实践项目P3：交叉编译和跨平台应用仿真

问题1

在 Ubuntu 上安装能够运行 aarch64 (64-bit ARM ISA)应用的 **Qemu 虚拟机**（qemu-aarch64）

1.安装*qemu-aarch64*

这里我们首先安装***qemu-aarch64***，这里我通过apt包管理工具来安装，并补全所需的库

```
sudo apt install qemu-user qemu-user-static
sudo apt install libc6-arm64-cross
```

接下来我们进行验证

```
harry@harry-virtual-machine:~$ qemu-aarch64 --version
qemu-aarch64 version 6.2.0 (Debian 1:6.2+dfsg-2ubuntu6.24)
Copyright (c) 2003-2021 Fabrice Bellard and the QEMU Project developers
```

2.使用 QEMU 运行完整的 `aarch64` 系统

1.根文件系统的制作

我们首先安装需要的工具库

```
$ sudo apt-get install debian-archive-keyring bison flex bc build-essential libncurses* libssl-dev
$ sudo apt-get install  qemu-user-static binfmt-support debootstrap
```

这里我要制作的是Debian12的根文件系统，我们用***deboostrap***命令来下载软件包

```
$ debootstrap --arch=arm64 --foreign bookworm linux_rootfs http://mirrors.ustc.edu.cn/debian/
```

这里我们指定了架构为arm64，版本代号为bookworm，即Debian12，从ustc源进行下载

接下来使用qemu-aarche64-static来模拟arm64环境的执行环境

```
$sudo cp /usr/bin/qemu-aarch64-static /home/harry/linux_rootfs/usr/bin/
```

下面使用debootstrap命令进行软件包的安装和配置

```
$ sudo chroot linux_rootfs/ debootstrap/debootstrap --second-stage
```

然后切换到制作好的根文件系统

```
$ chroot linux_rootfs/
```

接下来进行基础的设置，包括root密码的修改，host名根据本次实验设置为P3VMPC，网络设置

```
$ passwd root
$ echo P3PC > /etc/hostname
$ echo "auto lo" > /etc/network/interfaces
$ echo "iface lo inet loopback" >> /etc/network/interfaces
$ echo "allow-hotplug enp0s1" > /etc/network/interfaces
$ echo "iface enp0s1 inet dhcp" >> /etc/network/interfaces
$ apt update
$ apt install net-tools
$ exit
```

2.制作ext4文件系统

接下来我们来为Qemu虚拟机来制作ext4文件系统，首先用dd命令创建一个image文件并格式化

```
$ dd if=/dev/zero of=linux_rootfs.ext4 bs=1M count=2048
$ mkfs.ext4 linux_rootfs.ext4
```

bs=1M表示block大小，count=2048，表示该image大小为2GB

接下来挂载ext4文件系统并拷贝内容

```
$ mkdir -p tmpfs
$ sudo mount -t ext4 linux_rootfs.ext4 tmpfs/ -o loop
$ sudo cp -af linux_rootfs/* tmpfs/
$ sudo umount tmpfs
$ sudo chmod 777 linux_rootfs.ext4
```

3.编译Linux内核

接下来，我们需要下载Linux内核文件并编译，这里我下载的是6.1.100版本。

```
$ cd linux-6.1.100/
$ export ARCH=arm64
$ export CROSS_COMPILE=aarch64-linux-gnu-
$ make defconfig
$ make -j4
```

编译成功后，我们会得到vmlinux和Image文件。

4.使用qemu运行arm64的虚拟机

我们在工作目录下执行如下指令

```
sudo qemu-system-aarch64 -m 1024 -cpu cortex-a57 -M virt -nographic -smp 4 -kernel linux-6.1.100/arch/arm64/boot/Image -append "noinintrd sched_debug root=/dev/vda rootfstype=ext4 rw crashkernel=256M loglevel=8" -drive if=none,file=linux_rootfs.ext4,id=hd0 -device virtio-blk-device,drive=hd0
```

