Programming Design Homework 01 資工2B 408410120 鍾博丞

環境配置

Operating System: Ubuntu 20.04 LTS using KDE plasma

CPU: AMD R9 3900X 12C 24T @ 3.8GHz

RAM: 32GB DDR4 3600MHz (Double channel)

SSD: WD Black 256G WDS256G1X0C TLC (Seq. R: 2050MB/s, Seq. W: 700MB/s, Random R: 170K IOPS, Random W: 130K IOPS)

Github Link

https://reurl.cc/0DqKQ9

A. 操作方法

在 sortperf.c 裡，有接收 argv[0] 的參數作為要排序的方法，若直接執行 sortperf，將直接使用內建的 qsort 函式完成排序，執行 `make` 時，將自動產生 heapsort, mergesort, quicksort 共三個指向主程式 sortperf.c 的 symbolic link，使用者只需執行對應名稱的 symbolic link 即可使用該方法進行排序，舉例，執行 `./heapsort` 就可以使用 heapsort 進行排序

同樣的，在 sortperf_string.c 裡，也有相對應的 symbolic link

```
❯ ls -lash
總用量 1.2G
4.0K drwxrwxr-x 3 ubuntu2004 ubuntu2004 4.0K  4月  20 23:50 .
4.0K drwxrwxr-x 6 ubuntu2004 ubuntu2004 4.0K  4月  18 17:16 ..
4.0K drwxrwxr-x 2 ubuntu2004 ubuntu2004 4.0K  4月  18 17:21 img
4.0K -rw-rw-r-- 1 ubuntu2004 ubuntu2004  210  4月  20 23:18 .gitignore
   0 lrwxrwxrwx 1 ubuntu2004 ubuntu2004    8  4月  20 23:50 heapsort -> sortperf
   0 lrwxrwxrwx 1 ubuntu2004 ubuntu2004   15  4月  20 23:50 heapsort_string -> sortperf_string
4.0K -rw-rw-r-- 1 ubuntu2004 ubuntu2004  829  4月  20 23:50 makefile
4.0K -rw-rw-r-- 1 ubuntu2004 ubuntu2004  547  4月  18 17:12 make_tar.bz2.sh
   0 lrwxrwxrwx 1 ubuntu2004 ubuntu2004    8  4月  20 23:50 mergesort -> sortperf
   0 lrwxrwxrwx 1 ubuntu2004 ubuntu2004   15  4月  20 23:50 mergesort_string -> sortperf_string
   0 lrwxrwxrwx 1 ubuntu2004 ubuntu2004    8  4月  20 23:50 quicksort -> sortperf
   0 lrwxrwxrwx 1 ubuntu2004 ubuntu2004   15  4月  20 23:50 quicksort_string -> sortperf_string
 20K -rwxrwxr-x 1 ubuntu2004 ubuntu2004  20K  4月  20 23:50 random_int_generater
4.0K -rw-rw-r-- 1 ubuntu2004 ubuntu2004 1.5K  4月  20 23:37 random_int_generater.c
168M -rw-rw-r-- 1 ubuntu2004 ubuntu2004 168M  4月  20 23:47 random_int.txt
 24K -rwxrwxr-x 1 ubuntu2004 ubuntu2004  21K  4月  20 23:50 random_string_generater
4.0K -rw-rw-r-- 1 ubuntu2004 ubuntu2004 2.5K  4月  20 23:35 random_string_generater.c
1.1G -rw-rw-r-- 1 ubuntu2004 ubuntu2004 1.1G  4月  20 23:47 random_string.txt
4.0K -rw-rw-r-- 1 ubuntu2004 ubuntu2004 1.3K  4月  18 17:21 README.md
 24K -rwxrwxr-x 1 ubuntu2004 ubuntu2004  22K  4月  20 23:50 sortperf
8.0K -rw-rw-r-- 1 ubuntu2004 ubuntu2004 5.3K  4月  20 23:49 sortperf.c
 24K -rwxrwxr-x 1 ubuntu2004 ubuntu2004  23K  4月  20 23:50 sortperf_string
8.0K -rw-rw-r-- 1 ubuntu2004 ubuntu2004 6.4K  4月  20 23:49 sortperf_string.c
```

