Lab 4: Integer Stack Kernel Module Implementation

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May 4, 2025

Github repo: https://github.com/dExNight/Advanced-Linux-Lab4

1. Introduction

Linux kernel module that provides an integer stack data structure accessed through character device. The module supports basic stack operations (push/pop) and stack size configuration via ioctl system calls. User-space utility provides command-line interface for interacting with the kernel module

2. Objectives

- Implement a kernel module with dynamic memory allocation
- Implement thread-safe operations using mutex synchronization
- Create a character device driver with file operations
- Develop a user-space CLI utility for device interaction
- Handle edge cases and error conditions properly

3. Implementation

3.1 I created project structure

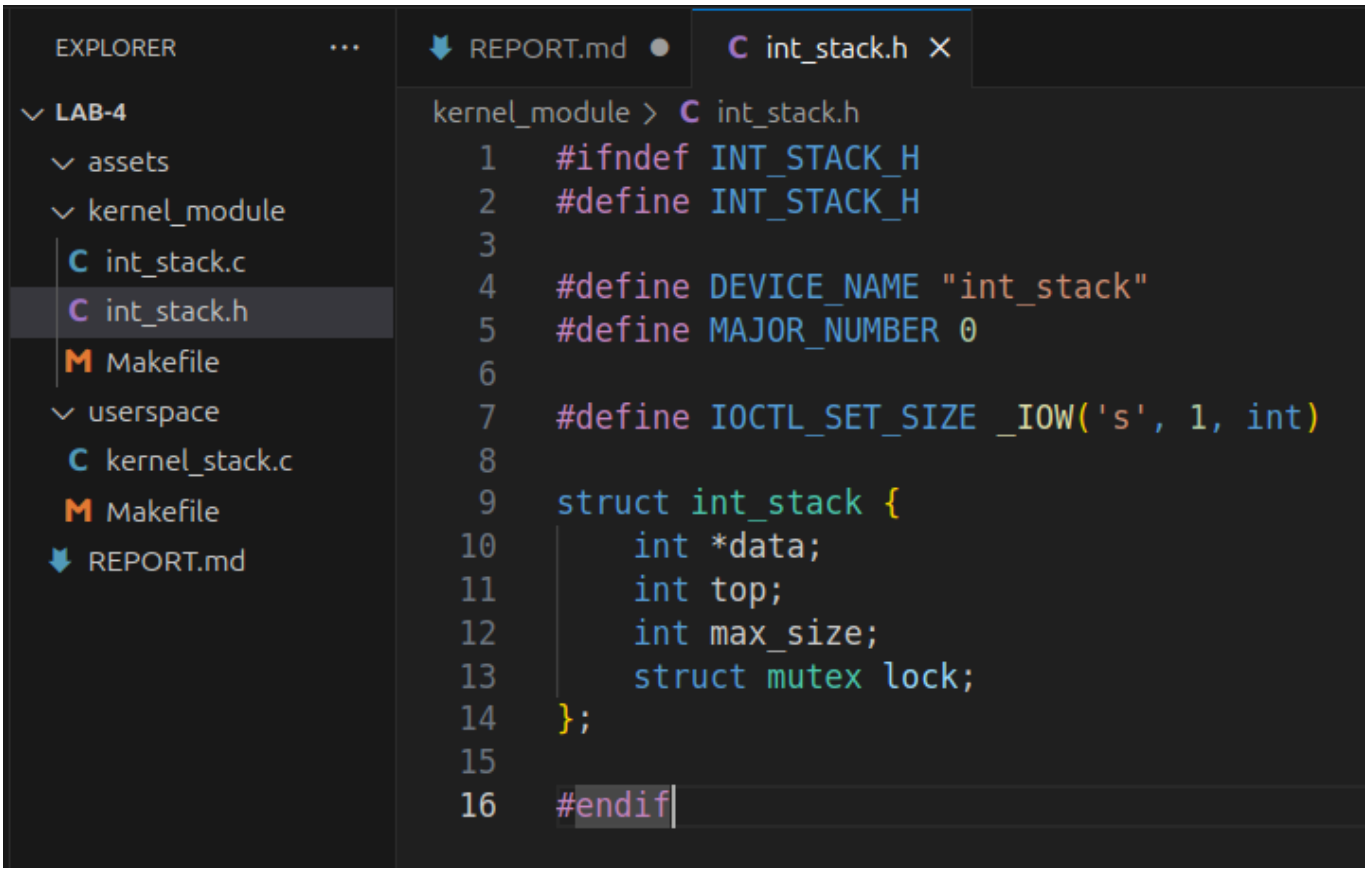
```
mkdir -p kernel_module userspace
```

