

Dynamic-Array Kernels

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Abstract. This report together with an accompanying `tar` ball contains the programs used in the benchmarks discussed in the paper “Worst-Case-Efficient Dynamic Arrays in Practice”. With this source code it should be possible for others to reproduce the reported results.

Keywords. Data structures, dynamic arrays, worst-case efficiency

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The authors have tried to produce correct and useful programs, but no warranty of any kind should be assumed.

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Kernels

The basic operations of a dynamic array are `operator[]`, `push_back`, and `pop_back`. The study “Worst-Case-Efficient Dynamic Arrays in Practice” was an examination of variations of dynamic arrays that support these operations at $O(1)$ worst-case cost. In that paper the dynamic-array kernels considered were characterized as follows:

`std::vector`: This was the standard-library implementation that shipped with our `g++` compiler (version 4.8.4). It stored the values in one segment, `push_back` relied on doubling, and `pop_back` was a noop—memory was released only at the time of destruction. Compared to the other alternatives, this version only supported `push_back` at $O(1)$ amortized cost.

`cphstl::resizable_array`: This solution relied on doubling, halving, and incremental copying.

`cphstl::pile`: This version implemented the level-wise-allocated pile described in [5]. The data was split into a logarithmic number of contiguous segments, values were not moved due to reorganizations, and the three operations of interest were all supported at $O(1)$ worst-case cost.

`cphstl::sliced_array`: This version imitated the standard-library implementation of a double-ended queue. It was like a page table where the directory was implemented as a resizable array and the pages (memory segments) were arrays of fixed capacity (512 values).

`cphstl::space_efficient_array`: This version was as the block-wise-allocated pile described in [5], but the implementation was simplified by seeing it as a pile of hashed array trees [7]. This version matched the space and time bounds proved to be optimal in [2].

Architecture

In the CPH STL [4], the container classes have been implemented using the bridge design pattern [8, Sect. 14.4]. Above the dynamic-array kernels, two application program interfaces (APIs) are available: `cphstl::vector` which provides the same functionality as `std::vector` from the C++ standard library [3, Clause 23.3.6], and `cphleda::array` which provides the same functionality as `leda::array` from the LEDA library [1]. Our LEDA APIs are discussed in length in [6].

An architectural overview of the dynamic-array part of the library is given in Fig. 1 in the form of a UML class diagram. The full allocator interface is described in the C++ standard [3, Clause 20.7.9]. Any of the kernels can be given as a template argument for both APIs. On purpose, the kernels have not been made minimal so they can also be used individually. The rank-iterator class template can be used to get both mutable and immutable iterators for all kernels. Based on the actual needs, a user can tailor the

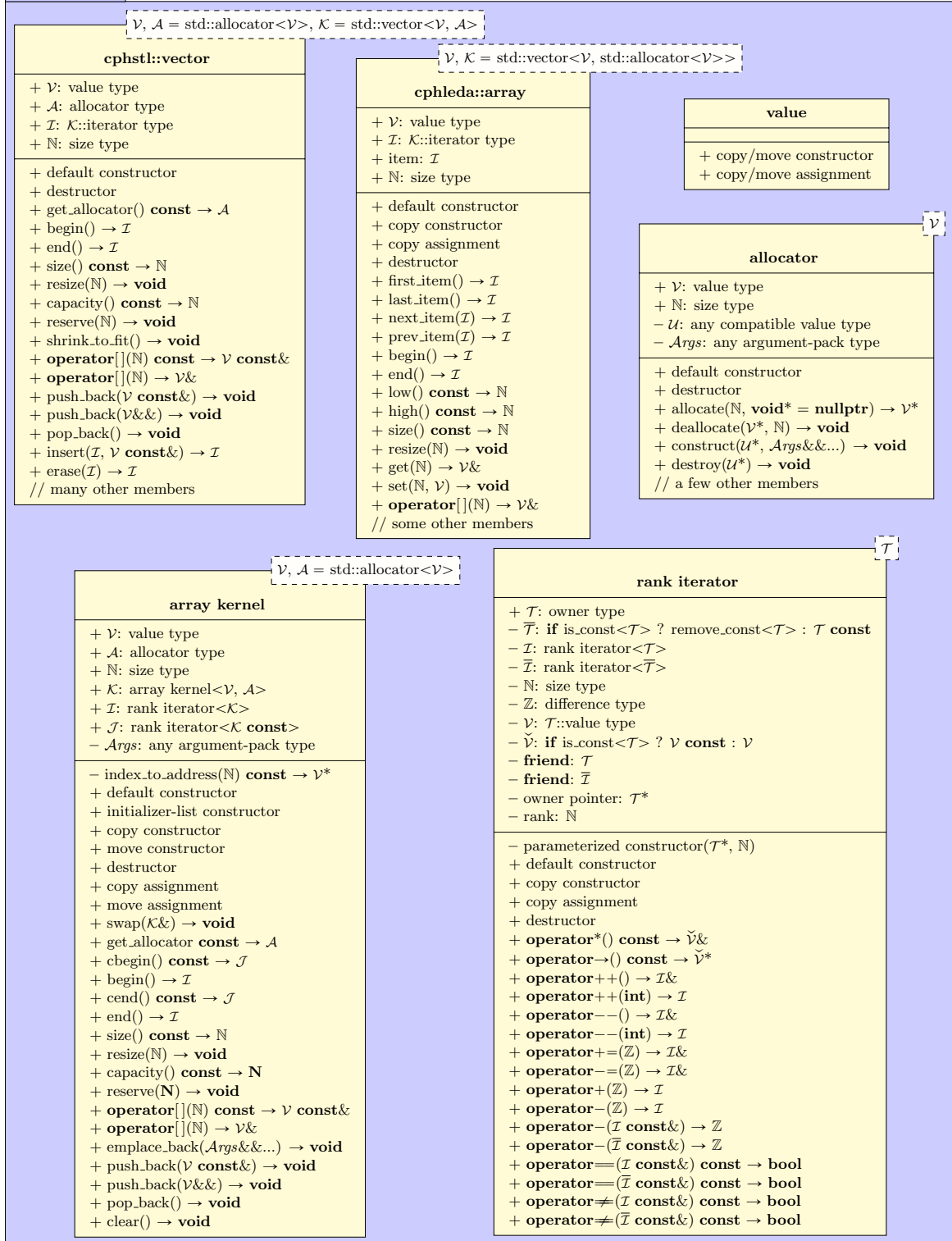


Figure 1. A UML class diagram illustrating the design of the dynamic-array part of the CPH STL; + means that a member is public and - that it is private

components to meet the desired safety and complexity requirements. A serious user can even build his own kernel and use it with the existing APIs. This kind of customization and easy of extension have been the main design objectives while creating the CPH STL.

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References

- [1] Algorithmic Solutions Software GmbH, The LEDA User Manual, version 6.4, Worldwide web document (2008). Retrieved from <http://www.algorithmic-solutions.com/leda/index.htm>.
- [2] A. Brodnik, S. Carlsson, E. D. Demaine, J. I. Munro, and R. Sedgwick, Resizable arrays in optimal time and space, *Proceedings of the 6th International Workshop on Algorithms and Data Structures, Lecture Notes in Computer Science* **1663**, Springer, Berlin/Heidelberg (1999), 37–48.
- [3] The C++ Standards Committee, Standard for Programming Language C++, Working Draft **N4296**, ISO/IEC, Geneva (2014).
- [4] Department of Computer Science, University of Copenhagen, The CPH STL, Website <http://cphstl.dk/> (2000–2016).
- [5] J. Katajainen and B. B. Mortensen, Experiences with the design and implementation of space-efficient dequeues, *Proceedings of the 5th Workshop on Algorithm Engineering, Lecture Notes in Computer Science* **2141**, Springer, Berlin/Heidelberg (2001), 39–50.
- [6] M. Neidhardt and B. Simonsen, Extending the CPH STL with LEDA APIs, CPH STL Report **2009-8**, Department of Computer Science, University of Copenhagen, Copenhagen (2009).
- [7] E. Sitarski, Algorithm alley: HATs: Hashed array trees: Fast variable-length arrays, *Dr. Dobbs' Journal* **21**, 11 (1996).
- [8] D. Vandervoorde and N. M. Josuttis, *C++ Templates: The Complete Guide*, Pearson Education, Inc., Boston (2003).

Kernels

contiguous_array.h++

```

1  /*
2  This is an experimental array which stores the elements contiguously
3  and has a fixed capacity. The capacity must be set using the
4  reserve() function.
5
6  Author: Jyrki Katajainen @ 2012, 2016
7  */
8
9  #include <cassert> // assert macro
10 #include <cstdint> // std::size_t and std::ptrdiff_t
11 #include <memory> // std::allocator, std::uninitialized_copy/fill
12 #include <utility> // std::forward, std::move, std::swap
13
14 namespace cphstl {
15
16     template <typename V, typename A = std::allocator<V>>
17     class contiguous_array {
18     public:
19
20         using value_type = V;
21         using allocator_type = typename A::template rebind<V>::other;
22         using reference = V&;
23         using const_reference = V const&;
24         using pointer = V*;
25         using const_pointer = V const*;
26         using difference_type = std::ptrdiff_t;
27         using size_type = std::size_t;
28         using iterator = V*;
29         using const_iterator = V const*;
30
31     protected:
32
33         allocator_type allocator;
34         V* X;
35         size_type X_size;
36         size_type X_capacity;
37
38         V* index_to_address(size_type rank) const {
39             return X + rank;
40         }
41
42     public:
43
44         explicit contiguous_array(A const& a = A())
45             : allocator(a), X(nullptr), X_size(0), X_capacity(0) {
46         }
47
48         contiguous_array(contiguous_array const& other)

```

```

49     : contiguous_array(other.allocator) {
50     V* tmp = nullptr;
51     size_type n = other.capacity();
52     if (n != 0) {
53         tmp = allocator.allocate(n);
54         std::uninitialized_copy(other.X, other.X + n, tmp);
55     }
56     X = tmp;
57     X_size = other.size();
58     X_capacity = n;
59 }
60
61 contiguous_array(contiguous_array&& other)
62     : contiguous_array(other.allocator) {
63     swap(other);
64 }
65
66 ~contiguous_array() {
67     clear();
68 }
69
70 contiguous_array& operator=(contiguous_array const& other) {
71     if (this != &other) {
72         contiguous_array tmp(other);
73         swap(tmp);
74     }
75     return *this;
76 }
77
78 contiguous_array& operator=(contiguous_array&& other) {
79     if (this != &other) {
80         contiguous_array tmp(std::move(other));
81         swap(tmp);
82     }
83     return *this;
84 }
85
86 void swap(contiguous_array& other) {
87     std::swap(allocator, other.allocator);
88     std::swap(X, other.X);
89     std::swap(X_size, other.X_size);
90     std::swap(X_capacity, other.X_capacity);
91 }
92
93 const_iterator begin() const {
94     return X;
95 }
96
97 iterator begin() {
98     return X;
99 }
100

```



```

101     const_iterator end() const {
102         return X + X_size;
103     }
104
105     iterator end() {
106         return X + X_size;
107     }
108
109     V* data() noexcept {
110         return X;
111     }
112
113     V const* data() const noexcept {
114         return X;
115     }
116
117     allocator_type get_allocator() const {
118         return allocator;
119     }
120
121     size_type size() const {
122         return X_size;
123     }
124
125     void resize(size_type n) {
126         assert(n ≤ capacity());
127         if (n ≤ X_size) {
128             for (size_type i = n; i < X_size; ++i) {
129                 allocator.destroy(X + i);
130             }
131         }
132         else {
133             std::uninitialized_fill(X + X_size, X + n, V());
134         }
135         X_size = n;
136     }
137
138     size_type capacity() const {
139         return X_capacity;
140     }
141
142     void reserve(size_type n) {
143         assert(X == nullptr); // capacity can only be set once
144         X = allocator.allocate(n);
145         X_size = 0;
146         X_capacity = n;
147     }
148
149     const_reference operator[](size_type i) const {
150         return *index_to_address(i);
151     }
152

```

```

153     reference operator[](size_type i) {
154         return *index_to_address(i);
155     }
156
157     template <typename... Args>
158     void emplace_back(Args&&... args) {
159         assert(X_size < X_capacity);
160         new (X + X_size) V(std::forward<Args>(args)...);
161         ++X_size;
162     }
163
164     void push_back(V const& x) {
165         assert(X_size < X_capacity);
166         allocator.construct(X + X_size, x);
167         ++X_size;
168     }
169
170     void push_back(V&& x) {
171         assert(X_size < X_capacity);
172         allocator.construct(X + X_size, std::move(x));
173         ++X_size;
174     }
175
176     void pop_back() {
177         assert(X_size  $\neq$  0);
178         allocator.destroy(X + X_size);
179         --X_size;
180     }
181
182     void clear() {
183         for (size_type i = 0; i  $\neq$  X_size; ++i) {
184             allocator.destroy(X + i);
185         }
186         X_size = 0;
187         if (X  $\neq$  nullptr) {
188             allocator.deallocate(X, X_capacity);
189         }
190         X = nullptr;
191         X_capacity = 0;
192     }
193 };
194 }

```

resizable_array.h++

```

1  /*
2   This is an experimental implementation of a resizable array based
3   on doubling, halving, and incremental copying.
4
5   Author: Jyrki Katajainen © 2012, 2013, 2015, 2016
6  */
7

```

```

8 #ifndef __CPHSTL_RESIZABLE_ARRAY__
9 #define __CPHSTL_RESIZABLE_ARRAY__
10
11 #include <algorithm> // std::max
12 #include <cassert> // assert macro
13 #include <cstddef> // std::size_t, std::ptrdiff_t
14 #include <initializer_list> // std::initializer_list
15 #include <iterator> // std::make_move_iterator
16 #include <memory> // std::allocator, std::uninitialized_copy
17 #include "rank-iterator.h++" // cphstl::rank_iterator
18 #include <utility> // std::forward, std::move, std::swap
19
20 namespace cphstl {
21
22     template <typename V, typename A = std::allocator<V>>
23     class resizable_array {
24     public:
25
26         using value_type = V;
27         using allocator_type = typename A::template rebind<V>::other;
28         using reference = V&;
29         using const_reference = V const&;
30         using pointer = V*;
31         using const_pointer = V const*;
32         using difference_type = std::ptrdiff_t;
33         using size_type = std::size_t;
34         using self_type = resizable_array<V, allocator_type>;
35         using iterator = cphstl::rank_iterator<self_type>;
36         using const_iterator = cphstl::rank_iterator<self_type const>;
37
38     private:
39
40         V* data() noexcept;
41         V const* data() const noexcept;
42
43     protected:
44
45         allocator_type allocator;
46         V* X;
47         V* Y;
48         size_type X_size;
49         size_type Y_size;
50         size_type X_capacity;
51         size_type Y_capacity;
52
53         V* index_to_address(size_type rank) const {
54             if (rank < X_size) {
55                 return X + rank;
56             }
57             return Y + rank;
58         }
59

```

```

60     template <typename I>
61     void append(I first, I past) {
62         I p = first;
63         I q = first;
64         try {
65             for ( ; q  $\neq$  past; ++q) {
66                 push_back(*q);
67             }
68         }
69         catch (...) {
70             for ( ; p  $\neq$  q; ++p) {
71                 pop_back();
72             }
73             throw;
74         }
75     }
76
77     void append_n(size_type k, V const& value) {
78         size_type i = 0;
79         size_type j = 0;
80         try {
81             for ( ; j  $\neq$  k; ++j) {
82                 push_back(value);
83             }
84         }
85         catch (...) {
86             for ( ; i  $\neq$  j; ++i) {
87                 pop_back();
88             }
89         }
90     }
91
92     public:
93
94     explicit resizable_array(A const& a = A())
95         : allocator(a), X(nullptr), Y(nullptr), X_size(0), Y_size(0),
96           X_capacity(0), Y_capacity(0) {
97         X = allocator.allocate(1);
98         X_capacity = 1;
99     }
100
101     resizable_array(std::initializer_list<V> s)
102         : resizable_array(A()) {
103         append(s.begin(), s.end());
104     }
105
106     resizable_array(size_type n, A const& a)
107         : resizable_array(a) {
108         append_n(n, V());
109     }
110
111     resizable_array(resizable_array const& other)

```

```

112     : resizable_array(other.get_allocator()) {
113     V* tmp = nullptr;
114     size_type n = other.capacity();
115     tmp = allocator.allocate(n);
116     std::uninitialized_copy(other.begin(), other.begin() + n, tmp);
117     X = tmp;
118     X_size = other.size();
119     X_capacity = n;
120 }
121
122     resizable_array(resizable_array&& other)
123     : resizable_array(other.get_allocator()) {
124     swap(other);
125 }
126
127     ~resizable_array() {
128     clear();
129     if (X  $\neq$  nullptr) {
130     allocator.deallocate(X, X_capacity);
131     }
132 }
133
134     resizable_array& operator=(resizable_array const& other) {
135     if (this  $\neq$  &other) {
136     resizable_array tmp(other);
137     swap(tmp);
138     }
139     return *this;
140 }
141
142     resizable_array& operator=(resizable_array&& other) {
143     if (this  $\neq$  &other) {
144     resizable_array tmp(std::move(other));
145     swap(tmp);
146     }
147     return *this;
148 }
149
150     void swap(resizable_array& other) {
151     std::swap(allocator, other.allocator);
152     std::swap(X, other.X);
153     std::swap(X_size, other.X_size);
154     std::swap(X_capacity, other.X_capacity);
155     std::swap(Y, other.Y);
156     std::swap(Y_size, other.Y_size);
157     std::swap(Y_capacity, other.Y_capacity);
158 }
159
160     const_iterator cbegin() const {
161     return (size()  $\neq$  0) ? const_iterator(this, 0) : const_iterator
162         (this);
163 }