執行 `make gen` 時，會自動執行亂數產生器並使用 strace 顯示出總共呼叫多少以及哪些 system call

```
time strace -c ./random_string_generater
Malloc time: 809093 us (equal 0.809093 sec)
Generate random string time: 20951939 us (equal 20.951939 sec)
Write to file time: 3429998 us (equal 3.429998 sec)
% time     seconds  usecs/call     calls    errors syscall
------ ----------- ----------- --------- --------- ----------------
 96.77    0.739523           2    266249           write
  3.23    0.024687           1     17876           brk
  0.00    0.000003           0         5           fstat
  0.00    0.000000           0         2           read
  0.00    0.000000           0         4         1 close
  0.00    0.000000           0        14           mmap
  0.00    0.000000           0         5           mprotect
  0.00    0.000000           0         1           munmap
  0.00    0.000000           0         2           rt_sigaction
  0.00    0.000000           0         1           rt_sigprocmask
  0.00    0.000000           0         8           pread64
  0.00    0.000000           0         1         1 access
  0.00    0.000000           0         1           execve
  0.00    0.000000           0         2         1 arch_prctl
  0.00    0.000000           0         1           set_tid_address
  0.00    0.000000           0         4           openat
  0.00    0.000000           0         1           set_robust_list
  0.00    0.000000           0         1           prlimit64
------ ----------- ----------- --------- --------- ----------------
100.00    0.764213                284178         3 total

real    0m25.249s
user    0m22.464s
sys     0m3.231s

time strace -c ./random_int_generater
Malloc time: 77 us (equal 0.000077 sec)
Generate random string time: 104485 us (equal 0.104485 sec)
Write to file time: 1482024 us (equal 1.482024 sec)
% time     seconds  usecs/call     calls    errors syscall
```

```
------ ----------- ----------- --------- --------- ----------------
 99.99    0.037884           0     42941           write
  0.01    0.000003           1         3           close
  0.00    0.000000           0         1           read
  0.00    0.000000           0         4           fstat
  0.00    0.000000           0         8           mmap
  0.00    0.000000           0         4           mprotect
  0.00    0.000000           0         1           munmap
  0.00    0.000000           0         3           brk
  0.00    0.000000           0         6           pread64
  0.00    0.000000           0         1         1 access
  0.00    0.000000           0         1           execve
  0.00    0.000000           0         2         1 arch_prctl
  0.00    0.000000           0         3           openat
------ ----------- ----------- --------- --------- ----------------
100.00    0.037887                42978         2 total

real    0m1.592s
user    0m1.174s
sys     0m0.503s
```

執行 `make clean` 時，將刪除所有執行檔和 symbolic link，不包含測試資料，因為測試資料量高達 2^24 (約 16.7M) 筆資料，生成所需耗費的資源與時間都較大

欲刪除測試資料，可執行 `make clean_gen`

B. 亂數資料生成方法

int 亂數較為簡單，主要生成方法為

```
arr = (int *)malloc(ARRSIZE * sizeof(int));
for (i = 0; i < ARRSIZE; ++i) {
    arr[i] = rand();
}
```

string 亂數較為複雜，首先 malloc 2^24 個 char * array，然後再對每個指標 malloc 128 bytes 的空間，再利用亂數產生不同長度的英數字混合字串

```
arr = (char **)malloc(ARRSIZE * sizeof(char *));
for (int i = 0; i < ARRSIZE; ++i) {
    arr[i] = (char *)malloc(128 * sizeof(char));
}
for (i = 0; i < ARRSIZE; ++i) {
    lineLen = rand() % 125 + 2;
    for (j = 0; j < lineLen; ++j) {
        // 生成英數字混合字串
    }
    arr[i][j] = '\n';
}
```

C. 演算法實作及複雜度

1. Merge Sort

Merge sort 使用 recursive call 形成 call stack，達成 divide，而最後使用 merge 函數將兩區域排序，達成 conquer，merge 函數會 malloc 出左陣列和右陣列，抄完之後再依照大小回推到原本的陣列，完成之後 free 掉兩個陣列

Time complexity: $O(n \cdot \lg n)$

Space complexity: $O(n)$

2. Quick Sort

這裡採用第一個元素當作 pivot 進行分堆，由於沒有使用中位數，故若遇到較為極端的例子，例如為一反序陣列，這時 quick sort 會非常慢

如果是 worst case，會有 $n-1$ 次 recursive call，故需執行

$\sum_{i=0}^{n}(n-i) = n^2 - \frac{n(n+1)}{2}$

次操作

Quick sort 為一種 inplace 的排序，故計算空間複雜度時，會以產生多少 call stack 作為參考，如果是 worst case，會有 $n-1$ 次 recursive call

Average time complexity: $O(n \cdot \lg n)$

Worst time complexity: $O(n^2)$

Average space complexity: $O(\lg n)$

Worst space complexity: $O(n)$

3. Heap Sort

首先對於每一個元素做 shift down，產生 Max heap，然後依序將第一個元素與最後一個元素對調，heap size - 1，然後對於第一個元素做 shift down，直到 heap size = 1 即完成排序

