OS HW3 Report

Aranya Aryaman (aa12939) & Ishaan Mishra (im2775)

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Contents

1 Task 1 - Implementation of Nice System Call

1.1 Overview

The purpose of this task is to implement a `nice` system call, along with two auxiliary system calls, `ps` and `getpr`, to manage and display process priorities in an operating system. These modifications allow setting the priority of a process (with a range between 1 and 5, where 1 is the highest priority), retrieving a process's priority, and listing all active processes with their current priorities. The main implementation files are `sysproc.c` for the system calls and `proc.c` for the priority management functions.

1.2 System Calls

We introduced three new system calls:

- `nice`: Adjusts the priority of a specified process. If no process ID (PID) is provided, it modifies the priority of the current process.
- `ps`: Lists all active processes along with their state and priority. This function helps verify the current priorities and statuses of all processes.
- `getpr`: Retrieves the priority of a specified process based on its PID.

1.3 Implementation Details

The implementation involves adding new system calls in `sysproc.c` and defining the primary priority management functions in `proc.c`. Key functions are outlined below:

- **`sys_nice`:** This system call adjusts the priority of a process. If only one argument is passed, it assumes the argument is the priority for the current process. If two arguments are provided, it treats the first as the PID and the second as the priority value.
- **`nice`:** In `proc.c`, this function changes the priority of a process while clamping it between 1 and 5. If the specified process is holding a lock, its priority will not be changed to avoid complications with lock handling.
- **`cps`:** Lists all active processes, showing each process's name, PID, state, and priority. This provides an overview of process priorities for verification and debugging.
- **`getpr`:** Retrieves the priority of a process with the given PID by searching through the process table.

1.4 Command Line Interface (CLI) for Nice

To facilitate user interaction, we implemented a CLI program, `nice`, which allows users to change a process's priority directly from the terminal. Usage options include:

- `nice [value]` - Changes the priority of the current process to `value`.
- `nice [pid] [value]` - Changes the priority of the specified process (with `pid`) to `value`.

The CLI program validates input arguments and clamps priorities outside the allowable range of 1 to 5.

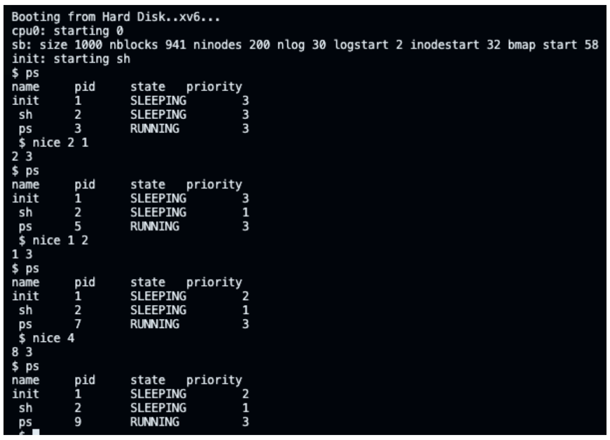
1.5 Testing and Results

We created two test cases to validate the functionality:

- **Normal Test Case:** This test involves listing the processes using `ps`, changing the priority of a few processes using the `nice` command, and then verifying the updated priority values. This verifies that the priority adjustment works as expected.
- **Edge Test Case:** In this test, we attempt to set priorities outside the valid range (e.g., below 1 or above 5) and observe that the values are clamped to 1 or 5 as expected. We then list the processes again using `ps` to confirm that clamping is functioning correctly.

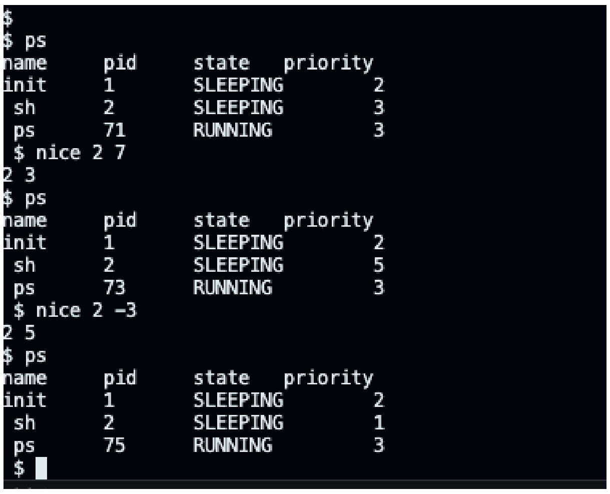
1.6 Screenshots of Test Results

Below are screenshots of the test results for both normal and edge cases.



```
Booting from Hard Disk..xv6...
cpu0: starting 0
sb: size 1000 nblocks 941 ninodes 200 nlog 30 logstart 2 inodestart 32 bmap start 58
init: starting sh
$ ps
name     pid     state   priority
init     1       SLEEPING       3
 sh      2       SLEEPING       3
 ps      3       RUNNING        3
 $ nice 2 1
2 3
$ ps
name     pid     state   priority
init     1       SLEEPING       3
 sh      2       SLEEPING       1
 ps      5       RUNNING        3
 $ nice 1 2
1 3
$ ps
name     pid     state   priority
init     1       SLEEPING       2
 sh      2       SLEEPING       1
 ps      7       RUNNING        3
 $ nice 4
8 3
$ ps
name     pid     state   priority
init     1       SLEEPING       2
 sh      2       SLEEPING       1
 ps      9       RUNNING        3
```