```

```
163
164     const_iterator begin() const {
165         return cbegin();
166     }
167
168     iterator begin() {
169         return (size()  $\neq$  0) ? iterator(this, 0) : iterator(this);
170     }
171
172     const_iterator cend() const {
173         return const_iterator(this);
174     }
175
176     const_iterator end() const {
177         return cend();
178     }
179
180     iterator end() {
181         return iterator(this);
182     }
183
184     allocator_type get_allocator() const {
185         return allocator;
186     }
187
188     size_type size() const {
189         return std::max(X_size, Y_size);
190     }
191
192     void resize(size_type n) {
193         if (size() > n) {
194             while (size() > n) {
195                 pop_back();
196             }
197             return;
198         }
199         append_n(n - size(), V());
200     }
201
202     size_type capacity() const {
203         if (Y_size  $\neq$  0) {
204             return Y_capacity;
205         }
206         return X_capacity;
207     }
208
209     void reserve(size_type n) {
210         if (n  $\leq$  capacity()) {
211             return;
212         }
213         V* tmp = allocator.allocate(n);
214         std::uninitialized_copy(std::make_move_iterator(X), std::
```

```

    make_move_iterator(X + X_size), tmp);
215 if (Y  $\neq$  nullptr) {
216     std::uninitialized_copy(std::make_move_iterator(Y + X_size),
        std::make_move_iterator(Y + Y_size), tmp + X_size);
217 }
218 allocator.deallocate(X, X_capacity);
219 if (Y  $\neq$  nullptr) {
220     allocator.deallocate(Y, Y_capacity);
221 }
222 X_size = size();
223 X_capacity = n;
224 X = tmp;
225 Y = nullptr;
226 Y_size = 0;
227 Y_capacity = 0;
228 }
229
230 const_reference operator[](size_type i) const {
231     return *index_to_address(i);
232 }
233
234 reference operator[](size_type i) {
235     return *index_to_address(i);
236 }
237
238 const_reference front() const {
239     return *index_to_address(0);
240 }
241
242 reference front() {
243     return *index_to_address(0);
244 }
245
246 const_reference back() const {
247     return *index_to_address(size() - 1);
248 }
249
250 reference back() {
251     return *index_to_address(size() - 1);
252 }
253
254 template <typename... Args>
255 void emplace_back(Args&&... args) {
256     if (Y_size == 0 and X_size < X_capacity) {
257         new (X + X_size) V(std::forward<Args>(args)...);
258         ++X_size;
259         return;
260     }
261     if (Y_size == 0 and X_size == X_capacity) {
262         Y_capacity = 2 * X_capacity;
263         Y = allocator.allocate(Y_capacity);
264         Y_size = X_size;

```

```

265     }
266     --X_size;
267     allocator.construct(Y + X_size, std::move(*(X + X_size)));
268     allocator.destroy(X + X_size);
269     new (Y + Y_size) V(std::forward<Args>(args)...);
270     ++Y_size;
271     if (X_size == 0) {
272         allocator.deallocate(X, X_capacity);
273         X = Y;
274         X_size = Y_size;
275         X_capacity = Y_capacity;
276         Y = nullptr;
277         Y_size = 0;
278         Y_capacity = 0;
279     }
280 }
281
282 void push_back(V const& x) {
283     if (Y_size == 0 and X_size < X_capacity) {
284         allocator.construct(X + X_size, x);
285         ++X_size;
286         return;
287     }
288     if (Y_size == 0 and X_size == X_capacity) {
289         Y_capacity = 2 * X_capacity;
290         Y = allocator.allocate(Y_capacity);
291         Y_size = X_size;
292     }
293     --X_size;
294     allocator.construct(Y + X_size, std::move(*(X + X_size)));
295     allocator.destroy(X + X_size);
296     allocator.construct(Y + Y_size, x);
297     ++Y_size;
298     if (X_size == 0) {
299         allocator.deallocate(X, X_capacity);
300         X = Y;
301         X_size = Y_size;
302         X_capacity = Y_capacity;
303         Y = nullptr;
304         Y_size = 0;
305         Y_capacity = 0;
306     }
307 }
308
309 void push_back(V&& x) {
310     if (Y_size == 0 and X_size < X_capacity) {
311         allocator.construct(X + X_size, std::move(x));
312         ++X_size;
313         return;
314     }
315     if (Y_size == 0 and X_size == X_capacity) {
316         Y_capacity = 2 * X_capacity;

```



```

317     Y = allocator.allocate(Y_capacity);
318     Y_size = X_size;
319 }
320 --X_size;
321 allocator.construct(Y + X_size, std::move(*(X + X_size)));
322 allocator.destroy(X + X_size);
323 allocator.construct(Y + Y_size, std::move(x));
324 ++Y_size;
325 if (X_size == 0) {
326     allocator.deallocate(X, X_capacity);
327     X = Y;
328     X_size = Y_size;
329     X_capacity = Y_capacity;
330     Y = nullptr;
331     Y_size = 0;
332     Y_capacity = 0;
333 }
334 }
335
336 void pop_back() {
337     assert(size() > 0);
338     if (Y_size == 0 and 4 * X_size > X_capacity) {
339         --X_size;
340         allocator.destroy(X + X_size);
341         return;
342     }
343     if (Y_size == 0 and 4 * X_size ≤ X_capacity) {
344         assert(Y_capacity == 0);
345         Y_capacity = 2 * X_size;
346         Y = allocator.allocate(Y_capacity);
347         Y_size = X_size;
348     }
349     --X_size;
350     allocator.construct(Y + X_size, std::move(*(X + X_size)));
351     allocator.destroy(X + X_size);
352     if (X_size ≠ 0) {
353         --X_size;
354         allocator.construct(Y + X_size, std::move(*(X + X_size)));
355         allocator.destroy(X + X_size);
356     }
357     --Y_size;
358     allocator.destroy(Y + Y_size);
359     if (X_size == 0) {
360         allocator.deallocate(X, X_capacity);
361         X = Y;
362         X_size = Y_size;
363         X_capacity = Y_capacity;
364         Y = nullptr;
365         Y_size = 0;
366         Y_capacity = 0;
367     }
368 }

```

```

369
370 void clear() {
371     for (size_type i = 0; i  $\neq$  X_size; ++i) {
372         allocator.destroy(X + i);
373     }
374     for (size_type j = 0; j  $\neq$  Y_size; ++j) {
375         allocator.destroy(Y + j);
376     }
377     if (X  $\neq$  nullptr) {
378         allocator.deallocate(X, X_capacity);
379     }
380     if (Y  $\neq$  nullptr) {
381         allocator.deallocate(Y, Y_capacity);
382     }
383     X = allocator.allocate(1);
384     Y = nullptr;
385     X_size = 0;
386     Y_size = 0;
387     X_capacity = 1;
388     Y_capacity = 0;
389 }
390 };
391 }
392
393 #endif

```

pile.h++

```

1 /*
2  This is an experimental implementation of a levelwise-allocated
3  pile; each level stores a fixed-capacity segment and the directory
4  is a (worst-case-efficient) resizable array.
5
6  Author: Jyrki Katajainen © 2012, 2013, 2015, 2016
7  */
8
9  #ifndef __CPHSTL_PILE__
10 #define __CPHSTL_PILE__
11
12 #include <algorithm> // std::min
13 #include <cassert> // assert macro
14 #include <cstddef> // std::size_t, std::ptrdiff_t
15 #include <initializer_list> // std::initializer_list
16 #include <memory> // std::allocator, std::uninitialized_copy
17 #include "rank-iterator.h++" // cphstl::rank_iterator
18 #include "resizable_array.h++" // cphstl::resizable_array
19 #include <utility> // std::forward, std::move, std::swap
20
21 #ifndef __POPULATION_COUNT__
22 #define __POPULATION_COUNT__
23
24 unsigned int population_count(unsigned int j) {

```

```

25     return __builtin_popcount(j);
26 }
27
28 unsigned long population_count(unsigned long j) {
29     return __builtin_popcountl(j);
30 }
31
32 unsigned long long population_count(unsigned long long j) {
33     return __builtin_popcountll(j);
34 }
35
36 #endif
37
38 #ifndef __WHOLE_NUMBER_LOGARITHM__
39 #define __WHOLE_NUMBER_LOGARITHM__
40
41 std::size_t whole_number_logarithm(std::size_t x) {
42     asm("bsr %0, %0\n"
43         : "=r"(x)
44         : "0" (x)
45     );
46     return x;
47 }
48
49 #endif
50
51 namespace cphstl {
52
53     template <typename V, typename A = std::allocator<V>>
54     class pile {
55     public:
56
57         using value_type = V;
58         using allocator_type = typename A::template rebind<V>::other;
59         using reference = V&;
60         using const_reference = V const&;
61         using pointer = V*;
62         using const_pointer = V const*;
63         using difference_type = std::ptrdiff_t;
64         using size_type = std::size_t;
65         using self_type = pile<V, allocator_type>;
66         using iterator = cphstl::rank_iterator<self_type>;
67         using const_iterator = cphstl::rank_iterator<self_type const>;
68
69     private:
70
71         V* data() noexcept;
72         V const* data() const noexcept;
73
74     protected:
75
76         using other_allocator_type = typename A::template rebind<V*>::

```

```

        other;
77     using directory_type = cphstl::resizable_array<V*,
        other_allocator_type>;
78
79     allocator_type allocator;
80     directory_type directory;
81     size_type n;
82
83     V* index_to_address(size_type rank) const {
84         if (rank < 2) {
85             return directory[0] + rank;
86         }
87         std::size_t h = whole_number_logarithm(rank);
88         return directory[h] + rank - (1 << h);
89     }
90
91     template <typename I>
92     void append(I first, I past) {
93         I p = first;
94         I q = first;
95         try {
96             for ( ; q ≠ past; ++q) {
97                 push_back(*q);
98             }
99         }
100        catch (...) {
101            for ( ; p ≠ q; ++p) {
102                pop_back();
103            }
104            throw;
105        }
106    }
107
108    void append_n(size_type k, V const& value) {
109        size_type i = 0;
110        size_type j = 0;
111        try {
112            for ( ; j ≠ k; ++j) {
113                push_back(value);
114            }
115        }
116        catch (...) {
117            for ( ; i ≠ j; ++i) {
118                pop_back();
119            }
120        }
121    }
122
123    public:
124
125    explicit pile(A const& a = A())
126        : allocator(a), directory(a), n(0) {

```

```

127     V* p = allocator.allocate(2);
128     directory.push_back(p);
129 }
130
131 pile(std::initializer_list<V> s)
132 : pile(A()) {
133     append(s.begin(), s.end());
134 }
135
136 pile(size_type n, A const& a)
137 : pile(a) {
138     append_n(n, V());
139 }
140
141 pile(pile const& other)
142 : allocator(other.get_allocator()), directory(other.
143     get_allocator()),
144     n(other.size()) {
145     size_type length = 2;
146     size_type i = 0;
147     do {
148         V* s = allocator.allocate(length);
149         size_type j = std::min(i + length, n);
150         std::uninitialized_copy(other.begin() + i, other.begin() + j,
151             s);
152         directory.push_back(s);
153         length = 1 << directory.size();
154         i = j;
155     } while (i != n);
156 }
157
158 template <typename S>
159 pile(S const& other)
160 : allocator(other.get_allocator()), directory(other.
161     get_allocator()),
162     n(other.size()) {
163     size_type length = 2;
164     size_type i = 0;
165     do {
166         V* s = allocator.allocate(length);
167         size_type j = std::min(i + length, n);
168         std::uninitialized_copy(other.begin() + i, other.begin() + j,
169             s);
170         directory.push_back(s);
171         length = 1 << directory.size();
172         i = j;
173     } while (i != n);
174 }
175
176 pile(pile&& other)
177 : allocator(other.get_allocator()), directory(other.
178     get_allocator()), n(0) {

```

```

174     swap(other);
175 }
176
177 ~pile() {
178     clear();
179     directory.clear();
180 }
181
182 pile& operator=(pile const& other) {
183     if (this ≠ &other) {
184         pile tmp(other);
185         swap(tmp);
186     }
187     return *this;
188 }
189
190 pile& operator=(pile&& other) {
191     if (this ≠ &other) {
192         pile tmp(std::move(other));
193         swap(tmp);
194     }
195     return *this;
196 }
197
198 const_iterator cbegin() const {
199     return (size() ≠ 0) ? const_iterator(this, 0) : const_iterator
200         (this);
201 }
202
203 const_iterator begin() const {
204     return cbegin();
205 }
206
207 iterator begin() {
208     return (size() ≠ 0) ? iterator(this, 0) : iterator(this);
209 }
210
211 const_iterator cend() const {
212     return const_iterator(this);
213 }
214
215 const_iterator end() const {
216     return cend();
217 }
218
219 iterator end() {
220     return iterator(this);
221 }
222
223 allocator_type get_allocator() const {
224     return allocator;
225 }

```

```

225
226     size_type size() const {
227         return n;
228     }
229
230     size_type capacity() const {
231         return 1 << directory.size();
232     }
233
234     void resize(size_type new_size) {
235         if (n > new_size) {
236             while (n > new_size) {
237                 pop_back();
238             }
239             return;
240         }
241         append_n(new_size - n, V());
242     }
243
244     void reserve(size_type) {
245         // do nothing
246     }
247
248     const_reference operator[](size_type i) const {
249         return *index_to_address(i);
250     }
251
252     reference operator[](size_type i) {
253         return *index_to_address(i);
254     }
255
256     const_reference front() const {
257         return *index_to_address(0);
258     }
259
260     reference front() {
261         return *index_to_address(0);
262     }
263
264     const_reference back() const {
265         return *index_to_address(size() - 1);
266     }
267
268     reference back() {
269         return *index_to_address(size() - 1);
270     }
271
272     template <typename... Args>
273     void emplace_back(Args&&... args) {
274         if (n > 1 and population_count(n) == 1) {
275             size_type h = directory.size();
276             V* p = allocator.allocate(1 << h);

```

```

277     directory.push_back(p);
278 }
279 new (index_to_address(n)) V(std::forward<Args>(args)...);
280 n += 1;
281 }
282
283 void push_back(V const& x) {
284     if (n > 1 and population_count(n) == 1) {
285         size_type h = directory.size();
286         V* p = allocator.allocate(1 << h);
287         directory.push_back(p);
288     }
289     allocator.construct(index_to_address(n), x);
290     n += 1;
291 }
292
293 void push_back(V&& x) {
294     if (n > 1 and population_count(n) == 1) {
295         size_type h = directory.size();
296         V* p = allocator.allocate(1 << h);
297         directory.push_back(p);
298     }
299     allocator.construct(index_to_address(n), std::move(x));
300     n += 1;
301 }
302
303 void pop_back() {
304     assert(n > 0);
305     n -= 1;
306     allocator.destroy(index_to_address(n));
307     size_type h = directory.size();
308     if (h != 1 and population_count(n) == 1) {
309         h -= 1;
310         allocator.deallocate(directory[h], 1 << h);
311         directory.pop_back();
312     }
313 }
314
315 void clear() {
316     while (size() > 0) {
317         pop_back();
318     }
319 }
320
321 void swap(pile& other) {
322     std::swap(allocator, other.allocator);
323     directory.swap(other.directory);
324     std::swap(n, other.n);
325 }
326 };
327 }
328

```



```

329 #endif

sliced_array.h++

1 /*
2  This is an experimental implementation of a page-table-like array
3  often used in the implementation of the standard-library deque;
4  each page is a fixed-capacity array and the directory is a
5  (worst-case-efficient) resizable array.
6
7  Author: Jyrki Katajainen @ 2012, 2013, 2015, 2016
8 */
9
10 #ifndef __CPHSTL_SLICED_ARRAY__
11 #define __CPHSTL_SLICED_ARRAY__
12
13 #include <cassert> // assert macro
14 #include <cstddef> // std::size_t, std::ptrdiff_t
15 #include <initializer_list> // std::initializer_list
16 #include <memory> // std::allocator, std::uninitialized_copy
17 #include "rank-iterator.h++" // cphstl::rank_iterator
18 #include "resizable_array.h++" // cphstl::resizable_array
19 #include <utility> // std::forward, std::move, std::swap
20
21 namespace cphstl {
22
23     template <typename V, typename A = std::allocator<V>>
24     class sliced_array {
25     public:
26
27         using value_type = V;
28         using allocator_type = typename A::template rebind<V>::other;
29         using reference = V&;
30         using const_reference = V const&;
31         using pointer = V*;
32         using const_pointer = V const*;
33         using difference_type = std::ptrdiff_t;
34         using size_type = std::size_t;
35         using self_type = sliced_array<V, allocator_type>;
36         using iterator = cphstl::rank_iterator<self_type>;
37         using const_iterator = cphstl::rank_iterator<self_type const>;
38
39     private:
40
41         V* data() noexcept;
42         V const* data() const noexcept;
43
44     protected:
45
46         size_type const slice_size = 512;
47         size_type const shift_amount = 9;
48         size_type const mask = 511;

