**Sort Race**

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Sorting is one of the oldest computing problems and is still very important in the age of big data. Numerous algorithms and implementation techniques have been proposed. In this study, we focus on comparison based, internal sorting algorithms. We created 12 types of data of various sizes for experiments and tested extensively various implementations in a single setting. Using effective techniques, we found that quicksort is adaptive to nearly sorted inputs and is still the best overall sorting algorithm. We also identified which techniques are effective in timsort, one of the most popular and efficient sorting method based on natural mergesort, and created our version of mergesort, which performs better than timsort on nearly sorted instances. Our implementations of quicksort and mergesort are different from other implementations reported in all textbooks or research articles, faster than any version of the C library qsort functions, not only for randomly generated data, but also for various types of nearly sorted data. This experiment can help the user to choose the best sorting algorithm for their hard sorting jobs. This work provides a platform for anyone to test their own sorting algorithm against the best in the field.

• **Sorting algorithms**

1. **INTRODUCTION**

What is the beat sorting algorithm? The best answer to this question is perhaps “it depends”. If you are asked to recommend a sorting algorithm for an unknown problem, what is your recommendation? According to a typical textbook on algorithms, the answer would be *heapsort* or *mergesort*, the two asymptotically optimal algorithms, which take *O*(*n* log *n*) time in the worst case, where *n* is the number of elements to be sorted. In practice, neither *heapsort* nor *mergesort* is a good choice. The most popular choice is a variant of *mergesort* called *natural mergesort*. An equally good choice is *quicksort*. Of course, our claim is based on experiments, not on asymptotical analysis, as nobody can do better than an optimal method.

Sorting is perhaps the most studied computing problem. Various algorithms and implementation techniques have been used to demonstrate various algorithm design techniques. At *http://www.sorting-algorithms.com*, eight different sorting methods, that is, *insertion sort, selection sort, bubble sort, shellsort, mergesort, heapsort*, and two versions of *quicksort* (both two-way and three-way splitting), are animated on four types of initial instances: Random, Nearly Sorted, Reversed, and Few Unique. Their conclusion is that “there is no best sorting algorithm”, and “the initial condition (input order and key distribution) affects performance as much as the algorithm choice.” Apparently, this conclusion does not provide any clue to the aforementioned recommendation. From now on, we will use *Demo* as shorthand for *http://www.sorting-algorithms.com*.

In a decathlon competition, the winner is not necessarily the fastest runner or the highest jumper, but is determined by the combined performance in all events. If we choose the best implementation for each sorting algorithm and put them in a rigorous sort race, the winner can be decided by the combined performance in all tests. As in any relay competition, the fairest performance metric would be the total time taken by each method and we will use it in our sort race.

To make the sort race simple, we choose only comparison-based internal sorting algorithms. We will call an input array of elements for sorting as an *instance* and use instances of at least one million elements. The same instance and the same comparison function will be used by all participants, and all implementations will be compiled into one single program. Since *selection sort* and *bubble sort* perform poorly on any large instance, they are disqualified from the race. Only one copy of *quicksort* is used as it should not be favored. Thus, we have five different sorting methods as participants in this race: *insertion sort*, *shellsort* [6], *mergesort* [8], *heapsort* [14], and *quicksort* [5].

In Table 1, we give the experimental results of our implementations of the five sorting methods plus the GNU C library *qsort* and *timsort* [10], on four types of instances as used in *[Demo](http://www.sorting-algorithms.com)*, i.e., random, reverse sorted, nearly sorted, and few unique. All the methods are implemented in C and compiled as a single executable by gcc with optimization “-O3”. The executable takes two parameters, the size and the type of the instance, and generates one instance and then run all the sorting methods on this instance. This way, the same set of instances is used for each method.

In Table 1, the column named “best time” is the fastest average time (in microseconds) over 100 instances (each has 2,000,000 elements) for each of the seven methods. Under each method, the ratio of its running time to the best time is given. That is, the actual running time of that method is the multiplication of the ratio and the best time. If the ratio is 1.00, then the best time is produced by that method. In the row named “Average time”', the average time (in microseconds) of all 400 runs for each method is given, again in the format of ratio to the best time.

Table 1: The average running time of seven sorting methods on 4 types of inputs

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **n=2000000** | **best time** | **insert** | **heap** | **shell** | **merge** | **quick** | **qsort** | **timsort** |
| random | 225876 | - | 3.47 | 1.73 | 1.16 | 1.00 | 1.18 | 1.15 |
| reverse sorted | 4728 | - | 113.78 | 26.34 | 1.00 | 1.78 | 19.74 | 1.07 |
| nearly sorted | 93185 | 1.62 | 5.73 | 1.92 | 1.00 | 1.54 | 1.50 | 1.11 |
| few unique | 128097 | - | 5.88 | 2.39 | 1.64 | 1.00 | 1.73 | 1.61 |
| Average time | 126509 | - | 5.18 | 1.98 | 1.15 | 1.00 | 1.42 | 1.13 |

It is clear from the table that *quicksort* (nicknamed hyb2 in section 4) is the best overall method according to the best average time. The second best method is *mergesort* (nicknamed mer6 in section 3), which has the best performance for reverse sorted and nearly sorted instance. The performance of *qsort*, the sorting function in the C Standard Library, and *timsort* [10], which are known as the best generic sorting methods, are given as a reference to show that our results are very competitive. The weak performance of *qsort* on reverse sorted instances is typical for the standard recursive *mergesort* algorithm on such inputs, as the latest *qsort* does not use natural mergesort.

Why the conclusion from our experiment is different from the one in Demo? There are two reasons: (1) size matters, and (2) implementation matters.

In *Demo*, up to 50 elements are used to test the idea of each sorting method, and this size is too small to demonstrate the strength of each method. For example, the overhead for choosing a good pivot in *quicksort* only pays off with a large size array. Moreover, it is very important to know that a sorting method works well or not for very large size problems. Every experienced programmer knows that different implementations of the same algorithm give different performances. For sort race, we should choose the best implementation possible for each method.

When talking about the best sorting implementation, we cannot ignore the existence of the qsort() function in the C Standard Library. Overtime, qsort() tries to represent the best sorting function and there are at least 14 different implementations of qsort() developed. Nowadays, the most popular qsort() is the GNU project’s libc implementation which powers most GNU/Linux distributions and several other operating systems. This qsort is interesting in that it shuns *quicksort* in favor of conventional topdown *mergesort*, due to the poor performance of *quicksort* on some types of instances [16]. Tim Peters created *timsort* [10] based on Peter McIlroy’s idea of natural *mergesort* [8], which consists of two phases: in phase 1, sorted subarrays (called *runs*) are identified from the input; in phase 2, two runs are merged into one run, until only one run remains. The two phases can be interleaved. There are several implementations based on natural *mergesort*, such as *timsort* [10] and *neatsort* [7]. Different techniques are used in these implementations. As the first goal of this article, we will try to identify which techniques are more effective and which are less effective through extensive experiments. From now on, by *mergesort*, we mean *natural mergesort* [8].