其中：

-m 1024 指定内存大小为 1 G；

-cpu指定了模拟的cpu为 cortex-a57；

-M machine选择模拟的机器；

-nographic禁止所有的图形输出；

-smp 4指定模拟的系统为 4 核处理器 ；

-kernel指定启动的内核镜像；

--append指定传递的命令行参数；

后面的“**-drive** if=none,file=myrootfs_arm64.ext4,id=hd0 -device virtio-blk-device,drive=hd0”添加根文件系统支持

然后我们用root登录，成功用Qemu搭建了一个arm虚拟机，通过***uname -a***进行验证

```
[  OK  ] Finished systemd-user-sess…ervice - Permit User Sessions.
[  OK  ] Started getty@tty1.service - Getty on tty1.
[  OK  ] Started getty@tty2.service - Getty on tty2.
[  OK  ] Started getty@tty3.service - Getty on tty3.
[  OK  ] Started getty@tty4.service - Getty on tty4.
[  OK  ] Started getty@tty5.service - Getty on tty5.
[  OK  ] Started getty@tty6.service - Getty on tty6.
[  OK  ] Started serial-getty@ttyAM…ice - Serial Getty on ttyAMA0.
[  OK  ] Reached target getty.target - Login Prompts.
[  OK  ] Reached target multi-user.target - Multi-User System.
[  OK  ] Reached target graphical.target - Graphical Interface.
         Starting systemd-update-ut… Record Runlevel Change in UTMP...
[  OK  ] Finished systemd-update-ut… - Record Runlevel Change in UTMP.

Debian GNU/Linux 12 P3VMPC ttyAMA0

P3VMPC login: root
Password:
Linux P3VMPC 6.1.100 #1 SMP PREEMPT Sun Dec 15 23:53:28 CST 2024 aarch64

The programs included with the Debian GNU/Linux system are free software;
the exact distribution terms for each program are described in the
individual files in /usr/share/doc/*/copyright.

Debian GNU/Linux comes with ABSOLUTELY NO WARRANTY, to the extent
permitted by applicable law.
Last login: Sun Dec 15 16:03:30 UTC 2024 on ttyAMA0
root@P3VMPC:~# uname -a
Linux P3VMPC 6.1.100 #1 SMP PREEMPT Sun Dec 15 23:53:28 CST 2024 aarch64 GNU/Linux
```

问题2

安装 aarch64 的 GCC 工具链(gcc-10-aarch64-linux-gnu)

通过apt包管理工具安装

```
sudo apt install gcc-10-aarch64-linux-gnu
```

然后验证安装

```
aarch64-linux-gnu-gcc --version
```

```
Elapsed execution time: 1.056277 sec; N: 1024, I: 500000, __OP__: +, __TYPE__
harry@harry-virtual-machine:~/P3_loop$ aarch64-linux-gnu-gcc --version
aarch64-linux-gnu-gcc (Ubuntu 11.4.0-1ubuntu1~22.04) 11.4.0
Copyright (C) 2021 Free Software Foundation, Inc.
This is free software; see the source for copying conditions.  There is NO
warranty; not even for MERCHANTABILITY or FITNESS FOR A PARTICULAR PURPOSE.
```

问题3

用 aarch64 的 GCC 工具链交叉编译 loop.c (-O2)，生成可执行文件 loop.aarch64.gcc，**并用**qemu-aarch64 **运行 loop.aarch64.gcc**

我们将下载好的loop.c进行编译，并运行，这里我们输入的参数为5

```
aarch64-linux-gnu-gcc -O2 -static -o loop.aarch64.gcc loop.c
qemu-aarch64 ./loop.aarch64.gcc
```

运行结果如下

```
[   90.307414] reboot: Power down
harry@harry-virtual-machine:~/P3_loop$ qemu-aarch64 ./loop.aarch64.gcc 5
Elapsed execution time: 1.056277 sec; N: 1024, I: 500000, __OP__: +, __TYPE__: uint32_t
```

问题4

用 clang 交叉编译 loop.c(-O2)，生成可执行文件**loop.aarch64.clang**，并用**qemu-aarch64 运行 loop.aarch64.clang**

我们利用clang来进行编译并运行，输入的参数依旧为5

```
clang -O2 -static -target aarch64-linux-gnu -o loop.aarch64.clang
loop.c
qemu-aarch64 ./loop.aarch64.clang
```

