Ptrace

Overview

- ptrace is a system call
- allow a process (tracer) to observe and control execution of another process (tracee)
    - memory read/write
    - register read/write
    - monitor runtime state changes
- `ptrace(2)`: `long ptrace(enum __ptrace_request request, pid_t pid, void *addr, void *data)`

`request`	Description
`PTRACE_ATTACH`	Attach to a process
`PTRACE_DETACH`	Detach from a tracee, and restart the process
`PTRACE_TRACEME`	Indicate that this process is to be traced by its parent
`PTRACE_CONT`	Restart the stopped tracee process
`PTRACE_SYSCALL`	`PTRACE_CONT`, but stop at the next entry to or exit from a syscall
`PTRACE_SINGLESTEP`	`PTRACE_CONT`, but stop after execution of a single instruction
`PTRACE_PEEKDATA`	Read a word from tracee's memory
`PTRACE_PEEKUSER`	Read a word from tracee's user data (usually registers)
`PTRACE_GETREGS`	Copy the tracee's general-purpose registers
`PTRACE_POKEDATA`	Write a word to tracee's memory
`PTRACE_POKEUSER`	Write a word to tracee's user data (usually registers)
`PTRACE_SETREGS`	Modify the tracee's general-purpose registers
`PTRACE_SETOPTIONS`	Set ptrace options

Basic Control

- `ptrace(PTRACE_ATTACH, child, 0, 0)`
    - return: 0 OK, -1 error
    - usually parent can trace its child
    - parent calls `PTRACE_ATTACH` or child calls `PTRACE_TRACEME`
    - `SIGSTOP` is sent to the tracee
        - use `waitpid(2)` to wait for the child process
        - determine the status of the child by using `WIFSTOPPED()`
    - restrictions: `/proc/sys/kernel/yama/ptrace_scope`

Number	Description
`0`	classic ptrace permission: no restriction
`1`	restricted ptrace: allow a parent and process having `CAP_SYS_PTRACE` ability
`2`	admin-only: allow only process having the `CAP_SYS_PTRACE` ability
`3`	no attach

- `ptrace(PTRACE_TRACEME, 0, 0, 0)`
    - return: 0 OK, -1 error
    - turn a process to a tracee, traced by its parent
    - typical implementation
        - parent fork a child
        - child calls `PTRACE_TRACEME`, then
            - raise `SIGSTOP` to stop itself or
            - `exec` another program, a `SIGTRAP` will be delivered to its parent
                - `PTRACE_O_TRACEEXEC` option should be disabled (default)
        - parent waits for the child, and then control it

- `ptrace(PTRACE_CONT, child, 0, sig)`
    - return: 0 OK, -1 error
    - restart the stopped tracee
    - a tracee is stopped if
        - attached by a tracer
        - child calls `PTRACE_TRACEME` and `exec`
    - `sig` is usually 0 -> no signal is delivered to the tracee

- Minimal Example

```
int main(int argc, char *argv[]) {
  pid_t child;
  if (argc < 2) {
    fprintf(stderr, "usage: %s program\n", argv[0]);
    return -1;
  }
  if ((child = fork()) < 0) errquit("fork");
  if (child == 0) {
    if (ptrace(PTRACE_TRACEME, 0, 0, 0) < 0) errquit("ptrace");
```

```
    execvp(argv[1], argv + 1);
    errquit("execvp");
  } else {
    int status;
    if (waitpid(child, &status, 0) < 0) errquit("wait");
    assert(WIFSTOPPED(status));
    // PTRACE_O_EXITKILL: kill tracee if tracer exits
    ptrace(PTRACE_SETOPTIONS, child, 0, PTRACE_O_EXITKILL);
    ptrace(PTRACE_CONT, child, 0, 0);
    waitpid(child, &status, 0);
    perror("done");
  }
  return 0;
}
```

