

Environment Variable and Set-UID Program Lab

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1 Overview

The learning objective of this lab is for students to understand how environment variables affect program and system behaviors. Environment variables are a set of dynamic named values that can affect the way running processes will behave on a computer. They are used by most operating systems, since they were introduced to Unix in 1979. Although environment variables affect program behaviors, how they achieve that is not well understood by many programmers. As a result, if a program uses environment variables, but the programmer does not know that they are used, the program may have vulnerabilities.

In this lab, students will understand how environment variables work, how they are propagated from parent process to child, and how they affect system/program behaviors. We are particularly interested in how environment variables affect the behavior of Set-UID programs, which are usually privileged programs. This lab covers the following topics:

- Environment variables
- Set-UID programs
- Securely invoke external programs
- Capability leaking
- Dynamic loader/linker

Readings and videos. Detailed coverage of the Set-UID mechanism, environment variables, and their related security problems can be found in the following:

- Chapters 1 and 2 of the SEED Book, *Computer & Internet Security: A Hands-on Approach*, 2nd Edition, by Wenliang Du. See details at <https://www.handsonsecurity.net>.
- Section 2 of the SEED Lecture at Udemy, *Computer Security: A Hands-on Approach*, by Wenliang Du. See details at <https://www.handsonsecurity.net/video.html>.

Lab environment. This lab has been tested on the SEED Ubuntu 20.04 VM. You can download a pre-built image from the SEED website, and run the SEED VM on your own computer. However, most of the SEED labs can be conducted on the cloud, and you can follow our instruction to create a SEED VM on the cloud.

2 Lab Tasks

Files needed for this lab are included in `Labsetup.zip`, which can be downloaded from the lab's website.

2.1 Task 1: Manipulating Environment Variables

In this task, we study the commands that can be used to set and unset environment variables. We are using Bash in the seed account. The default shell that a user uses is set in the `/etc/passwd` file (the last field of each entry). You can change this to another shell program using the command `chsh` (please do not do it for this lab). Please do the following tasks:

- Use `printenv` or `env` command to print out the environment variables. If you are interested in some particular environment variables, such as `PWD`, you can use `"printenv PWD"` or `"env | grep PWD"`.
- Use `export` and `unset` to set or unset environment variables. It should be noted that these two commands are not separate programs; they are two of the Bash's internal commands (you will not be able to find them outside of Bash).

2.2 Task 2: Passing Environment Variables from Parent Process to Child Process

In this task, we study how a child process gets its environment variables from its parent. In Unix, `fork()` creates a new process by duplicating the calling process. The new process, referred to as the child, is an exact duplicate of the calling process, referred to as the parent; however, several things are not inherited by the child (please see the manual of `fork()` by typing the following command: `man fork`). In this task, we would like to know whether the parent's environment variables are inherited by the child process or not.

Step 1. Please compile and run the following program, and describe your observation. The program can be found in the `Labsetup` folder; it can be compiled using `"gcc myprintenv.c"`, which will generate a binary called `a.out`. Let's run it and save the output into a file using `"a.out > file"`.

Listing 1: `myprintenv.c`

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

extern char **environ;
void printenv()
{
    int i = 0;
    while (environ[i] != NULL) {
        printf("%s\n", environ[i]);
        i++;
    }
}

void main()
{
    pid_t childPid;
    switch(childPid = fork()) {
        case 0: /* child process */
            printenv();           ①
            exit(0);
        default: /* parent process */
            //printenv();         ②
    }
}
```

```
    exit(0);  
}  
}
```

Step 2. Now comment out the `printenv()` statement in the child process case (Line ①), and uncomment the `printenv()` statement in the parent process case (Line ②). Compile and run the code again, and describe your observation. Save the output in another file. Files are Identical

Step 3. Compare the difference of these two files using the `diff` command. Please draw your conclusion.

2.3 Task 3: Environment Variables and `execve()`

In this task, we study how environment variables are affected when a new program is executed via `execve()`. The function `execve()` calls a system call to load a new command and execute it; this function never returns. No new process is created; instead, the calling process's text, data, bss, and stack are overwritten by that of the program loaded. Essentially, `execve()` runs the new program inside the calling process. We are interested in what happens to the environment variables; are they automatically inherited by the new program?

Step 1. Please compile and run the following program, and describe your observation. This program simply executes a program called `/usr/bin/env`, which prints out the environment variables of the current process. empty because argument on `execve` is `NULL`, therefore no variables are passed through

Listing 2: `myenv.c`