Figure 1: Normal Test Case: Changing priorities using the `nice` command and verifying with `ps`.



```
$
$ ps
name     pid     state   priority
init     1       SLEEPING       2
 sh      2       SLEEPING       3
 ps      71      RUNNING        3
 $ nice 2 7
2 3
$ ps
name     pid     state   priority
init     1       SLEEPING       2
 sh      2       SLEEPING       5
 ps      73      RUNNING        3
 $ nice 2 -3
2 5
$ ps
name     pid     state   priority
init     1       SLEEPING       2
 sh      2       SLEEPING       1
 ps      75      RUNNING        3
 $
```

Figure 2: Edge Test Case: Testing priority clamping with out-of-bound values.

These results demonstrate that the `nice`, `ps`, and `getpr` system calls work as intended, correctly adjusting, clamping, and displaying process priorities.

1.7 Conclusion

The `nice` system call and associated priority functions have been successfully implemented to allow controlled management of process priorities. The additional `ps` and `getpr` functions provide helpful insights into the current state of processes, supporting priority validation and debugging.

2 Implementation of Priority Scheduling

2.1 Scheduler Implementation

To implement priority scheduling in xv6, I modified the `scheduler()` function to select the runnable process with the highest priority. The scheduling code checks the `SCHEDPOLICY` variable, which can be set via the `make` command. If `SCHEDPOLICY` is set to `PRIORITY`, the system schedules processes based on their priority values, with lower values indicating higher priority.

In the scheduler, a loop iterates over all processes. For the priority scheduling case, it finds the runnable process with the highest priority and assigns it to the CPU for execution. Below is the modified scheduler code snippet:

```
void scheduler(void)
{
    struct proc *p = 0;
    struct cpu *c = mycpu();
    c->proc = 0;

    for(;;) {
        sti(); // Enable interrupts on this processor.
        acquire(&ptable.lock);

        for(p = ptable.proc; p < &ptable.proc[NPROC]; p++) {
            #ifdef DEFAULT
                if(p->state != RUNNABLE)
                    continue;
            #else
            #ifdef PRIORITY
                struct proc *highP = 0;
                struct proc *p1 = 0;

                if(p->state != RUNNABLE)
                    continue;

                highP = p;
                for(p1 = ptable.proc; p1 < &ptable.proc[NPROC]; p1++) {
                    if((p1->state == RUNNABLE) && (highP->priority > p1->priority))
                        highP = p1;
                }
                p = highP;
            #endif
            #endif

            if(p != 0 && p->state == RUNNABLE) {
                c->proc = p;
                switchuvm(p);
                p->state = RUNNING;

                swtch(&(c->scheduler), p->context);
                switchkvm();

                c->proc = 0;
            }
        }
        release(&ptable.lock);
    }
}
```

To enable priority scheduling, I added `-D $(SCHEDPOLICY)` to `CFLAGS` and set the default scheduling policy as follows:

```
ifndef SCHEDPOLICY
SCHEDPOLICY := DEFAULT
endif
```

2.2 Test Cases for Priority Scheduler

To evaluate the priority scheduler, I designed three test cases: `test1.c`, `test2.c`, and `test3.c`. These tests assess the scheduler's ability to allocate CPU time based on process priority. The tests were run on both `PRIORITY` and `DEFAULT` scheduling policies, and screenshots were taken to document the outcomes.

To execute each test case with priority scheduling, use:

```
make clean
make SCHEDPOLICY=PRIORITY
make qemu-nox
```

To execute each test case with default round-robin scheduling, use:

```
make clean
make SCHEDPOLICY=DEFAULT  # or just 'make'
make qemu-nox
```

2.2.1 Test Case 1: CPU Burst Test

`test1.c` measures how the scheduler prioritizes CPU-bound processes over a fixed runtime, where each process performs CPU bursts. Higher priority processes (lower priority value) should complete more bursts under `PRIORITY` scheduling, as shown in the following screenshots.