```

```

49     using B = typename A::template rebind<V*>::other;
50     using directory_type = cphstl::resizable_array<V*, B>;
51
52     allocator_type allocator;
53     B pointer_allocator;
54     directory_type directory;
55     size_type n;
56
57     V* index_to_address(size_type rank) const {
58         return directory[rank >> shift_amount] + (rank bitand mask);
59     }
60
61     template <typename I>
62     void append(I first, I past) {
63         I p = first;
64         I q = first;
65         try {
66             for ( ; q ≠ past; ++q) {
67                 push_back(*q);
68             }
69         }
70         catch (...) {
71             for ( ; p ≠ q; ++p) {
72                 pop_back();
73             }
74             throw;
75         }
76     }
77
78     void append_n(size_type k, V const& value) {
79         size_type i = 0;
80         size_type j = 0;
81         try {
82             for ( ; j ≠ k; ++j) {
83                 push_back(value);
84             }
85         }
86         catch (...) {
87             for ( ; i ≠ j; ++i) {
88                 pop_back();
89             }
90         }
91     }
92
93     public:
94
95     explicit sliced_array(A const& a = A())
96         : allocator(a), pointer_allocator(B(a)), directory(B(a)), n(0)
97         {
98
99     sliced_array(std::initializer_list<V> s)

```

```

100     : sliced_array(A()) {
101     append(s.begin(), s.end());
102     }
103
104     sliced_array(size_type n, A const& a)
105     : sliced_array(a) {
106     append_n(n, V());
107     }
108
109     sliced_array(sliced_array const& other)
110     : allocator(other.allocator), pointer_allocator(other.
111     pointer_allocator),
112     directory(other.pointer_allocator), n(0) {
113     directory_type tmp;
114     for (size_type i = 0; i < other.directory.size(); ++i) {
115     V* p = allocator.allocate(slice_size);
116     tmp.push_back(p);
117     std::uninitialized_copy(other.directory[i], other.directory[i
118     ] + slice_size, p);
119     }
120     directory = std::move(tmp);
121     n = other.size();
122     }
123
124     sliced_array(sliced_array&& other)
125     : allocator(other.allocator), pointer_allocator(other.
126     pointer_allocator),
127     directory(other.pointer_allocator), n(0) {
128     swap(other);
129     }
130
131     ~sliced_array() {
132     clear();
133     }
134
135     sliced_array& operator=(sliced_array const& other) {
136     if (this != &other) {
137     sliced_array tmp(other);
138     swap(tmp);
139     }
140     return *this;
141     }
142
143     sliced_array& operator=(sliced_array&& other) {
144     if (this != &other) {
145     sliced_array tmp(std::move(other));
146     swap(tmp);
147     }
148     return *this;
149     }
150
151     void swap(sliced_array& other) {

```

```

149     std::swap(allocator, other.allocator);
150     std::swap(pointer_allocator, other.pointer_allocator);
151     directory.swap(other.directory);
152     std::swap(n, other.n);
153 }
154
155     const_iterator cbegin() const {
156         return (size()  $\neq$  0) ? const_iterator(this, 0) : const_iterator
            (this);
157     }
158
159     const_iterator begin() const {
160         return cbegin();
161     }
162
163     iterator begin() {
164         return (size()  $\neq$  0) ? iterator(this, 0) : iterator(this);
165     }
166
167     const_iterator cend() const {
168         return const_iterator(this);
169     }
170
171     const_iterator end() const {
172         return cend();
173     }
174
175     iterator end() {
176         return iterator(this);
177     }
178
179     allocator_type get_allocator() const {
180         return allocator;
181     }
182
183     size_type size() const {
184         return n;
185     }
186
187     void resize(size_type new_size) {
188         if (n > new_size) {
189             while (n > new_size) {
190                 pop_back();
191             }
192             return;
193         }
194         append_n(new_size - n, V());
195     }
196
197     size_type capacity() const {
198         return size_type(-1);
199     }

```

```

200
201 void reserve(size_type) {
202 }
203
204 const_reference operator[](size_type i) const {
205     return *index_to_address(i);
206 }
207
208 reference operator[](size_type i) {
209     return *index_to_address(i);
210 }
211
212 const_reference front() const {
213     return *index_to_address(0);
214 }
215
216 reference front() {
217     return *index_to_address(0);
218 }
219
220 const_reference back() const {
221     return *index_to_address(size() - 1);
222 }
223
224 reference back() {
225     return *index_to_address(size() - 1);
226 }
227
228 template <typename... Args>
229 void emplace_back(Args&&... args) {
230     size_type offset = n bitand mask;
231     if (offset == 0) {
232         V* p = allocator.allocate(slice_size);
233         directory.push_back(p);
234     }
235     new (index_to_address(n)) V(std::forward<Args>(args)...);
236     n += 1;
237 }
238
239 void push_back(V const& x) {
240     size_type offset = n bitand mask;
241     if (offset == 0) {
242         V* p = allocator.allocate(slice_size);
243         directory.push_back(p);
244     }
245     allocator.construct(directory[n >> shift_amount] + offset, x);
246     n += 1;
247 }
248
249 void push_back(V&& x) {
250     size_type offset = n bitand mask;
251     if (offset == 0) {

```

```

252     V* p = allocator.allocate(slice_size);
253     directory.push_back(p);
254 }
255     allocator.construct(directory[n >> shift_amount] + offset, std
        ::move(x));
256     n += 1;
257 }
258
259 void pop_back() {
260     assert(n > 0);
261     n -= 1;
262     V* base = directory[n >> shift_amount];
263     size_type offset = n & mask;
264     allocator.destroy(base + offset);
265     if (offset == 0) {
266         allocator.deallocate(base, slice_size);
267         directory.pop_back();
268     }
269 }
270
271 void clear() {
272     while (n > 0) {
273         pop_back();
274     }
275 }
276 };
277 }
278
279 #endif

```

fixed_capacity_hat.h++

```

1  /*
2   This is an experimental implementation of a hashed array tree which
3   has a fixed capacity. The capacity must be set using the reserve()
4   function and it can only be set once.
5
6   Author: Jyrki Katajainen © 2012, 2013, 2016
7  */
8
9  #include <algorithm> // std::max
10 #include <cassert> // assert macro
11 #include <cmath> // ilogb
12 #include "contiguous_array.h++"
13 #include <cstdint> // std::size_t, std::ptrdiff_t
14 #include "rank-iterator.h++"
15 #include <utility> // std::forward, std::move, std::swap
16
17 namespace cphstl {
18
19     template <typename H, typename E>
20     class space_efficient_array;

```

```

21
22 template <typename V, typename A = std::allocator<V>>
23 class fixed_capacity_hat {
24 public:
25
26     using value_type = V;
27     using allocator_type = typename A::template rebind<V>::other;
28     using reference = V&;
29     using const_reference = V const&;
30     using pointer = V*;
31     using const_pointer = V const*;
32     using difference_type = std::ptrdiff_t;
33     using size_type = std::size_t;
34     using self_type = fixed_capacity_hat<V, allocator_type>;
35     using iterator = cphstl::rank_iterator<self_type>;
36     using const_iterator = cphstl::rank_iterator<self_type const>;
37
38 protected:
39
40     template <typename H, typename B>
41     friend class space_efficient_array;
42
43     using other_allocator_type = typename A::template rebind<V*>::
44         other;
45     using directory_type = cphstl::contiguous_array<V*,
46         other_allocator_type>;
47
48     allocator_type allocator;
49     directory_type directory;
50     size_type n;
51     size_type m; // a power of two
52     size_type shift_amount; // lg m
53     size_type mask;
54
55     V* index_to_address(size_type rank) const {
56         return directory[rank >> shift_amount] + (rank bitand mask);
57     }
58
59     void append_n(size_type k, V const& value) {
60         size_type i = 0;
61         size_type j = 0;
62         try {
63             for ( ; j  $\neq$  k; ++j) {
64                 push_back(value);
65             }
66         } catch (...) {
67             for ( ; i  $\neq$  j; ++i) {
68                 pop_back();
69             }
70         }

```

```

71
72 public:
73
74     explicit fixed_capacity_hat(A const& a = A())
75         : allocator(a), directory(a), n(0), m(0), shift_amount(0), mask
76           (0) {
77
78     fixed_capacity_hat(fixed_capacity_hat const& other)
79         : allocator(other.allocator), directory(other.allocator), n(0),
80           m(0), shift_amount(0), mask(0) {
81         directory_type tmp;
82         tmp.reserve(other.m);
83         for (size_type i = 0; i  $\neq$  other.directory.size(); ++i) {
84             V* p = allocator.allocate(m);
85             tmp.push_back(p);
86             std::uninitialized_copy(other.directory[i], other.directory[i
87                                   ] + m, p);
88         }
89         directory = std::move(tmp);
90         n = other.n;
91         m = other.m;
92         shift_amount = other.shift_amount;
93         mask = other.mask;
94     }
95
96     fixed_capacity_hat(fixed_capacity_hat&& other)
97         : allocator(other.allocator), directory(other.allocator), n(0),
98           m(0), shift_amount(0), mask(0) {
99         swap(other);
100     }
101
102     ~fixed_capacity_hat() {
103         clear();
104     }
105
106     fixed_capacity_hat& operator=(fixed_capacity_hat const& other)
107     {
108         if (this  $\neq$  &other) {
109             fixed_capacity_hat tmp(other);
110             swap(tmp);
111         }
112         return *this;
113     }
114
115     fixed_capacity_hat& operator=(fixed_capacity_hat&& other) {
116         if (this  $\neq$  &other) {
117             fixed_capacity_hat tmp(std::move(other));
118             swap(tmp);
119         }
120         return *this;
121     }

```



```
120
121 void swap(fixed_capacity_hat& other) {
122     std::swap(allocator, other.allocator);
123     directory.swap(other.directory);
124     std::swap(n, other.n);
125     std::swap(m, other.m);
126     std::swap(shift_amount, other.shift_amount);
127     std::swap(mask, other.mask);
128 }
129
130 const_iterator cbegin() const {
131     return (size()  $\neq$  0) ? const_iterator(this, 0) : const_iterator
        (this);
132 }
133
134 const_iterator begin() const {
135     return cbegin();
136 }
137
138 iterator begin() {
139     return (size()  $\neq$  0) ? iterator(this, 0) : iterator(this);
140 }
141
142 const_iterator cend() const {
143     return const_iterator(this);
144 }
145
146 const_iterator end() const {
147     return cend();
148 }
149
150 iterator end() {
151     return iterator(this);
152 }
153
154 allocator_type get_allocator() const {
155     return allocator;
156 }
157
158 size_type size() const {
159     return n;
160 }
161
162 void resize(size_type new_size) {
163     if (n > new_size) {
164         while (n > new_size) {
165             pop_back();
166         }
167     }
168     return;
169     append_n(new_size - n, V());
170     n = new_size;
```

```

171     }
172
173     size_type capacity() const {
174         return m * m;
175     }
176
177     void reserve(size_type n) {
178         assert(m == 0);
179         size_type lg_n = ilogb(std::max(size_type(1), n));
180         size_type new_m = 1 << (lg_n / 2); // about sqrt of n
181         if (new_m * new_m < n) {
182             new_m = 2 * new_m;
183         }
184         directory.reserve(new_m);
185         m = new_m;
186         shift_amount = ilogb(m);
187         mask = m - 1;
188     }
189
190     const_reference operator[](size_type i) const {
191         return *index_to_address(i);
192     }
193
194     reference operator[](size_type i) {
195         return *index_to_address(i);
196     }
197
198     template <typename... Args>
199     void emplace_back(Args&&... args) {
200         assert(n < capacity());
201         size_type offset = n bitand mask;
202         if (offset == 0) {
203             V* p = allocator.allocate(m);
204             directory.push_back(p);
205         }
206         new (index_to_address(n)) V(std::forward<Args>(args)...);
207         n += 1;
208     }
209
210     void push_back(V const& x) {
211         assert(n < capacity());
212         size_type offset = n bitand mask;
213         if (offset == 0) {
214             V* p = allocator.allocate(m);
215             directory.push_back(p);
216         }
217         allocator.construct(directory[n >> shift_amount] + offset, x);
218         n += 1;
219     }
220
221     void push_back(V&& x) {
222         assert(n < capacity());

```

```

223     size_type offset = n bitand mask;
224     if (offset == 0) {
225         V* p = allocator.allocate(m);
226         directory.push_back(p);
227     }
228     allocator.construct(directory[n >> shift_amount] + offset, std
        ::move(x));
229     n += 1;
230 }
231
232 void pop_back() {
233     assert(n != 0);
234     n -= 1;
235     V* base = directory[n >> shift_amount];
236     size_type offset = n bitand mask;
237     allocator.destroy(base + offset);
238     if (offset == 0) {
239         allocator.deallocate(base, m);
240         directory.pop_back();
241     }
242 }
243
244 void clear() {
245     while (n > 0) {
246         pop_back();
247     }
248     while (directory.size() > 0) {
249         directory.pop_back();
250     }
251     m = 0;
252     shift_amount = 0;
253     mask = 0;
254 }
255 };
256 }

```

space_efficient_array.h++

```

1  /*
2  This is an experimental implementation of a space-efficient array
3  that consists of a pool of fixed-capacity hashed array trees; the
4  directory is a (worst-case-efficient) resizable array.
5
6  Author: Jyrki Katajainen @ 2012, 2016
7  */
8
9  #ifndef __CPHSTL_SPACE_EFFICIENT_ARRAY__
10 #define __CPHSTL_SPACE_EFFICIENT_ARRAY__
11
12 #include <cassert> // assert macro
13 #include <cstddef> // std::size_t, std::ptrdiff_t
14 #include "fixed_capacity_hat.h++" // cphstl::fixed_capacity_hat

```

```

15 #include <initializer_list> // std::initializer_list
16 #include <memory> // std::allocator
17 #include "rank-iterator.h++" // cphstl::rank_iterator
18 #include "resizable_array.h++" // cphstl::resizable_array
19 #include <utility> // std::forward, std::move, std::swap
20
21 #ifndef __POPULATION_COUNT__
22 #define __POPULATION_COUNT__
23
24 unsigned int population_count(unsigned int j) {
25     return __builtin_popcount(j);
26 }
27
28 unsigned long population_count(unsigned long j) {
29     return __builtin_popcountl(j);
30 }
31
32 unsigned long long population_count(unsigned long long j) {
33     return __builtin_popcountll(j);
34 }
35
36 #endif
37
38 #ifndef __WHOLE_NUMBER_LOGARITHM__
39 #define __WHOLE_NUMBER_LOGARITHM__
40
41 std::size_t whole_number_logarithm(std::size_t x) {
42     asm("bsr %0, %0\n"
43         : "=r"(x)
44         : "0" (x)
45         );
46     return x;
47 }
48
49 #endif
50
51 namespace cphstl {
52
53     template <typename V, typename A = std::allocator<V>>
54     class space_efficient_array {
55     public:
56
57         using value_type = V;
58         using allocator_type = typename A::template rebind<V>::other;
59         using reference = V&;
60         using const_reference = V const&;
61         using pointer = V*;
62         using const_pointer = V const*;
63         using difference_type = std::ptrdiff_t;
64         using size_type = std::size_t;
65         using self_type = space_efficient_array<V, allocator_type>;
66         using iterator = rank_iterator<self_type>;

```

```

67     using const_iterator = rank_iterator<self_type const>;
68
69 private:
70
71     V* data() noexcept;
72     V const* data() const noexcept;
73
74 protected:
75
76     using H = cphstl::fixed_capacity_hat<V, allocator_type>;
77     using B = typename A::template rebind<H>::other;
78     using directory_type = cphstl::resizable_array<H, B>;
79
80     allocator_type allocator;
81     directory_type directory;
82     size_type n;
83
84     V* index_to_address(size_type rank) const {
85         if (rank < 2) {
86             return directory[0].index_to_address(rank);
87         }
88         std::size_t h = whole_number_logarithm(rank);
89         size_type offset = rank - (1 << h);
90         return directory[h].index_to_address(offset);
91     }
92
93     template <typename S, typename I>
94     void append(S& sequence, I some, I past) {
95         I p = some;
96         I q = some;
97         try {
98             for ( ; q  $\neq$  past; ++q) {
99                 sequence.push_back(*q);
100             }
101         }
102         catch (...) {
103             for ( ; p  $\neq$  q; ++p) {
104                 sequence.pop_back();
105             }
106             throw;
107         }
108     }
109
110     void append_n(size_type k, V const& value) {
111         size_type i = 0;
112         size_type j = 0;
113         try {
114             for ( ; j  $\neq$  k; ++j) {
115                 push_back(value);
116             }
117         }
118         catch (...) {

```

```

119         for ( ; i  $\neq$  j; ++i) {
120             pop_back();
121         }
122     }
123 }
124
125 public:
126
127     explicit space_efficient_array(A const& a = A())
128         : allocator(a), directory(a), n(0) {
129         directory.push_back(std::move(H(allocator)));
130         directory[0].reserve(2);
131     }
132
133     space_efficient_array(std::initializer_list<V> s)
134         : space_efficient_array(A()) {
135         append(*this, s.begin(), s.end());
136     }
137
138     space_efficient_array(space_efficient_array const& other)
139         : allocator(other.allocator), directory(other.allocator), n(0)
140         {
141         space_efficient_array tmp;
142         append(tmp, other.begin(), other.end());
143         (*this).swap(tmp);
144     }
145
146     space_efficient_array(space_efficient_array&& other)
147         : allocator(other.allocator), directory(other.allocator), n(0)
148         {
149         (*this).swap(other);
150     }
151
152     ~space_efficient_array() {
153         clear();
154         directory.clear();
155     }
156
157     space_efficient_array& operator=(space_efficient_array const&
158     other) {
159         if (this  $\neq$  &other) {
160             space_efficient_array tmp(other);
161             (*this).swap(tmp);
162         }
163         return *this;
164     }
165
166     space_efficient_array& operator=(space_efficient_array&& other)
167     {
168         if (this  $\neq$  &other) {
169             space_efficient_array tmp(std::move(other));
170             (*this).swap(tmp);