- Finer Program Control Flow Granularity
  - `ptrace(PTRACE_SINGLESTEP, child, 0, 0)`
    - return: 0 OK, -1 error
    - stop after execution of a single instruction
  - `ptrace(PTRACE_SYSCALL, child, 0, 0)`
    - return: 0 OK, -1 error
    - stop at the next entry to or exit from a syscall
    - differentiate between regular stop and syscall stop
      - pass `PTRACE_O_TRACESYSGOOD` option
      - then return status will add 0x80 if it is syscall stop
      - example

      ```
      ptrace(PTRACE_SETOPTIONS, child, 0, PTRACE_O_EXITKILL |
      PTRACE_O_TRACESYSGOOD);
      if (WSTOPSIG(status) & 0x80) {
        // it is syscall stop
      }
      ```

    - knowing syscall stop, differentiate between entry point and exit point
      - setup a counter
      - stop must start from entry, exit, entry, ... and so on
      - example

      ```
      int enter = 0x01;
      ...
      if (WSTOPSIG(status) & 0x80) {
        if (enter) { /* entry */ }
        else { /* exit */ }
      ```

```
    enter ^= 0x01
  }
```

- work with `PTRACE_GETREGS`
  - for entry point: syscall id will store in `orig_rax` of struct `user_regs_struct`
  - for exit point: syscal return will store in `rax` of struct `user_regs_struct`
  - the rest parameters follows calling convention

- Reading From a Tracee
  - **clear `errno` before calling PEEK* functions**
  - `ptrace(PTRACE_PEEKTEXT, child, addr, 0)`
    - return: a word, check `errno` for errors
    - same as `PTRACE_PEEKDATA`
    - read a word from tracee's memory address `addr`
    - `addr` alignment is hardware dependent
      - Intel: it is not necessary to be aligned, you can pass any address
  - `ptrace(PTRACE_PEEKUSER, child, offset, 0)`
    - return: a word, check `errno` for errors
    - read register word from tracee's user data area
    - `offset` usually has to be **word-aligned**
  - `ptrace(PTRACE_GETREGS, child, 0, data)`
    - return: 0 OK, -1 error
    - read general-purpose register to `data`
    - `data` should be stored in struct `user_regs_struct`

- Writing to a Tracee
  - `ptrace(PTRACE_POKETEXT, child, addr, word)`
    - return: 0 OK, -1 error
    - same as `PTRACE_POKEDATA`
    - write a word to tracee's memory address `addr`
    - `addr` alignment is hardware dependent
      - Intel: it is not necessary to be aligned, you can pass any address
  - `ptrace(PTRACE_POKEUSER, child, offset, word)`
    - return: 0 OK, -1 error
    - write register word to tracee's user data area
    - `offset` usually has to be **word-aligned**
  - `ptrace(PTRACE_SETREGS, child, 0, data)`
    - return: 0 OK, -1 error
    - write general-purpose register from `data`
    - `data` should be stored in struct `user_regs_struct`

- the term word is architecture dependent
  - 32-bit machine: 4 bytes
  - 64-bit machine: 8 bytes

Applications

Instruction Counter

```
int main(int argc, char *argv[]) {
  pid_t child;
  if (argc < 2) {
    fprintf(stderr, "usage: %s program [args ...]\n", argv[0]);
    return -1;
  }
  if ((child = fork()) < 0) errquit("fork");
  if (child == 0) {
    if (ptrace(PTRACE_TRACEME, 0, 0, 0) < 0) errquit("ptrace@child");
    execvp(argv[1], argv + 1);
    errquit("execvp");
  } else {
    uint64_t counter = 0;
    int wait_status;
    if (waitpid(child, &wait_status, 0) < 0) errquit("waitpid");
    ptrace(PTRACE_SETOPTIONS, child, 0, PTRACE_O_EXITKILL);
    while (WIFSTOPPED(wait_status)) {
      counter++;
      if (ptrace(PTRACE_SINGLESTEP, child, 0, 0) < 0)
errquit("ptrace@parent");
      if (waitpid(child, &wait_status, 0) < 0) errquit("waitpid");
    }
    fprintf(stderr, "## %ld instruction(s) executed\n", counter);
  }
  return 0;
}
```