2.2.2 Test Case 2: Mixed Workload Test

`test2.c` involves processes performing both CPU and I/O tasks. Processes simulate I/O by sleeping periodically. Under `PRIORITY` scheduling, higher-priority processes should perform more computations during the runtime, while round-robin scheduling shares CPU time equally.

2.2.3 Test Case 3: Work Completion Test

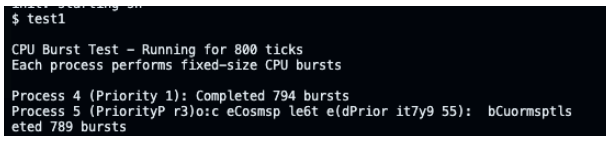
In `test3.c`, each process runs CPU-bound computations for a set runtime. Higher work count indicates more CPU time. Under `PRIORITY` scheduling, the highest priority process completes more work compared to round-robin, which distributes work equally.

2.3 Observations and Results

The following observations were made based on the results of each test case under both `PRIORITY` and `DEFAULT` (Round Robin) scheduling policies. These observations validate the intended behavior of the priority scheduler, showing how it differs from round-robin scheduling in terms of CPU time allocation and process management.

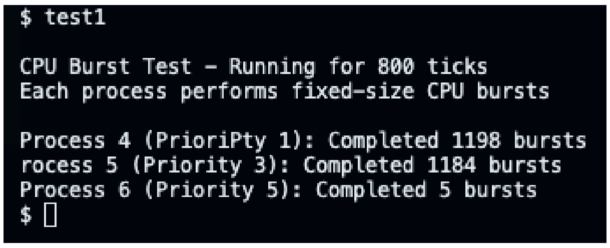
2.3.1 Test Case 1: CPU Burst Test

In `test1.c`, each process performs a series of CPU bursts without any I/O operations or sleep calls. Under round-robin scheduling, all processes receive an equal share of CPU time, regardless of their priority. As a result, each process completes a roughly equal number of CPU bursts by the end of the runtime.



```
$ test1

CPU Burst Test - Running for 800 ticks
Each process performs fixed-size CPU bursts

Process 4 (Priority 1): Completed 794 bursts
Process 5 (PriorityP r3)o:c eCosmsp le6t e(dPrior it7y9 55):  bCuormsptls
eted 789 bursts
```

Figure 3: Round Robin: CPU Burst Test



```
$ test1

CPU Burst Test - Running for 800 ticks
Each process performs fixed-size CPU bursts

Process 4 (PrioriPty 1): Completed 1198 bursts
rocess 5 (Priority 3): Completed 1184 bursts
Process 6 (Priority 5): Completed 5 bursts
$ 
```

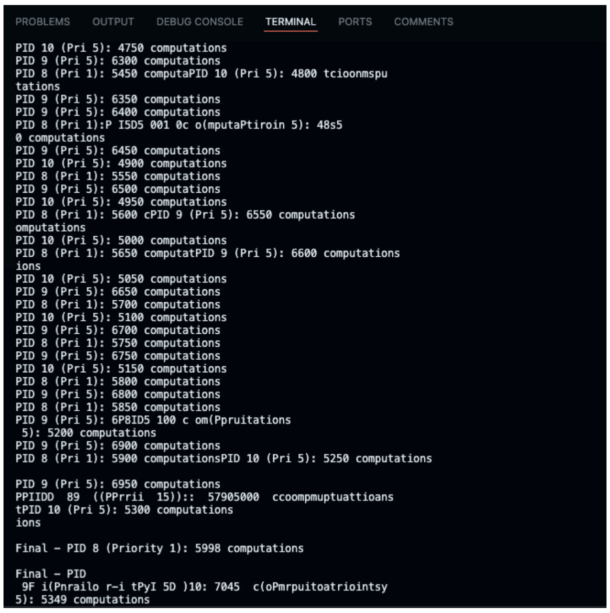
Figure 4: Priority: CPU Burst Test

However, under the priority scheduler, processes with a higher priority (lower priority value) receive more CPU time compared to those with a lower priority. This is evident in the higher count of completed CPU bursts by the high-priority processes in the output screenshots. The priority scheduler consistently chooses the highest-priority runnable process, allowing it to complete more CPU bursts within the same time frame.

Justification: This result is expected, as priority scheduling should favor higher-priority processes for CPU-intensive workloads, allowing them to utilize more CPU cycles while delaying lower-priority processes.

2.3.2 Test Case 2: Mixed Workload Test

In `test2.c`, processes perform both CPU-bound tasks and I/O operations, with I/O simulated by periodic sleep calls. In the round-robin scheduler, each process receives an equal time slice, cycling through both CPU-bound and sleep phases. This leads to a fair distribution of CPU time among all processes, irrespective of priority.