```

```

167     }
168     return *this;
169 }
170
171 void swap(space_efficient_array& other) {
172     std::swap(allocator, other.allocator);
173     directory.swap(other.directory);
174     std::swap(n, other.n);
175 }
176
177 const_iterator cbegin() const {
178     return (size() != 0) ? const_iterator(this, 0) : const_iterator
179         (this);
180 }
181
182 const_iterator begin() const {
183     return cbegin();
184 }
185
186 iterator begin() {
187     return (size() != 0) ? iterator(this, 0) : iterator(this);
188 }
189
190 const_iterator cend() const {
191     return const_iterator(this);
192 }
193
194 const_iterator end() const {
195     return cend();
196 }
197
198 iterator end() {
199     return iterator(this);
200 }
201
202 allocator_type get_allocator() const {
203     return allocator;
204 }
205
206 size_type size() const {
207     return n;
208 }
209
210 void resize(size_type new_size) {
211     if (n > new_size) {
212         while (n > new_size) {
213             pop_back();
214         }
215     }
216     return;
217 }

```

```

218
219     size_type capacity() const {
220         return size_type(-1);
221     }
222
223     void reserve(size_type) {
224     }
225
226     const_reference operator[](size_type i) const {
227         return *index_to_address(i);
228     }
229
230     reference operator[](size_type i) {
231         return *index_to_address(i);
232     }
233
234     const_reference front() const {
235         return *index_to_address(0);
236     }
237
238     reference front() {
239         return *index_to_address(0);
240     }
241
242     const_reference back() const {
243         return *index_to_address(size() - 1);
244     }
245
246     reference back() {
247         return *index_to_address(size() - 1);
248     }
249
250     template <typename... Args>
251     void emplace_back(Args&&... args) {
252         size_type h = directory.size();
253         if (n > 1 and population_count(n) == 1) {
254             directory.push_back(std::move(H(allocator)));
255             directory[h].reserve(1 << h);
256             h += 1;
257         }
258         directory[h - 1].emplace_back(std::forward<Args>(args)...);
259         n += 1;
260     }
261
262     void push_back(V const& x) {
263         size_type h = directory.size();
264         if (n > 1 and population_count(n) == 1) {
265             directory.push_back(std::move(H(allocator)));
266             directory[h].reserve(1 << h);
267             h += 1;
268         }
269         directory[h - 1].push_back(x);

```



```

270     n += 1;
271 }
272
273 void push_back(V&& x) {
274     size_type h = directory.size();
275     if (n > 1 and population_count(n) == 1) {
276         directory.push_back(std::move(H(allocator)));
277         directory[h].reserve(1 << h);
278         h += 1;
279     }
280     directory[h - 1].push_back(std::move(x));
281     n += 1;
282 }
283
284 void pop_back() {
285     assert(n != 0);
286     n -= 1;
287     size_type h = directory.size();
288     directory[h - 1].pop_back();
289     if (h != 1 and population_count(n) == 1) {
290         directory[h - 1].clear();
291         directory.pop_back();
292     }
293 }
294
295 void clear() {
296     while (size() > 0) {
297         pop_back();
298     }
299 }
300 };
301 }
302
303 #endif

```

Containers

leda-array.h++

```

1  /*
2   The interface of cphleda::array
3
4   Authors: Jyrki Katajainen, Bo Simonsen © 2009, 2016
5  */
6
7  #include <algorithm> // std::unique, std::sort, std::random_shuffle,
   std::lower_bound, std::upper_bound
8  #include <cassert> // assert macro
9  #include "leda-compare-functions.i++"
10 #include <memory> // std::allocator
11 #include <vector> // std::vector

```

```

12 #include <sstream> // std::stringstream
13 #include <utility> // std::swap, std::pair
14
15 namespace cphleda {
16
17     template <typename V, typename K = std::vector<V, std::allocator<V
18         >>>
19     class array {
20     public:
21         using value_type = V;
22         using kernel_type = K;
23         using iterator = typename K::iterator;
24         using const_iterator = typename K::const_iterator;
25         using item = iterator;
26         using size_type = int;
27
28         array(size_type, size_type);
29         array(size_type);
30         array();
31         array(size_type, V, V);
32         array(size_type, V, V, V);
33         array(size_type, V, V, V, V);
34
35         array(array const&);
36         array& operator=(array const&);
37
38         item first_item();
39         item last_item();
40         item next_item(item);
41         item prev_item(item);
42
43         V& inf(item);
44
45         iterator begin();
46         iterator end();
47         const_iterator begin() const;
48         const_iterator end() const;
49
50         V& get(size_type);
51         V const& get(size_type) const;
52         void set(size_type, V);
53         V& operator[](size_type);
54
55         void copy(size_type, array const&, size_type);
56         void copy(size_type, size_type);
57         void resize(size_type, size_type);
58         void resize(size_type);
59
60         size_type low() const;
61         size_type high() const;
62         size_type size() const;

```

```

63
64     void init(V);
65     bool C_style() const;
66
67     void swap(size_type, size_type);
68
69     void sort(size_type (*)(V const&, V const&));
70     void sort(size_type, size_type);
71     void sort();
72
73     void sort(size_type (*)(V const&, V const&), size_type,
74               size_type);
75     void permute();
76     void permute(size_type, size_type);
77
78     size_type binary_search(size_type (*)(V const&, V const&), V);
79     size_type binary_search(V);
80     size_type binary_locate(size_type (*)(V const&, V const&), V);
81     size_type binary_locate(V);
82
83     size_type unique();
84
85     void print(std::ostream&, char = '\n');
86     void print(char = '\n');
87     void print(char const*, char = '\n');
88
89     void read(std::istream&);
90     void read();
91     void read(char const*);
92
93 protected:
94
95     void fill(K&, size_type, size_type);
96
97     template <typename S, typename I>
98     void append(S&, I, I);
99
100    std::pair<iterator, iterator> get_iterators(size_type, size_type)
101    ;
102
103 private:
104
105     size_type s;
106     size_type e;
107     kernel_type kernel;
108 };
109
110 template <typename V, typename K>
111 std::istream& operator>>(std::istream&, array<V, K>&);
112
113 template <typename V, typename K>
114 std::ostream& operator<<(std::ostream&, array<V, K>&);

```

```

113 }
114
115 #include "leda-array.i++" // implementation

```

leda-array.i++

```

1 /*
2  An implementation of cphleda::array
3
4  Authors: Jyrki Katajainen, Bo Simonsen © 2009, 2016
5 */
6
7 namespace cphleda {
8
9  template <typename V, typename K>
10 array<V, K>::array(size_type a, size_type b)
11     : s(0), e(-1), kernel() {
12     fill(kernel, 0, b - a);
13     s = a;
14     e = b;
15 }
16
17 template <typename V, typename K>
18 array<V, K>::array(size_type n)
19     : s(0), e(-1), kernel() {
20     fill(kernel, 0, n);
21     e = n - 1;
22 }
23
24 template <typename V, typename K>
25 array<V, K>::array()
26     : s(0), e(-1), kernel() {
27 }
28
29 template <typename V, typename K>
30 array<V, K>::array(size_type low, V x, V y)
31     : s(0), e(-1), kernel() {
32     std::initializer_list<V> list = {x, y};
33     append(kernel, list.begin(), list.end());
34     s = low;
35     e = low + 1;
36 }
37
38 template <typename V, typename K>
39 array<V, K>::array(size_type low, V x, V y, V z)
40     : s(0), e(-1), kernel() {
41     std::initializer_list<V> list = {x, y, z};
42     append(kernel, list.begin(), list.end());
43     s = low;
44     e = low + 2;
45 }
46

```

```

47 template <typename V, typename K>
48 array<V, K>::array(size_type low, V x, V y, V z, V w)
49 : s(0), e(-1), kernel() {
50     std::initializer_list<V> list = {x, y, z, w};
51     append(kernel, list.begin(), list.end());
52     s = low;
53     e = low + 3;
54 }
55
56 template <typename V, typename K>
57 array<V, K>::array(array const& a)
58 : s(0), e(-1), kernel() {
59     K tmp;
60     append(tmp, a.begin(), a.end());
61     kernel.swap(tmp);
62     s = a.low();
63     e = a.high();
64 }
65
66 template <typename V, typename K>
67 array<V, K>& array<V, K>::operator=(array const& other) {
68     if (this != &other) {
69         K tmp;
70         append(tmp, other.begin(), other.end());
71         kernel.swap(tmp);
72         s = other.low();
73         e = other.high();
74     }
75     return *this;
76 }
77
78 template <typename V, typename K>
79 V& array<V, K>::get(size_type i) {
80     assert(low() ≤ i and i ≤ high());
81     return kernel[i - low()];
82 }
83
84 template <typename V, typename K>
85 V const& array<V, K>::get(size_type i) const {
86     assert(low() ≤ i and i ≤ high());
87     return kernel[i - low()];
88 }
89
90 template <typename V, typename K>
91 void array<V, K>::set(size_type i, V e) {
92     assert(low() ≤ i and i ≤ high());
93     get(i) = e;
94 }
95
96 template <typename V, typename K>
97 V& array<V, K>::operator[](size_type i) {
98

```

```

99 #if not defined(LED_A_CHECKING_OFF)
100
101     if (i < low() or i > high()) {
102         throw std::out_of_range{"ERROR array: index out of range"};
103     }
104
105 #endif
106
107     return get(i);
108 }
109
110 template <typename V, typename K>
111 void array<V, K>::copy(size_type x, array<V, K> const& other,
112     size_type y) {
113     assert(low() ≤ x and x ≤ high());
114     assert(other.low() ≤ y and y ≤ other.high());
115     set(x, other.get(y));
116 }
117
118 template <typename V, typename K>
119 void array<V, K>::copy(size_type x, size_type y) {
120     assert(low() ≤ x and x ≤ high());
121     assert(low() ≤ y and y ≤ high());
122     set(x, get(y));
123 }
124
125 template <typename V, typename K>
126 void array<V, K>::resize(size_type a, size_type b) {
127     assert(a ≤ b);
128     K tmp;
129     if (e < a) {
130         fill(tmp, 0, b - a + 1);
131     }
132     else if (e ≤ b) {
133         if (s < a) {
134             append(tmp, begin() + (a - s), end());
135             fill(tmp, e - a + 1, b - a + 1);
136         }
137         else {
138             fill(tmp, 0, s - a);
139             append(tmp, begin(), end());
140             fill(tmp, tmp.size(), b - a + 1);
141         }
142     }
143     else if (s < a) {
144         append(tmp, kernel.begin() + (a - s), kernel.begin() + (b - s +
145             1));
146     }
147     else if (s ≤ b) {
148         fill(tmp, 0, s - a);
149         append(tmp, kernel.begin(), kernel.begin() + (b - s + 1));
150     }
151 }

```

```

149     else {
150         assert(s > b);
151         fill(tmp, 0, b - a + 1);
152     }
153     kernel.swap(tmp);
154     s = a;
155     e = b;
156 }
157
158 template <typename V, typename K>
159 void array<V, K>::resize(size_type n) {
160     resize(0, n - 1);
161 }
162
163 template <typename V, typename K>
164 typename array<V, K>::size_type array<V, K>::low() const {
165     return s;
166 }
167
168 template <typename V, typename K>
169 typename array<V, K>::size_type array<V, K>::high() const {
170     return e;
171 }
172
173 template <typename V, typename K>
174 typename array<V, K>::size_type array<V, K>::size() const {
175     return e - s + 1;
176 }
177
178 template <typename V, typename K>
179 void array<V, K>::init(V x) {
180     for(size_type i = low(); i ≤ high(); ++i) {
181         set(i, x);
182     }
183 }
184
185 template <typename V, typename K>
186 bool array<V, K>::C_style() const {
187     return low() == 0;
188 }
189
190 template <typename V, typename K>
191 void array<V, K>::swap(size_type i, size_type j) {
192     std::swap(get(i), get(j));
193 }
194
195 template <typename V, typename K>
196 typename array<V, K>::size_type array<V, K>::unique() {
197     std::pair<iterator, iterator> p = get_iterators(low(), high());
198     iterator new_end = std::unique(p.first, p.second);
199     size_type i = (new_end - p.first) + low();
200     return i - 1;

```

```

201 }
202
203 /* sort functions */
204
205 template <typename V, typename K>
206 void array<V, K>::sort(size_type (*cmp)(V const&, V const&)) {
207     sort(cmp, low(), high());
208 }
209
210 template <typename V, typename K>
211 void array<V, K>::sort(size_type l, size_type h) {
212     sort(compare, l, h);
213 }
214
215 template <typename V, typename K>
216 void array<V, K>::sort() {
217     sort(compare);
218 }
219
220 template <typename V, typename K>
221 void array<V, K>::sort(size_type (*cmp)(V const&, V const&),
222     size_type l, size_type h) {
223     std::pair<iterator, iterator> p = get_iterators(l, h);
224     std::sort(p.first, p.second, stl_compare_less<V>(cmp));
225 }
226
227 /* permute functions */
228
229 template <typename V, typename K>
230 void array<V, K>::permute() {
231     permute(low(), high());
232 }
233
234 template <typename V, typename K>
235 void array<V, K>::permute(size_type l, size_type h) {
236     std::pair<iterator, iterator> p = get_iterators(l, h);
237     std::random_shuffle(p.first, p.second);
238 }
239
240 /* binary-search functions */
241
242 template <typename V, typename K>
243 typename array<V, K>::size_type
244 array<V, K>::binary_search(size_type (*cmp)(V const&, V const&),
245     V x) {
246     std::pair<iterator, iterator> p = get_iterators(low(), high());
247     iterator it = std::lower_bound(p.first, p.second, x,
248         stl_compare_less<V>(cmp));
249     if (it == p.second) {
250         return low() - 1;
251     }
252     return (it - p.first) + low();

```



```

250 }
251
252 template <typename V, typename K>
253 typename array<V, K>::size_type array<V, K>::binary_search(V x) {
254     return binary_search(compare, x);
255 }
256
257 template <typename V, typename K>
258 typename array<V, K>::size_type
259 array<V, K>::binary_locate(size_type (*cmp)(V const&, V const&),
260     V x) {
261     std::pair<iterator, iterator> p = get_iterators(low(), high());
262     iterator it = std::upper_bound(p.first, p.second, x,
263         stl_compare_less<V>(cmp));
264     if (it == p.second) {
265         return low() - 1;
266     }
267     size_type i = (it - p.first) - 1 + low();
268     if (cmp(x, get(i)) > 0) {
269         return low() - 1;
270     }
271     return i;
272 }
273
274 template <typename V, typename K>
275 typename array<V, K>::size_type array<V, K>::binary_locate(V x) {
276     return binary_locate(compare, x);
277 }
278
279 /* print functions */
280
281 template <typename V, typename K>
282 void array<V, K>::print(std::ostream& o, char space) {
283     std::stringstream sss;
284     sss << space;
285     for(size_type i = low(); i ≤ high(); ++i) {
286         std::stringstream ss;
287         ss << get(i);
288         o << ss.str();
289         if(i ≠ high()) {
290             o << sss.str();
291         }
292     }
293 }
294
295 template <typename V, typename K>
296 void array<V, K>::print(char space) {
297     print(std::cout, space);
298 }
299
300 template <typename V, typename K>
301 void array<V, K>::print(char const* header, char space) {

```

```

301     std::cout << header << std::endl;
302     print(std::cout, space);
303 }
304
305 /* read functions */
306
307 template <typename V, typename K>
308 void array<V, K>::read(std::istream& s) {
309     V v;
310     for(size_type i = low(); i ≤ high(); ++i) {
311         s >> v;
312         set(i, v);
313     }
314 }
315
316 template <typename V, typename K>
317 void array<V, K>::read() {
318     read(std::cin);
319 }
320
321 template <typename V, typename K>
322 void array<V, K>::read(const char* header) {
323     std::cout << header;
324     read();
325 }
326
327 /* helpers */
328
329 template <typename V, typename K>
330 void array<V, K>::fill(K& data, size_type j, size_type n) {
331     size_type k = j;
332     try {
333         for ( ; k ≠ n; ++k) {
334             data.push_back(V());
335         }
336     }
337     catch (...) {
338         for ( ; j ≠ k; ++j) {
339             data.pop_back();
340         }
341         throw;
342     }
343 }
344
345 template <typename V, typename K>
346 template <typename S, typename I>
347 void array<V, K>::append(S& sequence, I some, I past) {
348     I p = some;
349     I q = some;
350     try {
351         for ( ; q ≠ past; ++q) {
352             sequence.push_back(*q);

```

```

353     }
354   }
355   catch (...) {
356     for ( ; p  $\neq$  q; ++p) {
357       sequence.pop_back();
358     }
359     throw;
360   }
361 }
362
363 template <typename V, typename K>
364 std::pair<typename array<V, K>::iterator, typename array<V, K>::
    iterator>
365 array<V, K>::get_iterators(size_type l, size_type h) {
366   size_type start_index = l - low();
367   size_type end_index = h - low();
368   iterator begin_it = kernel.begin();
369   iterator end_it = kernel.begin();
370   begin_it += start_index;
371   end_it += end_index + 1;
372   return std::pair<iterator, iterator>(begin_it, end_it);
373 }
374
375 /* we use iterators to implement next_item, prev_item, and inf */
376
377 template <typename V, typename K>
378 typename array<V, K>::item array<V, K>::first_item() {
379   return kernel.begin();
380 }
381
382 template <typename V, typename K>
383 typename array<V, K>::item array<V, K>::last_item() {
384   return prev_item(kernel.end());
385 }
386
387 template <typename V, typename K>
388 typename array<V, K>::item array<V, K>::next_item(item a) {
389   iterator p(a);
390   ++p;
391   return p;
392 }
393
394 template <typename V, typename K>
395 typename array<V, K>::item array<V, K>::prev_item(item a) {
396   iterator p(a);
397   --p;
398   return p;
399 }
400
401 template <typename V, typename K>
402 V& array<V, K>::inf(item a) {
403   iterator p(a);