Execution Trace Dump

```
while (WIFSTOPPED(wait_status)) {
  counter++;
  long ret;
  uint8_t *ptr = (uint8_t *)&ret;
  uint64_t rip;
  struct user_regs_struct regs;
  uint8_t offset = ((uint8_t *)&regs.rip) - ((uint8_t *)&regs);  // 128
#if USE_PEEKUSER
  if ((rip = ptrace(PTRACE_PEEKUSER, child, offset, 0)) != 0) {
#else
  if (ptrace(PTRACE_GETREGS, child, 0, &regs) == 0) {
    rip = regs.rip;
#endif
    ret = ptrace(PTRACE_PEEKTEXT, child, rip, 0);
    fprintf(stderr,
            "0x%lx: %2.2x %2.2x %2.2x %2.2x %2.2x %2.2x %2.2x %2.2x\n",
rip,
```

```
                ptr[0], ptr[1], ptr[2], ptr[3], ptr[4], ptr[5], ptr[6],
ptr[7]);
  }
  if (ptrace(PTRACE_SINGLESTEP, child, 0, 0) < 0) errquit("ptrace@parent");
  if (waitpid(child, &wait_status, 0) < 0) errquit("waitpid");
}
```

- Revise Above Code
    - show module names: `/proc/{pid}/maps`
    - show assembly codes
        - Capstone
            - disassembler
            - `sudo apt install libcapstone3 libcapstone-dev`
            - header: `/usr/include/capstone/capstone.h`
            - library: `/usr/lib/x86_64-linux-gnu/libcapstone.so.3`
- Disassemble in Three Steps
    - `cs_err cs_open(cs_arch arch, cs_mode mode, csh *handle);`
    - `size_t CAPSTONE_API cs_disasm(csh handle, const uint8_t *code, size_t code_size, uint64_t address, size_t count, cs_insn **insn);`
    - `cs_err cs_close(csh *handle);`

```
csh cshhandle = 0;
if (cs_open(CS_ARCH_X86, CS_MODE_64, &cshandle) != CS_ERR_OK) {
  return -1;
}
...
cs_insn *insn;
if ((count = cs_disasm(cshandle, (uint8_t *)buf, bufsz, rip, 0,
&insn)) > 0) {
  for (int i = 0; i < count; i++) {
    instruction in;
    in.size = insn[i].size;
    in.opr = insn[i].mnemonic;
    in.opnd = insn[i].op_str;
    memcpy(in.bytes, insn[i].bytes, insn[i].size);
    instructions[insn[i].address] = in;
  }
  cs_free(insn, count);
}
...
cs_close(&schandle);
```

System Call Tracer

```
int enter = 0x01;
if (waitpid(child, &wait_status, 0) < 0) errquit("waitpid");
ptrace(PTRACE_SETOPTIONS, child, 0, PTRACE_O_EXITKILL |
PTRACE_O_TRACESYSGOOD);
while (WIFSTOPPED(wait_status)) {
  struct user_regs_struct regs;
  if (ptrace(PTRACE_SYSCALL, child, 0, 0) != 0) errquit("ptrace@parent");
  if (waitpid(child, &wait_status, 0) < 0) errquit("waitpid");
  if (!WIFSTOPPED(wait_status) || !(WSTOPSIG(wait_status) & 0x80))
continue;
  if (ptrace(PTRACE_GETREGS, child, 0, &regs) != 0)
errquit("ptrace@parent");
  if (enter) {
    /* rip has to subtract 2 because syscall is 0x0f 0x05 */
    /* print here */
    if (regs.orig_rax == 0x3c || regs.orig_rax == 0xe7)
      fprintf(stderr, "\n"); /* exit || exit_group */
    counter++;
  } else {
    fprintf(stderr, "0x%llx: ret = 0x%llx\n", regs.rip - 2, regs.rax);
  }
  enter ^= 0x01;
}
```