Before the GNU *qsort*, the most popular *qsort* is the BSD *qsort*, which is a version of *quicksort* based on Bentley and McIlroy’s sort function [1]. A significant deviation from Bentley and McIlroy’s *qsort* is that the BSD *qsort* resorts to *insertion sort*, not only for small arrays, but also whenever a partitioning round is completed without having moved any element. The latter is intended to capture nearly sorted inputs, since insertion sort will handle these cases efficiently. However, this technique may miss fire. We found by accident that the BSD *qsort* performs very poorly on a set of instances. By extensive experiments, we will try to identify which techniques used in the past [12] are effective and what new techniques can be used so that *quicksort* can handle better nearly sorted inputs and has better overall performances over all kinds of inputs. This is the second goal of this article.

The third goal of this article is to establish a software platform available in the public domain so that anyone can test their own sorting algorithm against other best implementations. Currently, the platform, called *sortrace*, is a C program which provides 12 types of inputs and over 20 implementations of sorting algorithms. Each type of inputs can take another parameter to decide its subtype. We have tested over a dozen of different input sequences in the *shellsort* algorithm to see which one works best. We hope that anyone who claims to have found a better sorting algorithm, can use this platform to sustain their claim by going through the sort race.

Before we select the best implementation for *quicksort* and *mergesort*, let us see what types of inputs are available in the platform.

1. **TWELVE CLASSES OF INPUTS**

For the first five classes of inputs, each array is randomly generated and each array item is one of the following five types: long integer, double, lists of integers of 64, 256, and 1024 bytes, respectively. For the next seven classes, besides the list length *n*, it takes another integer *k*, where 1≤*k* ≤ *n*. Before we present these seven classes, let us first review some concepts.

Many researchers prefer to usethe number of inversions, to measure how far (or close) the array is from being sorted. If the array is already sorted, then the inversion count is 0, but if the array is sorted in the reverse order, the inversion count is the maximum which is equal to *n*(*n*–1)/2. Formally speaking, two elements *ai* and *aj* form an inversion if *ai* > *aj* and *i* < j. Let *Inv*(*A*) denote the number of inversions in the array *A*, then

If we break the array *A* at every position *i*, where *ai* > *ai+*1, into a collection of disjoint subarrays, then each subarray is a run*,* i.e., a sorted sequence of elements*.* Let *Run*(*A*) be the number of such subarrays:

When *A* is sorted, *Run*(*A*) = 1. When *A* is reverse sorted, the number of runs is maximal (*Run*(*A*) = *n*); in this case, reversing the array, which takes *O*(*n*) time, will make *A* sorted. In other words, neither *Inv*(*A*) nor *Run*(*A*) reflects the difficulty of making *A* sorted. Hence, we prefer another measure over *Inv*(*A*) and *Run*(*A*). For instance, we are interested in the minimal number *k* such that *A* can be broken into *k* subarrays, each of which is *monotonic* (i.e., either sorted or reverse sorted).

Intuitively, if *Mono*(*A*) = *k*, then *A* is the concatenation of *k* monotonic subarrayssreverse. For instance, if *A* is sorted or reverse sorted, then *Mono*(*A*) = 1. If the first half of is reverse sorted and the second half of *A* is sorted, A is called an “organ-pipe” array and *Mono*(*A*) = 2.

Here are the five classes of inputs with an additional parameter *k*:

* ***k*-limited**: A simple way to create Few Unique instances is to restrict elements in a certain range. An array of integers is said to be *k-limited* if each element *x* in the array is a randomly generated number and 0 ≤ *x < 2k*. When *k* = 0, all elements of the array are the same, i.e., 0. When *k* = 1, the array is a randomized binary list. The Few Unique instance used in *Demo* can be mapped to a 2-limited array of 50 elements. If we keep the same ratio of 22/50 = 2*k*/2,000,000, we get *k* = 12. For the Few Unique instance in Table 1, we used 12-limited arrays. When *k* > 31, it is the same as randomized integers. The best sorting method for the *k*-limited is the 3-way *quicksort* used in *Demo* and is related to Dijkstra’s Dutch National Flag problem [15] (more details can be found in section 4).
* ***k*-equal teeth**: A *k*-*equal teeth* (or *k-equal saw teeth*) array can be constructed as follows: Divide an array of *n* elements into *k* disjoint, equal-length subarrays and each subarray is filled with the numbers from 1 to *n/k*. Obviously, if *A* is a *k*-equal teeth, *Run*(*A*) = *Mono*(*A*) = *k*. If *k* = 1, then *A* is sorted. Among all comparison-based sorting algorithms, *mergesort* is the best one for this class of instances.