Heap sort 為一種 inplace 的排序，故計算空間複雜度時，會以產生多少 call stack 作為參考，對於第一個元素做 shift down，使用的 call stack 會是整個 heap tree 的高度

Time complexity: $O(n \cdot \lg n)$

Space complexity: $O(\lg n)$

D. 測量結果

1. 2^24 (約16.7M) 筆 *int* 資料

(1) qsort

```
❯ time strace -c ./sortperf
qsort used 2338503 microseconds.
qsort used 2.34 seconds.
% time     seconds  usecs/call     calls    errors syscall
------ ----------- ----------- --------- --------- ----------------
 81.75    0.007541           0     42940           read
 18.25    0.001684         561         3           munmap
  0.00    0.000000           0         2           write
  0.00    0.000000           0         2           close
  0.00    0.000000           0         4           fstat
  0.00    0.000000           0         9           mmap
  0.00    0.000000           0         4           mprotect
  0.00    0.000000           0         3           brk
  0.00    0.000000           0         6           pread64
  0.00    0.000000           0         1         1 access
  0.00    0.000000           0         1           execve
  0.00    0.000000           0         1           sysinfo
  0.00    0.000000           0         2         1 arch_prctl
  0.00    0.000000           0         2           clock_gettime
  0.00    0.000000           0         3           openat
------ ----------- ----------- --------- --------- ----------------
100.00    0.009225                 42983         2 total
strace -c ./sortperf  3.65s user 0.33s system 102% cpu 3.897 total
```

(2) mergesort

```
❯ time strace -c ./mergesort
mergesort used 3257837 microseconds.
mergesort used 3.26 seconds.
% time     seconds  usecs/call     calls    errors syscall
------ ----------- ----------- --------- --------- ----------------
 80.33    0.009065           0     42940           read
 19.17    0.002163         113        19           munmap
  0.49    0.000055           1        49           brk
  0.01    0.000001           0         2           write
  0.01    0.000001           0        25           mmap
  0.00    0.000000           0         3           close
  0.00    0.000000           0         4           fstat
  0.00    0.000000           0         4           mprotect
  0.00    0.000000           0         6           pread64
  0.00    0.000000           0         1         1 access
  0.00    0.000000           0         1           execve
  0.00    0.000000           0         2         1 arch_prctl
  0.00    0.000000           0         3           openat
------ ----------- ----------- --------- --------- ----------------
100.00    0.011285                 43059         2 total
strace -c ./mergesort  4.66s user 0.38s system 101% cpu 4.962 total
```

(3) quicksort

```
❯ time strace -c ./quicksort
quicksort used 2511725 microseconds.
quicksort used 2.51 seconds.
% time     seconds  usecs/call     calls    errors syscall
------ ----------- ----------- --------- --------- ----------------
100.00    0.009234           0     42940           read
  0.00    0.000000           0         2           write
  0.00    0.000000           0         3           close
  0.00    0.000000           0         4           fstat
  0.00    0.000000           0         8           mmap
  0.00    0.000000           0         4           mprotect
  0.00    0.000000           0         2           munmap
  0.00    0.000000           0         3           brk
  0.00    0.000000           0         6           pread64
  0.00    0.000000           0         1         1 access
  0.00    0.000000           0         1           execve
  0.00    0.000000           0         2         1 arch_prctl
  0.00    0.000000           0         3           openat
------ ----------- ----------- --------- --------- ----------------
100.00    0.009234                 42979         2 total
strace -c ./quicksort  3.81s user 0.34s system 102% cpu 4.064 total
```

(4) heapsort

```
❯ time strace -c ./heapsort
heapsort used 7265267 microseconds.
heapsort used 7.27 seconds.
% time     seconds  usecs/call     calls    errors syscall
------ ----------- ----------- --------- --------- ----------------
100.00    0.010894           0     42940           read
  0.00    0.000000           0         2           write
  0.00    0.000000           0         3           close
  0.00    0.000000           0         4           fstat
  0.00    0.000000           0         8           mmap
  0.00    0.000000           0         4           mprotect
  0.00    0.000000           0         2           munmap
  0.00    0.000000           0         3           brk
  0.00    0.000000           0         6           pread64
  0.00    0.000000           0         1         1 access
  0.00    0.000000           0         1           execve
  0.00    0.000000           0         2         1 arch_prctl
  0.00    0.000000           0         3           openat
------ ----------- ----------- --------- --------- ----------------
100.00    0.010894                 42979         2 total
strace -c ./heapsort  8.58s user 0.38s system 100% cpu 8.897 total
```