Change Program Control Flow

- `JMP` Instruction

Assembly	OP Code	Description
`JMP rel8`	`E8` + offset	Jump to RIP + 8-bit sign-extended address
`JMP rel32`	`E9` + offset	Jump to RIP + 32-bit sign-extended address
`JMP r/m64`	`FF` + r/m64	Jump to the target address

- Patch Hidden Program
  - start address: 0x4000b0
  - hidden part: 0x4000cf to 0x40010e
  - strategy
    - jump to 0x4000cf from start
      - write 0xe8, offset to 0x4000b0
      - where `offset = 0x4000cf - 0x4000b0 - 2 = 0x1d`
      - because `eip` changes when perform 0xe8, offset

```
uint8_t code[] = {0xeb, 0x1d, 0x90, 0x90, 0x90, 0x90, 0x90,
0x90};
uint64_t *lcode = (uint64_t *)code;
if (ptrace(PTRACE_POKETEXT, child, 0x4000b0, *lcode) != 0) {
```

```
  errquit("poketext");
}
```

- remove code that blocks the program to get in hidden part
  - 0x4000cd has jmp instruction to skip the hidden part
  - nop, 0x90 can be used

```
uint64_t code = ptrace(PTRACE_PEEKTEXT, child, 0x4000cd, 0);
uint64_t replace = (code & 0xffffffffffff0000) | 0x9090;
if (ptrace(PTRACE_POKETEXT, child, 0x4000cd, replace) != 0)
{
  errquit("poketext");
}
```

Automated Debugger

- Patch Guess Program
  - compare `secret` with user input, success if same
  - GDB way
    - setup breakpoint right before check
    - change the value of `secret` (or the input)
      - high level
        - input 1234
        - `set secret = 1234`
      - low level
        - `print $rdx`, get 48125085
        - `set $rax = 48125085`
  - `LD_PRELOAD` way
    - replace `rand` or `strtol` function
    - but it changes all behavior that calls `rand` or `strtol`
  - ptrace provides a fine grained control of the program
- Steps to Patch with `ptrace`
  1. run and **suspend** the program
  2. identify the location we want to stop the program
  3. setup a breakpoint
  4. **continue the execution**
  5. program stopped
  6. change the value, **and restore the breakpoint**
  7. continue the execution
- Identify the Location
  - check PIE
    - `checksec` tool

    - `pip3 install git+https://github.com/arthaud/python3-pwntools.git`
    - `checksec <exec>`
  - for PIE enabled program, it is loaded into random locations of virtual memory
  - compile without PIE -> use `-no-pie` flag

