

# 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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### **Release date**

2016-03-28

## 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 [4]. 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 [4], but the implementation was simplified by seeing it as a pile of hashed array trees [6]. This version matched the space and time bounds proved to be optimal in [?].

## Architecture

In the CPH STL [3], the container classes have been implemented using the bridge design pattern [7, 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 [2, 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 [5].

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 [2, 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

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## 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 <cstddef> // 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     public:
39
40         explicit contiguous_array(A const& a = A())
41             : allocator(a), X(nullptr), X_size(0), X_capacity(0) {
42         }
43
44         contiguous_array(contiguous_array const& other)
45             : contiguous_array(other.allocator) {
46             V* tmp = nullptr;
47             size_type n = other.capacity();
48             if (n != 0) {

```

```

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

```



```

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

```

```

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

```

### *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 }
164
165 const_iterator begin() const {
166     return cbegin();
167 }

```

```

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     }
198     return;
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 ≠ 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*>::
77             other;
78         using directory_type = cphstl::resizable_array<V*,
79             other_allocator_type>;

```

```

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) {
179         swap(other);
180     }
181
182     ~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 }
226
227 size_type size() const {
228     return n;
229 }
```

```

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) {
152     std::swap(allocator, other.allocator);
153     std::swap(pointer_allocator, other.pointer_allocator);
154     directory.swap(other.directory);
155     std::swap(n, other.n);

```

```
153     }
154
155     const_iterator cbegin() const {
156         return (size()  $\neq$  0) ? const_iterator(this, 0) : const_iterator
157             (this);
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 B>
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         }
67         catch (...) {
68             for ( ; i  $\neq$  j; ++i) {
69                 pop_back();
70             }
71         }
72     }
73
74 public:
75
76     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     fixed_capacity_hat(fixed_capacity_hat&& other)
96     : allocator(other.allocator), directory(other.allocator), n(0),
97     m(0), shift_amount(0), mask(0) {
98     swap(other);
99     }
100
101     ~fixed_capacity_hat() {
102     clear();
103     }
104
105     fixed_capacity_hat& operator=(fixed_capacity_hat const& other)
106     {
107     if (this  $\neq$  &other) {
108     fixed_capacity_hat tmp(other);
109     swap(tmp);
110     }
111     return *this;
112     }
113
114     fixed_capacity_hat& operator=(fixed_capacity_hat&& other) {
115     if (this  $\neq$  &other) {
116     fixed_capacity_hat tmp(std::move(other));
117     swap(tmp);
118     }
119     return *this;
120     }
121
122     void swap(fixed_capacity_hat& other) {
123     std::swap(allocator, other.allocator);
124     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             return;
168         }
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 & 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 ≠ past; ++q) {
99                 sequence.push_back(*q);
100             }
101         }
102         catch (...) {
103             for ( ; p ≠ 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 ≠ k; ++j) {
115                 push_back(value);
116             }
117         }
118         catch (...) {
119             for ( ; i ≠ 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 != &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 != &other) {
169     space_efficient_array tmp(std::move(other));
170     (*this).swap(tmp);
171     }
172     return *this;
173     }