```

```

404     return *p;
405 }
406
407 /* iterators */
408
409 template <typename V, typename K>
410 typename array<V, K>::iterator array<V, K>::begin() {
411     return kernel.begin();
412 }
413
414 template <typename V, typename K>
415 typename array<V, K>::iterator array<V, K>::end() {
416     return kernel.end();
417 }
418
419 template <typename V, typename K>
420 typename array<V, K>::const_iterator array<V, K>::begin() const {
421     return kernel.begin();
422 }
423
424 template <typename V, typename K>
425 typename array<V, K>::const_iterator array<V, K>::end() const {
426     return kernel.end();
427 }
428
429 /* operator << and operator >> */
430
431 template <typename V, typename K>
432 std::istream& operator>>(std::istream& in, array<V, K>& a) {
433     a.read(in);
434     return in;
435 }
436
437 template <typename V, typename K>
438 std::ostream& operator<<(std::ostream& out, array<V, K>& a) {
439     a.print(out);
440     return out;
441 }
442 }

```

stl-vector.h++

```

1 /*
2  According to the C++ standard [2014], a vector is a sequence that
3  supports random-access iterators. More precisely, it satisfies all
4  of the requirements of a container, of a reversible container, and
5  of a sequence container, including most of the optional sequence
6  container requirements, of an allocator-aware container, and, for
7  an element type other than bool, of a contiguous container. The
8  exceptions are the push_front, pop_front, and emplace_front member
9  functions, which are not provided.
10

```

```

11 Performance Engineering Laboratory © 2008, 2016, 2018
12 */
13
14 #ifndef __CPHSTL_VECTOR__
15 #define __CPHSTL_VECTOR__
16
17 #include <algorithm> // std::equal std::lexicographical_compare std
   ::rotate
18 #include <cstddef> // std::size_t std::ptrdiff_t
19 #include <initializer_list> // std::initializer_list
20 #include <iterator> // std::reverse_iterator
21 #include <limits> // std::numeric_limits
22 #include <memory> // std::allocator std::allocator_traits
23 #include <stdexcept> // std::length_error std::out_of_range
24 #include <type_traits> // std::conditional std::is_integral
25 #include <vector> // std::vector
26 #include <utility> // std::swap std::move std::forward
27
28 namespace cphstl {
29
30 template<typename V, typename A = std::allocator<V>,
31 typename K = std::vector<V, A>>
32 class vector {
33 public:
34
35 // types
36
37 using value_type = V;
38 using allocator_type = A;
39 using reference = typename K::reference;
40 using const_reference = typename K::const_reference;
41 using pointer = typename std::allocator_traits<A>::pointer;
42 using const_pointer = typename std::allocator_traits<A>::
   const_pointer;
43 using size_type = std::size_t;
44 using difference_type = std::ptrdiff_t;
45 using iterator = typename K::iterator;
46 using const_iterator = typename K::const_iterator;
47 using reverse_iterator = std::reverse_iterator<iterator>;
48 using const_reverse_iterator = std::reverse_iterator<
   const_iterator>;
49
50 public:
51
52 // structors
53
54 vector() noexcept;
55 explicit vector(A const&) noexcept;
56 explicit vector(size_type, A const& = A());
57 vector(size_type, V const&, A const& = A());
58
59 template<typename I>

```

```

60     vector(I, I, A const& = A());
61
62     vector(vector const&);
63     vector(vector const&, A const&);
64     vector(vector&&) noexcept;
65     vector(vector&&, A const&) noexcept(
66         std::allocator_traits<A>::
67             propagate_on_container_move_assignment::value
68         or std::allocator_traits<A>::is_always_equal::value);
69     vector(std::initializer_list<V>, A const& = A());
70     ~vector();
71     vector& operator=(vector const&);
72     vector& operator=(vector&&) noexcept(
73         std::allocator_traits<A>::
74             propagate_on_container_move_assignment::value
75         or std::allocator_traits<A>::is_always_equal::value);
76     vector& operator=(std::initializer_list<V>);
77
78     template<typename I>
79     void assign(I, I);
80     void assign(size_type, V const&);
81     void assign(std::initializer_list<V>);
82
83     // iterators
84
85     iterator begin() noexcept;
86     const_iterator begin() const noexcept;
87     iterator end() noexcept;
88     const_iterator end() const noexcept;
89     reverse_iterator rbegin() noexcept;
90     const_reverse_iterator rbegin() const noexcept;
91     reverse_iterator rend() noexcept;
92     const_reverse_iterator rend() const noexcept;
93
94     const_iterator cbegin() const noexcept;
95     const_iterator cend() const noexcept;
96     const_reverse_iterator crbegin() const noexcept;
97     const_reverse_iterator crend() const noexcept;
98
99     // accessors
100
101     A get_allocator() const noexcept;
102     size_type size() const noexcept;
103     size_type max_size() const noexcept;
104     size_type capacity() const noexcept;
105     bool empty() const noexcept;
106
107     const_reference operator[](size_type) const;
108     const_reference at(size_type) const;
109     const_reference front() const;
110     const_reference back() const;

```

```

110     // modifiers
111
112     reference operator[](size_type);
113     reference at(size_type);
114     reference front();
115     reference back();
116
117     V* data() noexcept;
118     V const* data() const noexcept;
119
120     void resize(size_type);
121     void resize(size_type, V const&);
122     void reserve(size_type);
123     void shrink_to_fit();
124
125     template<typename... Args>
126     void emplace_back(Args&&...);
127
128     void push_back(V const&);
129     void push_back(V&&);
130     void pop_back();
131
132     template<typename... Args>
133     iterator emplace(iterator, Args&&...);
134
135     iterator insert(iterator, V const&);
136     iterator insert(iterator, V&&);
137     iterator insert(iterator, size_type, V const&);
138
139     template<typename I>
140     iterator insert(iterator, I, I);
141
142     iterator insert(iterator, std::initializer_list<V>);
143     iterator erase(iterator);
144     iterator erase(iterator, iterator);
145     void swap(vector&) noexcept(
146         std::allocator_traits<A>::propagate_on_container_swap::value
147         or std::allocator_traits<A>::is_always_equal::value);
148     void clear() noexcept;
149
150 protected:
151
152     // helpers
153
154     template<typename S, typename I>
155     void append(S&, I, I);
156
157     template<typename S>
158     void append_n(S&, size_type, V const&);
159
160     template<typename I>
161     void assign_dispatch(I, I, std::false_type);

```

```

162
163     template<typename I>
164     void assign_dispatch(I, I, std::true_type);
165
166     template<typename I>
167     iterator insert_dispatch(iterator, I, I, std::false_type);
168
169     template<typename I>
170     iterator insert_dispatch(iterator, I, I, std::true_type);
171
172     iterator insert_fill(iterator, size_type, V const&);
173
174     template<typename I>
175     iterator insert_range(iterator, I, I);
176
177     using kernel_type = K;
178     kernel_type kernel;
179
180 };
181
182 template<typename V, typename A, typename K>
183 bool operator==(vector<V, A, K> const&, vector<V, A, K> const&);
184
185 template<typename V, typename A, typename K>
186 bool operator<(vector<V, A, K> const&, vector<V, A, K> const&);
187
188 template<typename V, typename A, typename K>
189 bool operator!=(vector<V, A, K> const&, vector<V, A, K> const&);
190
191 template<typename V, typename A, typename K>
192 bool operator>(vector<V, A, K> const&, vector<V, A, K> const&);
193
194 template<typename V, typename A, typename K>
195 bool operator>=(vector<V, A, K> const&, vector<V, A, K> const&);
196
197 template<typename V, typename A, typename K>
198 bool operator<=(vector<V, A, K> const&, vector<V, A, K> const&);
199
200 template<typename V, typename A, typename K>
201 void swap(vector<V, A, K>& x, vector<V, A, K>& y) noexcept(
202     noexcept(x.swap(y)));
203 }
204
205 #include "stl-vector.i++" // implementation
206
207 #endif

```

stl-vector.i++

```

1 /*
2  A vector is a container that delegates its work to the given kernel
3  */

```



```

4  Performance Engineering Laboratory © 2008, 2016, 2018
5  */
6
7  namespace cphstl {
8
9      // helpers
10
11     template <typename V, typename A, typename K>
12     template <typename S, typename I>
13     void vector<V, A, K>::append(S& sequence, I some, I past) {
14         I p = some;
15         I q = some;
16         try {
17             for ( ; q  $\neq$  past; ++q) {
18                 sequence.push_back(*q);
19             }
20         }
21         catch (...) {
22             for ( ; p  $\neq$  q; ++p) {
23                 sequence.pop_back();
24             }
25             throw;
26         }
27     }
28
29     template <typename V, typename A, typename K>
30     template <typename S>
31     void vector<V, A, K>::append_n(S& sequence, size_type k, V const&
32         value) {
33         size_type i = 0;
34         size_type j = 0;
35         try {
36             for ( ; j  $\neq$  k; ++j) {
37                 sequence.push_back(value);
38             }
39         }
40         catch (...) {
41             for ( ; i  $\neq$  j; ++i) {
42                 sequence.pop_back();
43             }
44         }
45     }
46     // default constructor
47
48     template <typename V, typename A, typename K>
49     vector<V, A, K>::vector() noexcept
50     : kernel(A()) {
51     }
52
53     // explicit constructors
54

```

```

55  template <typename V, typename A, typename K>
56  vector<V, A, K>::vector(A const& a) noexcept
57      : kernel(a) {
58  }
59
60  template <typename V, typename A, typename K>
61  vector<V, A, K>::vector(size_type n, A const& a)
62      : kernel(a) {
63      append_n(kernel, n, V());
64  }
65
66  // parametrized constructors
67
68  template <typename V, typename A, typename K>
69  vector<V, A, K>::vector(size_type n, V const& v, A const& a)
70      : kernel(a) {
71      append_n(kernel, n, v);
72  }
73
74  template <typename V, typename A, typename K>
75  template <typename I>
76  vector<V, A, K>::vector(I p, I q, A const& a)
77      : kernel(a) {
78      append(kernel, p, q);
79  }
80
81  // copy constructors
82
83  template <typename V, typename A, typename K>
84  vector<V, A, K>::vector(vector const& other)
85      : kernel(other.get_allocator()) {
86      K tmp(other.get_allocator());
87      append(tmp, other.begin(), other.end());
88      kernel.swap(tmp);
89  }
90
91  template <typename V, typename A, typename K>
92  vector<V, A, K>::vector(vector const& other, A const& a)
93      : kernel(a) {
94      K tmp(a);
95      append(tmp, other.begin(), other.end());
96      kernel.swap(tmp);
97  }
98
99  // move constructors
100
101  template <typename V, typename A, typename K>
102  vector<V, A, K>::vector(vector&& other) noexcept
103      : kernel(other.get_allocator()) {
104      kernel.swap(other.kernel);
105  }
106

```

```

107 template <typename V, typename A, typename K>
108 vector<V, A, K>::vector(vector&& other, A const& a) noexcept(
109     std::allocator_traits<A>::propagate_on_container_move_assignment
110     ::value
111     or std::allocator_traits<A>::is_always_equal::value)
112 : kernel(a) {
113     kernel.swap(other.kernel);
114 }
115 // initializer-list constructor
116
117 template <typename V, typename A, typename K>
118 vector<V, A, K>::vector(std::initializer_list<V> other, A const& a
119 )
120 : kernel(a) {
121     K tmp(a);
122     append(tmp, other.begin(), other.end());
123     kernel.swap(tmp);
124 }
125 // destructor
126
127 template <typename V, typename A, typename K>
128 vector<V, A, K>::~~vector() {
129     clear();
130 }
131
132 // copy assignment
133
134 template <typename V, typename A, typename K>
135 vector<V, A, K>& vector<V, A, K>::operator=(vector const& other)
136 {
137     if (this != &other) {
138         K tmp(other.kernel);
139         kernel.swap(tmp);
140     }
141     return *this;
142 }
143 // move assignment
144
145 template <typename V, typename A, typename K>
146 vector<V, A, K>& vector<V, A, K>::operator=(vector&& other)
147 noexcept(
148     std::allocator_traits<A>::propagate_on_container_move_assignment
149     ::value
150     or std::allocator_traits<A>::is_always_equal::value) {
151     if (this != &other) {
152         clear();
153         kernel.swap(other.kernel);
154     }
155     return *this;

```

```

154 }
155
156 // initializer-list assignment
157
158 template <typename V, typename A, typename K>
159 vector<V, A, K>& vector<V, A, K>::operator=(std::initializer_list<
    V> other) {
160     assign_dispatch(other.begin(), other.end(), std::false_type());
161     return *this;
162 }
163
164 // assign
165
166 template <typename V, typename A, typename K>
167 void vector<V, A, K>::assign(size_type n, V const& v) {
168     K tmp(kernel.get_allocator());
169     append_n(tmp, n, v);
170     kernel.swap(tmp);
171 }
172
173 template <typename V, typename A, typename K>
174 template <typename I>
175 void vector<V, A, K>::assign(I p, I q) {
176     assign_dispatch(p, q, typename std::conditional<std::is_integral<
        I>::value, std::true_type, std::false_type>::type());
177 }
178
179 template <typename V, typename A, typename K>
180 void vector<V, A, K>::assign(std::initializer_list<V> other) {
181     assign_dispatch(other.begin(), other.end(), std::false_type());
182 }
183
184 template <typename V, typename A, typename K>
185 template <typename Integer>
186 void vector<V, A, K>::assign_dispatch(Integer n, Integer v, std::
    true_type) {
187     K tmp(kernel.get_allocator());
188     append_n(tmp, static_cast<size_type>(n), static_cast<V>(v));
189     kernel.swap(tmp);
190 }
191
192 template <typename V, typename A, typename K>
193 template <typename I>
194 void vector<V, A, K>::assign_dispatch(I p, I q, std::false_type) {
195     K tmp(kernel.get_allocator());
196     append(tmp, p, q);
197     kernel.swap(tmp);
198 }
199
200 // begin
201
202 template <typename V, typename A, typename K>

```

```

203 typename vector<V, A, K>::iterator vector<V, A, K>::begin()
      noexcept {
204     return kernel.begin();
205 }
206
207 template <typename V, typename A, typename K>
208 typename vector<V, A, K>::const_iterator vector<V, A, K>::begin()
      const noexcept {
209     return const_iterator(kernel.begin());
210 }
211
212 // end
213
214 template <typename V, typename A, typename K>
215 typename vector<V, A, K>::iterator vector<V, A, K>::end() noexcept
      {
216     return kernel.end();
217 }
218
219 template <typename V, typename A, typename K>
220 typename vector<V, A, K>::const_iterator vector<V, A, K>::end()
      const noexcept {
221     return const_iterator(kernel.end());
222 }
223
224 // rbegin
225
226 template <typename V, typename A, typename K>
227 typename vector<V, A, K>::reverse_iterator vector<V, A, K>::rbegin()
      noexcept {
228     return reverse_iterator(end());
229 }
230
231 template <typename V, typename A, typename K>
232 typename vector<V, A, K>::const_reverse_iterator vector<V, A, K>::
      rbegin() const noexcept {
233     return const_reverse_iterator(end());
234 }
235
236 // rend
237
238 template <typename V, typename A, typename K>
239 typename vector<V, A, K>::reverse_iterator vector<V, A, K>::rend()
      noexcept {
240     return reverse_iterator(begin());
241 }
242
243 template <typename V, typename A, typename K>
244 typename vector<V, A, K>::const_reverse_iterator vector<V, A, K>::
      rend() const noexcept {
245     return const_reverse_iterator(begin());
246 }

```

```

247
248 // cbegin
249
250 template <typename V, typename A, typename K>
251 typename vector<V, A, K>::const_iterator vector<V, A, K>::cbegin()
        const noexcept {
252     return const_iterator(kernel.begin());
253 }
254
255 // cend
256
257 template <typename V, typename A, typename K>
258 typename vector<V, A, K>::const_iterator vector<V, A, K>::cend()
        const noexcept {
259     return const_iterator(kernel.end());
260 }
261
262 // crbegin
263
264 template <typename V, typename A, typename K>
265 typename vector<V, A, K>::const_reverse_iterator vector<V, A, K>::
        crbegin() const noexcept {
266     return const_reverse_iterator(end());
267 }
268
269 // crend
270
271 template <typename V, typename A, typename K>
272 typename vector<V, A, K>::const_reverse_iterator vector<V, A, K>::
        crend() const noexcept {
273     return const_reverse_iterator(begin());
274 }
275
276 // get_allocator
277
278 template <typename V, typename A, typename K>
279 A vector<V, A, K>::get_allocator() const noexcept {
280     return kernel.get_allocator();
281 }
282
283 // size
284
285 template <typename V, typename A, typename K>
286 typename vector<V, A, K>::size_type vector<V, A, K>::size() const
        noexcept {
287     return kernel.size();
288 }
289
290 // max_size
291
292 template <typename V, typename A, typename K>
293 typename vector<V, A, K>::size_type vector<V, A, K>::max_size()