- ELF format

  - **executable and linkable format**

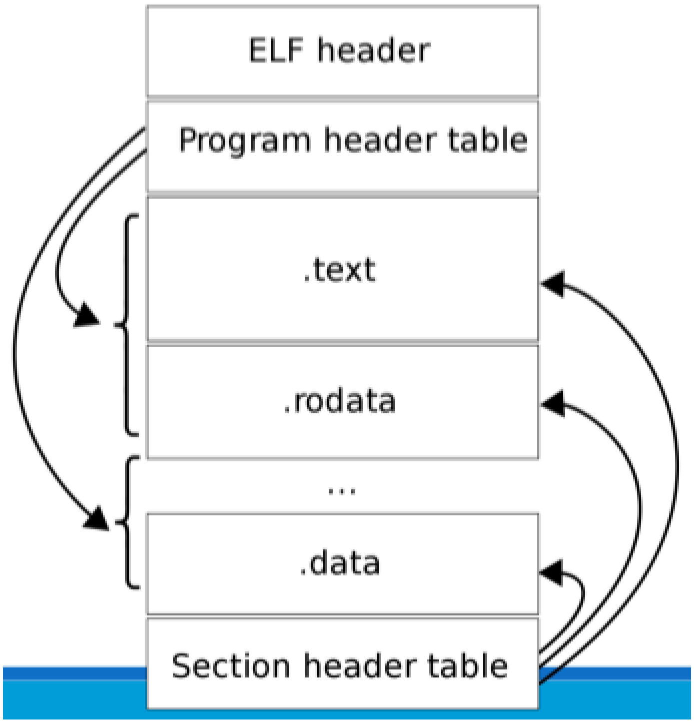
  - elf header

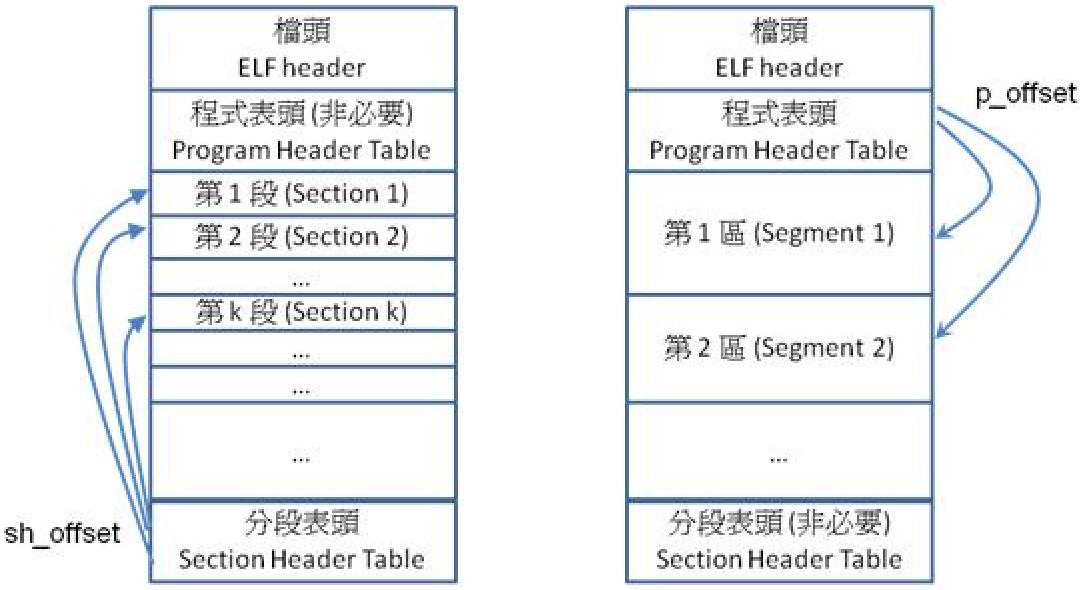
  - program header (zero or more)

  - section header (zero or more)

mode	elf header	program header	section header
32-bits	52 bytes	32 bytes each	40 bytes each
64-bits	64 bytes	56 bytes each	64 bytes each

  - data, referred by program and section header





(a) 連結時期觀點 (Linking View) (b) 執行時期觀點 (Execution View)

64-Bit (64 bytes, 0x40)

0	1	2	3	4	5	6	7	8	9	A	B	C	D	E	F
7F	'E'	'L'	'F'	Cla	End	Ver	ABI	Av	Unused						
Type		Machine		Version				Entry Point (8-byte)							
Program Header Offset (0x40)								Section Header Offset							
Flags				Size (64)		PH Size		# of PH		SH Size		# of SH		SH Idx	

32-bit (52 bytes, 0x34)

0	1	2	3	4	5	6	7	8	9	A	B	C	D	E	F
7F	'E'	'L'	'F'	Cla	End	Ver	ABI	Av	Unused						
Type		Machine		Version				Entry Point (4-byte)				PH Offset (0x34)			
SH Offset				Flags		Size (52)		PH Size		# of PH		SH Size		# of SH	
SH Idx															