运行结果如下

```
harry@harry-virtual-machine:~/P3_loop$ qemu-aarch64 ./loop.aarch64.clang 5
Elapsed execution time: 0.441408 sec; N: 1024, I: 500000, __OP__: +, __TYPE__: uint32_t
```

问题5

用 qemu-aarch64 分 别 运 行 前 面 编 译 出 来 的 loop.aarch64.gcc 和**loop.aarch64.clang** 分别用参数5、15、30、60、90进行测试），记下每次测试的执行时间并以图形方式呈现。

问题6

用host机器上的gcc和clang分别编译(-O2)出loop.x64.gcc和loop.x64.clang，**并对这两个执行文件分别用参数** 5、15、30、60、90进行测试，记下每次测试的执行时间并以图形方式呈现，进而与前一步**qemu 仿真测试的结果进行比较。**

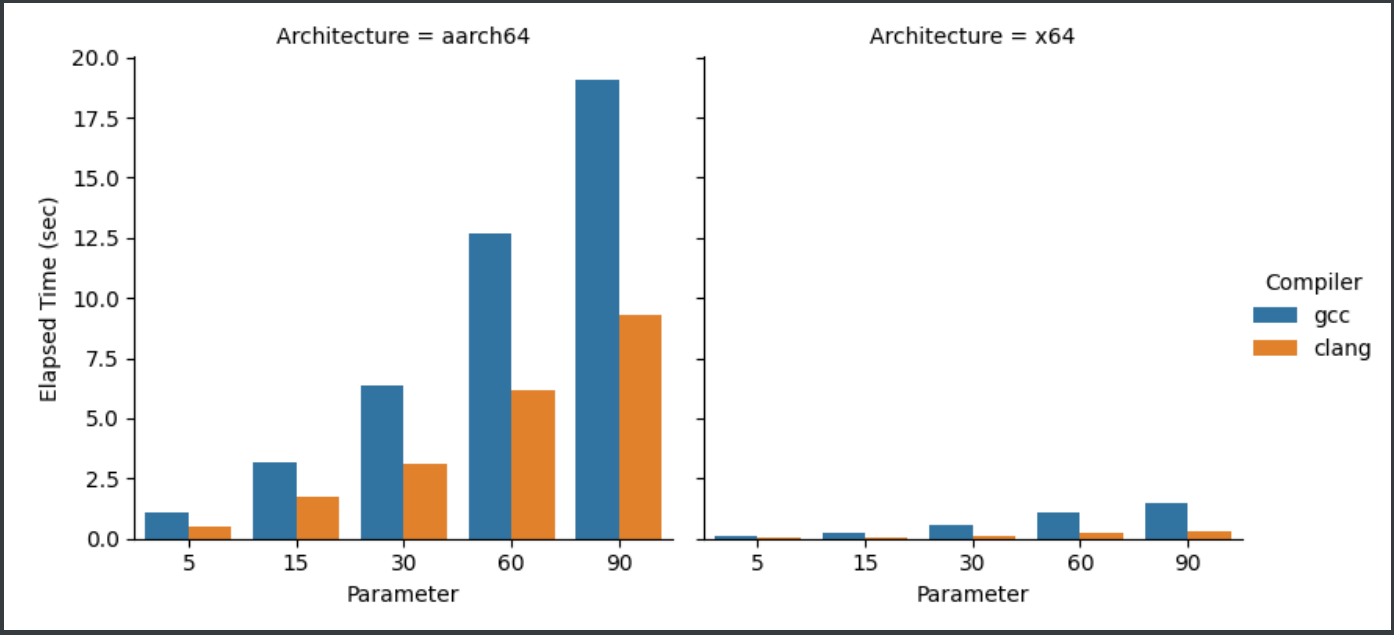
问题5问题6这里我放在一起来进行。这里我编写了一个***Makefile***用于批量生成、运行并记录结果