2. 2^24 (約16.7M) 筆 *string* 資料

每筆字長度介於 2 ~ 128 字元 (包含 \0)，其長度也是亂數產生

(1) qsort

```
❯ time strace -c ./sortperf_string
qsort used 8434124 microseconds.
qsort used 8.43 microseconds.
% time     seconds  usecs/call     calls    errors syscall
------ ----------- ----------- --------- --------- ----------------
 95.03    0.451660           1    266275           read
  4.96    0.023582           1     17876           brk
  0.00    0.000010           3         3           openat
  0.00    0.000007           0         9           mmap
  0.00    0.000005           5         1           sysinfo
  0.00    0.000003           0         4           fstat
  0.00    0.000000           0         2           write
  0.00    0.000000           0         3           close
  0.00    0.000000           0         4           mprotect
  0.00    0.000000           0         3           munmap
  0.00    0.000000           0         6           pread64
  0.00    0.000000           0         1         1 access
  0.00    0.000000           0         1           execve
  0.00    0.000000           0         2         1 arch_prctl
------ ----------- ----------- --------- --------- ----------------
100.00    0.475267                284190         2 total
strace -c ./sortperf_string  12.72s user 3.00s system 103% cpu 15.175 total
```

(2) mergesort

```
❯ time strace -c ./mergesort_string
qsort used 8289562 microseconds.
qsort used 8.29 microseconds.
% time     seconds  usecs/call     calls    errors syscall
------ ----------- ----------- --------- --------- ----------------
 93.48    0.406785           1    266275           read
  6.52    0.028366           1     17876           brk
  0.00    0.000000           0         2           write
  0.00    0.000000           0         3           close
  0.00    0.000000           0         4           fstat
  0.00    0.000000           0         9           mmap
  0.00    0.000000           0         4           mprotect
  0.00    0.000000           0         3           munmap
  0.00    0.000000           0         6           pread64
  0.00    0.000000           0         1         1 access
  0.00    0.000000           0         1           execve
  0.00    0.000000           0         1           sysinfo
  0.00    0.000000           0         2         1 arch_prctl
  0.00    0.000000           0         3           openat
------ ----------- ----------- --------- --------- ----------------
100.00    0.435151                284190         2 total
strace -c ./mergesort_string  12.82s user 3.10s system 103% cpu 15.310 total
```

(3) quicksort

```
❯ time strace -c ./quicksort_string
qsort used 8842610 microseconds.
qsort used 8.84 microseconds.
% time     seconds  usecs/call     calls    errors syscall
------ ----------- ----------- --------- --------- ----------------
 93.03    0.353104           1    266275           read
  6.96    0.026421           1     17876           brk
  0.00    0.000012           4         3           openat
  0.00    0.000007           0         9           mmap
  0.00    0.000005           5         1           sysinfo
  0.00    0.000004           1         4           fstat
  0.00    0.000000           0         2           write
  0.00    0.000000           0         3           close
  0.00    0.000000           0         4           mprotect
  0.00    0.000000           0         3           munmap
  0.00    0.000000           0         6           pread64
  0.00    0.000000           0         1         1 access
  0.00    0.000000           0         1           execve
  0.00    0.000000           0         2         1 arch_prctl
------ ----------- ----------- --------- --------- ----------------
100.00    0.379553                284190         2 total
strace -c ./quicksort_string  13.13s user 2.89s system 103% cpu 15.463 total
```

(4) heapsort

```
❯ time strace -c ./heapsort_string
qsort used 8076633 microseconds.
qsort used 8.08 microseconds.
% time     seconds  usecs/call     calls    errors syscall
------ ----------- ----------- --------- --------- ----------------
 94.34    0.360570           1    266275           read
  5.66    0.021616           1     17876           brk
  0.00    0.000005           0         9           mmap
  0.00    0.000003           3         1           sysinfo
  0.00    0.000000           0         2           write
  0.00    0.000000           0         3           close
  0.00    0.000000           0         4           fstat
  0.00    0.000000           0         4           mprotect
  0.00    0.000000           0         3           munmap
  0.00    0.000000           0         6           pread64
  0.00    0.000000           0         1         1 access
  0.00    0.000000           0         1           execve
  0.00    0.000000           0         2         1 arch_prctl
  0.00    0.000000           0         3           openat
------ ----------- ----------- --------- --------- ----------------
100.00    0.382194                284190         2 total
strace -c ./heapsort_string  12.29s user 2.94s system 104% cpu 14.641 total
```

E. 結論

OS 在 malloc 記憶體時，較大的空間會以 mmap 的方式分配，較小空間會以 brk 的方式 malloc

```
void *mmap(void *addr, size_t length, int prot, int flags, int fd, off_t offset);
int brk(void *addr);
```

mmap() creates a new mapping in the virtual address space of the calling process. The starting address for the new mapping is specified in **addr**. The **length** argument specifies the length of the mapping (which must be greater than 0).