The project is organized into two main components:

```
lab-4/
├── kernel_module/
│   ├── int_stack.h
│   ├── int_stack.c
│   └── Makefile
└── userspace/
    ├── kernel_stack.c
    └── Makefile
```

3.2 Header file implementation

Hheader file (int_stack.h) defines the core data structures, constants:

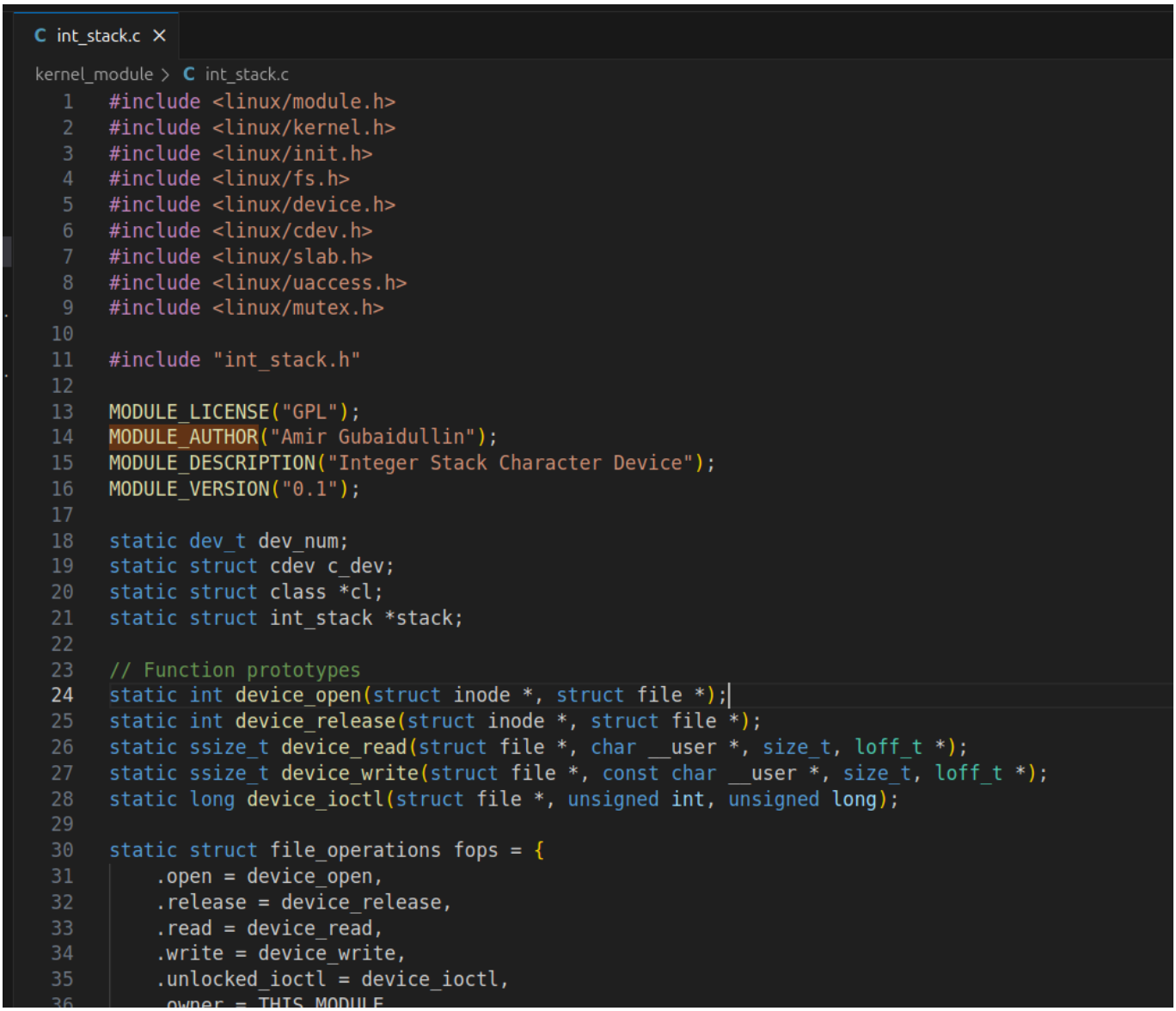


Key components:

- Device name definition for registration
- IOCTL command for stack size configuration
- Stack structure with dynamic array, top pointer, maximum size
- Mutex for thread synchronization

3.3 Kernel module implementation

The kernel module (int_stack.c) implements the character device driver:



