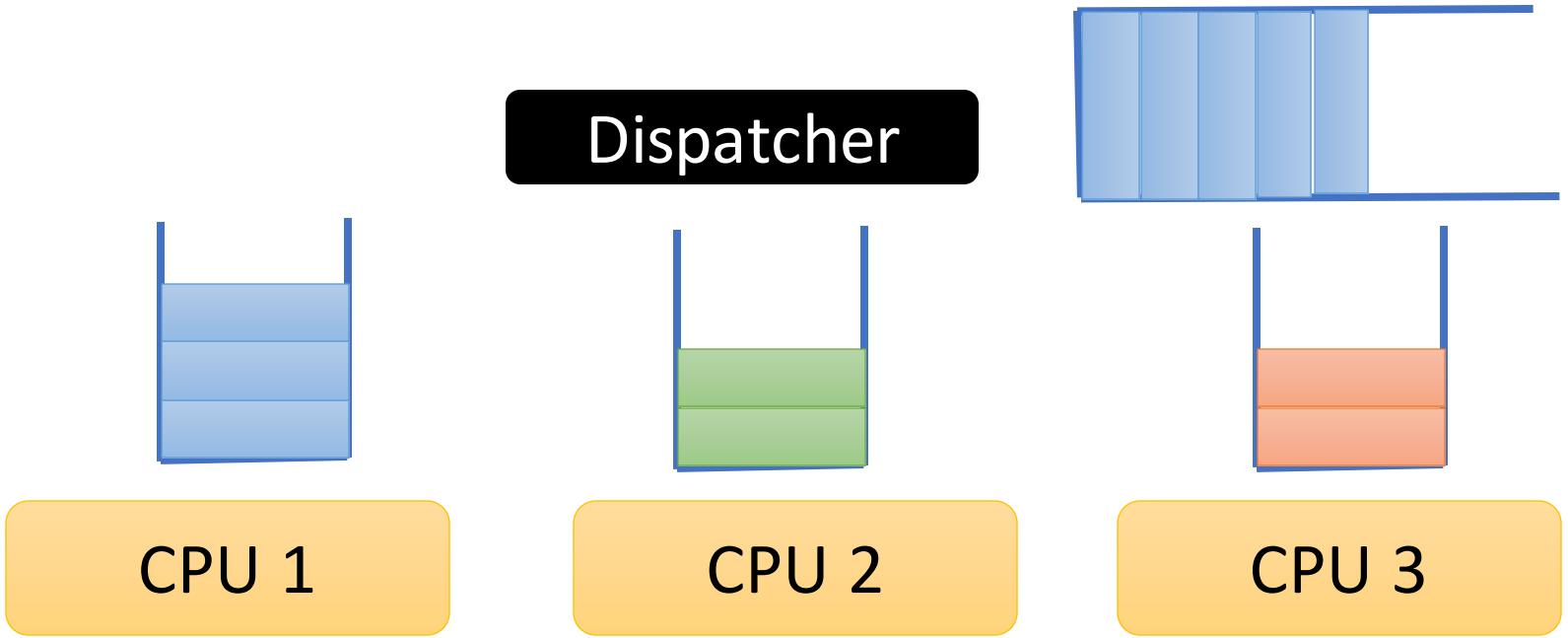
- Linux has 140 different priority levels. It is the job of the system administrator and OS to assign priorities to running tasks
- The sys admin. can also change the priorities dynamically
- Other OSes have different priority classes
  - Real time
  - Interactive
  - Regular
  - Batch
- Windows gives a 3X priority boost to foreground processes

Queue-based Scheduling

Multi-level Feedback Queue

- Different queues have different priorities. They could have different scheduling policies as well.
- Choose the queue with the highest priority that is non-empty
- Schedule a process from it
- Move processes between queues based on factors such as interactivity and age

Multi-Processor Scheduling



- Different CPUs maintain their queues.
- The dispatcher also has a central queue. It picks a task from the queue and sends it to a CPU-specific queue.