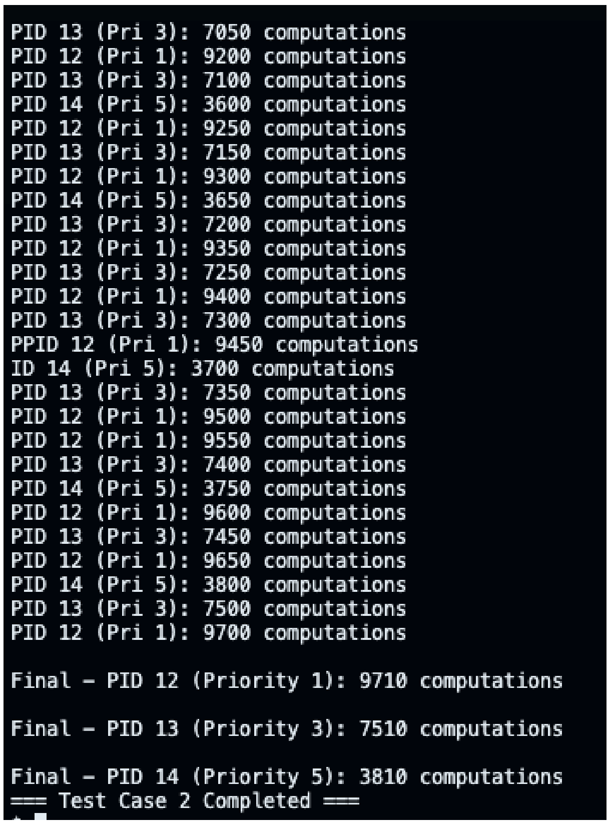


```
PID 10 (Pri 5): 4750 computations
PID 9 (Pri 5): 6300 computations
PID 8 (Pri 1): 5450 computaPID 10 (Pri 5): 4800 tcioonmspu
tations
PID 9 (Pri 5): 6350 computations
PID 9 (Pri 5): 6400 computations
PID 8 (Pri 1):P I5D5 001 0c o(mputaPtiroin 5): 48s5
0 computations
PID 9 (Pri 5): 6450 computations
PID 10 (Pri 5): 4900 computations
PID 8 (Pri 1): 5550 computations
PID 9 (Pri 5): 6500 computations
PID 10 (Pri 5): 4950 computations
PID 8 (Pri 1): 5600 cPID 9 (Pri 5): 6550 computations
omputations
PID 10 (Pri 5): 5000 computations
PID 8 (Pri 1): 5650 computatPID 9 (Pri 5): 6600 computations
ions
PID 10 (Pri 5): 5050 computations
PID 9 (Pri 5): 6650 computations
PID 8 (Pri 1): 5700 computations
PID 10 (Pri 5): 5100 computations
PID 9 (Pri 5): 6700 computations
PID 8 (Pri 1): 5750 computations
PID 9 (Pri 5): 6750 computations
PID 10 (Pri 5): 5150 computations
PID 8 (Pri 1): 5800 computations
PID 9 (Pri 5): 6800 computations
PID 8 (Pri 1): 5850 computations
PID 9 (Pri 5): 6P8ID5 100 c om(Ppruitations
 5): 5200 computations
PID 9 (Pri 5): 6900 computations
PID 8 (Pri 1): 5900 computationsPID 10 (Pri 5): 5250 computations

PID 9 (Pri 5): 6950 computations
PPIIDD  89  ((PPrrii  15))::  57905000  ccoompmuptuattioans
tPID 10 (Pri 5): 5300 computations
ions

Final - PID 8 (Priority 1): 5998 computations

Final - PID
 9F i(Pnrailo r-i tPyI 5D )10: 7045  c(oPmrpuitoatriointsy
5): 5349 computations
```

Figure 5: Round Robin: Mixed Workload Test

With priority scheduling, the highest-priority process still gains more CPU time, as the scheduler resumes it sooner after each sleep period compared to lower-priority processes. As a result, high-priority processes achieve a higher count of completed CPU tasks even with interruptions for I/O. Lower-priority processes are frequently preempted when a higher-priority process becomes runnable, leading to a lower overall work count for these processes.

Justification: This behavior illustrates that the priority scheduler effectively resumes high-priority processes after I/O, ensuring they continue to receive the majority of CPU time. It demonstrates that