1. **Module Initialization (`int_stack_init`):**
   - Dynamic device number allocation
   - Device class creation for automatic device file generation
   - Character device registration
   - Stack structure allocation and initialization

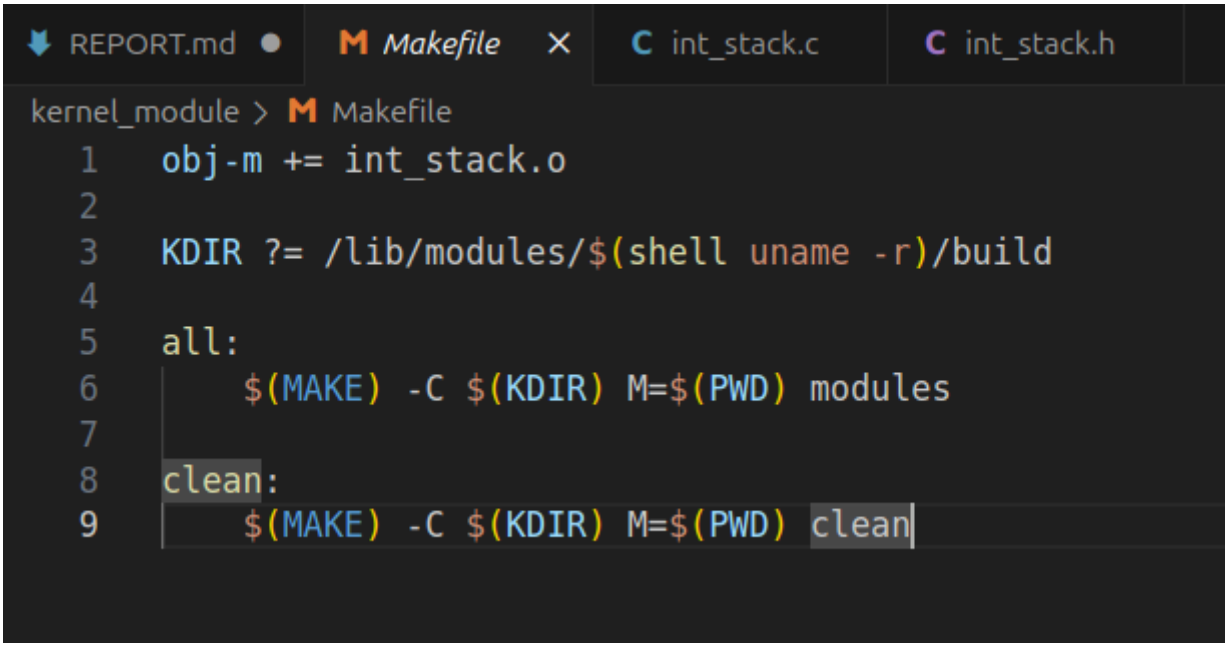
2. **File Operations:**
   - `open()` and `release()`: Basic file operations (currently minimal implementation)
   - `read()`: Implements pop operation, returns 0 bytes when stack is empty
   - `write()`: Implements push operation, returns -ERANGE when stack is full
   - `ioctl()`: Configures stack size, validates input, manages memory allocation