Cla (Class):
1 – 32-bit
2 – 64-bit

End (Endianness):
1 – Little
2 – Big

ABI: 03 – Linux

Av (ABI version)

Type:
02 – Executable
03 – Dynamic

Machine:
03 – x86

```
$ hexdump -C /lib/x86_64-linux-gnu/libc.so.6 | head -n 4
00000000  7f 45 4c 46 02 01 01 03  00 00 00 00 00 00 00 00
|.ELF............|
00000010  03 00 3e 00 01 00 00 00  b0 1c 02 00 00 00 00 00
|..>.............|
00000020  40 00 00 00 00 00 00 00  90 e9 1e 00 00 00 00 00
|@...............|
00000030  00 00 00 00 40 00 38 00  0a 00 40 00 49 00 48 00
|....@.8...@.I.H.|
$ readelf -h /lib/x86_64-linux-gnu/libc.so.6
ELF Header:
  Magic:   7f 45 4c 46 02 01 01 03 00 00 00 00 00 00 00 00
  Class:                             ELF64
  Data:                              2's complement, little
endian
  Version:                           1 (current)
  OS/ABI:                            UNIX - GNU
  ABI Version:                       0
  Type:                              DYN (Shared object file)
  Machine:                           Advanced Micro Devices X86-
64
  Version:                           0x1
  Entry point address:               0x21cb0
  Start of program headers:          64 (bytes into file)
  Start of section headers:          2025872 (bytes into file)
  Flags:                             0x0
  Size of this header:               64 (bytes)
  Size of program headers:           56 (bytes)
  Number of program headers:         10
  Size of section headers:           64 (bytes)
  Number of section headers:         73
  Section header string table index: 72
$ hexdump -C guess | head -n 4
00000000  7f 45 4c 46 02 01 01 00  00 00 00 00 00 00 00 00
|.ELF............|
00000010  03 00 3e 00 01 00 00 00  20 08 00 00 00 00 00 00
|..>..... .......|
00000020  40 00 00 00 00 00 00 00  d0 24 00 00 00 00 00 00
|@........$......|
00000030  00 00 00 00 40 00 38 00  09 00 40 00 22 00 21 00
|....@.8...@.".!.|
$ readelf -h guess
ELF Header:
  Magic:   7f 45 4c 46 02 01 01 00 00 00 00 00 00 00 00 00
  Class:                             ELF64
  Data:                              2's complement, little
endian
  Version:                           1 (current)
  OS/ABI:                            UNIX - System V
  ABI Version:                       0
  Type:                              DYN (Shared object file)
  Machine:                           Advanced Micro Devices X86-
64
```

```
  Version:                           0x1
  Entry point address:               0x820
  Start of program headers:          64 (bytes into file)
  Start of section headers:          9424 (bytes into file)
  Flags:                             0x0
  Size of this header:               64 (bytes)
  Size of program headers:           56 (bytes)
  Number of program headers:         9
  Size of section headers:           64 (bytes)
  Number of section headers:         34
  Section header string table index: 33
```