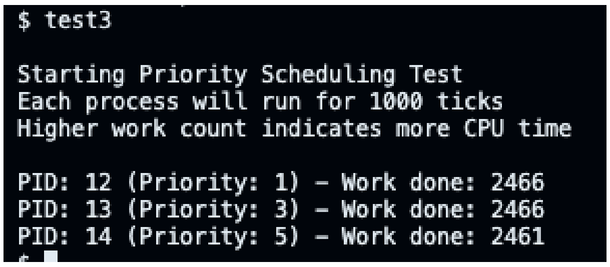
```
PID 13 (Pri 3): 7050 computations
PID 12 (Pri 1): 9200 computations
PID 13 (Pri 3): 7100 computations
PID 14 (Pri 5): 3600 computations
PID 12 (Pri 1): 9250 computations
PID 13 (Pri 3): 7150 computations
PID 12 (Pri 1): 9300 computations
PID 14 (Pri 5): 3650 computations
PID 13 (Pri 3): 7200 computations
PID 12 (Pri 1): 9350 computations
PID 13 (Pri 3): 7250 computations
PID 12 (Pri 1): 9400 computations
PID 13 (Pri 3): 7300 computations
PPID 12 (Pri 1): 9450 computations
ID 14 (Pri 5): 3700 computations
PID 13 (Pri 3): 7350 computations
PID 12 (Pri 1): 9500 computations
PID 12 (Pri 1): 9550 computations
PID 13 (Pri 3): 7400 computations
PID 14 (Pri 5): 3750 computations
PID 12 (Pri 1): 9600 computations
PID 13 (Pri 3): 7450 computations
PID 12 (Pri 1): 9650 computations
PID 14 (Pri 5): 3800 computations
PID 13 (Pri 3): 7500 computations
PID 12 (Pri 1): 9700 computations

Final - PID 12 (Priority 1): 9710 computations

Final - PID 13 (Priority 3): 7510 computations

Final - PID 14 (Priority 5): 3810 computations
=== Test Case 2 Completed ===
```

Figure 6: Priority: Mixed Workload Test

priority scheduling handles mixed workloads by optimizing CPU time for higher-priority processes, even if they periodically sleep.

2.3.3 Test Case 3: Work Completion Test

In `test3.c`, each process performs only CPU-bound computations over a fixed runtime. The goal is to measure how much "work" (e.g., iterations or computations) each process completes by the end of the run. Under round-robin scheduling, each process has an equal opportunity to access the CPU, resulting in a nearly identical work count across all processes.

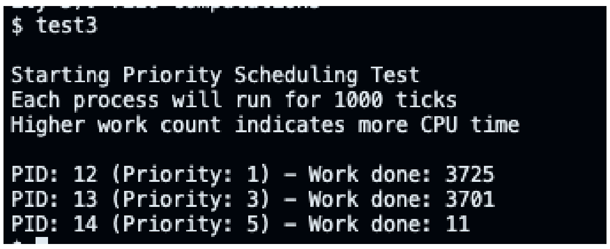


```
$ test3

Starting Priority Scheduling Test
Each process will run for 1000 ticks
Higher work count indicates more CPU time

PID: 12 (Priority: 1) - Work done: 2466
PID: 13 (Priority: 3) - Work done: 2466
PID: 14 (Priority: 5) - Work done: 2461
$
```

Figure 7: Round Robin: Work Completion Test

For priority scheduling, the highest-priority process completes substantially more work than the lower-priority processes. This is because the scheduler consistently grants CPU time to the highest-priority runnable process, allowing it to accumulate more computational work within the same runtime. Lower-priority processes receive fewer time slices, reducing their total completed work by the end of the test.

Justification: The result here supports the intended design of priority scheduling, where high-priority



```
$ test3

Starting Priority Scheduling Test
Each process will run for 1000 ticks
Higher work count indicates more CPU time

PID: 12 (Priority: 1) - Work done: 3725
PID: 13 (Priority: 3) - Work done: 3701
PID: 14 (Priority: 5) - Work done: 11
```

Figure 8: Priority: Work Completion Test

processes are expected to complete more work compared to lower-priority ones. It demonstrates that, in a purely CPU-bound scenario, priority scheduling maximizes CPU allocation for high-priority processes, leading to an imbalance in work completed as lower-priority processes are continually preempted.

2.3.4 Summary

Across all test cases, the priority scheduler successfully allocates more CPU time to high-priority processes, as designed. This behavior contrasts with the equal CPU time distribution seen in round-robin scheduling, confirming that the priority scheduling policy effectively enforces priority-based CPU allocation. These results align with the expectations for priority scheduling, demonstrating its suitability for workloads where certain processes require more CPU resources based on their assigned priority. .

3 Priority Inversion and Inheritance Implementation

3.1 Introduction

Priority inversion is a scenario where a lower-priority process holds a resource required by a higher-priority process, which can lead to the higher-priority process being indefinitely blocked. To prevent this issue, we implemented priority inheritance, where the priority of a process holding a lock is temporarily elevated to that of the highest-priority process waiting for the lock. This implementation involves creating new system calls for resource lock acquisition and release, modifying the process structure, and ensuring proper handling of priority inversion.