```

```

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()  $\neq$  0) ? const_iterator(this, 0) : const_iterator
        (this);
179 }
180
181 const_iterator begin() const {
182     return cbegin();
183 }
184
185 iterator begin() {
186     return (size()  $\neq$  0) ? iterator(this, 0) : iterator(this);
187 }
188
189 const_iterator cend() const {
190     return const_iterator(this);
191 }
192
193 const_iterator end() const {
194     return cend();
195 }
196
197 iterator end() {
198     return iterator(this);
199 }
200
201 allocator_type get_allocator() const {
202     return allocator;
203 }
204
205 size_type size() const {
206     return n;
207 }
208
209 void resize(size_type new_size) {
210     if (n > new_size) {
211         while (n > new_size) {
212             pop_back();
213         }
214         return;
215     }
216     append_n(new_size - n, V());
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 class array {
19 public:
20
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 = '_');
86     void print(char = '_');
87     void print(char const*, char = '_');
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>&);
115 }
116
117 #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(LEDA_CHECKING_OFF)
100     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         else {
152             assert(s > b);
153             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 /* permute functions */
227
228 template <typename V, typename K>
229 void array<V, K>::permute() {
230     permute(low(), high());
231 }
232
233 template <typename V, typename K>
234 void array<V, K>::permute(size_type l, size_type h) {
235     std::pair<iterator, iterator> p = get_iterators(l, h);
236     std::random_shuffle(p.first, p.second);
237 }
238
239 /* binary-search functions */
240
241 template <typename V, typename K>
242 typename array<V, K>::size_type
243 array<V, K>::binary_search(size_type (*cmp)(V const&, V const&),
244     V x) {
245     std::pair<iterator, iterator> p = get_iterators(low(), high());
246     iterator it = std::lower_bound(p.first, p.second, x,
247         stl_compare_less<V>(cmp));
248     if (it == p.second) {
249         return low() - 1;
250     }
251     return (it - p.first) + low();
252 }
253
254 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&),
    V x) {
260     std::pair<iterator, iterator> p = get_iterators(low(), high());
261     iterator it = std::upper_bound(p.first, p.second, x,
    stl_compare_less<V>(cmp));
262
263     if (it == p.second) {
264         return low() - 1;
265     }
266     size_type i = (it - p.first) - 1 + low();
267     if (cmp(x, get(i)) > 0) {
268         return low() - 1;
269     }
270     return i;
271 }
272
273 template <typename V, typename K>
274 typename array<V, K>::size_type array<V, K>::binary_locate(V x) {
275     return binary_locate(compare, x);
276 }
277
278 /* print functions */
279
280 template <typename V, typename K>
281 void array<V, K>::print(std::ostream& o, char space) {
282     std::stringstream sss;
283     sss << space;
284     for(size_type i = low(); i ≤ high(); ++i) {
285         std::stringstream ss;
286         ss << get(i);
287         o << ss.str();
288         if(i ≠ high()) {
289             o << sss.str();
290         }
291     }
292 }
293
294 template <typename V, typename K>
295 void array<V, K>::print(char space) {
296     print(std::cout, space);
297 }
298
299 template <typename V, typename K>
300 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.hpp*

```

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
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::true_type, std::
    false_type
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>::
            propagate_on_container_move_assignment::value);
67 // C++17 or std::allocator_traits<A>::is_always_equal::value);
68     vector(std::initializer_list<V>, A const& = A());
69     ~vector();
70     vector& operator=(vector const&);
71     vector& operator=(vector&&) noexcept(
72         std::allocator_traits<A>::
            propagate_on_container_move_assignment::value);
73 // C++17 or std::allocator_traits<A>::is_always_equal::value);
74     vector& operator=(std::initializer_list<V>);
75
76     template <typename I>
77     void assign(I, I);
78     void assign(size_type, V const&);
79     void assign(std::initializer_list<V>);
80
81     // iterators
82
83     iterator begin() noexcept;
84     const_iterator begin() const noexcept;
85     iterator end() noexcept;
86     const_iterator end() const noexcept;
87     reverse_iterator rbegin() noexcept;
88     const_reverse_iterator rbegin() const noexcept;
89     reverse_iterator rend() noexcept;
90     const_reverse_iterator rend() const noexcept;
91
92     const_iterator cbegin() const noexcept;
93     const_iterator cend() const noexcept;
94     const_reverse_iterator crbegin() const noexcept;
95     const_reverse_iterator crend() const noexcept;
96
97     // accessors
98
99     A get_allocator() const noexcept;
100    size_type size() const noexcept;
101    size_type max_size() const noexcept;
102    size_type capacity() const noexcept;
103    bool empty() const noexcept;
104
105    const_reference operator[](size_type) const;
106    const_reference at(size_type) const;
107    const_reference front() const;
108    const_reference back() const;
109
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 // C++17      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 void shrink_to_fit_dispatch(std::false_type);
167 void shrink_to_fit_dispatch(std::true_type);
168
169 template <typename I>
170 iterator insert_dispatch(iterator, I, I, std::false_type);
171
172 template <typename I>
173 iterator insert_dispatch(iterator, I, I, std::true_type);
174
175 iterator insert_fill(iterator, size_type, V const&);
176
177 template <typename I>
178 iterator insert_range(iterator, I, I);
179
180 using kernel_type = K;
181 kernel_type kernel;
182
183 };
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 bool operator<=(vector<V, A, K> const&, vector<V, A, K> const&);
202
203 template <typename V, typename A, typename K>
204 void swap(vector<V, A, K>& x, vector<V, A, K>& y) noexcept(
205     noexcept(x.swap(y)));
206 }
207
208 #include "stl-vector.i++" // implementation
209
210 #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
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     : kernel(a) {
112     kernel.swap(other.kernel);
113 }
114 // initializer-list constructor
115
116 template <typename V, typename A, typename K>
117 vector<V, A, K>::vector(std::initializer_list<V> other, A const& a
118     )
119     : kernel(a) {
120     K tmp(a);
121     append(tmp, other.begin(), other.end());
122     kernel.swap(tmp);
123 }
124 // destructor
125
126 template <typename V, typename A, typename K>
127 vector<V, A, K>::~~vector() {
128     clear();
129 }
130
131 // copy assignment
132
133 template <typename V, typename A, typename K>
134 vector<V, A, K>& vector<V, A, K>::operator=(vector const& other)
135     {
136     if (this ≠ &other) {
137         K tmp(other.kernel);
138         kernel.swap(tmp);
139     }
140     return *this;
141 }
142 // move assignment
143
144 template <typename V, typename A, typename K>
145 vector<V, A, K>& vector<V, A, K>::operator=(vector&& other)
146     noexcept(
147     std::allocator_traits<A>::propagate_on_container_move_assignment
148         ::value) {
149     // C++17 or std::allocator_traits<A>::is_always_equal::value) {
150     if (this ≠ &other) {
151         clear();
152         kernel.swap(other.kernel);
153     }
154     return *this;

```