Some Theoretical Definitions

- The main aim is to minimize the makespan: C_{max}
- Pre-emptible variants are easier to schedule. Non-preemptive versions are mostly NP-Complete

Examples

$P|pmtn|C_{max}$ Evenly divide the work among the CPUs

$P||C_{max}$ NP-Hard

The Bin Packing and Partition Problems

- These are some common NP-Complete problems that are used to prove the NP hardness of scheduling problems

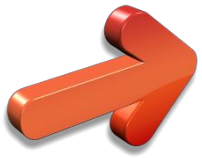
Bin Packing

- We have a finite number of bins
- Each bin has a fixed capacity
- There are *n* items, where each item's size is n_i
- We need to pack items into bins without exceeding their capacity

Each item is a job and each bin is a CPU

Partition Problem

- Consider a set *S* that contains a set of numbers
- Find a subset whose sum is equal to a given number *A* (if it exists)
- This is an NP-Complete problem



In a non-preemptive setting, this indicates that it is computationally hard to schedule exactly a certain amount of work on a given CPU.

Heuristics for Multiprocessor Scheduling

List Scheduling

1. Maintain a list of ready jobs
2. Order them according to some priority scheme
3. Choose the first job, assign it to a free CPU. So on and so forth until there are no more free CPUs.
4. Once a job finishes executing, check if there are any ready jobs.
5. Add the ready jobs to the queue. Keep executing.

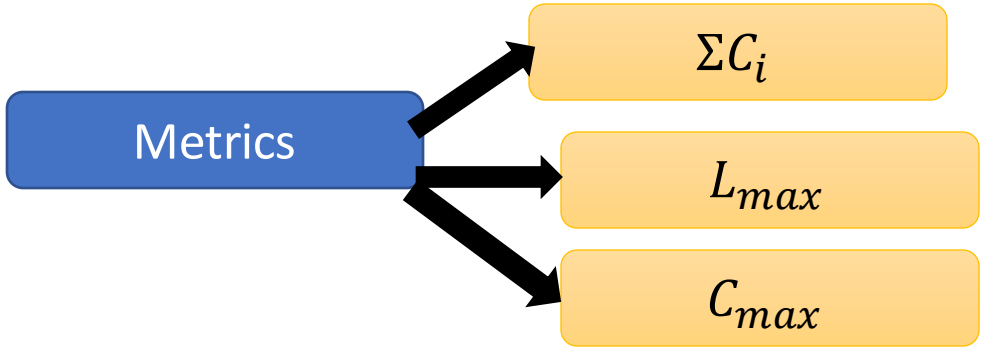
Different List Scheduling Strategies

- Order them in descending order of processing times
- Find the critical path (longest path) in the graph of jobs. Choose jobs on the longest path first.
- Order the jobs in descending order of out-degree

It is often near-optimal. The computed makespan is often less than 2 times the optimal makespan.

Banker's Algorithm to Create Schedules and Avoid Deadlocks

- We now have a complex schedule with the following attributes:
  - Task arrival times
  - Preemption or no preemption
  - Deadlines
  - Priorities
  - Dependences: pre-defined or dynamic (created by lock usage)
  - CPU affinities



What about the correctness of the schedule? Need to avoid deadlocks. Checking for circular waits is not enough when there are multiple copies of each resource.

Data Structures in the Banker's Algorithm

n processes

m types of resources

Data structures	Remarks
avlbl [0 … (m-1)]	avlbl[i] = #copies of the resource *i*
max [0 … (n-1)][0 … (m-1)]	Process *i* can request at the most max[i][j] copies of resource *j* *(maximum allocation)*
acq [0 … (n-1)][0 … (m-1)]	Process *i* has acquired acq [i][j] copies of resource *j* *(resources acquired)*
need [0 … (n-1)][0 … (m-1)]	Process *i* may request req [i][j] copies of resource *j*. ***acq + need = max***

Check if the system is in a safe state

Complexity: $O(mn^2)$

Initialize	cur_cnt = avlbl done[i] = false (0 … n-1)
Find an *i* such that	(done[i] == false) && (need[i][…] ≤ cur_cnt) If such an *i* cannot be found, jump to the last step
Update	cur_cnt += acq[i][…] done[i] = true
Safety check	If $\forall i,\ done[i] == true$ → Safe Else Unsafe

requirement ≤ availability

Assume the process finishes and releases its resources. Increment cur_cnt accordingly. Elementwise array addition.