* ***k*-even teeth**: A *k-even teeth* array can be constructed from *k*-equal teeth as follows: Reverse each odd numbered subarray of a *k*-equal teeth. When *k* = 1, the array is reverse sorted. For *k* = 2, it is an “organ-pipe” array. Obviously, for *k* ≤ *n*/3, if *A* is a *k*-even teeth, *Mono*(*A*) = *k*. When *k* = *n*/2, the list is a 2-limited list starting with (2,1,1,2,2,1,1,2, ...), and *Mono*(*A*) = *n*/4+1, because we may group the elements as (2,1,1), (2,2,1,1), (2,2,1,1), …. The best sorting method for this class of instances is *mergesort*.
* ***k*-sharp teeth**: A *k-sharp teeth* array is constructed as follows: Initially, the array contains a sorted list from 1 to *n*. We divide the array into *k* disjoint, equal-length subarrays and reverse the odd numbered subarrays. When *k* =1, the array is reverse sorted. If *A* is a *k*-sharp teeth, *Mono*(*A*) = *k*. The best sorting method for this class of instances is a special version of *mergesort*. We like to point out that the BSD *qsort* performs very poorly on this type of inputs. For instance, when *n* = 2,000,000 and *k* = 8, *mergsort* takes 0.01 sec., Bentley & McIlroy's function takes 0.1 sec., and the BSD *qsort* takes 279.4 sec. This might explain why *quicksort* was shunned from the C library.
* ***k-*shuffled teeth**: A *k-shuffled teeth* array is constructed as follows: The array is first initialized with a *k*-sharp saw-teeth, and then all *k* subarrays are randomly shuffled bypreserving the relative order of the elements in each subarray. The concept of *k*-shuffled teeth lists is related to the SMS measure in [9], the least value *k* such that the input list can be formed by interleaving *k* monotone (either descending or ascending) sequences. Like the class of *k*-sharp teeth, *mergesort* is the best for this class when *k* < *n*/10; when *k* > *n*/10, *quicksort* is the best.
* ***k-*distance:** An array *A =* (*a1, a2,* …, *an*) is said to be *k-distance* if |*rank*(*ai*) – *i*| ≤ *k* for all 1≤ *i* ≤ *n*, where *rank*(*a*i) is the position of *a*i in the array after *A* is sorted.That is, for each *ai* in *A*, thedistance from its initial position to its final position is bound by *k*. To create a *k*-distance list, we first construct a sorted list and then divide the list into *n*/(*k*+1) subarrays and shuffle each subarray of *k*+1 elements randomly. If *k* = *n* –1, the result is a random list. The Nearly Sorted instance used in *Demo* appears to be a 1-distance array of 50 elements. If we keep the same ratio of 1/50, we would use a40000-distancearray of 2,000,000 elements. Instead,we used 256-distance lists in Table 1. Indeed, the best performer for this class on 2,000,000 elements is *insert sort* if *k* ≤ 32; for *k* > 32, *mergesort* is the best.
* ***k*-exchange**: An array *A* is said to be a *k-exchange* array if it becomes sorted after no more than exchanges of *k* pairs elements in *A*. In this case, |{ *ai* : *rank*(*ai*) ≠ *i* }| ≤ 2*k*. To create a *k*-exchange array, we first create a sorted list, and then repeat the following operation *k* times: randomly choose two positions to exchange them. The model of *k-exchange* arrays is related to the *Rem* measure (the minimal number of items that must be removed to leave a sorted sequence) in [9]. It can be shown that if *A* is a *k-exchange* array, then *Mono*(*A*) ≤ 2*k*+1. Like the class of *k-shuffled* teeth, *mergesort* is the best for this class when *k* ≤ *n*; when *k* > *n*, *quicksort* is the best.

The last six classes contain some kind of presortedness and can be called *nearly sorted* with proper *k*. We will present experimental results of various sorting methods on these instances in later sections. Roughly speaking, *quicksort* is the best method for the first six classes of inputs: five random arrays plus *k*-limited arrays. *Mergesort* is the best method for the remaining six classes of inputs, with the exception of *k-distance* arrays when *k* ≤ 32 (*n* = 2,000,000); in this case *insertion sort* is slightly faster than *mergesort*. Both *k*-distance and *k*-exchange arrays model nearly sorted arrays by several researchers [2]. Our experimental results show clearly that *mergesort* is the best choice for nearly sorted arrays. The second best is *quicksort*, which is much better than the *splaysort* method reported in [9]. Whenever we use the above 12 classes of instances, we will always include the best performers for each class so that the ratios of each method’s run time to the best time for that class will be kept the same.

**3. SELECT BEST MERGESORT**

The first choice for selecting the best implementation of *natural mergesort* is perhaps *timsort* [10]. *Timsort* is a highly optimized implementation of *natural mergesort* with at least the following techniques:

1. When scanning the input, if it finds a reverse sorted subsequence, it will reverse the subsequence to create a run. If the stable property is required, either the reverse sorted subsequence cannot contain equal elements (as done in *timsort*) or subarrays of equal elements are reversed twice (as done in our implementation).
2. If a run in the input is less than the minimal length for a run, *insertion sort* is called to create a longer run.
3. The minimal length of runs can be preset, or adjusted so that the number of runs is (or slightly less than) a power of two.
4. A binary search is used in *insertion sort* to locate the position of the element to be inserted in the sorted list.
5. Runs are inserted in a stack. Let X, Y, Z be the sizes of the top three runs in the stack, then it maintains that X > Y+Z and Y > Z. If X < Y+Z, then Y is merged with the smaller of X and Z until the two conditions are satisfied.
6. Merge is always done among two consecutive sorted subarrays, say A and B. Any element in A no bigger than the first element of B is removed from the merge process. Similarly, any element of B bigger than the last element of A is also removed from the merge process. If A is shorter than B, then A is copied into a temporary memory; otherwise B is copied before the merge process.
7. Merge goes into the galloping mode if A (or B) wins for a consecutive number of times (a preset number). In the galloping mode, the binary search is used to locate the position in A where the current element in B should go.

**Example**: Suppose the input *A* = (1, 15, 18, 19, 20, 16, 11, 10, 9, 8, 7, 6, 5, 4, 3, 2). *Run*(*A*) = 12 and *Mono*(*A*) = 2, because *A* consists of one sorted subarray from 1 to 20 (a run) and one reverse sorted subarray from 16 to 2 (a reversed run). *Timsort* will reverse the second subarray and merge two runs into one. During the merge process, the first number in *A*, i.e., 1, will be skipped because it is smaller than 2, the first number of the second run. Then 15 through 20 in the first run will be copied into a temporary memory. Once 1, 2, 3, 4 are moved into the final position, since the second run won three times in a row, it goes into the galloping mode: Using binary search, it finds that 15 falls in between 11 and 16 of the second run. So 5 through 11 will be moved to the final position without comparing them one by one against 15.

For *neatsort* [7], (a) and (f) are used; a heuristic different from (e) is used to select two runs to be merged. We have implemented our own *mergesort* and have tested (a) – (g) except (d). We found that (a), (f) and (g) have great impact to the performance of *mergesort*, so all of our implementations will use them. We also found that (b) provides a little performance improvement for most cases. However, we found that (c) has almost no impact. The motivation behind (c) is to avoid the merge of a very long run with a very short run. If the sizes of each run cannot be the same, the number of runs can hardly be an expected power of two. For (d), we found that using binary search in *insertion sort*, the impact to the running time is marginal, but it reduces the number of comparisons substantially. When expensive comparison functions are used, we still do not see the gain on running time. Instead of (e), we have tested two new strategies to select runs to merge:

(e1) Merge of runs takes multiple rounds: in each round, all runs are paired and merged into one.

(e2) Maintain a list of runs such that the length of each run is less than the half of the length of its predecessor. If the condition is not true, merge this run with its predecessor. Such a list is called “half-down list”.

It turns out that (e), (e1), (e2) or *neatsort*’s heuristic have a small impact to the overall performance.