3. **Thread Safety:**
   - All stack operations are protected by mutex locks
   - Proper lock/unlock sequences in error paths
   - Prevents race conditions during concurrent access

4. **Module Cleanup (`int_stack_exit`):**

- Frees allocated memory
- Unregisters character device
- Destroys device class
- Releases device number

Then created kernel module makefile:



Features:

- Out-of-tree module compilation
- Automatic kernel version detection
- Clean target for build artifacts

3.4 User-space utility

The user-space program (kernel_stack.c) provides a CLI interface:

REPORT.md ● | kernel_stack.c × | int_stack.c | int_stack.h

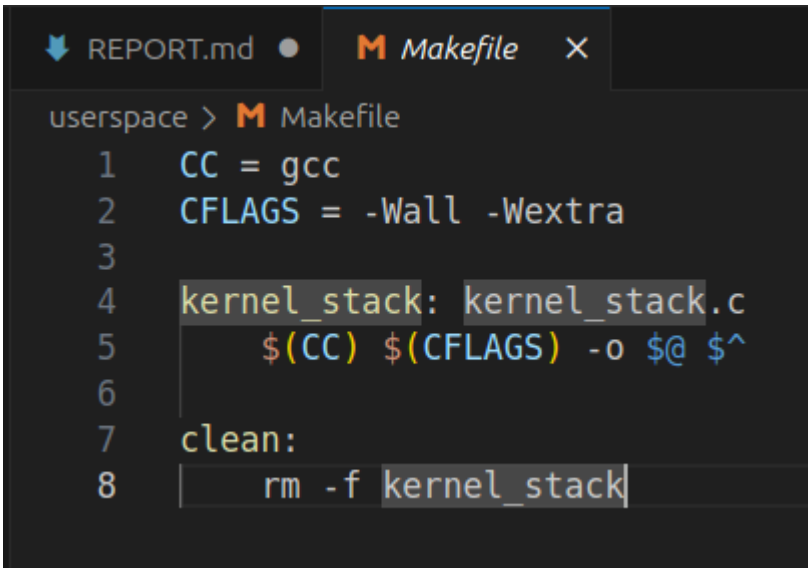
userspace > kernel_stack.c

```c
#include <stdio.h>
#include <stdlib.h>
#include <fcntl.h>
#include <unistd.h>
#include <sys/ioctl.h>
#include <string.h>
#include <errno.h>

#define DEVICE_PATH "/dev/int_stack"
#define IOCTL_SET_SIZE _IOW('s', 1, int)

void print_usage(const char *prog_name) {
    printf("Usage:\n");
    printf("  %s set-size <size>\n", prog_name);
    printf("  %s push <value>\n", prog_name);
    printf("  %s pop\n", prog_name);
    printf("  %s unwind\n", prog_name);
}

int main(int argc, char *argv[]) {
    int fd;
    int value, size;
    int ret;

    if (argc < 2) {
        print_usage(argv[0]);
        return 1;
    }

    fd = open(DEVICE_PATH, O_RDWR);
    if (fd < 0) {
        perror("Failed to open device");
        return errno;
    }

    if (strcmp(argv[1], "set-size") == 0) {
```

Supported commands:

- `set-size <size>`: Configure stack size
- `push <value>`: Add element to stack
- `pop`: Remove and display top element
- `unwind`: Remove and display all elements

Then created user-space makefile:



Features:

- Strict compilation flags (-Wall -Wextra)
- Simple build process for CLI utility

3.5 Building and testing

Successfully built both components:

- Kernel module compiled without warnings
- User-space utility compiled with strict flags