```
#include <unistd.h>  
  
extern char **environ;  
int main()  
{  
    char *argv[2];  
  
    argv[0] = "/usr/bin/env";  
    argv[1] = NULL;  
    execve("/usr/bin/env", argv, NULL);    ①  
  
    return 0 ;  
}
```

Step 2. Change the invocation of `execve()` in Line ① to the following; describe your observation.

```
execve("/usr/bin/env", argv, environ);
```

When using `environ` variable instead of `NULL`, now the output will show the variables

Step 3. Please draw your conclusion regarding how the new program gets its environment variables.

The function `int execve()` has the last argument : `char *const envp[]` (same type as our `environ`, so when this argument is present we get the variables but in the beginning when using the null argument there, makes it so no variables are passed through

2.4 Task 4: Environment Variables and `system()`

In this task, we study how environment variables are affected when a new program is executed via the `system()` function. This function is used to execute a command, but unlike `execve()`, which directly executes a command, `system()` actually executes `"/bin/sh -c command"`, i.e., it executes `/bin/sh`, and asks the shell to execute the command.

If you look at the implementation of the `system()` function, you will see that it uses `execl()` to execute `/bin/sh`; `execl()` calls `execve()`, passing to it the environment variables array. Therefore, using `system()`, the environment variables of the calling process is passed to the new program `/bin/sh`. Please compile and run the following program to verify this.

```
#include <stdio.h>
#include <stdlib.h>

int main()
{
    system("/usr/bin/env");
    return 0;
}
```

Prints the environment variable

Running man system we see that it uses the `execl()` command

Running `execl` system we see that it gets the environment variables with `extern char **environ`; therefore, it gets and passes the environment variables to the program it is calling.

2.5 Task 5: Environment Variable and Set-UID Programs

Set-UID is an important security mechanism in Unix operating systems. When a Set-UID program runs, it assumes the owner's privileges. For example, if the program's owner is root, when anyone runs this program, the program gains the root's privileges during its execution. Set-UID allows us to do many interesting things, but since it escalates the user's privilege, it is quite risky. Although the behaviors of Set-UID programs are decided by their program logic, not by users, users can indeed affect the behaviors via environment variables. To understand how Set-UID programs are affected, let us first figure out whether environment variables are inherited by the Set-UID program's process from the user's process.

Step 1. Write the following program that can print out all the environment variables in the current process.

```
#include <stdio.h>
#include <stdlib.h>

extern char **environ;

int main()
{
    int i = 0;
    while (environ[i] != NULL) {
        printf("%s\n", environ[i]);
        i++;
    }
}
```

Step 2. Compile the above program, change its ownership to root, and make it a Set-UID program.

```
// Assume the program's name is foo
$ sudo chown root foo
$ sudo chmod 4755 foo
```

Step 3. In your shell (you need to be in a normal user account, not the `root` account), use the `export` command to set the following environment variables (they may have already exist):

- `PATH`
- `LD_LIBRARY_PATH`
- `ANY_NAME` (this is an environment variable defined by you, so pick whatever name you want).

These environment variables are set in the user's shell process. Now, run the Set-UID program from Step 2 in your shell. After you type the name of the program in your shell, the shell forks a child process, and uses the child process to run the program. Please check whether all the environment variables you set in the shell process (parent) get into the Set-UID child process. Describe your observation. If there are surprises to you, describe them.

2.6 Task 6: The PATH Environment Variable and Set-UID Programs

Because of the shell program invoked, calling `system()` within a Set-UID program is quite dangerous. This is because the actual behavior of the shell program can be affected by environment variables, such as `PATH`; these environment variables are provided by the user, who may be malicious. By changing these variables, malicious users can control the behavior of the Set-UID program. In Bash, you can change the `PATH` environment variable in the following way (this example adds the directory `/home/seed` to the beginning of the `PATH` environment variable):