Table 2: Performances of 8 *mergesort* implementations for 12 classes of inputs

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **n=2000000** | **best** | **qsort** | **mer2** | **mer3** | **mer4** | **mer5** | **mer6** | **Tim** | **neat** |
| random 16-list | 764548 | 1.43 | 1.74 | 1.80 | 1.77 | 1.32 | 1.27 | 1.21 | 1.80 |
| random 64-list | 1279070 | 1.25 | 1.84 | 1.99 | 1.89 | 1.26 | 1.25 | 1.19 | 2.00 |
| random 256-list | 1530270 | 1.24 | 1.81 | 1.92 | 1.83 | 1.19 | 1.20 | 1.16 | 1.88 |
| random double | 249758 | 1.14 | 1.07 | 1.12 | 1.08 | 1.07 | 1.01 | 1.11 | 1.15 |
| random integer | 231084 | 1.17 | 1.11 | 1.16 | 1.12 | 1.12 | 1.06 | 1.13 | 1.17 |
| k-limited | 142186 | 1.53 | 1.30 | 1.39 | 1.30 | 1.37 | 1.26 | 1.35 | 1.51 |
| k-equal teeth | 25180 | 3.24 | 1.38 | 1.03 | 1.05 | 1.00 | 1.03 | 1.10 | 1.20 |
| k-even teeth | 24712 | 3.56 | 2.90 | 1.04 | 1.19 | 1.00 | 1.14 | 1.11 | 1.21 |
| k-sharp teeth | 13846 | 6.14 | 4.47 | 1.15 | 1.34 | 1.00 | 1.26 | 1.22 | 1.61 |
| k-shuffled teeth | 96920 | 1.54 | 1.04 | 1.14 | 1.00 | 1.16 | 1.01 | 1.07 | 1.49 |
| k-distance | 51051 | 2.15 | 1.00 | 1.43 | 1.05 | 1.49 | 1.10 | 1.27 | 1.38 |
| k-exchange | 10075 | 8.55 | 1.78 | 1.21 | 1.24 | 1.00 | 1.09 | 1.11 | 3.28 |
| **Average (12)** | 400872 | 1.24 | 1.56 | 1.64 | 1.57 | 1.11 | 1.09 | 1.08 | 1.65 |
| **Average (8)** | 82566 | 1.65 | 1.18 | 1.10 | 1.03 | 1.08 | 1.00 | 1.07 | 1.23 |

The value of *k* is 2*i*, where *i* = 0, 1, …, 8, for the last seven classes of inputs. In the column named “best”, the best average running time of 100 executions, in microseconds, is given. It may be produced by other implementations not listed in the table. The running times of each method are given as a ratio to the best average time. If it is 1.00, then this is the best performer among all sorting methods in our experiment. The column “qsort” gives the running time of the GNU *qsort*. The columns mer2–mer6 give the running times of our five versions of *mergesort*, which differ by the used techniques:

* mer2: uses (b), (f), (g), (e1)
* mer3: uses (a), (f), (g), (e1)
* mer4: uses (a), (b), (f), (g), (e1)
* mer5: uses (a), (f), (g), (e2)
* mer6: uses (a), (b), (f), (g), (e2)

In fact, mer2 is not *natural mergesort*, as runs are not discovered from the input but created by insertion sort. The code of mer6 is given in the appendix for reference.

The last row gives the average running times of the last 8 classes of inputs (not the average of ratios). The second last row gives the average time of all 12 classes. Mer6 is the best performer of the last 8 classes of inputs; mer4 is the second best (3% slower) and *timsort* is the third (7% slower). The GNU *qsort* is the worst performer in the table (65% slower).

When all the 12 classes are considered, *timsort* is the best among all *mergesort* implementations in our experiment, and is only 7% slower than the best *quicksort* implementation. Mer6 is the second best (1% slower than *timsort*). The advantage of *timsort* over mer6 is shown on the first three randomized classes where expensive comparison functions are used; for random integers or doubles, mer6 is still faster than *timesort*. The idea of (d) cannot reduce the running time of mer6 while it can reduce the number of comparisons. This may suggest that (e) is better than (e1) and (e2) for large size lists with high comparison costs.

For the three contrived classes, *k-equal* *teeth*, *k-even* *teeth*, and *k-sharp teeth*, mer5 is the best performer among all implementations, while the GNU *qsort* is at least three times slower than mer5. For *k-exchange*, *qsort* is almost eight times slower than mer5.

1. **SELECT BEST QUICKSORT**

As the most popular sorting algorithm, *quicksort* [5] has been extensively studied by many researchers and various techniques have been proposed. To select the best implementation of *quicksort*, the first consideration will be Bentley and McIlory’s *qsort* function [1]. Let *n* be the input array size, the following techniques are in Bentley and McIlory’s qsort function:

1. If *n* < α, call *insertion sort*. Bentley and McIlroy used α = 7.
2. If *n* < β, use the median of the first, middle and the last elements as pivot for splitting the array. Bentley and McIlory used β = 40.
3. If *n* ≥ β, use the pseudo-median of 9 elements (taken at every *n*/8th position plus the first element) as pivot.
4. During the splitting process, all elements equal to the pivot are placed either at the beginning or end of the array. When the splitting is done, these elements equal to the pivot are moved in the middle of the array and are spared from the recursive calls.
5. Do not identify the position of the pivot in the array. Bentley and McIlroy use this idea for all eight byte elements.

The use of (c) is to guarantee that a good pivot element is chosen, to avoid the quadratic worst-case time complexity. The use of (a) is to avoid the overhead of choosing a better pivot. The idea behind (d) is called 3-*way splitting*, and quicksort using (d) is called the 3-way quicksort. Evidently, when no repeated elements are present, 3-way splitting is slower than the classic 2-way splitting [3]. The idea of (e) is to avoid swapping the pivot with other elements so that the presortedness of the input is not disturbed.

For the 3-way splitting, at the end of splitting, the array is divided into three parts: the first part contains elements less than the pivot; the middle part contains elements equal to the pivot and the last part contains elements greater than the pivot. Recursive calls apply to the first and the last parts. The 2-way splitting in any standard textbook [3] also splits the array into three parts: the elements less than the pivot, the pivot, and the elements no less than the pivot. Using (e) without (d), the array is split into two parts: the elements no greater than the pivot and the elements no less than the pivot.