All the requests can be satisfied

Resource Request Algorithm

Initialize	The *req[]* array is an array of resource requests for array *i* . If req[j] = k, then it means that process *i* needs *k* copies of resource *j.*
Basic check	If req > need[i][…], then the requirements cannot be satisfied. If req > avlbl, wait until resources are available
Dummy Allocation	avlbl = avlbl - req acq[i][…] = acq[i][…] + req need[i][…] = need[i][…] – req

Then check if the state is safe or not. If it is not safe, undo the current allocation and wait

Deadlock Detection Algorithm

reqs is an nxm matrix that stores resource requests (for each process)

Initialize	cur_cnt = avlbl $\forall i$, done[i] = false if acq[i][…] ≠ 0, else true
Find an *i* such that	(done[i] == false) && ($reqs[i][\ldots] \leq$ cur_cnt) If such an *i* cannot be found, jump to the last step
Update	cur_cnt = cur_cnt + acq[i][…] done[i] = true
Deadlock check	If $\forall i$, $done[i] == true$ → NO deadlock Else Deadlock

Can satisfy

What happens if you find a deadlock?

Don’t allow a deadlock to perform by delaying a request or kill one of the processes involved in a circular wait.

- Don’t enter an unsafe state
- If we have entered an unsafe state, then perform a deadlock check when the system does not appear to make any progress
- Kill one of the processes in the deadlock. Choose a process that has not executed for a very long time.

Scheduling in Linux

The *schedule* function

/kernel/sched/core.c

https://www.mail-archive.com/linux-kernel@vger.kernel.org/msg1740572.html

```
void schedule(void)
{
        struct task_struct *tsk = current;

        sched_submit_work(tsk);

        do {
                preempt_disable();
                __schedule(SM_NONE);
                sched_preempt_enable_no_resched();
        } while (need_resched());

        sched_update_worker(tsk);
}
```

To avoid deadlocks, dispatch work to other kernel threads

Update the status of the worker threads.

The main scheduler function: __schedule

- There are several ways that one can enter the *schedule* function
  - A blocking call to a mutex, semaphore, etc.
  - The TIF_NEED_RESCHED flag is set while returning from an interrupt or system call.
  - One process pre-empts another one
- Every CPU has a runqueue, which is the main data structure that queues tasks
- *struct rq*  /kernel/sched/sched.h
- Encapsulates three different run queues (one for each scheduler): completely fair scheduler, real time, deadline driven

The runqueue

```
struct rq {
    raw_spinlock_t      __lock;

    unsigned int        nr_running;
    u64                 nr_switches;
    int                 cpu;

    struct cfs_rq       cfs;
    struct rt_rq        rt;
    struct dl_rq        dl;

    struct task_struct __rcu  *curr;
    struct task_struct        *idle;
    struct mm_struct          *prev_mm;

    struct task_struct  *core_pick;
};
```

Lock the runqueue for all operations

Basic stats about the CPU

All three runqueues: one for each scheduling class

Pointers to the current task, idle task, and mm_struct

The task selected for running

Notion of Scheduling Classes

Descending order of priority

- STOP TASK → Stops everything and runs (like a kernel panic)
- DL (Deadline Scheduling)
  - Tasks that need to finish before a deadline.
  - Audio and video encoding
- RT (Real Time)
  - SoftIRQ threads
  - Custom software with mission critical requirements
- Fair (CFS – completely fair scheduler)
  - Default
- Idle
  - Idle process (nothing running basically)

struct *sched_class*

- Defines a bunch of function pointers
  - All scheduling classes need to provide an implementation for these functions
  - Examples
    - enqueue_task
    - dequeue_task
    - pick_task
    - pick_next_task
    - migrate_task_rq
    - update_curr
- Object-oriented languages define child classes.
  - This is C's way of doing the same.
  - Just call the function pointer