- `PT_LOAD` program header (phdr)
  - 1, defined in `elf.h`
  - parts in elf file that can be loaded
    - `.text` and `.data`
  - kernel calls `mmap` to map them into virtual memory
- section header (shdr)
  - describe what sections are available
  - `.text`, `.symtab`, `.strtab`, ...
- example without PIE enable
  - loaded memory region: 0x0000~0x00d3 @ 0x400000
  - text segment: offset 0x00b0 (176), size 0x23 (35)
  - data segment: offset 0x00d4 (212), size 0x0f (15)
  - offset 211 contains 0x00, in order to align data segment
  - see maps and code from GDB
    - `gdb hello64`
    - `starti`
    - `info proc mapping`
    - `x/35bx 0x4000b0`

```
$ readelf -l hello64
Elf file type is EXEC (Executable file)
Entry point 0x4000b0
There are 2 program headers, starting at offset 64

Program Headers:
  Type           Offset             VirtAddr           PhysAddr
                 FileSiz            MemSiz              Flags
Align
  LOAD           0x0000000000000000 0x0000000000400000
0x0000000000400000
                 0x00000000000000d3 0x00000000000000d3  R E
0x200000
  LOAD           0x00000000000000d4 0x00000000006000d4
```

```
0x00000000006000d4
                 0x000000000000000f 0x000000000000000f  RW
0x200000

 Section to Segment mapping:
  Segment Sections...
   00     .text
   01     .data
$ readelf -S hello64
There are 6 section headers, starting at offset 0x218:

Section Headers:
  [Nr] Name              Type             Address
Offset
       Size              EntSize          Flags  Link  Info
Align
  [ 0]                   NULL             0000000000000000
00000000
       0000000000000000  0000000000000000           0     0     0
  [ 1] .text             PROGBITS         00000000004000b0
000000b0
       0000000000000023  0000000000000000  AX       0     0
16
  [ 2] .data             PROGBITS         00000000006000d4
000000d4
       000000000000000f  0000000000000000  WA       0     0     4
  [ 3] .symtab           SYMTAB           0000000000000000
000000e8
       00000000000000d8  0000000000000018           4     5     8
  [ 4] .strtab           STRTAB           0000000000000000
000001c0
       000000000000002b  0000000000000000           0     0     1
  [ 5] .shstrtab         STRTAB           0000000000000000
000001eb
       0000000000000027  0000000000000000           0     0     1
Key to Flags:
  W (write), A (alloc), X (execute), M (merge), S (strings), I
(info),
  L (link order), O (extra OS processing required), G (group), T
(TLS),
  C (compressed), x (unknown), o (OS specific), E (exclude),
  l (large), p (processor specific)
$ objdump -d -M intel hello64
hello64:     file format elf64-x86-64


Disassembly of section .text:

00000000004000b0 <_start>:
  4000b0: b8 04 00 00 00        mov    eax,0x4
  4000b5: bb 01 00 00 00        mov    ebx,0x1
  4000ba: b9 d4 00 60 00        mov    ecx,0x6000d4
  4000bf: ba 0e 00 00 00        mov    edx,0xe
  4000c4: cd 80                 int    0x80
```

```
  4000c6: b8 01 00 00 00        mov    eax,0x1
  4000cb: bb 00 00 00 00        mov    ebx,0x0
  4000d0: cd 80                 int    0x80
  4000d2: c3                    ret
$ dd if=hello64 bs=1 skip=172 count=35 | hexdump -C
35+0 records in
35+0 records out
35 bytes copied, 0.000245707 s, 142 kB/s
00000000  b8 04 00 00 00 bb 01 00  00 00 b9 d4 00 60 00 ba
|.............`..|
00000010  0e 00 00 00 cd 80 b8 01  00 00 00 bb 00 00 00 00
|................|
00000020  cd 80 c3                                         |...|
00000023
$ dd if=hello64 bs=1 skip=212 count=15 | hexdump -C
15+0 records in
15+0 records out
15 bytes copied, 0.000139912 s, 107 kB/s
00000000  68 65 6c 6c 6f 2c 20 77  6f 72 6c 64 21 0a 00
|hello, world!..|
0000000f
```