The BSD *qsort* function in the C library has some deviation from Bentley and McIlroy’s *qsort*: the BSD *qsort* also uses insertion sort instead of recursive calls of qsort, whenever a splitting round is completed without having moved any elements. This idea is intended to capture nearly sorted inputs and may perform poorly for certain inputs. For instance, if an array contains 2*m*+1 distinct integers, the first *m* integers are the reversed list of numbers 1 through *m*, the middle element is *m*+1, and the last *m* integers are the reversed list of numbers *m*+2 through 2*m*+1, then the BSD *qsort* will use *insertion sort* to sort two reversed lists of *m* elements. We have tested the BSD *qsort* on the 12 classes of inputs and its performance is very poor for the class of *k*-sharp teeth arrays. Besides the ideas used by Bentley and McIlroy, we also have tested the following three ideas:

1. If *n* ≥ α, test if the array is already sorted; if yes, exit.
2. At first, use the 2-way splitting. If the array contains more than γ = 2 elements equal to the pivot, use the 3-way splitting in the recursive calls.

The use of (f) is to avoid wasting time on already sorted subarrays, which occur often in nearly sorted inputs. The use of (g) is a typical example of hybrid algorithms: The program starts with the 2-way quicksort; when it identifies repeated elements, it turns to the 3-way quicksort.

Combing (e) and (f), reverse sorted lists are no longer a problem for *quicksort*: Using the median of the input as pivot, the splitting will reverse the list and the two recursive calls will finish quickly with the use of (f). In other words, *quicksort* becomes adaptive as it takes O(*n*) time on sorted or reverse sorted lists. It also works well for some other troublesome instances including organ-pipe lists.

Table 3: Performances of quicksort and mergesort implementations for 12 classes of inputs

|  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **n=2000000** | **best** | **B&M** | **3-way** | **2-way** | **hyb1** | **hyb2** | **hyb3** | **hyb4** | **mer5** | **mer6** | **Tim** | **qsort** |
| random 16-list | 764548 | 1.11 | 1.12 | 1.28 | 1.10 | 1.00 | 1.08 | 1.00 | 1.32 | 1.27 | 1.21 | 1.43 |
| random 64-list | 1279070 | 1.06 | 1.05 | 1.02 | 1.03 | 1.02 | 1.03 | 1.00 | 1.26 | 1.25 | 1.19 | 1.25 |
| random 256-list | 1530270 | 1.13 | 1.09 | 1.04 | 1.04 | 1.00 | 1.04 | 1.03 | 1.19 | 1.20 | 1.14 | 1.24 |
| random double | 249758 | 1.17 | 1.13 | 1.05 | 1.04 | 1.05 | 1.00 | 1.06 | 1.07 | 1.01 | 1.11 | 1.14 |
| random integer | 231084 | 1.18 | 1.11 | 1.03 | 1.03 | 1.05 | 1.00 | 1.05 | 1.12 | 1.06 | 1.13 | 1.17 |
| k-limited | 142186 | 1.13 | 1.07 | 1.10 | 1.03 | 1.04 | 1.00 | 1.04 | 1.37 | 1.26 | 1.35 | 1.53 |
| k-equal teeth | 25180 | 5.54 | 4.71 | 4.93 | 4.67 | 4.36 | 4.17 | 4.66 | 1.00 | 1.03 | 1.10 | 3.24 |
| k-even teeth | 24712 | 5.72 | 4.84 | 4.97 | 4.82 | 4.52 | 4.28 | 4.81 | 1.00 | 1.14 | 1.11 | 3.56 |
| k-sharp teeth | 13846 | 6.14 | 2.42 | 1.94 | 2.28 | 2.12 | 1.85 | 2.04 | 1.00 | 1.26 | 1.22 | 6.14 |
| k-shuffled teeth | 96920 | 2.37 | 2.09 | 1.95 | 1.96 | 1.97 | 1.88 | 1.98 | 1.16 | 1.01 | 1.07 | 1.54 |
| k-distance | 51051 | 2.53 | 2.41 | 2.04 | 2.09 | 2.17 | 1.85 | 2.21 | 1.49 | 1.10 | 1.27 | 2.15 |
| k-exchange | 10075 | 9.52 | 2.95 | 2.44 | 2.69 | 2.69 | 2.18 | 2.46 | 1.00 | 1.09 | 1.11 | 8.55 |
| **Average (12)** | 400872 | 1.23 | 1.06 | 1.04 | 1.02 | 1.00 | 1.01 | 1.01 | 1.11 | 1.09 | 1.08 | 1.24 |
| **Average (8)** | 82566 | 1.93 | 1.56 | 1.48 | 1.47 | 1.46 | 1.37 | 1.49 | 1.08 | 1.00 | 1.07 | 1.65 |

In Table 3, we provide the performances of seven implementations of *quicksort* on the same set of inputs used in Table 2. For reference, we also copied four versions of *mergesort* from Table 2: mer5, mer6, Tim and qsort. The seven *quicksort* implementations are: (1) B&M, Bentley and McIlroy’s *qsort* function. (2) 3-way: the 3-way *quicksort* uses the ideas of (a) to (f), and is almost identical to B&M except (f), i.e., test if the array is sorted as a preprocessing step. (3) 2-way: the 2-way quicksort using the ideas of (a), (b), (c), (e), and (f). (4)-(7): Four variants of hybrid *quicksort* using the ideas of (a)-(g), i.e., hyb1, hyb2, hyb3, and hyb4, with (α, β) = (16, 16), (32, 32), (32, 64), (16, 32), respectively. The Java code of the hybrid quicksort is given in Appendix B for reference. The BSD *qsort* is excluded here because it performs poorly on the *k*-sharp teeth instances when *k* ≥ 5.

The performances of all methods on randomized inputs (the first five classes) are about the same, with the GNU *qsort* being the worst performer. The high cost on the class of random 256-lists is due to an expensive comparison function and high number of cache misses. Comparing to *mergesort*, *quicksort* as a group is slower on non-randomized inputs. However, the hybrid *quicksort* is the best performer over all the 12 classes of inputs. If we have to select one *quicksort*, then hyb2 (α = β = 32) is the choice according to Table 3. The GNU *qsort* and Bentley and McIlroy’s *qsort* [1] are about 23% slower than hyb2. The use of idea (f) is indispensible for this performance as it helps *quicksort* to save time on nearly sorted inputs.

Sarwar *et al*. [11] once conducted an extensive experimentation of *quicksort* and tried various methods for selecting a pivot (from 1, 3, 5, 9, and 17 elements). They concluded that *quicksort* performs best when the pivot is the median of three elements and there is no need to call *insertion sort*. Our experiment shows that their claims are true only for randomized inputs. For 2-equal teeth or 2-even teeth, which are called the organ-pipe shape inputs, if we let β = ∞, quicksort will always pick the median of three elements as pivot and in this case, it exhibits the O(*n*2) worst-case behavior. The idea of (c), i.e., use the pseudo-median of 9 elements as pivot, essentially prevents the worse-case from happening. In this case, the idea of (a) helps to reduce the overhead of (c). When α = β, (b) is excluded and (c) becomes the only strategy for selecting a pivot. Our experiment shows that as long as 16 ≤ α ≤ β ≤ 100, the performance of quicksort has little difference on random inputs.