```

153 }
154
155 // initializer-list assignment
156
157 template <typename V, typename A, typename K>
158 vector<V, A, K>& vector<V, A, K>::operator=(std::initializer_list<
159     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<
177         I>::value, std::true_type, std::false_type>::type());
178 }
179
180 template <typename V, typename A, typename K>
181 void vector<V, A, K>::assign(std::initializer_list<V> other) {
182     assign_dispatch(other.begin(), other.end(), std::false_type());
183 }
184
185 template <typename V, typename A, typename K>
186 template <typename Integer>
187 void vector<V, A, K>::assign_dispatch(Integer n, Integer v, std::
188     true_type) {
189     K tmp(kernel.get_allocator());
190     append_n(tmp, static_cast<size_type>(n), static_cast<V>(v));
191     kernel.swap(tmp);
192 }
193
194 template <typename V, typename A, typename K>
195 template <typename I>
196 void vector<V, A, K>::assign_dispatch(I p, I q, std::false_type) {
197     K tmp(kernel.get_allocator());
198     append(tmp, p, q);
199     kernel.swap(tmp);
200 }
201
202 // begin
203
204 template <typename V, typename A, typename K>

```

```

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

```

```

246
247 // cbegin
248
249 template <typename V, typename A, typename K>
250 typename vector<V, A, K>::const_iterator vector<V, A, K>::cbegin()
        const noexcept {
251     return const_iterator(kernel.begin());
252 }
253
254 // cend
255
256 template <typename V, typename A, typename K>
257 typename vector<V, A, K>::const_iterator vector<V, A, K>::cend()
        const noexcept {
258     return const_iterator(kernel.end());
259 }
260
261 // rbegin
262
263 template <typename V, typename A, typename K>
264 typename vector<V, A, K>::const_reverse_iterator vector<V, A, K>::
        crbegin() const noexcept {
265     return const_reverse_iterator(end());
266 }
267
268 // rend
269
270 template <typename V, typename A, typename K>
271 typename vector<V, A, K>::const_reverse_iterator vector<V, A, K>::
        crend() const noexcept {
272     return const_reverse_iterator(begin());
273 }
274
275 // get_allocator
276
277 template <typename V, typename A, typename K>
278 A vector<V, A, K>::get_allocator() const noexcept {
279     return kernel.get_allocator();
280 }
281
282 // size
283
284 template <typename V, typename A, typename K>
285 typename vector<V, A, K>::size_type vector<V, A, K>::size() const
        noexcept {
286     return kernel.size();
287 }
288
289 // max_size
290
291 template <typename V, typename A, typename K>
292 typename vector<V, A, K>::size_type vector<V, A, K>::max_size()

```