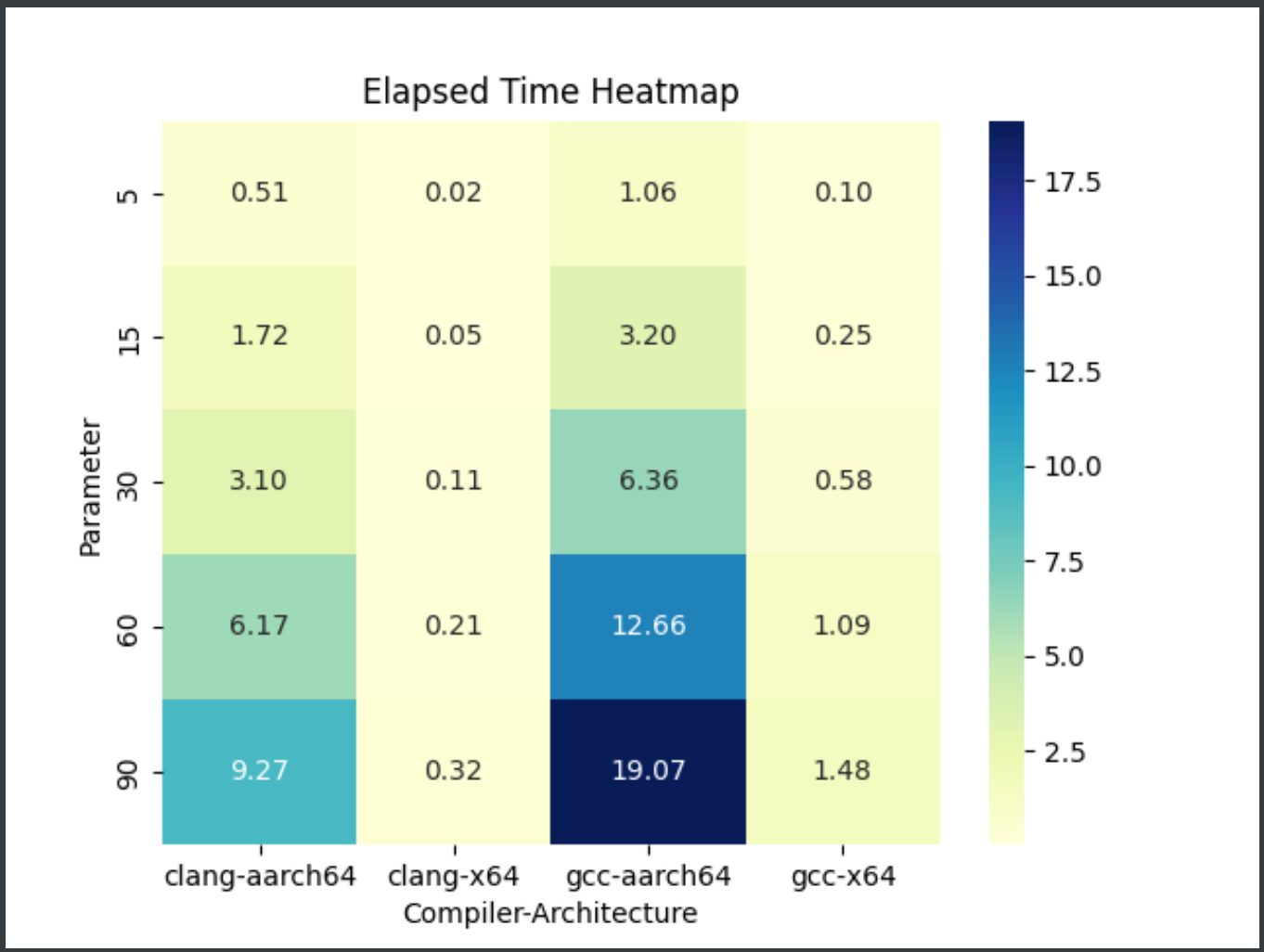
```
# 定义变量
CC_AARCH64_GCC = aarch64-linux-gnu-gcc
CC_AARCH64_CLANG = clang --target=aarch64-linux-gnu
CC_X64_GCC = gcc
CC_X64_CLANG = clang
QEMU_AARCH64 = qemu-aarch64

# 优化级别
OPT_LEVEL = -O2

# 测试参数
```

```
TEST_PARAMS = 5 15 30 60 90

# 目标文件
TARGETS = loop.aarch64.gcc loop.aarch64.clang loop.x64.gcc
loop.x64.clang

# 默认目标
all: report.txt

# 清理目标
clean:
  rm -f $(TARGETS) report.txt results.csv

# 编译 aarch64 的 gcc 版本
loop.aarch64.gcc: loop.c
  $(CC_AARCH64_GCC) $(OPT_LEVEL) -static -o $@ $<

# 编译 aarch64 的 clang 版本
loop.aarch64.clang: loop.c
  $(CC_AARCH64_CLANG) $(OPT_LEVEL) -static -o $@ $<

# 编译 x64 的 gcc 版本
loop.x64.gcc: loop.c
  $(CC_X64_GCC) $(OPT_LEVEL) -static -o $@ $<

# 编译 x64 的 clang 版本
loop.x64.clang: loop.c
  $(CC_X64_CLANG) $(OPT_LEVEL) -static -o $@ $<

# 运行测试并生成报告
report.txt: $(TARGETS)
  echo "Test Results:" > report.txt
  echo "Parameter,Compiler,Architecture,Elapsed Time (sec)" >
results.csv
  for param in $(TEST_PARAMS); do \
    # 运行 aarch64 gcc 版本并记录结果 \
```

```
    echo "Running loop.aarch64.gcc with parameter $$param..." >>
report.txt; \
    ELAPSED_TIME=$$($(QEMU_AARCH64) ./loop.aarch64.gcc $$param | grep