```

```

    const noexcept {
294     return std::numeric_limits<difference_type>::max();
295     }
296
297     // capacity
298
299     template <typename V, typename A, typename K>
300     typename vector<V, A, K>::size_type vector<V, A, K>::capacity()
        const noexcept {
301         return kernel.capacity();
302     }
303
304     // empty
305
306     template <typename V, typename A, typename K>
307     bool vector<V, A, K>::empty() const noexcept {
308         return size() == size_type(0);
309     }
310
311     // operator []
312
313     template <typename V, typename A, typename K>
314     typename vector<V, A, K>::reference vector<V, A, K>::operator[](
        size_type i) {
315         return reference(kernel.operator[](i));
316     }
317
318     template <typename V, typename A, typename K>
319     typename vector<V, A, K>::const_reference vector<V, A, K>::operator
        [](size_type i) const {
320         return const_reference(kernel.operator[](i));
321     }
322
323     // at
324
325     template <typename V, typename A, typename K>
326     typename vector<V, A, K>::reference vector<V, A, K>::at(size_type i
        ) {
327         if (i ≥ size()) {
328             throw std::out_of_range("index out of bounds");
329         }
330         return reference(operator[](i));
331     }
332
333     template <typename V, typename A, typename K>
334     typename vector<V, A, K>::const_reference vector<V, A, K>::at(
        size_type i) const {
335         if (i ≥ size()) {
336             throw std::out_of_range("index out of bounds");
337         }
338         return const_reference(operator[](i));
339     }

```

```

340
341 // front
342
343 template <typename V, typename A, typename K>
344 typename vector<V, A, K>::reference vector<V, A, K>::front() {
345     iterator first = kernel.begin();
346     return reference(*first);
347 }
348
349 template <typename V, typename A, typename K>
350 typename vector<V, A, K>::const_reference vector<V, A, K>::front()
351     const {
352     const_iterator first = kernel.begin();
353     return const_reference(*first);
354 }
355 // back
356
357 template <typename V, typename A, typename K>
358 typename vector<V, A, K>::reference vector<V, A, K>::back() {
359     iterator const last = --end();
360     return reference(*last);
361 }
362
363 template <typename V, typename A, typename K>
364 typename vector<V, A, K>::const_reference vector<V, A, K>::back()
365     const {
366     const_iterator const last = --end();
367     return const_reference(*last);
368 }
369 // data
370
371 template <typename V, typename A, typename K>
372 V* vector<V, A, K>::data() noexcept {
373     return kernel.data();
374 }
375
376 template <typename V, typename A, typename K>
377 V const* vector<V, A, K>::data() const noexcept {
378     return kernel.data();
379 }
380
381 // resize
382
383 template <typename V, typename A, typename K>
384 void vector<V, A, K>::resize(size_type n) {
385     resize(n, V());
386 }
387
388 template <typename V, typename A, typename K>
389 void vector<V, A, K>::resize(size_type n, V const& v) {

```



```

390     if (size() > n) {
391         while (size() > n) {
392             pop_back();
393         }
394         return;
395     }
396     append_n(kernel, n - size(), v);
397 }
398
399 // reserve
400
401 template <typename V, typename A, typename K>
402 void vector<V, A, K>::reserve(size_type s) {
403     kernel.reserve(s);
404 }
405
406 // shrink_to_fit
407
408 namespace {
409
410     template<typename T>
411     concept bool has_shrink_to_fit =
412         requires(T x) {
413             { x.shrink_to_fit() } → void; // member function
414         };
415 }
416
417 template <typename V, typename A, typename K>
418 void vector<V, A, K>::shrink_to_fit() {
419     if constexpr (has_shrink_to_fit<K>) {
420         kernel.shrink_to_fit();
421     }
422     else {
423         // do nothing
424     }
425 }
426
427 // emplace_back
428
429 template <typename V, typename A, typename K>
430 template <typename... Args>
431 void vector<V, A, K>::emplace_back(Args&&... args) {
432     kernel.emplace_back(std::forward<Args>(args)...);
433 }
434
435 // push_back
436
437 template <typename V, typename A, typename K>
438 void vector<V, A, K>::push_back(V const& v) {
439     kernel.push_back(v);
440 }
441

```

```

442 template <typename V, typename A, typename K>
443 void vector<V, A, K>::push_back(V&& v) {
444     kernel.push_back(std::move(v));
445 }
446
447 // pop_back
448
449 template <typename V, typename A, typename K>
450 void vector<V, A, K>::pop_back() {
451     kernel.pop_back();
452 }
453
454 // emplace
455
456 template <typename V, typename A, typename K>
457 template <typename... Args>
458 typename vector<V, A, K>::iterator vector<V, A, K>::emplace(
459     iterator p, Args&&... args) {
460     size_type i = p - begin();
461     size_type j = size();
462     emplace_back(std::forward<Args>(args)...);
463     std::rotate(begin() + i, begin() + j, end());
464     return begin() + i;
465 }
466
467 // single-element insert
468
469 template <typename V, typename A, typename K>
470 typename vector<V, A, K>::iterator vector<V, A, K>::insert(iterator
471     p, V const& v) {
472     size_type i = p - begin();
473     size_type j = size();
474     push_back(v);
475     std::rotate(begin() + i, begin() + j, end());
476     return begin() + i;
477 }
478
479 template <typename V, typename A, typename K>
480 typename vector<V, A, K>::iterator vector<V, A, K>::insert(iterator
481     p, V&& v) {
482     size_type i = p - begin();
483     size_type j = size();
484     push_back(std::move(v));
485     std::rotate(begin() + i, begin() + j, end());
486     return begin() + i;
487 }
488
489 // multiple-element inserts
490
491 template <typename V, typename A, typename K>
492 typename vector<V, A, K>::iterator vector<V, A, K>::insert(iterator
493     p, size_type n, V const& v) {

```

```

490     return insert_fill(p, n, v);
491 }
492
493 template <typename V, typename A, typename K>
494 template <typename I>
495 typename vector<V, A, K>::iterator vector<V, A, K>::insert(iterator
    p, I q, I r) {
496     return insert_dispatch(p, q, r, typename std::conditional<std::
        is_integral<I>::value, std::true_type, std::false_type>::type
        ());
497 }
498
499 template <typename V, typename A, typename K>
500 template <typename I>
501 typename vector<V, A, K>::iterator vector<V, A, K>::insert_dispatch
    (iterator p, I n, I v, std::true_type) {
502     return insert_fill(p, static_cast<size_type>(n), static_cast<V>(v
        ));
503 }
504
505 template <typename V, typename A, typename K>
506 template <typename I>
507 typename vector<V, A, K>::iterator vector<V, A, K>::insert_dispatch
    (iterator p, I q, I r, std::false_type) {
508     return insert_range(p, q, r);
509 }
510
511 template <typename V, typename A, typename K>
512 typename vector<V, A, K>::iterator vector<V, A, K>::insert(iterator
    p, std::initializer_list<V> l) {
513     return insert_range(p, l.begin(), l.end());
514 }
515
516 template <typename V, typename A, typename K>
517 typename vector<V, A, K>::iterator vector<V, A, K>::insert_fill(
    iterator p, size_type n, V const& v) {
518     size_type i = p - begin();
519     size_type j = size();
520     append_n(kernel, n, v);
521     std::rotate(begin() + i, begin() + j, end());
522     return begin() + i;
523 }
524
525 template <typename V, typename A, typename K>
526 template <typename I>
527 typename vector<V, A, K>::iterator vector<V, A, K>::insert_range(
    iterator p, I q, I r) {
528     size_type i = p - begin();
529     size_type j = size();
530     append(kernel, q, r);
531     std::rotate(begin() + i, begin() + j, end());
532     return begin() + i;

```

```

533 }
534
535 // single-element erase
536
537 template <typename V, typename A, typename K>
538 typename vector<V, A, K>::iterator vector<V, A, K>::erase(iterator
539     p) {
540     assert(p  $\neq$  end());
541     size_type i = p - begin();
542     std::rotate(begin() + i, begin() + i + 1, end());
543     pop_back();
544     return begin() + i;
545 }
546
547 // multiple-element erase
548
549 template <typename V, typename A, typename K>
550 typename vector<V, A, K>::iterator vector<V, A, K>::erase(iterator
551     p, iterator q) {
552     size_type i = p - begin();
553     size_type j = q - begin();
554     std::rotate(begin() + i, begin() + j, end());
555     while (i  $\neq$  j) {
556         pop_back();
557         ++i;
558     }
559     return begin() + i;
560 }
561
562 // clear
563
564 template <typename V, typename A, typename K>
565 void vector<V, A, K>::clear() noexcept {
566     while (not empty()) {
567         pop_back();
568     }
569 }
570
571 // swap
572
573 template <typename V, typename A, typename K>
574 void vector<V, A, K>::swap(vector<V, A, K>& other) noexcept(
575     std::allocator_traits<A>::propagate_on_container_swap::value
576     or std::allocator_traits<A>::is_always_equal::value) {
577     kernel.swap(other.kernel);
578 }
579
580 template <typename V, typename A, typename K>
581 void swap(vector<V, A, K>& x, vector<V, A, K>& y) noexcept(
582     noexcept(x.swap(y))) {
583     x.swap(y);
584 }

```

```

583
584 // operator ==
585
586 template <typename V, typename A, typename K>
587 bool operator==(vector<V, A, K> const& r, vector<V, A, K> const&
588     s) {
589     return (r.size() == s.size() and std::equal(r.begin(), r.end(), s
590         .begin()));
591 }
592
593 // operator <
594
595 template <typename V, typename A, typename K>
596 bool operator<(vector<V, A, K> const& r, vector<V, A, K> const& s
597     ) {
598     return std::lexicographical_compare(r.begin(), r.end(), s.begin()
599         , s.end());
600 }
601
602 // operator !=
603
604 template <typename V, typename A, typename K>
605 bool operator!=(vector<V, A, K> const& r, vector<V, A, K> const&
606     s) {
607     return not (r == s);
608 }
609
610 // operator >
611
612 template <typename V, typename A, typename K>
613 bool operator>(vector<V, A, K> const& r, vector<V, A, K> const& s
614     ) {
615     return (s < r);
616 }
617
618 // operator ≥
619
620 template <typename V, typename A, typename K>
621 bool operator≥(vector<V, A, K> const& r, vector<V, A, K> const& s
622     ) {
623     return not (r < s);
624 }
625
626 // operator ≤
627
628 template <typename V, typename A, typename K>
629 bool operator≤(vector<V, A, K> const& r, vector<V, A, K> const& s
630     ) {
631     return not (s < r);
632 }
633 }

```

Helpers

rank-iterator.h++

```

1  /*
2   A rank iterator encapsulates a location of an element by storing a
3   (pointer, rank) pair; the pointer refers to a data structure,
4   called the owner, that contains the element referred to and the
5   rank is the index of that element within the data structure.
6
7   Authors: Jyrki Katajainen, Andreas Milton Maniotis, Bo Simonsen
8   © 2008, 2012, 2013
9  */
10
11 #ifndef __CPHSTL_RANK_ITERATOR__
12 #define __CPHSTL_RANK_ITERATOR__
13
14 #include <cassert>
15 #include <iterator> // std::random_access_iterator_tag
16 #include <limits> // std::numeric_limits
17 #include <type_traits> // std::conditional, std::is_const, std::
    remove_const
18
19 namespace cphstl {
20
21     template <typename R>
22     class rank_iterator {
23
24     public:
25
26         // associated types
27
28         using owner_type = R;
29         using opposite_type = typename std::conditional<std::is_const<R>
    >::value, typename std::remove_const<R>::type, R const>::type
    ;
30         using size_type = typename R::size_type;
31         using difference_type = typename R::difference_type;
32         using value_type = typename R::value_type;
33         using pointer = typename std::conditional<std::is_const<R>::value
    , value_type const*, value_type*>::type;
34         using reference = typename std::conditional<std::is_const<R>::
    value, typename R::const_reference, typename R::reference>::
    type;
35         using iterator_category = std::random_access_iterator_tag;
36
37         // friends
38
39         friend R;
40
41         friend class rank_iterator<opposite_type>;
42

```

```

43 private:
44
45     // classes
46
47     template <typename X, typename Y>
48     struct is_comparable;
49
50     template <typename X>
51     struct is_comparable<X, typename std::remove_const<X>::type> {
52         class yes;
53     };
54
55     template <typename X>
56     struct is_comparable<X, typename std::add_const<X>::type> {
57         class yes;
58     };
59
60     // constants
61
62     static size_type constexpr sentinel = std::numeric_limits<
63         size_type>::max();
64
65     // variables
66
67     owner_type* owner_p;
68     size_type rank;
69
70     // parameterized constructor
71
72     rank_iterator(owner_type* p, size_type offset = sentinel)
73     : owner_p(p), rank(offset) {
74     }
75 public:
76
77     // default constructor
78
79     rank_iterator()
80     : owner_p(nullptr), rank(sentinel) {
81     }
82
83     // copy constructors
84
85     // generated by the compiler if needed
86     // rank_iterator(const rank_iterator&) = default;
87
88     rank_iterator(rank_iterator<typename std::remove_const<R>::type>
89     const& x)
90     : owner_p(x.owner_p), rank(x.rank) {
91     }
92
93     // assignments

```

```

93
94 // generated by the compiler if needed
95 // rank_iterator& operator=(rank_iterator const&) = default;
96
97 rank_iterator& operator=(rank_iterator<typename std::
    remove_const<R>::type> const& x) {
98     owner_p = x.owner_p;
99     rank = x.rank;
100    return *this;
101 }
102
103 // destructor
104
105 ~rank_iterator() {
106 };
107
108 // operator *
109
110 reference operator*() const {
111     assert(owner_p ≠ nullptr and rank ≠ sentinel);
112     return (*owner_p)[rank];
113 }
114
115 // operator →
116
117 pointer operator→() const {
118     assert(owner_p ≠ nullptr and rank ≠ sentinel);
119     return &(*owner_p)[rank];
120 }
121
122 // operator ++; pre-increment
123
124 rank_iterator& operator++() {
125     assert(owner_p ≠ nullptr and rank ≠ sentinel);
126     ++rank;
127     if (rank == (*owner_p).size()) {
128         rank = sentinel;
129     }
130     return *this;
131 }
132
133 // operator ++; post-increment
134
135 rank_iterator operator++(int) {
136     rank_iterator return_value(*this);
137     operator++;
138     return return_value;
139 }
140
141 // operator --; pre-decrement
142
143 rank_iterator& operator--() {

```



```

144     assert(owner_p  $\neq$  nullptr and (*owner_p).size()  $\neq$  0);
145     if (rank == sentinel) {
146         rank = (*owner_p).size() - 1;
147     }
148     else {
149         --rank;
150     }
151     return *this;
152 }
153
154 // operator --; post-decrement
155
156 rank_iterator operator--(int) {
157     rank_iterator return_value(*this);
158     operator--();
159     return return_value;
160 }
161
162 // operator +=
163
164 rank_iterator& operator+=(difference_type n) {
165     assert(owner_p  $\neq$  nullptr);
166     difference_type new_point = rank;
167     if (rank == sentinel) {
168         new_point = (*owner_p).size();
169     }
170     new_point += n;
171     if (new_point < 0) {
172         rank = sentinel;
173         return *this;
174     }
175     rank = size_type(new_point);
176     if (rank  $\geq$  (*owner_p).size()) {
177         rank = sentinel;
178     }
179     return *this;
180 }
181
182 // operator -=
183
184 rank_iterator& operator-=(difference_type n) {
185     return operator+=(-n);
186 }
187
188 // operator +
189
190 rank_iterator operator+(difference_type n) const {
191     rank_iterator temporary = *this;
192     temporary.operator+=(n);
193     return temporary;
194 }
195

```

```

196 // operator -
197
198 rank_iterator operator-(difference_type n) const {
199     return operator+(-n);
200 }
201
202 // iterator distance
203
204 template <typename S, typename = typename is_comparable<S, R>::
    yes>
205 difference_type operator-(rank_iterator<S> const& other) const {
206     assert(owner_p == other.owner_p);
207     size_type y = rank;
208     if (rank == sentinel) {
209         y = (*owner_p).size();
210     }
211     size_type x = other.rank;
212     if (other.rank == sentinel) {
213         x = (*owner_p).size();
214     }
215     return y - x;
216 }
217
218 // operator ==
219
220 template <typename S, typename = typename is_comparable<S, R>::
    yes>
221 bool operator==(rank_iterator<S> const& other) const {
222     return rank == other.rank and owner_p == other.owner_p;
223 }
224
225 // operator !=
226
227 template <typename S>
228 bool operator!=(rank_iterator<S> const& other) const {
229     return not (*this == other);
230 }
231
232 // operator <
233
234 template <typename S>
235 bool operator<(rank_iterator<S> const& other) const {
236     return ((*this) - other) < difference_type(0);
237 }
238
239 // operator >
240
241 template <typename S>
242 bool operator>(rank_iterator<S> const& other) const {
243     return other < *this;
244 }
245

```

```

246 // operator ≤
247
248 template <typename S>
249 bool operator≤(rank_iterator<S> const& other) const {
250     return not (other < *this);
251 }
252
253 // operator ≥
254
255 template <typename S>
256 bool operator≥(rank_iterator<S> const& other) const {
257     return not (*this < other);
258 }
259 };
260
261 // operator +(int, iterator)
262
263 template <typename R>
264 rank_iterator<R>
265 operator+(typename R::difference_type n, rank_iterator<R> const& a
266     ) {
267     return a + n;
268 }
269 #endif

```

leda-compare-functions.i++

```

1 /*
2  A predefined compare functor is provided for each type, for which
3  operator< is defined.
4
5  Authors: Jyrki Katajainen, Michael Neidhardt, Bo Simonsen © 2009,
6           2016
7 */
8 #ifndef __LEDA_COMPARE_FUNCTIONS__
9 #define __LEDA_COMPARE_FUNCTIONS__
10
11 #include <functional> // std::binary_function
12 #include <type_traits> // std::is_convertible
13 #include <utility> // std::pair
14
15 namespace cphleda {
16
17     template <typename K, typename L = K>
18     class comparator
19     : public std::binary_function<K, L, int> {
20     public:
21
22         int operator()(K const& x, L const& y) const {