1. **COUNT NUMBERS OF COMPARISONS**

In the previous sections, we used the running time as the metric to select the best performer. In the C library *qsort* function, the comparison function must be passed as a parameter to qsort() and we use the interface of qsort() as a model for every sorting method. Since we have control over the comparison function, we can count how many comparisons a sorting algorithm performs, which is also a pretty good metric.

In Table 4, we give the average number of comparisons per item for the inputs in Table 3 (*n* = 2,000,000) for the selected 10 sorting methods, the first five from *quicksort*, and the second five from *mergesort*. That is, each number is the average of 100 numbers of comparisons per item for randomized arrays. To compute the average number of comparisons for each *k*-class, we chose 9 values for *k*: The value of *k* is 2*i*, where *i* = 0, 1, …, 8. For each class, we took the average number of comparisons from 50 executions and then took the average for the whole class. The use of binary search in insertion sort can reduce the number of comparisons by about 10% (not shown here) for those methods using insertion sort.

For *n* = 2,000,000, hyb4 makes on average 19*n* comparisons for *k*-equal teeth and *k*-even teeth arrays, lower than 23*n* comparisons for randomized lists (and much lower than 38*n* of heapsort for *k*-equal teeth and *k*-even teeth arrays). The idea of testing whether an array is already sorted is used in the first four *quicksort* methods. However, Table 4 does not show any significant increases in the number of comparisons. In fact, the small values for the *k*-sharp teeth and *k*-exchange classes tell that this idea is very useful.

Table 4: Average number of comparisons per element (*n* = 2,000,000)

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **cmp per item** | **3-way** | **2-way** | **hyb2** | **hyb4** | **B&M** | **qsort** | **mer4** | **mer5** | **mer6** | **Tim** |
| random 16-list | 22.51 | 24.62 | 24.47 | 23.47 | 22.57 | 19.68 | 21.62 | 20.77 | 21.81 | 19.20 |
| random 64-list | 22.74 | 24.73 | 24.70 | 23.41 | 22.08 | 19.67 | 21.62 | 21.09 | 22.22 | 19.64 |
| random 256-list | 22.92 | 24.83 | 24.80 | 23.50 | 22.07 | 19.67 | 21.62 | 21.04 | 22.17 | 19.64 |
| random double | 22.79 | 24.83 | 24.79 | 23.51 | 22.08 | 19.67 | 21.62 | 21.09 | 22.16 | 19.64 |
| random integer | 22.95 | 24.80 | 24.77 | 23.48 | 22.13 | 19.67 | 21.62 | 21.03 | 22.15 | 19.64 |
| k-limited | 13.65 | 16.64 | 14.63 | 14.06 | 13.30 | 18.89 | 15.89 | 15.23 | 16.17 | 14.19 |
| k-equal teeth | 19.24 | 22.86 | 19.68 | 19.24 | 20.59 | 11.23 | 4.02 | 4.02 | 4.02 | 4.02 |
| k-even teeth | 18.78 | 22.51 | 19.36 | 18.91 | 20.44 | 11.31 | 4.67 | 4.05 | 4.49 | 4.16 |
| k-sharp teeth | 6.65 | 6.39 | 6.46 | 6.58 | 19.90 | 9.32 | 1.33 | 0.89 | 1.33 | 0.89 |
| k-shuffled teeth | 19.07 | 20.54 | 20.48 | 19.49 | 21.61 | 16.57 | 8.52 | 7.18 | 8.43 | 6.71 |
| k-distance | 20.26 | 20.62 | 20.53 | 20.85 | 20.63 | 11.72 | 5.40 | 5.31 | 5.35 | 4.99 |
| k-exchange | 6.07 | 6.07 | 6.07 | 6.07 | 19.69 | 12.36 | 1.00 | 1.00 | 1.00 | 1.00 |
| Average cmp | 17.64 | 19.70 | 18.56 | 17.96 | 20.09 | 15.81 | 12.41 | 11.89 | 12.61 | 11.14 |

As an approximation, we may assume that the number of comparisons is defined by a function *f*(*n*) = *sn*log(*n*) + *tn* on an input array of *n* elements, where *s* and *t* are constants. The number of comparisons per item is *g*(*n*) = *f*(*n*)/*n* = *s*log(*n*) + *t*, which happens to be a line on log(*n*). To determine the values of *s* and *t*, we run our implementations on the 12 classes of inputs of various sizes: there are five values for *n* = *j*∙106, where *j* = 1 to 5. We then used linear regression to compute the approximate values of *s* and *t* (each line is computed over 5 points).

The following two tables give the values of *s* and *t* for the selected 10 sorting methods.

Table 5: Value of *s* in the number of comparisons function *f*(*n*) = *sn*log(*n*) + *tn*

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **value of s** | **3-way** | **2-way** | **hyb2** | **hyb4** | **B&M** | **qsort** | **mer4** | **mer5** | **mer6** | **Tim** |
| random 16-list | 1.03 | 1.06 | 1.01 | 1.04 | 1.10 | 1.00 | 1.13 | 1.02 | 1.01 | 1.02 |
| random 64-list | 1.14 | 1.11 | 1.11 | 1.11 | 1.13 | 1.01 | 1.13 | 1.02 | 1.01 | 1.02 |
| random 256-list | 1.09 | 1.07 | 1.07 | 1.07 | 1.07 | 1.01 | 1.13 | 1.03 | 1.05 | 1.02 |
| random double | 1.07 | 1.02 | 1.01 | 1.02 | 1.09 | 1.01 | 1.13 | 1.01 | 1.02 | 1.02 |
| random integer | 1.06 | 1.12 | 1.12 | 1.12 | 1.06 | 1.01 | 1.13 | 1.04 | 1.05 | 1.02 |
| k-limited | 0.46 | 0.50 | 0.46 | 0.48 | 0.48 | 0.96 | 0.54 | 0.49 | 0.50 | 0.51 |
| k-equal teeth | 1.24 | 1.27 | 1.23 | 1.23 | 1.31 | 0.41 | 0.01 | 0.01 | 0.01 | 0.00 |
| k-even teeth | 1.22 | 1.21 | 1.27 | 1.27 | 1.31 | 0.45 | 0.00 | 0.00 | 0.00 | 0.00 |
| k-sharp teeth | 0.04 | 0.03 | 0.03 | 0.02 | 0.98 | 0.45 | 0.00 | 0.00 | 0.00 | 0.00 |
| k-shuffled teeth | 0.79 | 0.77 | 0.78 | 0.79 | 1.07 | 0.84 | 0.00 | 0.00 | 0.00 | 0.00 |
| k-distance | 1.11 | 1.10 | 1.10 | 1.08 | 1.02 | 0.49 | 0.00 | 0.00 | 0.00 | 0.00 |
| k-exchange | 0.02 | 0.02 | 0.02 | 0.02 | 1.06 | 0.45 | 0.00 | 0.00 | 0.00 | 0.00 |