"Elapsed execution time" | awk '{print $$4}'); \
    echo "$$param,gcc,aarch64,$$ELAPSED_TIME" >> results.csv; \
    echo "Result: $$ELAPSED_TIME sec" >> report.txt; \
    # 运行 aarch64 clang 版本并记录结果 \
    echo "Running loop.aarch64.clang with parameter $$param..." >>
report.txt; \
    ELAPSED_TIME=$$($(QEMU_AARCH64) ./loop.aarch64.clang $$param |
grep "Elapsed execution time" | awk '{print $$4}'); \
    echo "$$param,clang,aarch64,$$ELAPSED_TIME" >> results.csv; \
    echo "Result: $$ELAPSED_TIME sec" >> report.txt; \
    # 运行 x64 gcc 版本并记录结果 \
    echo "Running loop.x64.gcc with parameter $$param..." >>
report.txt; \
    ELAPSED_TIME=$$(./loop.x64.gcc $$param | grep "Elapsed execution
time" | awk '{print $$4}'); \
    echo "$$param,gcc,x64,$$ELAPSED_TIME" >> results.csv; \
    echo "Result: $$ELAPSED_TIME sec" >> report.txt; \
    # 运行 x64 clang 版本并记录结果 \
    echo "Running loop.x64.clang with parameter $$param..." >>
report.txt; \
    ELAPSED_TIME=$$(./loop.x64.clang $$param | grep "Elapsed execution
time" | awk '{print $$4}'); \
    echo "$$param,clang,x64,$$ELAPSED_TIME" >> results.csv; \
    echo "Result: $$ELAPSED_TIME sec" >> report.txt; \
  done
  echo "Results saved to results.csv" >> report.txt
```