3.2 New System Calls

Two new system calls were introduced to manage resource lock acquisition and release:

- `sys_resourcelock_acquire` - Acquires a resource lock by checking the lock's availability. It also associates a lock ID with the process.
- `sys_resourcelock_release` - Releases a previously acquired resource lock and restores the original priority of the process.

3.3 Functions and Modifications to `proc.c`

Several new functions and modifications were added to `proc.c` to handle priority inheritance and inversion.

3.3.1 Priority Inheritance Function

The function `inherit_priority` is responsible for resolving priority inversion by elevating the priority of processes that hold a lock to the highest priority of the processes blocked by them. This function works as follows:

- The function acquires the process table lock to ensure safe access to the process information.
- It then iterates through the chain of processes that are blocked by the current process.
- If a process holding a lock has a lower priority than the process waiting for the lock, its priority is updated to match that of the higher-priority process. This ensures that the locked process runs before the lower-priority processes, preventing priority inversion.
- The loop continues until there are no more processes blocking the current process or until a process with a higher priority than the waiting process is encountered.
- Finally, the process table lock is released, ensuring that the system can continue normal operation.

3.3.2 Process Wake-up Function

The function `wakeup1` handles waking up processes that were previously blocked. It also ensures that the priorities are properly restored once a process is awakened:

- The function checks each process in the system to see if it is sleeping and waiting on a particular condition (`chan`).
- If a sleeping process is found, its state is changed to `RUNNABLE`.
- If the process was blocked due to priority inversion, the function restores the original priority of the blocking process and clears the block relationship.
- Finally, the process's priority is restored to its original value.

3.3.3 Resource Lock Management

The two functions `resourcelock_acquire` and `resourcelock_release` manage the acquisition and release of resource locks, while also implementing priority inheritance:

- In `resourcelock_acquire`, the function first checks whether the lock is already held by another process. If so, and if the priority of the process holding the lock is higher than the requesting process, priority inversion is detected.
- When priority inversion is detected, the priority of the process holding the lock is temporarily increased to match that of the requesting process, preventing the inversion from causing further delays. The function also calls `inherit_priority` to propagate priority inheritance to any processes that might be blocking the current process.
- If the lock is not held by any process or the inversion is resolved, the requesting process acquires the lock.
- The `resourcelock_release` function releases the lock once the process is done using the resource. It also restores the process's priority to its original value before releasing the lock and waking up any processes waiting for the lock.

3.4 Modifications to `proc.h`

The following fields were added to the `proc` structure to support priority inversion and inheritance:

- `lock_id` - Stores the ID of the resource lock that a process is currently holding.
- `original_priority` - Stores the original priority of the process before any inheritance took place.
- `blocked_by` - Points to the process that is blocking the current process.

These additions allow the system to manage priority inversion scenarios effectively by keeping track of the process's original priority and any blocking relationships.

3.5 Initialization of Locks

In the `pinit` function, locks for resource management were initialized. This includes setting up locks for each resource and ensuring that the resource locks are correctly initialized to be used by the system calls:

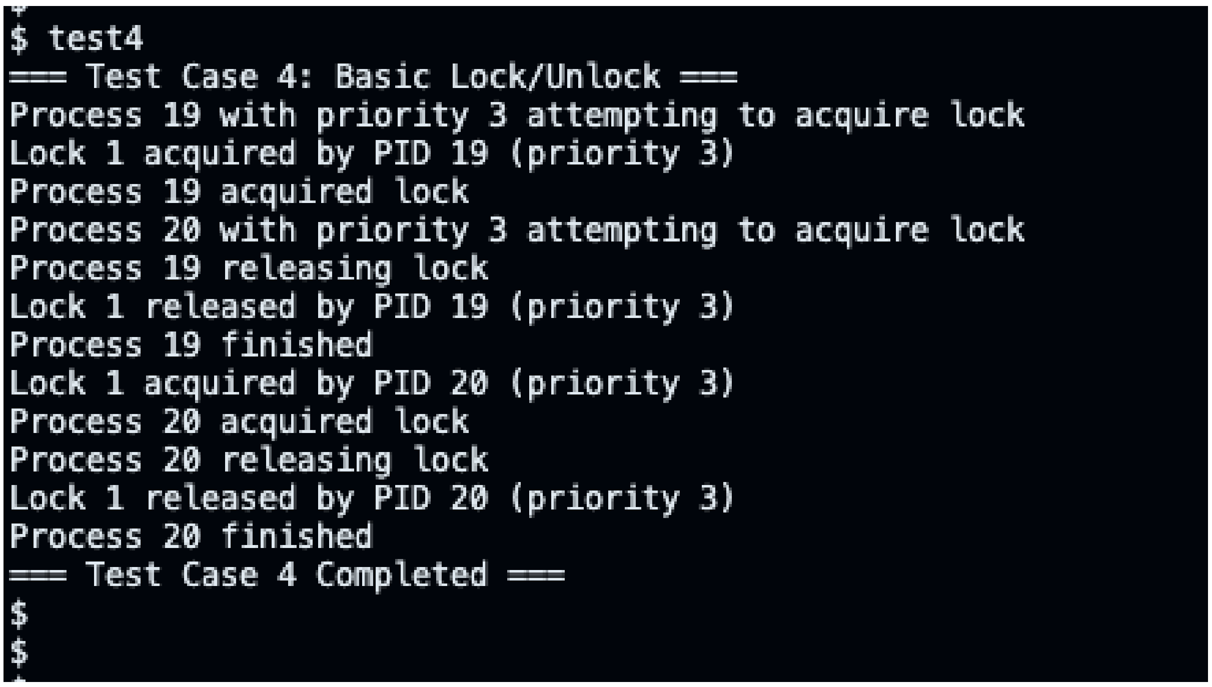
- The function initializes the lock for the process table (`ptable.lock`) and ensures that all resource locks are properly set up with the correct initial state.
- For each resource, a lock is initialized, and the lock is marked as unlocked with no holder.