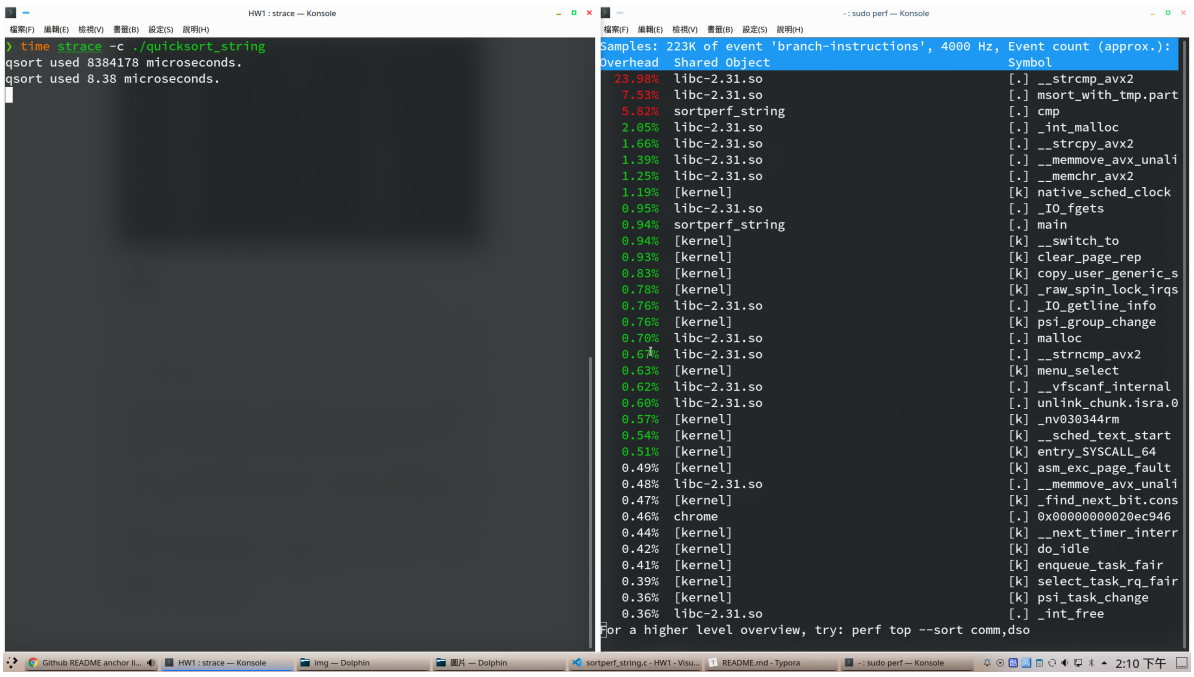
If **addr** is NULL, then the kernel chooses the (page-aligned) address at which to create the mapping; this is the most portable method of creating a new mapping. If **addr** is not NULL, then the kernel takes it as a hint about where to place the mapping; on Linux, the kernel will pick a nearby page boundary (but always above or equal to the value specified by **/proc/sys/vm/mmap_min_addr**) and attempt to create the mapping there. If another mapping already exists there, the kernel picks a new address that may or may not depend on the hint. The address of the new mapping is returned as the result of the call.

The contents of a file mapping (as opposed to an anonymous mapping; see **MAP_ANONYMOUS** below), are initialized using **length** bytes starting at offset **offset** in the file (or other object) referred to by the file descriptor **fd**. **offset** must be a multiple of the page size as returned by **sysconf(_SC_PAGE_SIZE)**.

After the **mmap**() call has returned, the file descriptor, **fd**, can be closed immediately without invalidating the mapping.

尤其從字串的排序就可以知道，要分配 arr$[2^{24}][128]$，需要 mmap 9 次 (2^{24}) 而 brk 17876 次 (對於每個 char * 分配 128 bytes)，而排序最花時間的當然就是 read 元素進行比較

隨便取一種排序方法，`sudo perf top -e branch-instructions` 就可以證明這一切了



F. Reference

4102150_02 System Programming, instructor: Prof. Shi-Wu Lo

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