最终将结果进行可视化，这里我绘制了两张，分别为分面图和热力图





我们可以根据结果得到如下结论

- `clang` 的耗时显著低于 `gcc` 。
- `aarch64` 交叉编译版本的耗时显著高于原生 `x64` 版本。

- 随着 `Parameter` 的增加，耗时近似呈线性增长。

问题7

安装支持多 ISA 的 gdb 调试器（gdb-multiarch）

我们可以通过apt包管理工具进行安装

```
sudo apt install gdb-multiarch
```

并通过如下指令验证

```
gdb-multiarch --version
```

```
harry@harry-virtual-machine:~/P3_loop$ gdb-multiarch --version
GNU gdb (Ubuntu 12.1-0ubuntu1~22.04.2) 12.1
Copyright (C) 2022 Free Software Foundation, Inc.
License GPLv3+: GNU GPL version 3 or later <http://gnu.org/licenses/gpl.html>
This is free software: you are free to change and redistribute it.
There is NO WARRANTY, to the extent permitted by law.
```

问题8

用 gdb-multiarch 结合 qemu-aarch64 对 loop.aarch64.gcc.debug 进行源码级调试

我们首先编译生成带调试信息的 loop.aarch64.gcc.debug

```
aarch64-linux-gnu-gcc -static -g -o loop.aarch64.gcc.debug loop.c
```

接下来我们将loop.aarch64.gcc.debug以调试模式运行在本地端口上

```
qemu-aarch64 -g 1235 ./loop.aarch64.gcc.debug
```

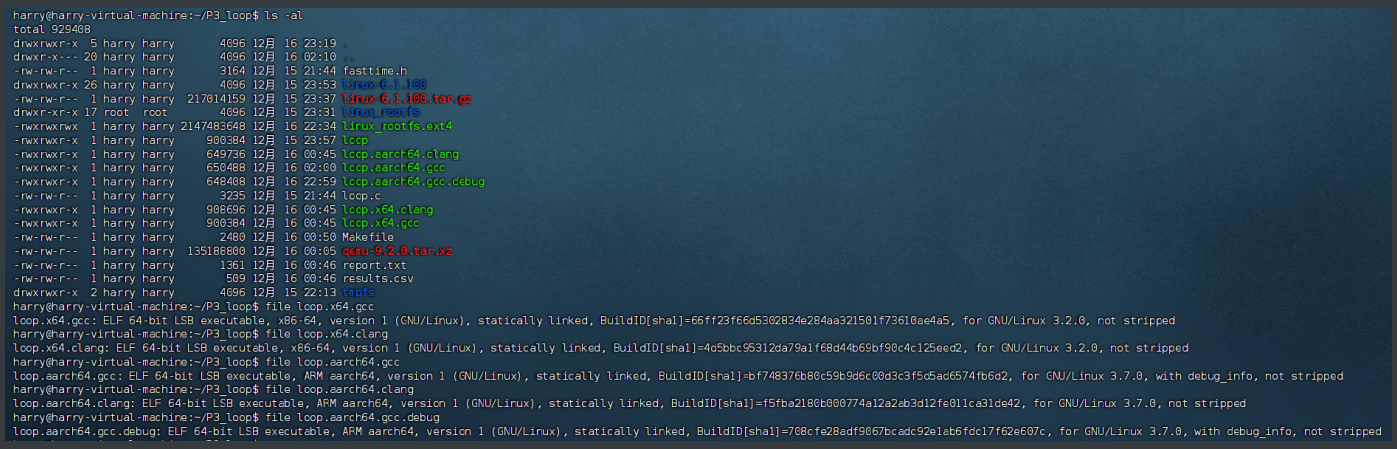
我们再开启一个终端进行连接

```
gdb-multiarch ./loop.aarch64.gcc.debug
target remote localhost:1235
```

接下来就可以进行调试了

```
harry@harry-virtual-machine:~/P3_loop$ gdb-multiarch ./loop.aarch64.gcc.debug
GNU gdb (Ubuntu 12.1-0ubuntu1~22.04.2) 12.1
Copyright (C) 2022 Free Software Foundation, Inc.
License GPLv3+: GNU GPL version 3 or later <http://gnu.org/licenses/gpl.html>
This is free software: you are free to change and redistribute it.
There is NO WARRANTY, to the extent permitted by law.
Type "show copying" and "show warranty" for details.
This GDB was configured as "x86_64-linux-gnu".
Type "show configuration" for configuration details.
For bug reporting instructions, please see:
<https://www.gnu.org/software/gdb/bugs/>.
Find the GDB manual and other documentation resources online at:
    <http://www.gnu.org/software/gdb/documentation/>.

For help, type "help".
Type "apropos word" to search for commands related to "word"...
Reading symbols from ./loop.aarch64.gcc.debug...
(gdb) target remote localhost:1235
Remote debugging using localhost:1235
0x0000000000400580 in _start ()
(gdb) set args 5
(gdb) b main
Breakpoint 1 at 0x4007d0: file loop.c, line 49.
(gdb) continue
Continuing.

Breakpoint 1, main (argc=1, argv=0x55008003d8) at loop.c:49
49      int main(int argc, char *argv[]) {
(gdb)
```