```
$ export PATH=/home/seed:$PATH
```

The Set-UID program below is supposed to execute the `/bin/ls` command; however, the programmer only uses the relative path for the `ls` command, rather than the absolute path:

```
int main()
{
    system("ls");
    return 0;
}
```

Please compile the above program, change its owner to `root`, and make it a Set-UID program. Can you get this Set-UID program to run your own malicious code, instead of `/bin/ls`? If you can, is your malicious code running with the root privilege? Describe and explain your observations.

Note: The `system(cmd)` function executes the `/bin/sh` program first, and then asks this shell program to run the `cmd` command. In Ubuntu 20.04 (and several versions before), `/bin/sh` is actually a symbolic link pointing to `/bin/dash`. This shell program has a countermeasure that prevents itself from being executed in a Set-UID process. Basically, if `dash` detects that it is executed in a Set-UID process, it immediately changes the effective user ID to the process's real user ID, essentially dropping the privilege.

Since our victim program is a Set-UID program, the countermeasure in `/bin/dash` can prevent our attack. To see how our attack works without such a countermeasure, we will link `/bin/sh` to another shell that does not have such a countermeasure. We have installed a shell program called `zsh` in our Ubuntu 20.04 VM. We use the following commands to link `/bin/sh` to `/bin/zsh`:

```
$ sudo ln -sf /bin/zsh /bin/sh
```

2.7 Task 7: The LD_PRELOAD Environment Variable and Set-UID Programs

In this task, we study how Set-UID programs deal with some of the environment variables. Several environment variables, including LD_PRELOAD, LD_LIBRARY_PATH, and other LD_* influence the behavior of dynamic loader/linker. A dynamic loader/linker is the part of an operating system (OS) that loads (from persistent storage to RAM) and links the shared libraries needed by an executable at run time.

In Linux, ld.so or ld-linux.so, are the dynamic loader/linker (each for different types of binary). Among the environment variables that affect their behaviors, LD_LIBRARY_PATH and LD_PRELOAD are the two that we are concerned in this lab. In Linux, LD_LIBRARY_PATH is a colon-separated set of directories where libraries should be searched for first, before the standard set of directories. LD_PRELOAD specifies a list of additional, user-specified, shared libraries to be loaded before all others. In this task, we will only study LD_PRELOAD.

Step 1. First, we will see how these environment variables influence the behavior of dynamic loader/linker when running a normal program. Please follow these steps:

1. Let us build a dynamic link library. Create the following program, and name it mylib.c. It basically overrides the sleep() function in libc:

```
#include <stdio.h>
void sleep (int s)
{
    /* If this is invoked by a privileged program,
       you can do damages here! */
    printf("I am not sleeping!\n");
}
```

2. We can compile the above program using the following commands (in the -lc argument, the second character is *l*):

```
$ gcc -fPIC -g -c mylib.c
$ gcc -shared -o libmylib.so.1.0.1 mylib.o -lc
```

3. Now, set the LD_PRELOAD environment variable:

```
$ export LD_PRELOAD=./libmylib.so.1.0.1
```

4. Finally, compile the following program myprog, and in the same directory as the above dynamic link library libmylib.so.1.0.1:

```
/* myprog.c */
#include <unistd.h>
int main()
{
    sleep(1);
    return 0;
}
```

Step 2. After you have done the above, please run myprog under the following conditions, and observe what happens.

- Make `myprog` a regular program, and run it as a normal user.
- Make `myprog` a Set-UID root program, and run it as a normal user.
- Make `myprog` a Set-UID root program, export the `LD_PRELOAD` environment variable again in the root account and run it.
- Make `myprog` a Set-UID `user1` program (i.e., the owner is `user1`, which is another user account), export the `LD_PRELOAD` environment variable again in a different user's account (not-root user) and run it.

Step 3. You should be able to observe different behaviors in the scenarios described above, even though you are running the same program. You need to figure out what causes the difference. Environment variables play a role here. Please design an experiment to figure out the main causes, and explain why the behaviors in Step 2 are different. (Hint: the child process may not inherit the `LD_*` environment variables).

2.8 Task 8: Invoking External Programs Using `system()` versus `execve()`

Although `system()` and `execve()` can both be used to run new programs, `system()` is quite dangerous if used in a privileged program, such as Set-UID programs. We have seen how the `PATH` environment variable affect the behavior of `system()`, because the variable affects how the shell works. `execve()` does not have the problem, because it does not invoke shell. Invoking shell has another dangerous consequence, and this time, it has nothing to do with environment variables. Let us look at the following scenario.

Bob works for an auditing agency, and he needs to investigate a company for a suspected fraud. For the investigation purpose, Bob needs to be able to read all the files in the company's Unix system; on the other hand, to protect the integrity of the system, Bob should not be able to modify any file. To achieve this goal, Vince, the superuser of the system, wrote a special set-root-uid program (see below), and then gave the executable permission to Bob. This program requires Bob to type a file name at the command line, and then it will run `/bin/cat` to display the specified file. Since the program is running as a root, it can display any file Bob specifies. However, since the program has no write operations, Vince is very sure that Bob cannot use this special program to modify any file.

Listing 3: `catall.c`

```
int main(int argc, char *argv[])
{
    char *v[3];
    char *command;

    if(argc < 2) {
        printf("Please type a file name.\n");
        return 1;
    }

    v[0] = "/bin/cat"; v[1] = argv[1]; v[2] = NULL;
    command = malloc(strlen(v[0]) + strlen(v[1]) + 2);
    sprintf(command, "%s %s", v[0], v[1]);

    // Use only one of the followings.
    system(command);
    // execve(v[0], v, NULL);
```

```
    return 0 ;  
}
```

Step 1: Compile the above program, make it a root-owned Set-UID program. The program will use `system()` to invoke the command. If you were Bob, can you compromise the integrity of the system? For example, can you remove a file that is not writable to you?

Step 2: Comment out the `system(command)` statement, and uncomment the `execve()` statement; the program will use `execve()` to invoke the command. Compile the program, and make it a root-owned Set-UID. Do your attacks in Step 1 still work? Please describe and explain your observations.

2.9 Task 9: Capability Leaking

To follow the Principle of Least Privilege, Set-UID programs often permanently relinquish their root privileges if such privileges are not needed anymore. Moreover, sometimes, the program needs to hand over its control to the user; in this case, root privileges must be revoked. The `setuid()` system call can be used to revoke the privileges. According to the manual, “`setuid()` sets the effective user ID of the calling process. If the effective UID of the caller is root, the real UID and saved set-user-ID are also set”. Therefore, if a Set-UID program with effective UID 0 calls `setuid(n)`, the process will become a normal process, with all its UIDs being set to `n`.

When revoking the privilege, one of the common mistakes is capability leaking. The process may have gained some privileged capabilities when it was still privileged; when the privilege is downgraded, if the program does not clean up those capabilities, they may still be accessible by the non-privileged process. In other words, although the effective user ID of the process becomes non-privileged, the process is still privileged because it possesses privileged capabilities.

Compile the following program, change its owner to root, and make it a Set-UID program. Run the program as a normal user. Can you exploit the capability leaking vulnerability in this program? The goal is to write to the `/etc/zzz` file as a normal user.

Listing 4: `cap_leak.c`

```
void main()  
{  
    int fd;  
    char *v[2];  
  
    /* Assume that /etc/zzz is an important system file,  
     * and it is owned by root with permission 0644.  
     * Before running this program, you should create  
     * the file /etc/zzz first. */  
    fd = open("/etc/zzz", O_RDWR | O_APPEND);  
    if (fd == -1) {  
        printf("Cannot open /etc/zzz\n");  
        exit(0);  
    }  
  
    // Print out the file descriptor value  
    printf("fd is %d\n", fd);
```



```
// Permanently disable the privilege by making the
// effective uid the same as the real uid
setuid(getuid());

// Execute /bin/sh
v[0] = "/bin/sh"; v[1] = 0;
execve(v[0], v, 0);
}
```

3 Submission

You need to submit a detailed lab report, with screenshots, to describe what you have done and what you have observed. You also need to provide explanation to the observations that are interesting or surprising. Please also list the important code snippets followed by explanation. Simply attaching code without any explanation will not receive credits.