Each Scheduler Class corresponds to a Scheduler

- Mapping between *sched_classes* and files that implement the corresponding schedulers.
- All expose the same API

Scheduler	File
Stop Task Scheduler	stop_task.c
Deadline Scheduler	deadline.c
Real-Time Scheduler	rt.c
Completely Fair Scheduler (CFS)	cfs.c
Idle	idle.c

schedule → *pick_next_task* → __pick_next_task

Regular non-real time processes

- If the currently executing task is in the CFS class or above and there are no tasks in any other higher classes
  - Find the next fair task (as per CFS)
- Else, iterate through the classes in descending order
  - Find the first eligible task and schedule.
- Select the current core
- Add to the runqueue
- Run the scheduling algorithm of the appropriate scheduling class
- Effect context switches (back to user mode or another task)

Relevant fields in *task_struct*

```
struct sched_entity          se;
struct sched_rt_entity       rt;
struct sched_dl_entity       dl;
const struct sched_class     *sched_class;

struct rb_node               core_node;
unsigned long                core_cookie;
```

Scheduling statistics

Node in an RB tree

Uniquely identifies a group of jobs

Completely Fair Scheduler

```
struct sched_entity {

    struct load_weight      load;       /* load balancing*/
    struct rb_node          run_node;

    u64                 exec_start;
    u64                 sum_exec_runtime;
    u64                 vruntime;
    u64                 prev_sum_exec_runtime;
    u64                 nr_migrations;
    struct cfs_rq               *cfs_rq;
    struct sched_avg            avg;        /* statistics */
};
```

Key concept: Virtual runtime of a process. Lower it is, higher the priority

/kernel/sched/fair.c

pick_next_task_fair (for CFS Scheduling)

- Update the current task
  - Update the scheduling statistics
  - Update the virtual runtime of the task
    - Consider the current execution interval (current time – when the task started executing last) (= δ)
    - Let it be delta (δ)

$$\delta_{vruntime} = \delta * \frac{weight\ (nice{=}0)}{weight\ (nice)}$$

$$curr \rightarrow vruntime \mathrel{+}= \delta_{vruntime}$$

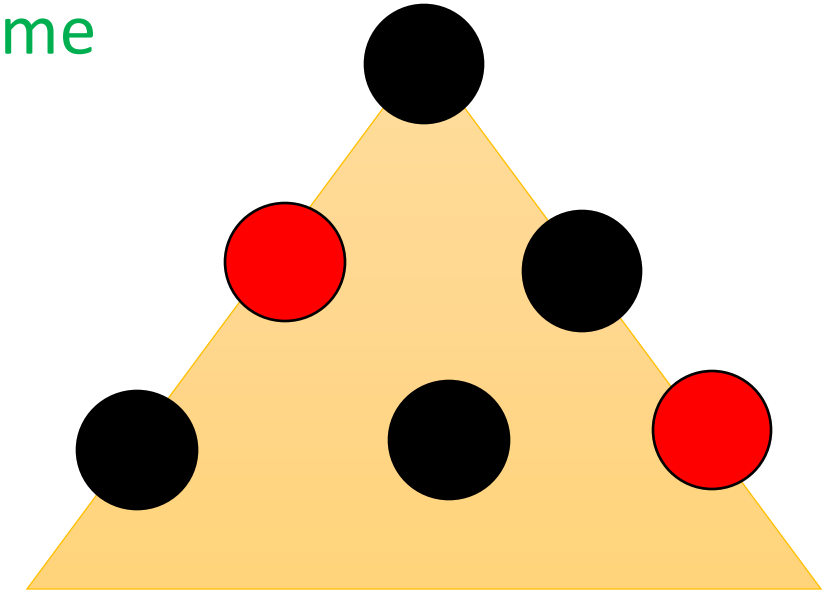
The increment to the virtual runtime is a function of the priority