附录：工作目录截图


harry@harry-virtual-machine:~/P3_loop$ ls -al
total 929408
drwxrwxr-x 5 harry harry   4096 12月 16 23:19 .
drwxr-x--- 20 harry harry   4096 12月 16 02:10 ..
-rw-rw-r-- 1 harry harry   3164 12月 15 21:44 fasttime.h
drwxrwxr-x 26 harry harry   4096 12月 15 23:53 linux-6.1.100
-rw-rw-r-- 1 harry harry 217014159 12月 15 23:37 linux-6.1.100.tar.gz
drwxr-xr-x 17 root root   4096 12月 15 23:31 linux_rootfs
-rwxrwxrwx 1 harry harry 2147483648 12月 16 22:34 linux_rootfs.ext4
-rwxrwxr-x 1 harry harry   900384 12月 15 23:57 lccp
-rwxrwxr-x 1 harry harry   649736 12月 16 00:45 lccp.aarch64.clang
-rwxrwxr-x 1 harry harry   650488 12月 16 02:00 lccp.aarch64.gcc
-rwxrwxr-x 1 harry harry   648408 12月 16 22:59 lccp.aarch64.gcc.debug
-rw-rw-r-- 1 harry harry   3235 12月 15 21:44 lccp.c
-rwxrwxr-x 1 harry harry   908696 12月 16 00:45 lccp.x64.clang
-rwxrwxr-x 1 harry harry   900384 12月 16 00:45 lccp.x64.gcc
-rw-rw-r-- 1 harry harry   2480 12月 16 00:50 Makefile
-rw-rw-r-- 1 harry harry 135188800 12月 16 00:05 qemu-9.2.0.tar.xz
-rw-rw-r-- 1 harry harry   1361 12月 16 00:46 report.txt
-rw-rw-r-- 1 harry harry   509 12月 16 00:46 results.csv
drwxrwxr-x 2 harry harry   4096 12月 15 22:13 tmprs
harry@harry-virtual-machine:~/P3_loop$ file loop.x64.gcc
loop.x64.gcc: ELF 64-bit LSB executable, x86-64, version 1 (GNU/Linux), statically linked, BuildID[sha1]=66ff23f66d5302834e284aa321501f73610ae4a5, for GNU/Linux 3.2.0, not stripped
harry@harry-virtual-machine:~/P3_loop$ file loop.x64.clang
loop.x64.clang: ELF 64-bit LSB executable, x86-64, version 1 (GNU/Linux), statically linked, BuildID[sha1]=4d5bbc95312da79a1f68d44b69bf90c4c125eed2, for GNU/Linux 3.2.0, not stripped
harry@harry-virtual-machine:~/P3_loop$ file loop.aarch64.gcc
loop.aarch64.gcc: ELF 64-bit LSB executable, ARM aarch64, version 1 (GNU/Linux), statically linked, BuildID[sha1]=bf748376b80c59b9d6c00d3c3f5d5ac6574fb6d2, for GNU/Linux 3.7.0, with debug_info, not stripped
harry@harry-virtual-machine:~/P3_loop$ file loop.aarch64.clang
loop.aarch64.clang: ELF 64-bit LSB executable, ARM aarch64, version 1 (GNU/Linux), statically linked, BuildID[sha1]=f5fba2180b800774a12a2ab3d12fe011ca31de42, for GNU/Linux 3.7.0, not stripped
harry@harry-virtual-machine:~/P3_loop$ file loop.aarch64.gcc.debug
loop.aarch64.gcc.debug: ELF 64-bit LSB executable, ARM aarch64, version 1 (GNU/Linux), statically linked, BuildID[sha1]=708cfe28adf9067bcadc92e1ab6fdc17f62e607c, for GNU/Linux 3.7.0, with debug_info, not stripped