Builded kernel module:

```
→ lab-4 cd kernel_module
→ kernel_module make
make -C /lib/modules/6.11.0-24-generic/build M=/home/amir/IU/AdvLinux/lab-4/kernel_module modules
make[1]: Entering directory '/usr/src/linux-headers-6.11.0-24-generic'
warning: the compiler differs from the one used to build the kernel
  The kernel was built by: x86_64-linux-gnu-gcc-13 (Ubuntu 13.3.0-6ubuntu2~24.04) 13.3.0
  You are using:           gcc-13 (Ubuntu 13.3.0-6ubuntu2~24.04) 13.3.0
  CC [M]  /home/amir/IU/AdvLinux/lab-4/kernel_module/int_stack.o
  MODPOST /home/amir/IU/AdvLinux/lab-4/kernel_module/Module.symvers
  CC [M]  /home/amir/IU/AdvLinux/lab-4/kernel_module/int_stack.mod.o
  LD [M]  /home/amir/IU/AdvLinux/lab-4/kernel_module/int_stack.ko
  BTF [M] /home/amir/IU/AdvLinux/lab-4/kernel_module/int_stack.ko
Skipping BTF generation for /home/amir/IU/AdvLinux/lab-4/kernel_module/int_stack.ko due to unavailability of vmlinux
make[1]: Leaving directory '/usr/src/linux-headers-6.11.0-24-generic'
→ kernel_module
```

Built user-space utility:

```
→ userspace make
gcc -Wall -Wextra -o kernel_stack kernel_stack.c
→ userspace
```

I faced some issues due to Secure Boot being enabled, the module required signing before loading:

```
# Create signing keys
cd ~
```

```
mkdir kernel-signing
cd kernel-signing
openssl req -new -x509 -newkey rsa:2048 -keyout MOK.priv -outform DER -out
MOK.der -nodes -days 36500 -subj "/CN=Local Kernel Module Signing/"
openssl x509 -in MOK.der -inform DER -outform PEM -out MOK.pem
sudo mokutil --import MOK.der

# Reboot and enroll MOK

# Sign the module
cd /home/amir/IU/AdvLinux/lab-4/kernel_module
sudo /usr/src/linux-headers-$(uname -r)/scripts/sign-file sha256 \
    ~/kernel-signing/MOK.priv \
    ~/kernel-signing/MOK.der \
    int_stack.ko
```