```

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

```

```

339
340 // front
341
342 template <typename V, typename A, typename K>
343 typename vector<V, A, K>::reference vector<V, A, K>::front() {
344     iterator first = kernel.begin();
345     return reference(*first);
346 }
347
348 template <typename V, typename A, typename K>
349 typename vector<V, A, K>::const_reference vector<V, A, K>::front()
350     const {
351     const_iterator first = kernel.begin();
352     return const_reference(*first);
353 }
354 // back
355
356 template <typename V, typename A, typename K>
357 typename vector<V, A, K>::reference vector<V, A, K>::back() {
358     iterator const last = --end();
359     return reference(*last);
360 }
361
362 template <typename V, typename A, typename K>
363 typename vector<V, A, K>::const_reference vector<V, A, K>::back()
364     const {
365     const_iterator const last = --end();
366     return const_reference(*last);
367 }
368 // data
369
370 template <typename V, typename A, typename K>
371 V* vector<V, A, K>::data() noexcept {
372     return kernel.data();
373 }
374
375 template <typename V, typename A, typename K>
376 V const* vector<V, A, K>::data() const noexcept {
377     return kernel.data();
378 }
379
380 // resize
381
382 template <typename V, typename A, typename K>
383 void vector<V, A, K>::resize(size_type n) {
384     resize(n, V());
385 }
386
387 template <typename V, typename A, typename K>
388 void vector<V, A, K>::resize(size_type n, V const& v) {

```



```

389     if (size() > n) {
390         while (size() > n) {
391             pop_back();
392         }
393         return;
394     }
395     append_n(kernel, n - size(), v);
396 }
397
398 // reserve
399
400 template <typename V, typename A, typename K>
401 void vector<V, A, K>::reserve(size_type s) {
402     kernel.reserve(s);
403 }
404
405 // shrink_to_fit
406
407 template <typename T>
408 class has_shrink_to_fit {
409
410     template <typename U, void (U::*)()>
411     struct check;
412
413     template <typename U>
414     static char member(check<U, &U::shrink_to_fit>*);
415
416     template <typename U>
417     static int member(...);
418
419 public:
420
421     enum { value = sizeof(member<T>(nullptr)) == sizeof(char) };
422 };
423
424 template <typename V, typename A, typename K>
425 void vector<V, A, K>::shrink_to_fit() {
426     shrink_to_fit_dispatch(typename std::conditional<
427         has_shrink_to_fit<K>::value, std::true_type, std::false_type
428     >::type());
429 }
430
431 template <typename V, typename A, typename K>
432 void vector<V, A, K>::shrink_to_fit_dispatch(std::true_type) {
433     kernel.shrink_to_fit();
434 }
435
436 template <typename V, typename A, typename K>
437 void vector<V, A, K>::shrink_to_fit_dispatch(std::false_type) {
438     // do nothing
439 }

```

```

439 // emplace_back
440
441 template <typename V, typename A, typename K>
442 template <typename... Args>
443 void vector<V, A, K>::emplace_back(Args&&... args) {
444     kernel.emplace_back(std::forward<Args>(args)...);
445 }
446
447 // push_back
448
449 template <typename V, typename A, typename K>
450 void vector<V, A, K>::push_back(V const& v) {
451     kernel.push_back(v);
452 }
453
454 template <typename V, typename A, typename K>
455 void vector<V, A, K>::push_back(V&& v) {
456     kernel.push_back(std::move(v));
457 }
458
459 // pop_back
460
461 template <typename V, typename A, typename K>
462 void vector<V, A, K>::pop_back() {
463     kernel.pop_back();
464 }
465
466 // emplace
467
468 template <typename V, typename A, typename K>
469 template <typename... Args>
470 typename vector<V, A, K>::iterator vector<V, A, K>::emplace(
471     iterator p, Args&&... args) {
472     size_type i = p - begin();
473     size_type j = size();
474     emplace_back(std::forward<Args>(args)...);
475     std::rotate(begin() + i, begin() + j, end());
476     return begin() + i;
477 }
478 // single-element insert
479
480 template <typename V, typename A, typename K>
481 typename vector<V, A, K>::iterator vector<V, A, K>::insert(iterator
482     p, V const& v) {
483     size_type i = p - begin();
484     size_type j = size();
485     push_back(v);
486     std::rotate(begin() + i, begin() + j, end());
487     return begin() + i;
488 }

```