Priority (nice value) → Weight

```
const int sched_prio_to_weight[40] = {
 /* -20 */     88761,     71755,     56483,     46273,     36291,
 /* -15 */     29154,     23254,     18705,     14949,     11916,
 /* -10 */      9548,      7620,      6100,      4904,      3906,
 /*  -5 */      3121,      2501,      1991,      1586,      1277,
 /*   0 */      1024,       820,       655,       526,       423,
 /*   5 */       335,       272,       215,       172,       137,
 /*  10 */       110,        87,        70,        56,        45,
 /*  15 */        36,        29,        23,        18,        15,
};
```

Next Steps …

- Update the vruntime



Red-black tree indexed by the *vruntime*

Reduce the virtual executed time of the entire cfs_rq

- A red-black tree stores a list of tasks indexed by the vruntime.
- The leftmost entry stores the task with the least vruntime
- Store the current minimum in cfs_rq->vruntime (u64)

pick_next_entity

- This is called by *pick_next_task_fair*
- Default: Choose the leftmost entity that has the least vruntime
- Otherwise: If the current task has executed for more than a quantum, then try a pre-emption
  - Choose the second leftmost entity
- Each group of processes is treated as a single unit for the purposes of allocation of vruntime

Fairness Aspects of CFS

- sysctl_sched_latency: A period of task when all ready tasks run at least once. Referred to as a scheduling period.
- sched_nr_latency: maximum number of runnable tasks that should be able to execute once
- sysctl_sched_min_granularity: The minimum amount of time that a task needs to run in a scheduling period.

More about the scheduling slice

```
u64 __sched_period(unsigned long nr_running)
{
    if (unlikely(nr_running > sched_nr_latency))
        return nr_running * sysctl_sched_min_granularity;
    else
        return sysctl_sched_latency;
}
```

sched_nr_latency = sysctl_sched_latency/ sysctl_sched_min_granuarlity

Every task gets the minimum

$$Scheduling\ Slice = sched_{period} * \frac{weight\ of\ the\ task}{Sum\ of\ weights}$$

Updating vruntime

The *vruntime* will keep on increasing. Wouldn't that heavily prioritize new tasks?

1. The *cfs_rq* maintains a variable called min_vruntime (lowest vruntime of all processes)
2. Let *se* be the *sched_entity* that is being enqueued to the run queue
3. If an old task is being restored or a new task is being added, then set:
   se->vruntime += cfs_rq->min_vruntime
4. This ensures that other tasks have a **fair** chance of getting scheduled
5. Always ensure that the all vruntimes monotonically increase (in the *cfs_rq* and *sched_entity* structures)
6. When a child process is created, it inherits the vruntime of the parent
7. Upon a task migration or block/unblock, subtract cfs_rq->vruntime from the source rq and add the corresponding number for the destination rq (while enqueueing back again in the same or a different rq)

/kernel/sched/pelt.c

Load Averages and Decaying

Computing the load average is important for taking decisions such as allocating CPUs and modulating the CPU frequency.

Solution:

- Divide the timeline into 1 ms intervals
- Let the intervals be p_0, p_1, p_2, …
- Let u_i denote the fraction of time p_i was runnable

$$Load_{avg} = u_0 + u_1 * y + u_2 * y^2 + \ \ldots$$

$$y^{32} = 0.5$$

/kernel/sched/deadline.c

Deadline Scheduler

- We have an analogous function: *pick_next_task_dl*
- Maintain a red-black tree
  - The task with the earliest (smallest) deadline is the leftmost
  - Maintain *sched_dl_entity* structures indexed by their deadline

```
#define rb_entry(ptr, type, member) container_of(ptr, type, member)
```

Find the *sched_dl_entity* for a given *rb_node* using this macro and return it. Find the *task_struct* from *sched_dl_entity* using the same method.