```

```

23     static_assert(std::is_convertible<L, K>::value,
24                   "Only convertible types can be compared");
25     if (x < y) {
26         return -1;
27     }
28     if (y < x) {
29         return 1;
30     }
31     return 0;
32 }
33 };
34
35 template <typename T>
36 class stl_compare_less
37     : public std::binary_function<T, T, bool> {
38 public:
39
40     stl_compare_less(int (*_f)(T const&, T const&)) {
41         (*this).f = _f;
42     }
43
44     bool operator()(T const& a, T const& b) const {
45         if ((*this).f(a, b) == -1) {
46             return true;
47         }
48         return false;
49     }
50
51 private:
52
53     int (*f)(T const&, T const&);
54 };
55
56 template <typename P, typename I>
57 class stl_compare_less_pair
58     : public std::binary_function<P, I, bool> {
59 public:
60
61     stl_compare_less_pair(int (*_f)(P const&, P const&)) {
62         (*this).f = _f;
63     }
64
65     bool operator()(std::pair<P, I> const& a, std::pair<P, I> const
66                   & b) const {
67         if ((*this).f(a.first, b.first) == 1) {
68             return true;
69         }
70         return false;
71     }
72
73 private:

```

```

74     int (*f)(P const&, P const&);
75 };
76
77 template <typename T>
78 int compare(T const& a, T const& b) {
79     if (a < b) {
80         return -1;
81     }
82     else if (a > b) {
83         return 1;
84     }
85     return 0;
86 }
87 }
88
89 #endif

```

counting-allocator.h++

```

1  /* -*- C++ -*-
2
3  An allocator that counts the number of bytes allocated and
4  delegates the actual work to std::allocator.
5
6  Define VERBOSE to get information on every allocation and
7  deallocation.
8
9  Authors: Jyrki Katajainen, Bjarke Buur Mortensen © 2001, 2012
10 */
11
12 #ifndef __CPHSTL_COUNTING_ALLOCATOR__
13 #define __CPHSTL_COUNTING_ALLOCATOR__
14
15 #include <iostream> // std streams
16 #include <memory> // std::allocator
17 #include <utility> // std::forward
18
19 // Use base class to have a single object counter
20
21 class counting_allocator_base {
22
23 public:
24
25     using count_type = unsigned long;
26
27     static count_type bytes_in_use() {
28         return current_bytes;
29     }
30
31     static count_type allocators_in_use() {
32         return allocators;
33     }

```

```

34
35     static count_type max_bytes_allocated() {
36         return max_bytes;
37     }
38
39     // reset total statistics
40
41     static void reset_counts() {
42         allocators = 0;
43         current_bytes = 0;
44         max_bytes = 0;
45     }
46
47 protected:
48
49     static count_type allocators; // number of allocators derived from
        this class
50     static count_type current_bytes; // current number of allocated
        bytes
51     static count_type max_bytes; // max number of bytes allocated
52 };
53
54 template <typename T>
55 class counting_allocator
56     : public counting_allocator_base {
57
58 private:
59
60     count_type alloc_id; // id of the allocator
61     std::allocator<T> alloc;
62     count_type elements; // current number of elements allocated
63     count_type max_elements; // max number of elements allocated
64
65 public:
66
67     using value_type = typename std::allocator<T>::value_type;
68     using size_type = typename std::allocator<T>::size_type;
69     using difference_type = typename std::allocator<T>::difference_type
        ;
70
71     using pointer = typename std::allocator<T>::pointer;
72     using const_pointer = typename std::allocator<T>::const_pointer;
73
74     using reference = typename std::allocator<T>::reference;
75     using const_reference = typename std::allocator<T>::const_reference
        ;
76
77     pointer address(reference r) const {
78         return &r;
79     }
80
81     const_pointer address(const_reference r) const {

```

```

82     return &r;
83 }
84
85 counting_allocator() throw()
86 : alloc(), elements(0), max_elements(0) {
87     alloc_id = allocators++;
88 }
89
90 template <typename U>
91 counting_allocator(counting_allocator<U> const&) throw()
92 : alloc(), elements(0), max_elements(0) {
93     alloc_id = allocators++;
94 }
95
96 // note that, if allocation fails, we update our variables wrongly
97
98 pointer allocate(size_type n) {
99     elements += n;
100    current_bytes += n * sizeof(T);
101    if (max_elements < elements) {
102        max_elements = elements;
103    }
104    if (max_bytes < current_bytes) {
105        max_bytes = current_bytes;
106    }
107
108 #ifdef VERBOSE
109
110     std::cout << __PRETTY_FUNCTION__ << std::endl;
111     std::cout << "[" << alloc_id << "]" \t << "Allocating " << n
112         << " elements (" << n * sizeof(T) << " bytes)" << std::endl
113         << "\tTotal = " << elements << " ("
114         << elements * sizeof(T) << " bytes)" << std::endl;
115     std::cout << "[T] = " << current_bytes << " bytes" << std::endl;
116
117 #endif
118
119     return alloc.allocate(n);
120 }
121
122 void deallocate(pointer p, size_type n) {
123     alloc.deallocate(p, n);
124     elements -= n;
125     current_bytes -= n * sizeof(T);
126
127 #ifdef VERBOSE
128
129     std::cout << __PRETTY_FUNCTION__ << std::endl;
130     std::cout << "[" << alloc_id << "]" \t << "Deallocating " << n
131         << " elements (" << n * sizeof(T) << " bytes)" << std::endl
132         << "\tTotal = " << elements << " ("
133         << elements * sizeof(T) << " bytes)" << std::endl;

```

```

134     std::cout << "[T] = " << current_bytes << " bytes" << std::endl;
135
136 #endif
137
138 }
139
140 void construct(pointer p, const T& val) {
141     alloc.construct(p, val);
142 }
143
144 void construct(pointer p, T&& val) {
145     alloc.construct(p, std::forward<T>(val));
146 }
147
148 void destroy(pointer p) {
149     alloc.destroy(p);
150 }
151
152 size_type max_size() const throw() {
153     return alloc.max_size();
154 }
155
156 template <typename U>
157 struct rebind {
158     using other = counting_allocator<U>;
159 };
160
161 // accounting functions
162
163 count_type elements_allocated() {
164     return elements;
165 }
166
167 count_type max_elements_allocated() {
168     return max_elements;
169 }
170
171 count_type bytes_allocated() {
172     return elements_allocated() * sizeof(T);
173 }
174
175 count_type max_bytes_allocated() {
176     return max_elements_allocated() * sizeof(T);
177 }
178 };
179
180 // initialize static members
181
182 counting_allocator_base::count_type counting_allocator_base::
183     allocators = 0;
184 counting_allocator_base::count_type counting_allocator_base::
185     current_bytes = 0;

```



```

184 counting_allocator_base::count_type counting_allocator_base::
    max_bytes = 0;
185
186 #endif

```

Includes

swap_based.i++

```

1 #include <utility> // std::swap
2
3 namespace swap_based {
4
5     template <typename iterator>
6     void __reverse(iterator first, iterator last) {
7         while (true) {
8             if (first == last or first == --last) {
9                 return;
10            }
11            else {
12                std::swap(*first, *last);
13                ++first;
14            }
15        }
16    }
17
18    template <typename S>
19    void reverse(S& s) {
20        __reverse(s.begin(), s.end());
21    }
22 }

```

move_based.i++

```

1 #include <utility> // std::move
2
3 namespace move_based {
4
5     template <typename S, typename T>
6     void reverse_copy(S& input, T& output) {
7         auto n = input.size();
8         while (n != 0) {
9             --n;
10            output.push_back(std::move(input[n]));
11            input.pop_back();
12        }
13    }
14
15    template <typename S>
16    void reverse(S& s) {
17        S tmp;

```

82

```
18     reverse_copy(s, tmp);
19     s.swap(tmp);
20 }
21 }
```

std.i++

```
1 #include <vector>
2
3 using X = std::vector<V, A>;
```

resizable_array.i++

```
1 #include "resizable_array.h++"
2
3 using X = cphstl::resizable_array<V, A>;
```

pile.i++

```
1 #include "pile.h++"
2
3 using X = cphstl::pile<V, A>;
```

sliced_array.i++

```
1 #include "sliced_array.h++"
2
3 using X = cphstl::sliced_array<V, A>;
```

space_efficient_array.i++

```
1 #include "space_efficient_array.h++"
2
3 using X = cphstl::space_efficient_array<V, A>;
```

Drivers

reverse-driver.cpp

```
1 #if ! defined(MAXSIZE)
2
3 #define MAXSIZE (64 * 1024 * 1024)
4
5 #endif
6
7 #include <ctime> // std::clock_t, std::clock, CLOCKS_PER_SEC
8 #include <iostream> // std::cout, std::cerr
9 #include <memory> // std::allocator
10 #include <utility> // std::move
11
```

```

12 #include "resizable_array.h++"
13 #include "sliced_array.h++"
14 #include "space_efficient_array.h++"
15 #include <vector> // std::vector
16
17 #include "algorithm.i++" // ALGORITHM::reverse
18
19 #ifdef MEASURE_MOVES
20
21 long volatile moves = 0;
22
23 template <typename T>
24 class move_counter {
25 private:
26
27     T datum;
28
29     move_counter(move_counter const&) = delete;
30     move_counter& operator=(move_counter const&) = delete;
31
32 public:
33
34     explicit move_counter()
35         : datum(0) {
36         moves += 1;
37     }
38
39     template <typename number>
40     explicit move_counter(number x = 0)
41         : datum(x) {
42         moves += 1;
43     }
44
45     move_counter(move_counter&& other) {
46         datum = std::move(other.datum);
47         moves += 1;
48     }
49
50     move_counter& operator=(move_counter&& other) {
51         datum = std::move(other.datum);
52         moves += 1;
53         return *this;
54     }
55
56     operator T() const {
57         return datum;
58     }
59
60     template <typename U>
61     friend bool operator<(move_counter<U> const&, move_counter<U>
62         const&);

```

```

63  template <typename U>
64  friend bool operator==(move_counter<U> const&, move_counter<U>
        const&);
65
66  };
67
68  template <typename T>
69  bool operator<(move_counter<T> const& x, move_counter<T> const& y)
        {
70      return x.datum < y.datum;
71  }
72
73  template <typename T>
74  bool operator==(move_counter<T> const& x, move_counter<T> const& y)
        {
75      return x.datum == y.datum;
76  }
77
78  #endif
79
80  void usage(int argc, char **argv) {
81      std::cerr << "Usage: " << argv[0] << " <n>\n";
82      exit(1);
83  }
84
85  int main(int argc, char** argv) {
86
87      #ifdef MEASURE_MOVES
88
89          using V = move_counter<int>;
90
91      #else
92
93          using V = int;
94
95      #endif
96
97          using A = std::allocator<V>;
98
99      #ifdef STD
100
101          using X = std::vector<V, A>;
102
103      #else
104
105          using X = cphstl::STRUCTURE<V, A>;
106
107      #endif
108
109      unsigned int n = 0;
110      if (argc == 2) {
111          n = atoi(argv[1]);

```

```

112 }
113 else {
114     usage(argc, argv);
115 }
116 if (n < 1 or n > MAXSIZE) {
117     std::cerr << "n out of bounds [1.." << MAXSIZE << "]\n";
118     usage(argc, argv);
119 };
120
121 unsigned int const repetitions = MAXSIZE / n;
122 X* many = new X[repetitions];
123 for (volatile unsigned int t = 0; t ≠ repetitions; ++t) {
124     for (unsigned int i = 0; i ≠ n; ++i) {
125         many[t].push_back(i);
126     }
127 }
128
129 #if defined(MEASURE_MOVES)
130     moves = 0;
131
132 #else
133     std::clock_t start = std::clock();
134
135 #endif
136
137 for (volatile unsigned int t = 0; t ≠ repetitions; ++t) {
138     ALGORITHM::reverse(many[t]);
139 }
140
141 #if ! defined(MEASURE_MOVES)
142     std::clock_t stop = std::clock();
143
144 #endif
145
146 double scale = double(repetitions) * double(n);
147
148 #if defined(MEASURE_MOVES)
149     std::cout.precision(3);
150     std::cout << n << '\t' << double(moves) / double(scale) << std::endl;
151
152 #else
153     double ns = 1.0e9 * double(stop - start) / double(CLOCKS_PER_SEC);
154     std::cout.precision(4);
155     std::cout << n << '\t' << ns / double(scale) << std::endl;
156
157 #endif

```

```

163
164     delete[] many;
165     return 0;
166 }

```

space-driver.cpp

```

1  /*
2   Measures the amount of space taken up by a data structure
3
4   Authors: Jyrki Katajainen, Bjarke Buur Mortensen © 2001, 2012
5  */
6
7  #include <cassert> // assert macro
8  #include "counting_allocator.h++"
9  #include <cstddef> // std::size_t
10 #include <cstdlib> // random, srand, RANDMAX
11 #include <iomanip>
12 #include <iostream> // std streams
13
14 using V = int;
15 using A = counting_allocator<V>;
16
17 #include "data-structure.i++" // defines X using V and A
18
19 float run(std::size_t n) {
20     assert(RAND_MAX > n);
21     counting_allocator_base::reset_counts();
22     X container;
23     for (std::size_t i = 0; i < n; ++i) {
24         container.push_back(V(random()));
25     }
26     assert(container.size() == n);
27     return float(counting_allocator_base::bytes_in_use());
28 }
29
30 int main(int argc, char* argv[]) {
31     srand(1837362);
32     for (std::size_t n = 100000; n <= 10000000; n += 100000) {
33         std::cout.setf(std::ios::fixed, std::ios::floatfield);
34         std::cout.precision(3);
35         float bytes_in_use = run(n);
36         float overhead = bytes_in_use - float(n * sizeof(V));
37         float in_procents = 100.0 * overhead / float(n * sizeof(V));
38         std::cout << n << "\t" << in_procents << std::endl;
39     }
40     return 0;
41 }

```

sort-driver.cpp

```

1 #if ! defined(MAXSIZE)
2
3 #define MAXSIZE (64 * 1024 * 1024)
4
5 #endif
6
7 #include <algorithm> // std::random_shuffle, std::sort, std::
   partial_sort
8 #include <cmath> // ilogb
9 #include <ctime> // std::clock_t, std::clock, CLOCKS_PER_SEC
10 #include <functional> // std::less
11 #include <iostream> // std::cout, std::cerr
12 #include <iterator> // std::iterator_traits
13 #include <memory> // std::allocator
14 #include <vector> // std::vector
15
16 extern int ilogb(double) throw();
17
18 template <typename iterator>
19 bool is_permutation(iterator first, iterator beyond) {
20     using V = typename std::iterator_traits<iterator>::value_type;
21     std::vector<V> copy(first, beyond);
22     std::sort(copy.begin(), copy.end());
23     for (auto q = copy.begin(); q != copy.end(); ++q) {
24         V i = V(q - copy.begin());
25         if (*q != i) {
26             std::cerr << i << ": element missing " << *q << " instead\n";
27             std::cerr << "n: " << beyond - first << std::endl;
28             return false;
29         }
30     }
31     return true;
32 }
33
34 template <typename iterator, typename comparator>
35 bool is_sorted(iterator a, iterator o, comparator less) {
36     using Z = typename std::iterator_traits<iterator>::difference_type;
37     Z const n = o - a;
38     bool violated = false;
39     if (n < 2) {
40         return true;
41     }
42     for (Z i = n - 1; i > 0; --i) {
43         if (less(*(a + i), *(a + i - 1))) {
44             std::cerr << i << ": me " << *(a + i) << "; before " << *(a + i
               - 1) << std::endl;
45             violated = true;
46         }
47     }
48     return not violated;
49 }
50

```

```

51 using V = int;
52 using A = std::allocator<V>;
53
54 #include "data-structure.i++" // defines X using V and A
55
56 void usage(int argc, char **argv) {
57     std::cerr << "Usage: " << argv[0] << " <n>\n";
58     exit(1);
59 }
60
61 int main(int argc, char** argv) {
62     using C = std::less<V>;
63
64     unsigned int n = 0;
65     if (argc == 2) {
66         n = atoi(argv[1]);
67     }
68     else {
69         usage(argc, argv);
70     }
71     if (n < 1 or n > MAXSIZE) {
72         std::cerr << "n out of bounds [1.. " << MAXSIZE << "]\n";
73         usage(argc, argv);
74     }
75
76     X b;
77     b.reserve(MAXSIZE);
78     unsigned int const repetitions = MAXSIZE / n;
79     for (unsigned int i = 0; i ≠ repetitions; ++i) {
80         for (unsigned int i = 0; i ≠ n; ++i) {
81             b.push_back(V(i));
82         }
83         std::random_shuffle(b.end() - n, b.end());
84     }
85
86     auto c = b.begin();
87     std::clock_t start = std::clock();
88     for (volatile unsigned int t = 0; t ≠ repetitions; ++t) {
89
90     #if defined(INTROSORT)
91
92         std::sort(c, c + n, C());
93
94     #endif
95
96     #if defined(HEAPSORT)
97
98         std::partial_sort(c, c + n, c + n, C());
99
100    #endif
101
102        c = c + n;

```



```

103 }
104 std::clock_t stop = std::clock();
105
106 auto d = b.begin();
107 for (volatile unsigned int t = 0; t  $\neq$  repetitions; ++t) {
108     bool ok = ::is_sorted(d, d + n, C());
109     if (! ok) {
110         return 1;
111     }
112     ok = ::is_permutation(d, d + n);
113     if (! ok) {
114         return 2;
115     }
116     d = d + n;
117 }
118
119 double scale = double(repetitions) * double(n) * double(ilogb(n));
120 double ns = 1.0e9 * double(stop - start) / double(CLOCKS_PER_SEC);
121 std::cout.precision(3);
122 std::cout << n << '\t' << ns / double(scale) << '\n';
123
124 return 0;
125 }