```

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

```

```

531     size_type j = size();
532     append_n(kernel, n, v);
533     std::rotate(begin() + i, begin() + j, end());
534     return begin() + i;
535 }
536
537 template <typename V, typename A, typename K>
538 template <typename I>
539 typename vector<V, A, K>::iterator vector<V, A, K>::insert_range(
540     iterator p, I q, I r) {
541     size_type i = p - begin();
542     size_type j = size();
543     append(kernel, q, r);
544     std::rotate(begin() + i, begin() + j, end());
545     return begin() + i;
546 }
547 // single-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) {
552     assert(p  $\neq$  end());
553     size_type i = p - begin();
554     std::rotate(begin() + i, begin() + i + 1, end());
555     pop_back();
556     return begin() + i;
557 }
558 // multiple-element erase
559
560 template <typename V, typename A, typename K>
561 typename vector<V, A, K>::iterator vector<V, A, K>::erase(iterator
562     p, iterator q) {
563     size_type i = p - begin();
564     size_type j = q - begin();
565     std::rotate(begin() + i, begin() + j, end());
566     while (i  $\neq$  j) {
567         pop_back();
568         ++i;
569     }
570     return begin() + i;
571 }
572 // clear
573
574 template <typename V, typename A, typename K>
575 void vector<V, A, K>::clear() noexcept {
576     while (not empty()) {
577         pop_back();
578     }
579 }

```

```

580
581 // swap
582
583 template <typename V, typename A, typename K>
584 void vector<V, A, K>::swap(vector<V, A, K>& other) noexcept(
585     std::allocator_traits<A>::propagate_on_container_swap::value) {
586 // C++17      or std::allocator_traits<A>::is_always_equal::value) {
587     kernel.swap(other.kernel);
588 }
589
590 template <typename V, typename A, typename K>
591 void swap(vector<V, A, K>& x, vector<V, A, K>& y) noexcept(
592     noexcept(x.swap(y))) {
593     x.swap(y);
594 }
595
596 // operator ==
597
598 template <typename V, typename A, typename K>
599 bool operator==(vector<V, A, K> const& r, vector<V, A, K> const& s) {
600     return (r.size() == s.size() and std::equal(r.begin(), r.end(), s
601         .begin()));
602 }
603 // operator <
604
605 template <typename V, typename A, typename K>
606 bool operator<(vector<V, A, K> const& r, vector<V, A, K> const& s
607     ) {
608     return std::lexicographical_compare(r.begin(), r.end(), s.begin()
609         , s.end());
610 }
611 // operator !=
612
613 template <typename V, typename A, typename K>
614 bool operator!=(vector<V, A, K> const& r, vector<V, A, K> const& s) {
615     return not (r == s);
616 }
617 // operator >
618
619 template <typename V, typename A, typename K>
620 bool operator>(vector<V, A, K> const& r, vector<V, A, K> const& s
621     ) {
622     return (s < r);
623 }
624 // operator ≥
625

```

```

626 template <typename V, typename A, typename K>
627 bool operator>=(vector<V, A, K> const& r, vector<V, A, K> const& s
        ) {
628     return not (r < s);
629 }
630
631 // operator ≤
632
633 template <typename V, typename A, typename K>
634 bool operator<=(vector<V, A, K> const& r, vector<V, A, K> const& s
        ) {
635     return not (s < r);
636 }
637 }

```

## 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<
        size_type>::max();
63
64     // variables
65
66     owner_type* owner_p;
67     size_type rank;
68
69     // parameterized constructor
70
71     rank_iterator(owner_type* p, size_type offset = sentinel)
72         : owner_p(p), rank(offset) {
73     }
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
94
95     // generated by the compiler if needed
96     // rank_iterator& operator=(rank_iterator const&) = default;
97
98     rank_iterator& operator=(rank_iterator<typename std::
99                               remove_const<R>::type> const& x) {
100        owner_p = x.owner_p;
101        rank = x.rank;
102        return *this;
103    }
104
105    // destructor
106
107    ~rank_iterator() {
108    };
109
110    // operator *
111
112    reference operator*() const {
113        assert(owner_p != nullptr and rank != sentinel);
114        return (*owner_p)[rank];
115    }
116
117    // operator →
118
119    pointer operator→() const {
120        assert(owner_p != nullptr and rank != sentinel);
121        return &(*owner_p)[rank];
122    }
123
124    // operator ++; pre-increment
125
126    rank_iterator& operator++() {
127        assert(owner_p != nullptr and rank != sentinel);
128        ++rank;
129        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 != nullptr and (*owner_p).size() != 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 != 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 >= (*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>::
205         yes>
206     difference_type operator-(rank_iterator<S> const& other) const {
207         assert(owner_p == other.owner_p);
208         size_type y = rank;
209         if (rank == sentinel) {
210             y = (*owner_p).size();
211         }
212         size_type x = other.rank;
213         if (other.rank == sentinel) {
214             x = (*owner_p).size();
215         }
216         return y - x;
217     }
218
219     // operator ==
220
221     template <typename S, typename = typename is_comparable<S, R>::
222         yes>
223     bool operator==(rank_iterator<S> const& other) const {
224         return rank == other.rank and owner_p == other.owner_p;
225     }
226
227     // operator !=
228
229     template <typename S>
230     bool operator!=(rank_iterator<S> const& other) const {
231         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
270 #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 */