Table 6: Value of *t* in the number of comparisons function f(*n*) = *sn*log(*n*) + *tn*

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **value of t** | **3-way** | **2-way** | **hyb2** | **hyb4** | **B&M** | **qsort** | **mer4** | **mer5** | **mer6** | **Tim** |
| random 16-list | -1.03 | 1.36 | 1.31 | 0.56 | -0.59 | -1.34 | -1.53 | -0.43 | 0.16 | -1.80 |
| random 64-list | -1.09 | 1.47 | 1.44 | 0.13 | -1.53 | -1.40 | -1.98 | -0.38 | 1.08 | -1.77 |
| random 256-list | 0.12 | 2.40 | 2.38 | 1.09 | -0.34 | -1.39 | -1.97 | -0.53 | 0.22 | -1.77 |
| random double | 0.47 | 3.47 | 3.69 | 2.16 | -0.76 | -1.38 | -1.94 | -0.11 | 0.74 | -1.81 |
| random integer | 0.83 | 1.33 | 1.40 | 0.01 | -0.15 | -1.39 | -1.95 | -0.80 | 0.13 | -1.79 |
| k-limited | 3.93 | 6.27 | 4.93 | 4.00 | 3.29 | -1.13 | 4.57 | 5.05 | 5.66 | 3.49 |
| k-equal teeth | -6.66 | -3.77 | -6.03 | -6.46 | -6.93 | 2.72 | 3.80 | 3.80 | 3.80 | 4.02 |
| k-even teeth | -6.85 | -2.83 | -7.33 | -7.77 | -7.06 | 1.86 | 4.67 | 4.05 | 4.49 | 4.16 |
| k-sharp teeth | 5.73 | 5.70 | 5.75 | 6.90 | -0.55 | -0.09 | 3.36 | 3.89 | 3.35 | 4.91 |
| k-shuffled teeth | 2.53 | 4.32 | 4.17 | 3.05 | -0.71 | -0.97 | 8.48 | 5.43 | 5.55 | 6.68 |
| k-distance | -2.91 | -2.46 | -2.47 | -1.67 | -0.68 | 1.42 | 5.73 | 5.32 | 5.36 | 5.53 |
| k-exchange | 5.65 | 5.65 | 5.65 | 5.65 | -2.41 | 2.92 | 1.05 | 1.05 | 1.05 | 1.05 |

For randomized inputs, the values of *s* for the 10 methods are close to 1, indicating these are very good sorting methods. For instance, for hyb4 over random doubles, the number of comparisons is *f*(*n*) = 1.02*n*log(*n*) + 2.16*n.* These numbers also indicate that the relative strength of these method tend to be the same as comparison functions of different costs are used.

For the classes of *k*-equal teeth and *k*-even teeth arrays, the *s* values of *quicksort* are slightly larger than 1, indicating apparently that these are hard problems for *quicksort*.

For the last six classes, with the exception of the GNU *qsort*, the *s* values of the *mergesort* methods are (almost) zero. That is, these methods take linear time to sort these six classes. That explains why these methods are so fast on these inputs.

1. **CONCLUSIONS**

Through extensive experiments, we have achieved our goals for this project.

* We have suggested 12 classes of inputs which exhibit different degree of presortedness and can be easily generated by a program. Using them, we can identify the best sorting methods and test any other method against them. For instance, we have tested a dozen of series for *shellsort* [6] and found that the best *shellsort* is still 180% slower than the best *mergesort* or *quicksort* over the 12 classes of inputs. The biggest disappointment is *heapsort*, which has the optimal complexity of O(*n*log*n*), but performs poorly. For the bottom-up *heapsort* [14], which is claimed to be much faster than *quicksort* in [13], it is about three times slower over the 12 classes of inputs and 7 times slower over the six classes of nearly sorted inputs. *Smoothsort* [4], a variant of *heapsort*, runs about two times slower than *quicksort*. *Splaysort* [9] is also much slower than *mergesort* and *quicksort* on nearly sorted inputs. All the sorting methods mentioned above and in the previous sections are implemented in a C program called *sortrace*. The 12 inputs can also be generated from the same program. That is the software platform we plan to extend, as we will add more types of inputs into the platform. The C code of *sortrace* is available from the authors upon request and will be available to the public soon.
* For sorting methods based on *natural mergesort* [8], we have identified three techniques of *timsort* [10] as important: (1) reversing revered runs; (2) the galloping merge, and (3) management of runs to decide which and when to merge two runs. The weakness of *neatsort* [7] is perhaps due to the missing of (2). We proposed a new way to manage runs (in mer5 and mer6 using the half-down list) which has better performance than *timsort* for nearly sorted inputs. The use of *insertion sort* is helpful as evident by the slight gain of mer6 over mer5. The use of binary search in *insertion sort* has high impact on the number of comparisons but little impact on running time. The adjustment of the minimal run length is easy to implement but does not have any significant impact on performance.
* For sorting methods based on quicksort, we confirmed that Bentley and McIlroy’s method of choosing a pseudo-median over 9 elements as pivot is crucial to avoid the worst case complexity of O(*n*2). We proposed two new ideas to improve quicksort: (1) testing sortedness as a preprocessing step in each recursive call; (2) a hybrid quicksort combing the 2-way quicksort with the 3-way quicksort. The idea of (1) is to make quicksort adaptive to nearly sorted inputs. The idea of (2) is to avoid the overhead of 3-way splitting when there are few identical elements. As a result, our quicksort is the overall champion for the 12 classes of inputs. For the 8 *k*-classes of inputs, our *quicksort* also beats the GNU *qsort*, even though the worst-case time complexity of *quicksort* is worse than that of *mergesort* (or *heapsort*). For the textbook version of the *quicksort* algorithm [3], the worst-case time complexity comes when the input list is already sorted or near-sorted. This property was regarded as a significant drawback of quicksort. Our experiment shows that using the proposed techniques in this article, we can not only avoid the worst-case complexity completely but also make *quicksort* adaptive to nearly sorted inputs. Apparently, the C library should not shun quicksort.