/kernel/sched/rt.c

Realtime Scheduler

- Maintain a queue for each priority level
- Maintain a bitmap: one bit for each queue.
- Find the highest priority queue that has an entry.
- Pick the first task and run it.
- Two policies: FIFO and RR

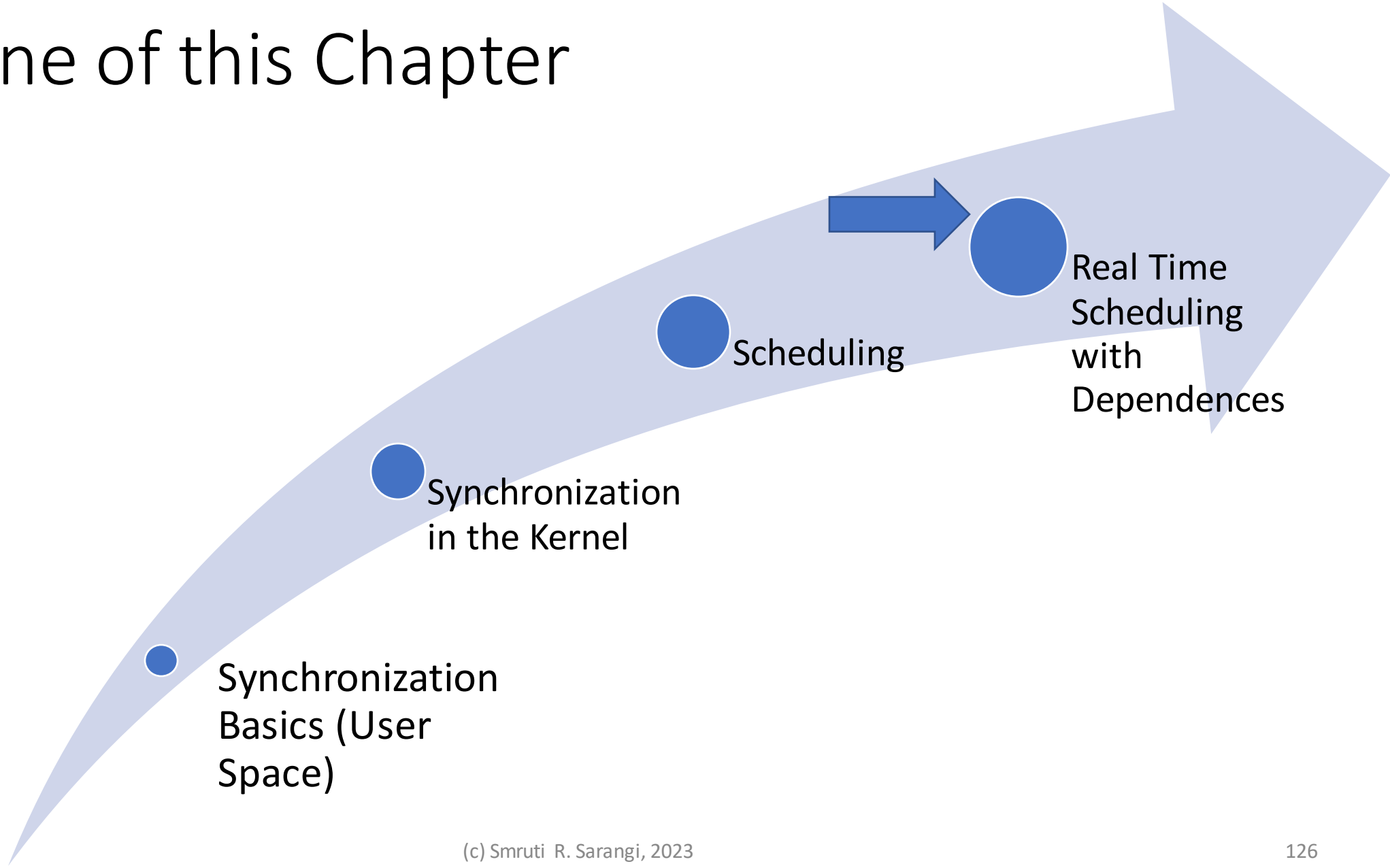
FIFO

- Tasks are queued in FIFO order
- We scan every queue in FIFO order
- The FIFO ordering is always maintained

RR

- If a task has executed for more than its time slice
- Put it at the end of its queue
- Find the next task and mark it ready. Set the re-schedule flag to *true*.