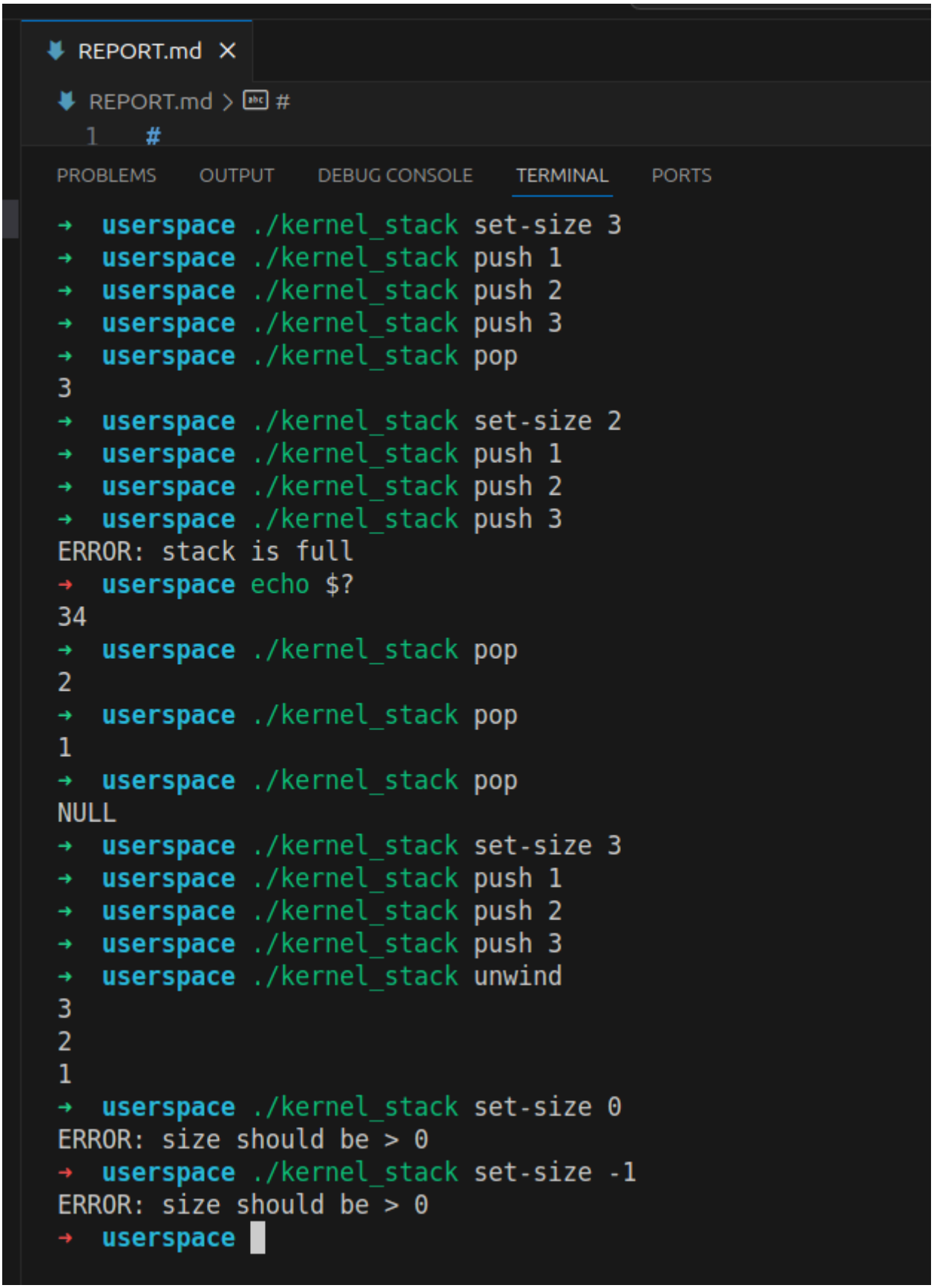
3.6 Module loading

After signing, the module was successfully loaded:

```
→  lab-4 cd /home/amir/IU/AdvLinux/lab-4/kernel_module
→  kernel_module sudo /usr/src/linux-headers-$(uname -r)/scripts/sign-file sha256 \
    ~/kernel-signing/MOK.priv \
    ~/kernel-signing/MOK.der \
    int_stack.ko
→  kernel_module sudo insmod int_stack.ko
→  kernel_module sudo chmod 666 /dev/int_stack
→  kernel_module
```

3.7 Test cases

I ran test cases:



Executed test cases demonstrating:

1. **Basic Operations:**
    - Setting stack size
    - Push operations
    - Pop operations

- Stack full error handling
- Stack empty handling

2. **Edge Cases:**

- Invalid size values (≤0)
- Stack overflow behavior
- Empty stack pop
- Unwind operation
- Error code verification

3.8 Resubmission

Check items are saved when the stack size increases

```
● → kernel_module sudo /usr/src/linux-headers-$(uname -r)/scripts/sign-file sha256 \
  ~/kernel-signing/MOK.priv \
  ~/kernel-signing/MOK.der \
  int_stack.ko
● → kernel_module sudo insmod int_stack.ko
● → kernel_module lsmod | grep int_stack
  int_stack              12288  0
● → kernel_module sudo chmod 666 /dev/int_stack
● → kernel_module cd ../userspace
● → userspace ./kernel_stack set-size 3
● → userspace ./kernel_stack push 1
● → userspace ./kernel_stack push 2
● → userspace ./kernel_stack push 3
● → userspace ./kernel_stack set-size 5
● → userspace ./kernel_stack unwind
  3
  2
  1
○ → userspace
```

Check for deleting items when reducing the stack size

```
● → userspace ./kernel_stack set-size 5
● → userspace ./kernel_stack push 1
● → userspace ./kernel_stack push 2
● → userspace ./kernel_stack push 3
● → userspace ./kernel_stack push 4
● → userspace ./kernel_stack push 5
● → userspace ./kernel_stack set-size 3
● → userspace ./kernel_stack unwind
3
2
1
○ → userspace
```

Check correctness of operations after resizing

```
● → userspace ./kernel_stack set-size 2
● → userspace ./kernel_stack push 10
● → userspace ./kernel_stack push 20
⊗ → userspace ./kernel_stack push 30
ERROR: stack is full
● → userspace ./kernel_stack pop
20
● → userspace ./kernel_stack pop
10
● → userspace ./kernel_stack pop
NULL
○ → userspace
```