We have tried to avoid theoretic analysis and technical details in this article. As further research, we are interested in a formal analysis of the adaptiveness of *quicksort* when sortedness testing is used as a preprocessing step. Apparently such testing uses more comparisons. However, the experiment shows no significant increase in the number of comparisons. For instance, for hyb4 on *n* randomized doubles, the number of comparisons is *f*(*n*) = 1.02*n*log(*n*) + 2.16*n*, while Bentley and McIlroy’s *qsort* uses *f*(*n*) = 1.09*n*log(*n*) – 0.76*n*. Moreover, we would like to see how the complexity of mergsort and quicksort is related to the metric *Mono*(*A*).

One advantage of *mergesort* over quicksort is that *mergesort* is stable. In general, *mergesort* takes O(*n*) more working memory than quicksort as required by merging. In our experiments, we see that both methods slow down on long lists of heavy items. *Timsort* works better than our *mergesort* on such case, but is still slower than *quicksort*. Our experiment has been run on a linux machine with an Intel(R) Xeon(R) CPU E5-2667 (20M Cache and 3.20GHz) and 64GB memory. Further experiments are needed to test the limits of both methods and search for better techniques to deal with memory shortage. We would also like to test our program on different machines and investigate the impact of cache memory.

Regarding the question raised in the beginning of this article, “if you are asked to recommend a sorting algorithm for an unknown problem, what is your recommendation?” What will be your answer after reading this article? Our answer is *quicksort*, especially our hybrid *quicksort*, if stable sorting is not required. When stable sorting is required, or the input contains some kind of presortedness and the memory is not a concern, then *mergesort*, either *timsort* or ours.

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<https://github.com/patperry/timsort>, <https://en.wikibooks.org/wiki/Algorithm_Implementation/Sorting/Smoothsort>, <https://github.com/Maxime2/heapsort/blob/master/dps_bottom_up_heapsort.c>, and <http://people.eng.unimelb.edu.au/ammoffat/splaysort>.

We thank the authors of these codes for making them available.

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**APPENDIX A.** **The C code of our mergesort**

// merge(arr, left, middle, right) merges arr[left, middle-1] and arr[middle, right-1] into arr[left, right-1]

// reverse(arr, left, right) reverse the subarray arr[left, right].

void mergesort6 (WORD \*arr, size\_t n, size\_t es, int (\*cmp)(const void \*, const void \*)) {

int \*run, next, j, s, t, runnum, start;

run = (int \*) malloc(64\*sizeof(int)); // size of run is log(n) – 64 is more than enough.

runnum = run[0] = start = 0; next=1;

while (next < n) {

if (cmp(arr+next-1, arr+next)>0) { // i.e., if (arr[next-1] > arr[next])

if (start+minrun > next) { // make sure each run has at least minrun elements

j = next+1; s = 0; // look for reversed run and reverse equal elements

while (j < n && ((t=cmp(arr+j-1, arr+j))>=0)) {

if (t == 0) s++;

else if (s > 0) { reverse(arr, j-1-s, j-1); s = 0; } // i.e., reverse arr[j-1-s .. j-1].

j++;

}

if (next > start+1) {

reverse(arr, next, j-1); // reverse from next to j-1, then merge two parts.

merge(arr, start, next, j);

} else { reverse(arr, start, j-1); } // reverse from start to j-1

next = j;

if (start+minrun > next) { // still too short, use insertion sort to extend the run

j = (start+minrun<n)? start+minrun : n;

isort(arr, start, next, j); // insertion sort arr[start..j-1] where arr[next..next-1] is sorted.

next = j;

} else { // of (start+minrun > next)

// record a new run

run[++runnum] = start = next++;

// merge two runs if the current run > 1/2 of its predecessor

while (runnum > 1 && (run[runnum]-run[runnum-1]) > (run[runnum-1]-run[runnum-2])>>1) {

j = run[runnum-2];

merge(arr, j, run[runnum-1], run[runnum]);

run[runnum-1] = run[runnum];

runnum--;

}

}

} else next++;

}

// merge all runs into one, from last to first.

while (runnum > 0) {

j = run[runnum-1];

merge(arr, j, run[runnum--], n);

}

free(run);

}

**APPENDIX B.** **The java code of hybrid quicksort**

To better present our ideas, we give below the Java code of our algorithm, while the experiment is conducted using a C implementation and the C code will be available at the time of publication.

**public** **void** qsort\_hyb(Item[] arr, **int** low, **int** high) {

Item v;

**int** i, j, r, c=0, n=high-low+1;

**if** (n < alpha) { isort(arr, low, high); **return**; }

**if** (is\_sorted(arr, low, high)) **return**;

**if** (n < beta) v = pick\_pivot3(arr, low, high); // v is the pivot

**else** v = pick\_pivot9(arr, low, high); // v is the pivot

i = low; j = high;

**while** (true) {

**while** ((r=v.compareTo(arr[i])) < 0) i++; **if** (r==0) c++;

**while** ((r=v.compareTo(arr[j])) > 0) j--; **if** (r==0) c++;

**if** (i >= j) **break**;

exchange(arr, i++, j--);

}

**if** (c > 2) {

**if** (low < j) qsort\_3way(arr, low, j);

**if** (i < high) qsort\_3way(arr, i, high);

} **else** {

**if** (low < j) qsort\_hyb(arr, low, j);

**if** (i < high) qsort\_hyb(arr, i, high);

}

}

The following methods are used in the method qsort\_hyp:

// insert sort on subarray arr[low..high]:

**public** **void** isort(Item[] arr, **int** low, **int** high) { }

// return true iff arr[low..high] is sorted:

**public** **boolean** is\_sorted(Item[] arr, **int** low, **int** high) { }

// return the median of arr[low], arr[(low+high)/2], and arr[high]:

**public** Item pick\_pivot3(Item[] arr, **int** low, **int** high) { }

// return the pseudo-median of nine elements:

**public** Item pick\_pivot9(Item[] arr, **int** low, **int** high) { }

// exchange elements at positions i and j in arr:

**public** **void** exchange(Item[] arr, **int** i, **int** j) { }

// an implementation of 3-way quicksort (qsort\_3way is used in the recursive calls):

**public** **void** qsort\_3way(Item[] arr, **int** low, **int** high) { }

Note that integers alpha and beta are cutoff values for using isort, pick\_pivot3, or pick\_pivot9. Besides adding the test is\_sorted and selecting better pivots, this version of *quicksort* is different from the textbook version of *quicksort* [3] in that the position of the pivot element is not identified and there is no attempt to move the pivot element inbetween the two subarrays after the splitting.