Outline of this Chapter



Real-Time Systems

Every task has an associated deadline

Soft real-time system

- If a task misses its deadline, its utility reduces, does not become zero.

Firm real-time system

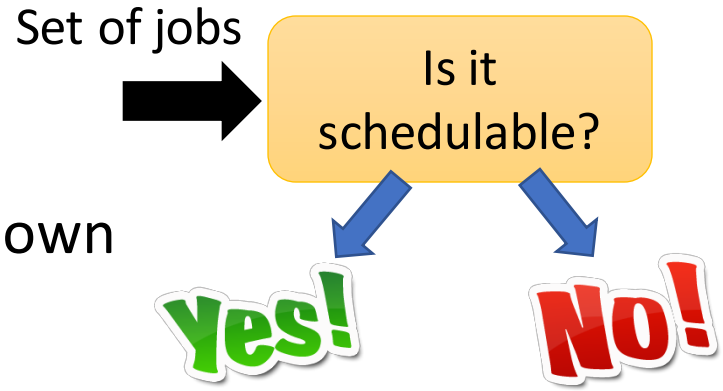
- Missing a few deadlines is acceptable. Even though the utility is zero, we will not have a total failure.

Hard real-time system

- No task can miss its deadline

The Notion of Schedulability

- In real-time systems such as rockets or avionics
  - The tasks are known
  - They are often periodic
  - The maximum processing time is also (more or less) known
  - The deadlines are known



This makes the process of scheduling easier and it is also easier to provide guarantees.

A set of jobs is schedulable with an algorithm *A*, if no job misses its deadline in the final schedule.

EDF (Earliest Deadline First)

Uniprocessors

- We already know that

Priority ∝ 1 / <time till deadline>

EDF minimizes L_{max}

- This means that if we have a set of tasks and associated deadlines, if it is schedulable, we have $L_{max} \leq 0$
- Furthermore, if it is schedulable, EDF will always be able to find a feasible schedule.

If pre-emption is enabled, EDF is optimal, and furthermore it provides the test of schedulability

A Stronger Result for EDF on Uniprocessor Machines and Periodic Jobs

Zero overheads for preemption and scheduling

- Let the duration of a job be d_i
- Let its period be P_i
- Let its deadline be same as the period (needs to complete before the next instance of the job arrives).

$$U = \sum_{i=1}^{n} \frac{d_i}{P_i}$$

  - If $U \leq 1$, we can always find a feasible schedule for it using EDF

The scheduler computes U and if $U \leq 1$, it reports that the set of jobs are not schedulable. The same algorithm is followed if new tasks arrive in the middle of the execution.

Rate-monotonic Scheduling (RMS Scheduling) [2]

- In EDF, priorities are decided dynamically.
  - If a new job arrives with an earlier deadline, then it gets a higher priority.
- Consider a system with periodic jobs where
  - All the priorities are assigned statically (at start-up time)
  - The priority is inversely proportional to the job's period
- A periodic task *i* has two attributes: P_i (time period) and d_i (execution duration)
  - For each periodic task, the deadline is the time period

$$U = \sum_{i=1}^{n} \frac{d_i}{P_i}$$

Total utilization

Liu and Layland '73

A set of *n* jobs is RMS-schedulable ***if*** $U \leq n(2^{\frac{1}{n}} - 1)$

For n=2, U ≈ 0.83

For n = ∞, U ≈ 0.69 (ln 2)

More about RMS [3]