- compare between PIE enable and PIE not enable
  - program header

```
$ readelf -l nopie
Elf file type is EXEC (Executable file)
Entry point 0x400400
...
  LOAD           0x0000000000000000 0x0000000000400000
0x0000000000400000
                 0x00000000000006d0 0x00000000000006d0  R E
0x200000
  LOAD           0x0000000000000e10 0x0000000000600e10
0x0000000000600e10
                 0x0000000000000220 0x0000000000000228  RW
0x200000
...
$ readelf -l pie
Elf file type is DYN (Shared object file)
Entry point 0x530
...
  LOAD           0x0000000000000000 0x0000000000000000
0x0000000000000000
                 0x0000000000000838 0x0000000000000838  R E
0x200000
  LOAD           0x0000000000000db8 0x0000000000200db8
0x0000000000200db8
                 0x0000000000000258 0x0000000000000260  RW
0x200000
...
```

```
```

- section header

  ```
  $ readelf -S nopie
  There are 29 section headers, starting at offset 0x18e8:

  Section Headers:
  ...
    [13] .text             PROGBITS         0000000000400400
  00000400
         0000000000000172  0000000000000000  AX       0     0
  16
  ...
  $ readelf -S pie
  There are 29 section headers, starting at offset 0x1930:

  Section Headers:
  ...
    [14] .text             PROGBITS         0000000000000530
  00000530
         00000000000001a2  0000000000000000  AX       0     0
  16
  ...
  ```

- vmmap

  ```
  # nopie
  0000000000400000-0000000000401000 r-xp 0        .../nopie
  0000000000600000-0000000000602000 rw-p 0        .../nopie
  # pie
  0000557a39a2c000-0000557a39a2d000 r-xp 0        .../pie
  0000557a39c2c000-0000557a39c2e000 rw-p 0        .../pie
  # pie in gdb will always map .text to 0x0000555555554000 for
  debug
  0000555555554000-0000555555555000 r-xp 0        .../pie
  0000555555755000-0000555555756000 rw-p 0        .../pie
  ```

Handle Breakpoints

- `INT` Instruction
  - `int 0x??` -> machine code `0xcd 0x??`
  - `int 0x13`: x86 BIOS disk IO functions (real-mode)
  - `int 0x10`: x86 BIOS video functions (read-mode)
  - `int 0x21`: x86 DOS APIs (real-mode)
  - `int 0x80`: x86 Linux system call functions
- `0xcc` Machine Code

- used for breakpoints in debuggers
- similar to `int 0x03`, but only one byte
- good for code patching, and fit to any size of instructions
- operation
    - trigger `int 0x03`
    - send `SIGTRAP` to tracer
    - child stop right after `0xcc`

- Breakpoints
    - setup: replace code with `0xcc`
    - once a break point is hit
        - determine which break point is hit by `rip`
        - do anything about monitor or change state
        - restore the code, `0xcc` must be replace with the original byte
        - restore rip
        - continue program execution
    - solution of reuse the breakpoint
        - use `PTRACE_SINGLESTEP` to run the restored instruction
        - then put `0xcc` back to the address

- Example

```
uint64_t code = ptrace(PTRACE_PEEKTEXT, child, target, 0);
uint64_t replace = (code & 0xffffffffffffff00) | 0xcc;
if (ptrace(PTRACE_POKETEXT, child, target, replace) != 0)
  errquit("ptrace(POKETEXT)");
ptrace(PTRACE_CONT, child, 0, 0);
while (waitpid(child, &status, 0) > 0) {
  struct user_regs_struct regs;
  if (!WIFSTOPPED(status)) continue;
  if (ptrace(PTRACE_GETREGS, child, 0, &regs) != 0)
errquit("ptrace(GETREGS)");
  if (regs.rip - 1 == target) {
    /* restore break point */
    if (ptrace(PTRACE_POKETEXT, child, target, code) != 0)
      errquit("ptrace(POKETEXT)");
    /* set registers */
    regs.rip = regs.rip - 1;
    regs.rdx = regs.rax;
    if (ptrace(PTRACE_SETREGS, child, 0, &regs) != 0)
      errquit("ptrace(SETREGS)");
  }
  ptrace(PTRACE_CONT, child, 0, 0);
}
```