```

scan-driver.cpp

```

1 #if ! defined(MAXSIZE)
2
3 #define MAXSIZE (128 * 1024 * 1024)
4
5 #endif
6
7 #include <cassert> // assert macro
8 #include <ctime> // std::clock_t, std::clock, CLOCKS_PER_SEC
9 #include <iostream> // std::cout, std::cerr
10 #include <memory> // std::allocator
11 #include <vector> // std::vector
12
13 using V = int;
14 using A = std::allocator<V>;
15
16 #include "data-structure.i++" // defines X using V and A
17
18 void usage(int argc, char **argv) {
19     std::cerr << "Usage: " << argv[0] << " <n>\n";
20     exit(1);
21 }
22
23 int main(int argc, char** argv) {
24     unsigned int n = 0;
25     if (argc == 2) {
26         n = atoi(argv[1]);

```

```

27 }
28 else {
29     usage(argc, argv);
30 }
31 if (n < 1 or n > MAXSIZE) {
32     std::cerr << "n out of bounds [1.." << MAXSIZE << "]\n";
33     usage(argc, argv);
34 }
35
36 std::vector<X> v;
37 unsigned int const repetitions = MAXSIZE / n;
38 v.resize(repetitions);
39 for (unsigned int t = 0; t ≠ repetitions; ++t) {
40     // v[t].reserve(n);
41     for (unsigned int i = 0; i ≠ n; ++i) {
42         v[t].push_back(V(i));
43     }
44 }
45
46 std::clock_t start = std::clock();
47 for (volatile unsigned int t = 0; t ≠ repetitions; ++t) {
48     auto c = v[t].begin();
49     auto e = v[t].end();
50     for (; c ≠ e; ++c) {
51         *c = V(0);
52     }
53 }
54 std::clock_t stop = std::clock();
55
56 for (unsigned int t = 0; t ≠ repetitions; ++t) {
57     for (unsigned int i = n; i ≠ 0; ) {
58         --i;
59         assert(v[t][i] == V(0));
60         v[t].pop_back();
61     }
62 }
63
64 double ns = 1.0e9 * double(stop - start) / double(CLOCKS_PER_SEC);
65 std::cout.precision(3);
66 std::cout << n << '\t' << ns / double(repetitions * n) << '\n';
67
68 return 0;
69 }

```

jump-driver.cpp

```

1 #if ! defined(MAXSIZE)
2
3 #define MAXSIZE (64 * 1024 * 1024)
4
5 #endif
6

```

```

7 #include <cassert> // assert macro
8 #include <ctime> // std::clock_t, std::clock, CLOCKS_PER_SEC
9 #include <iostream> // std::cout, std::cerr
10 #include <memory> // std::allocator
11 #include <vector> // std::vector
12
13 using V = int;
14 using A = std::allocator<V>;
15
16 #include "data-structure.i++" // defines X using V and A
17
18 void usage(int argc, char **argv) {
19     std::cerr << "Usage: " << argv[0] << " <n>\n";
20     exit(1);
21 }
22
23 int main(int argc, char** argv) {
24     unsigned int n = 0;
25     if (argc == 2) {
26         n = atoi(argv[1]);
27     }
28     else {
29         usage(argc, argv);
30     }
31     if (n < 1 or n > MAXSIZE) {
32         std::cerr << "n out of bounds [1.." << MAXSIZE << "]\n";
33         usage(argc, argv);
34     }
35
36     std::vector<X> v;
37     unsigned int const repetitions = MAXSIZE / n;
38     v.resize(repetitions);
39     for (unsigned int t = 0; t ≠ repetitions; ++t) {
40         // v[t].reserve(n);
41         for (unsigned int i = 0; i ≠ n; ++i) {
42             v[t].push_back(i);
43         }
44     }
45
46     unsigned int const prime = 617;
47     unsigned int const mask = n - 1;
48     std::clock_t start = std::clock();
49     for (volatile unsigned int t = 0; t ≠ repetitions; ++t) {
50         auto c = v[t].begin();
51         if (c ≠ v[t].end()) {
52             *c = V(0);
53         }
54         for (unsigned int i = prime; i ≠ 0; i = (i + prime) bitand mask)
55             {
56                 *(c + i) = V(0);
57             }
58     }

```

```

58  std::clock_t stop = std::clock();
59
60  for (unsigned int t = 0; t  $\neq$  repetitions; ++t) {
61      for (unsigned int i = n; i  $\neq$  0; ) {
62          --i;
63          assert(v[t][i] == V(0));
64          v[t].pop_back();
65      }
66  }
67
68  double ns = 1.0e9 * double(stop - start) / double(CLOCKS_PER_SEC);
69  std::cout.precision(3);
70  std::cout << n << '\t' << ns / double(repetitions * n) << '\n';
71
72  return 0;
73 }

```

grow-driver.cpp

```

1  #if ! defined(MAXSIZE)
2
3  #define MAXSIZE (128 * 1024 * 1024)
4
5  #endif
6
7  #include <ctime> // std::clock_, std::clock, CLOCKS_PER_SEC
8  #include <iostream> // std::cout, std::cerr
9  #include <memory> // std::allocator
10 #include <vector> // std::vector
11
12 using V = int;
13 using A = std::allocator<V>;
14
15 #include "data-structure.i++" // defines X using V and A
16
17 void usage(int argc, char **argv) {
18     std::cerr << "Usage: " << argv[0] << " <n>\n";
19     exit(1);
20 }
21
22 int main(int argc, char** argv) {
23     unsigned int n = 0;
24     if (argc == 2) {
25         n = atoi(argv[1]);
26     }
27     else {
28         usage(argc, argv);
29     }
30     if (n < 1 or n > MAXSIZE) {
31         std::cerr << "n out of bounds [1.. " << MAXSIZE << "]\n";
32         usage(argc, argv);
33     }

```

```

34
35  std::vector<X> v;
36  unsigned int const repetitions = MAXSIZE / n;
37  v.resize(repetitions);
38
39  std::clock_t start = std::clock();
40  for (unsigned int t = 0; t  $\neq$  repetitions; ++t) {
41      // v[t].reserve(n);
42      for (unsigned int i = 0; i  $\neq$  n; ++i) {
43          v[t].push_back(V(i));
44      }
45  }
46  std::clock_t stop = std::clock();
47
48  for (unsigned int t = 0; t  $\neq$  repetitions; ++t) {
49      for (unsigned int i = n; i  $\neq$  0; ) {
50          --i;
51          v[t].pop_back();
52      }
53  }
54
55  double ns = 1.0e9 * double(stop - start) / double(CLOCKS_PER_SEC);
56  std::cout.precision(3);
57  std::cout << n << '\t' << ns / double(repetitions * n) << '\n';
58
59  return 0;
60 }

```

shrink-driver.cpp

```

1  #if ! defined(MAXSIZE)
2
3  #define MAXSIZE (128 * 1024 * 1024)
4
5  #endif
6
7  #include <ctime> // std::clock_t, std::clock, CLOCKS_PER_SEC
8  #include <iostream> // std::cout, std::cerr
9  #include <memory> // std::allocator
10 #include <vector> // std::vector
11
12 using V = int;
13 using A = std::allocator<V>;
14
15 #include "data-structure.i++" // defines X using V and A
16
17 void usage(int argc, char **argv) {
18     std::cerr << "Usage: " << argv[0] << " <n>\n";
19     exit(1);
20 }
21
22 int main(int argc, char** argv) {

```

```

23 unsigned int n = 0;
24 if (argc == 2) {
25     n = atoi(argv[1]);
26 }
27 else {
28     usage(argc, argv);
29 }
30 if (n < 1 or n > MAXSIZE) {
31     std::cerr << "n out of bounds [1.." << MAXSIZE << "]\n";
32     usage(argc, argv);
33 }
34
35 std::vector<X> v;
36 unsigned int const repetitions = MAXSIZE / n;
37 v.resize(repetitions);
38 for (unsigned int t = 0; t ≠ repetitions; ++t) {
39     // v[t].reserve(n);
40     for (unsigned int i = 0; i ≠ n; ++i) {
41         v[t].push_back(V(i));
42     }
43 }
44
45 std::clock_t start = std::clock();
46 for (unsigned int t = 0; t ≠ repetitions; ++t) {
47     for (unsigned int i = n; i ≠ 0; ) {
48         --i;
49         v[t].pop_back();
50     }
51 }
52 clock_t stop = std::clock();
53
54 double ns = 1.0e9 * double(stop - start) / double(CLOCKS_PER_SEC);
55 std::cout.precision(3);
56 std::cout << n << '\t' << ns / double(repetitions * n) << '\n';
57
58 return 0;
59 }

```

many-driver.cpp

```

1 /*
2  Advice: A good guess is a must!
3 */
4
5 #include <iostream> // standard streams
6 #include <memory> // std::allocator
7 #include <vector> // std::vector
8
9 using V = int;
10 using A = std::allocator<V>;
11
12 #include "data-structure.i++" // defines X using V and A

```

```

13
14 void usage(int argc, char **argv) {
15     std::cerr << "Usage: " << argv[0] << " [<guess>]\n";
16     exit(1);
17 }
18
19 int main(int argc, char** argv) {
20     unsigned int mega = 1024 * 1024;
21     std::vector<X> v;
22     unsigned int t = 0;
23     if (argc == 1) {
24     }
25     else if (argc == 2) {
26         t = atoi(argv[1]);
27     }
28     else {
29         usage(argc, argv);
30     }
31
32     while (true) {
33         unsigned int n = 0;
34         try {
35             for ( ; n ≠ t; ++n) {
36                 v.push_back(std::move(X()));
37                 v[n].push_back(V(n));
38             }
39         }
40         catch (...) {
41             for (unsigned int i = 0; i ≠ n; ++i) {
42                 v[i].clear();
43             }
44             v.clear();
45             t = t - mega;
46             continue;
47         }
48         break;
49     }
50
51     while (true) {
52         try {
53             std::cout << t << std::endl;
54             v.push_back(std::move(X()));
55             for (unsigned int n = 0; n ≠ mega; ++n) {
56                 v[t].push_back(V(n));
57             }
58             for (unsigned int n = 0; n ≠ mega - 1; ++n) { // leave one!
59                 v[t].pop_back();
60             }
61             ++t;
62         }
63         catch (...) {
64             std::cerr << t << std::endl;

```

```

65     break;
66     }
67 }
68 return 0;
69 }

```

gap-driver.cpp

```

1 #if ! defined(MAXSIZE)
2
3 #define MAXSIZE (128 * 1024 * 1024)
4
5 #endif
6
7 #include <ctime> // std::clock_t, std::clock, CLOCKS_PER_SEC
8 #include <iostream> // std::cout, std::cerr
9 #include <memory> // std::allocator
10 #include <vector> // std::vector
11
12 using V = int;
13 using A = std::allocator<V>;
14
15 #include "data-structure.i++" // defines X using V and A
16
17 void usage(int argc, char **argv) {
18     std::cerr << "Usage: " << argv[0] << " <n>\n";
19     exit(1);
20 }
21
22 int main(int argc, char** argv) {
23     if (argc != 2) {
24         usage(argc, argv);
25     }
26     unsigned int n = atoi(argv[1]);
27     if (n < 1 or n > MAXSIZE) {
28         std::cerr << "n out of bounds [1.. " << MAXSIZE << "]\n";
29         exit(2);
30     }
31
32     std::vector<X> v;
33     unsigned int const repetitions = MAXSIZE / n;
34     v.resize(repetitions);
35     std::vector<unsigned int> gap;
36
37     for (unsigned int t = 0; t != repetitions ; ++t) {
38         V* previous = nullptr;
39         for (unsigned int i = 0; i != n; ++i) {
40             v[t].push_back(V(i));
41             V* current = &v[t].back();
42             if ((current - previous) > 4 or (previous - current) > 4) {
43                 gap.push_back(i);
44             }

```



```

45     previous = current;
46     }
47 }
48
49 unsigned int gaps_per_case = gap.size() / repetitions;
50 std::cout << "n, gaps: " << n << ", " << gaps_per_case << '\n';
51 unsigned int const rounds = 20 * n / gaps_per_case;
52
53 auto p = gap.begin();
54 std::clock_t start = std::clock();
55 for (unsigned int t = 0; t < repetitions ; ++t) {
56     for (unsigned int i = 0; i < n; ++i) {
57         v[t].push_back(V(i));
58         if (i == *p) {
59             for (volatile unsigned int j = 0; j < rounds; ++j) {
60                 v[t].pop_back();
61                 v[t].push_back(V(i));
62             }
63             ++p;
64         }
65     }
66     while (v[t].size() > 0) {
67         v[t].pop_back();
68     }
69 }
70 std::clock_t stop = std::clock();
71
72 double scale = double(21 * n * repetitions);
73 double ns = 1.0e9 * double(stop - start) / double(CLOCKS_PER_SEC);
74 std::cout.precision(3);
75 std::cout << n << '\t' << ns / scale << '\n';
76
77 return 0;
78 }

```

Makefile

makefile

```

1 CXX=g++
2 CXXFLAGS=-O3 -std=c++17 -x c++ -Wall -Wextra -fconcepts -DNDEBUG -
  msse4.2 -mabm
3
4 includes:= $(wildcard *.i++)
5 arrays:= $(basename $(includes))
6 swap:= $(addsuffix .swap-reverse, $(arrays))
7 move:= $(addsuffix .move-reverse, $(arrays))
8 space:= $(addsuffix .space, $(arrays))
9 introsort:= $(addsuffix .introsort, $(arrays))
10 heapsort:= $(addsuffix .heapsort, $(arrays))
11 scan:= $(addsuffix .scan, $(arrays))

```

```

12 jump:= $(addsuffix .jump, $(arrays))
13 grow:= $(addsuffix .grow, $(arrays))
14 shrink:= $(addsuffix .shrink, $(arrays))
15 many:= $(addsuffix .many, $(arrays))
16 gap:= $(addsuffix .gap, $(arrays))
17
18 N = 1024 32768 1048576 33554432
19
20 # Variants for reversals: -DMEASURE_MOVES -DSTD
21
22 $(swap): %.swap-reverse : %.i++
23   @cp swap_based.i++ algorithm.i++
24   $(CXX) $(CXXFLAGS) -DALGORITHM=swap_based -DSTRUCTURE=$* reverse-
      driver.c++
25   @for n in $(N) ; do \
26     ./a.out $$n ; \
27   done; \
28   rm -f ./a.out algorithm.i++
29
30 $(move): %.move-reverse : %.i++
31   @cp move_based.i++ algorithm.i++
32   $(CXX) $(CXXFLAGS) -DALGORITHM=move_based -DSTRUCTURE=$* reverse-
      driver.c++
33   @for n in $(N) ; do \
34     ./a.out $$n ; \
35   done; \
36   rm -f ./a.out algorithm.i++
37
38 $(space): %.space : %.i++
39   @echo "#" $* "space-driver.c++"
40   @cp $.i++ data-structure.i++
41   @$(CXX) $(CXXFLAGS) space-driver.c++
42   @./a.out;
43   @rm -f ./a.out data-structure.i++
44
45 $(introsort): %.introsort : %.i++
46   @cp $.i++ data-structure.i++
47   $(CXX) $(CXXFLAGS) -DINTROSORT sort-driver.c++
48   @for n in $(N) ; do \
49     ./a.out $$n ; \
50   done; \
51   rm -f ./a.out data-structure.i++
52
53 $(heapsort): %.heapsort : %.i++
54   @cp $.i++ data-structure.i++
55   $(CXX) $(CXXFLAGS) -DHEAPSORT sort-driver.c++
56   @for n in $(N) ; do \
57     ./a.out $$n ; \
58   done; \
59   rm -f ./a.out data-structure.i++
60
61 $(scan): %.scan : %.i++

```

```

62 @cp *.i++ data-structure.i++
63 $(CXX) $(CXXFLAGS) scan-driver.c++
64 @for n in $(N) ; do \
65     ./a.out $$n ; \
66 done; \
67 rm -f ./a.out data-structure.i++
68
69 $(jump): %.jump : %.i++
70 @cp *.i++ data-structure.i++
71 $(CXX) $(CXXFLAGS) jump-driver.c++
72 @for n in $(N) ; do \
73     ./a.out $$n ; \
74 done; \
75 rm -f ./a.out data-structure.i++
76
77 $(grow): %.grow : %.i++
78 @cp *.i++ data-structure.i++
79 $(CXX) $(CXXFLAGS) grow-driver.c++
80 @for n in $(N) ; do \
81     ./a.out $$n ; \
82 done; \
83 rm -f ./a.out data-structure.i++
84
85 $(shrink): %.shrink : %.i++
86 @cp *.i++ data-structure.i++
87 $(CXX) $(CXXFLAGS) shrink-driver.c++
88 @for n in $(N) ; do \
89     ./a.out $$n ; \
90 done; \
91 rm -f ./a.out data-structure.i++
92
93 $(many): %.many : %.i++
94 @cp *.i++ data-structure.i++
95 $(CXX) $(CXXFLAGS) many-driver.c++
96 ./a.out
97 rm -f ./a.out data-structure.i++
98
99 $(gap): %.gap : %.i++
100 @cp *.i++ data-structure.i++
101 $(CXX) $(CXXFLAGS) gap-driver.c++
102 @for n in $(N) ; do \
103     ./a.out $$n ; \
104 done; \
105 rm -f ./a.out data-structure.i++
106
107 clean:
108 - rm -f temp core a.out algorithm.i++ data-structure.i++ *.o 2>/
    dev/null or true
109
110 veryclean: clean
111 - rm -f *~ */*~ 2>/dev/null or true
112

```

100

113 **find:**

114 `find . -type f -print -exec grep $(word) {} \; | less`