- The Liu-Layland bound is a very conservative bound. Often, we can do better.
- It can be proven that the worst case occurs when all the tasks are in phase (start together).
- Lehoczky Test
  - Assume the worst case (zero phasings)
  - Check whether every task is meeting its first deadline
  - Then, the we have schedulability (even if *U* exceeds the Liu-Layland bound)

Arrange the tasks in descending order of RMS priority

$$W_i(t) = \sum_{j=1}^{i} d_j \lceil \frac{t}{P_j} \rceil$$

Find the number of periods within a time interval and account for all the tasks' execution. This is the total load of the first *i tasks.*

$$L_i(t) = \frac{W_i(t)}{t} \Rightarrow L_i = \min_{\{0<t\leq P_i\}} L_i(t) \Rightarrow L = \max_{\{1\leq i\leq n\}} L_i \leq 1$$

Necessary and sufficient condition

i^{th} task is schedulable if and only if $L_i \leq 1$

All tasks are schedulable

DMS: Deadline Monotonic Scheduling [4]

RMS

$deadline = period$

DMS

$deadline \leq period$

$$Priority \propto \frac{1}{deadline}$$

Every task should be schedulable

$$\frac{I_i}{D_i} + \frac{d_i}{D_i} \leq 1$$

1. D_i is the deadline for task *i*
2. I_i is the interference that it suffers because of other tasks

Not enough

Exact Algorithm

foreach task τ_i

$t = \sum_{j=1}^{i} d_j$

cont = true

while (cont)

if $\left(\frac{I_i(t)}{t} + \frac{d_i}{t} \leq 1\right)$ cont = false

else $t = I_i(t) + d_i$

if $(t > D_i)$ return **false;**

}

}

return **true**;

Interference

$$I_i(t) = \sum_{j=1}^{i-1} \left\lceil \frac{t}{P_j} \right\rceil * d_j$$

Schedulable

Iterate

Not schedulable

Priority Inheritance Protocol (PIP) [5]

- What happens if a low-priority process holds a resource, and this stops high priority processes from making progress? Priority inversion
- A high priority process could be blocked for a long time if a medium priority process decides to run.

Solution:

Raise the priority of the lock-holding low-priority task to that of the high-priority task (until it holds the resource).

Chain blocking

There is a problem if a high-priority process needs many resources and this process has to be carried out for every resource.

Highest Locker Protocol (HLP)

For Uniprocessors

- Let us assume some facts are known a priori
  - Let ceil(resource) be the priority of the highest-priority process that can possibly acquire the resource.
  - Once a process acquires a resource, raise its priority to ceil(resource)
- The moment a process acquires a resource, it cannot be blocked any more by a low-priority process. 

We cannot have any deadlocks.

Quite unfair for intermediate priority tasks that can't run now.

Inheritance blocking

Uni and multi-processors

Priority Ceiling Protocol (PCP)

- Each resource has a highest ceiling priority
- Don't allocate a resource, even if it is free 
- System ceiling (CSC) = max (ceilings of all resources that are in use)
- Resource grant clause ⊖ Does not change the priority
  - Either a task holds a resource that set the current system ceiling
  - OR its priority needs to be higher than the CSC (also set the new CSC in this case)
- Inheritance clause Changes the priority
  - The process holding a resource inherits the priority of the blocked task, if its priority is lower

Revert the priority accordingly on a resource release.

Brief Note about PCP

No deadlocks and chain blocking

Bibliography

[1] Karger, David, Cliff Stein, and Joel Wein. "Scheduling algorithms." *Algorithms and Theory of Computation Handbook: special topics and techniques*. 2010. 20-20.

[2] Scheduling Algorithms for Multiprogramming in a Hard-Real-Time Environment, Liu and Layland, Journal of the ACM, 1973

[3] The Rate Monotonic Scheduling Algorithm: Event Characterization and Average Case Behavior, Lehoczky, Sha, and Ding. IEEE Real Time Systems Symposium, 1989

[4] Deadline Monotonic Scheduling, Audsley, 1990

[5] Real-Time Systems: Theory and Practice, Rajib Mall, 2006. Pearson Publishers.

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