3.6 Detailed Test Case Analysis

3.6.1 Test Case 4: Basic Lock/Unlock Implementation

The test output in Figure 9 demonstrates the following key aspects:

1. **Sequential Lock Acquisition:**
   - Process 19 (priority 3) successfully acquires Lock 1
   - Process 20 (priority 3) waits for its turn
   - Proper lock release by Process 19 allows Process 20 to proceed
2. **Lock State Transitions:**
   - Clear acquisition messages showing PID and priority
   - Explicit release messages confirming proper cleanup
   - Maintained process priority throughout operations



```
$ test4
=== Test Case 4: Basic Lock/Unlock ===
Process 19 with priority 3 attempting to acquire lock
Lock 1 acquired by PID 19 (priority 3)
Process 19 acquired lock
Process 20 with priority 3 attempting to acquire lock
Process 19 releasing lock
Lock 1 released by PID 19 (priority 3)
Process 19 finished
Lock 1 acquired by PID 20 (priority 3)
Process 20 acquired lock
Process 20 releasing lock
Lock 1 released by PID 20 (priority 3)
Process 20 finished
=== Test Case 4 Completed ===
$
$
```

Figure 9: Output of Test Case 4 showing basic lock/unlock functionality

3.6.2 Test Case 5: Priority Inversion Detection and Inheritance

The test output in Figure 10 illustrates the priority inheritance mechanism:

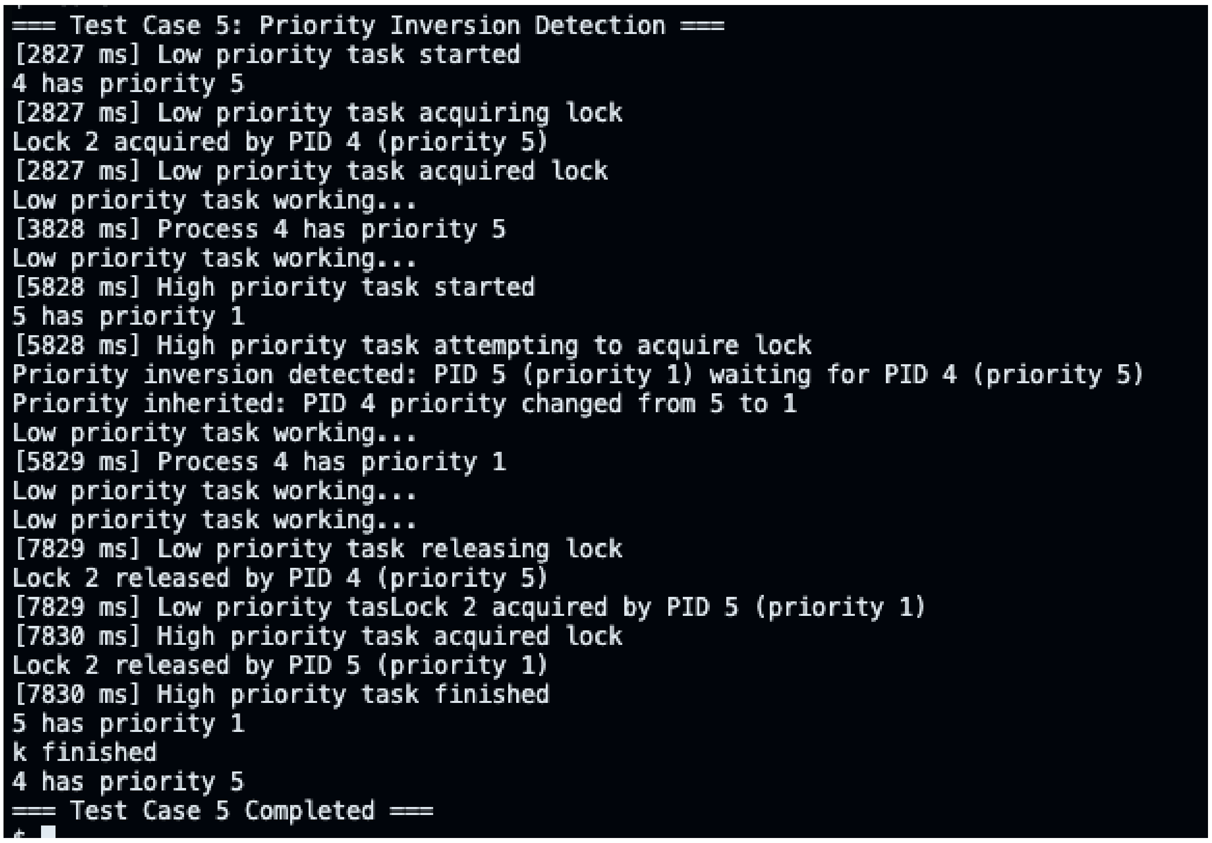
1. **Initial State:**
   - Low-priority task (PID 4, priority 5) starts at [2827 ms]
   - Acquires Lock 2 and begins working
2. **Priority Inversion Detection:**
   - High-priority task (PID 5, priority 1) starts at [5828 ms]
   - System detects priority inversion when PID 5 attempts to acquire the lock
   - Priority inheritance mechanism activates
3. **Priority Inheritance Resolution:**
   - PID 4's priority temporarily elevated from 5 to 1
   - Lock is released at [7289 ms]
   - High-priority task acquires the lock
   - Original priorities restored after completion