```

```

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
        & b) const {
66         if ((*this).f(a.first, b.first) == 1) {
67             return true;
68         }
69         return false;
70     }
71
72 private:
73
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     return alloc.allocate(n);
119 }
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;
186 counting_allocator_base::count_type counting_allocator_base::
187     max_bytes = 0;
188
189 #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;
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
64 template <typename U>
65 friend bool operator==(move_counter<U> const&, move_counter<U>
66     const&);
67
68 template <typename T>
69 bool operator<(move_counter<T> const& x, move_counter<T> const& y)
70     {
71     return x.datum < y.datum;
72     }
73
74 template <typename T>
75 bool operator==(move_counter<T> const& x, move_counter<T> const& y)
76     {
77     return x.datum == y.datum;
78     }
79
80 #endif
81
82 void usage(int argc, char **argv) {
83     std::cerr << "Usage: " << argv[0] << " <n>\n";
84     exit(1);
85 }
86
87 int main(int argc, char** argv) {
88
89     #ifdef MEASURE_MOVES
90     using V = move_counter<int>;
91
92     #else
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
131  moves = 0;
132
133  #else
134
135  std::clock_t start = std::clock();
136
137  #endif
138
139  for (volatile unsigned int t = 0; t ≠ repetitions; ++t) {
140      ALGORITHM::reverse(many[t]);
141  }
142
143  #if ! defined(MEASURE_MOVES)
144
145  std::clock_t stop = std::clock();
146
147  #endif
148

```

```

149 double scale = double(repetitions) * double(n);
150
151 #if defined(MEASURE_MOVES)
152
153     std::cout.precision(3);
154     std::cout << n << '\t' << double(moves) / double(scale) << std::
        endl;
155
156 #else
157
158     double ns = 1.0e9 * double(stop - start) / double(CLOCKS_PER_SEC);
159     std::cout.precision(4);
160     std::cout << n << '\t' << ns / double(scale) << std::endl;
161
162 #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.c++*

```

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
45             - 1) << std::endl;
46         violated = true;
47     }
48 }
49 return not violated;
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  $\neq$  repetitions; ++t) {
50     auto c = v[t].begin();
51     if (c  $\neq$  v[t].end()) {
52         *c = V(0);
53     }
54     for (unsigned int i = prime; i  $\neq$  0; i = (i + prime) & mask)
55         {
56             *(c + i) = V(0);
57         }
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 ≠ repetitions; ++t) {
41         // v[t].reserve(n);
42         for (unsigned int i = 0; i ≠ 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 ≠ repetitions; ++t) {
49         for (unsigned int i = n; i ≠ 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  $\neq$  mega; ++n) {
56             v[t].push_back(V(n));
57         }
58         for (unsigned int n = 0; n  $\neq$  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  $\neq$  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 -Wall -DNDEBUG -std=c++11 -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-
25         driver.c++
26     @for n in $(N) ; do \
27         ./a.out $$n ; \
28     done; \
29     rm -f ./a.out algorithm.i++
30
31 $(move): %.move-reverse : %.i++
32     @cp move_based.i++ algorithm.i++
33     $(CXX) $(CXXFLAGS) -DALGORITHM=move_based -DSTRUCTURE=$* reverse-
34         driver.c++
35     @for n in $(N) ; do \
36         ./a.out $$n ; \
37     done; \
38     rm -f ./a.out algorithm.i++
39
40 $(space): %.space : %.i++
41     @echo "#" $* "space-driver.c++"
42     @cp $.i++ data-structure.i++
43     @$(CXX) $(CXXFLAGS) space-driver.c++
44     @./a.out;
45     @rm -f ./a.out data-structure.i++
46
47 $(introsort): %.introsort : %.i++
48     @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.cpp
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>/
109         dev/null
110
111 veryclean: clean
112     - rm -f *~ */*~ 2>/dev/null
113
114 find:
115     find . -type f -print -exec grep $(word) {} \; | less
```