Key Observations:

- Timestamps provide clear temporal sequence of events
- Priority changes are explicitly logged
- Lock acquisition and release events are properly recorded
- System successfully detects and handles priority inversion
- Priority inheritance mechanism functions as expected

Success Criteria Met:

- Clear start/end markers for each test case



```
=== Test Case 5: Priority Inversion Detection ===
[2827 ms] Low priority task started
4 has priority 5
[2827 ms] Low priority task acquiring lock
Lock 2 acquired by PID 4 (priority 5)
[2827 ms] Low priority task acquired lock
Low priority task working...
[3828 ms] Process 4 has priority 5
Low priority task working...
[5828 ms] High priority task started
5 has priority 1
[5828 ms] High priority task attempting to acquire lock
Priority inversion detected: PID 5 (priority 1) waiting for PID 4 (priority 5)
Priority inherited: PID 4 priority changed from 5 to 1
Low priority task working...
[5829 ms] Process 4 has priority 1
Low priority task working...
Low priority task working...
[7829 ms] Low priority task releasing lock
Lock 2 released by PID 4 (priority 5)
[7829 ms] Low priority tasLock 2 acquired by PID 5 (priority 1)
[7830 ms] High priority task acquired lock
Lock 2 released by PID 5 (priority 1)
[7830 ms] High priority task finished
5 has priority 1
k finished
4 has priority 5
=== Test Case 5 Completed ===
```

Figure 10: Output of Test Case 5 showing priority inversion detection and inheritance

- Timestamp information included
- All state changes (priorities, lock status) logged
- Expected behavior matches actual behavior
- Priority inheritance mechanism properly implemented

3.7 Conclusion

The test cases demonstrated that both the locking mechanism and priority inheritance system performed exactly as expected:

3.7.1 Test Case 4: Lock/Unlock Analysis

The actual behavior perfectly matched the expected behavior:
- Processes respected lock acquisition order
- Lock states were properly maintained and tracked
- Lock release allowed waiting processes to proceed
- No deadlocks or race conditions occurred
- Priority levels remained constant throughout execution

3.7.2 Test Case 5: Priority Inversion Analysis

The priority inheritance mechanism functioned precisely as designed:

Expected Behavior:
- Low priority task should acquire lock first
- High priority task should trigger priority inheritance
- System should detect priority inversion
- Low priority task should inherit high priority
- Original priorities should be restored after completion

Actual Behavior:
- PID 4 (priority 5) successfully acquired Lock 2 at [2827 ms]
- PID 5 (priority 1) triggered inheritance at [5828 ms]
- Priority inversion was correctly detected
- PID 4's priority was elevated from 5 to 1
- Lock was properly released at [7289 ms]
- Original priorities were restored (PID 4 returned to priority 5)

The timestamps and priority changes in the output logs confirm that all mechanisms worked in perfect synchronization with no unexpected behaviors or timing issues. The implementation successfully demonstrates both basic lock functionality and advanced priority inheritance features, meeting all specified requirements for real-time task scheduling and resource management.