TDDD38/726G82 - Advanced programming in C++

Introduction STL

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1 Introduction
2 IO
3 Sequential Containers

Introduction

What is the STL?

- Library accessible everywhere
- Solving common problems
- Modular design
- Efficiency

Introduction

What is the STL?

- Library accessible everywhere
  - Same behaviour independent of platform
  - Shipped with the compiler itself
  - ISO C++ requires the full library to be accessible
- Solving common problems
- Modular design
- Efficiency

Introduction

What is the STL?

- Library accessible everywhere
- Solving common problems
  - Having to reinvent the wheel is costly
  - There are problems most programmers face
  - Designed to be as widely usable as possible
- Modular design
- Efficiency

Introduction

What is the STL?

- Library accessible everywhere
- Solving common problems
- Modular design
  - Don’t pay for what you don’t use
  - Only import the parts that you need
  - All modules are compatible with each other
- Efficiency

Introduction

What is the STL?

- Library accessible everywhere
- Solving common problems
- Modular design
- Efficiency
  - Library writers are very skilled
  - Components are highly optimized
  - Maintenance is not your responsibility

Introduction

Standard **T**emplate **L**ibrary

Introduction

Design principles of STL

- Should be as general as possible

Introduction

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- Solves common problems

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- Must work together with user-defined code

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- Should be as general as possible
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- Must work together with user-defined code
- Efficient enough to replace hand-written alternatives

Introduction

Design principles of STL

- Should be as general as possible
- Solves common problems
- The common case should be convenient
- Must work together with user-defined code
- Efficient enough to replace hand-written alternatives
- Should have robust error handling

Introduction

Components

- Algorithms
- Containers
- Functions
- Iterators

Introduction

Components

- Algorithms
  - General facilities for solving common problems
  - A large amount of algorithms exist in the STL
  - Highly optimized for both speed and memory
- Containers
- Functions
- Iterators

Introduction

Components

- Algorithms
- Containers
  - General data structures
  - Based on high level abstractions
  - Should not be required to understand the underlying implementation
- Functions
- Iterators

Introduction

Components

- Algorithms
- Containers
- Functions
  - General utility functions
  - Should be usable for as many types as possible
  - Solves all manner of problems
- Iterators

Introduction

Components

- Algorithms
- Containers
- Functions
- Iterators
  - Abstraction which allows for general traversal of data
  - Used in conjunction with algorithms
  - An interface that works with all containers without the need to specify the container type

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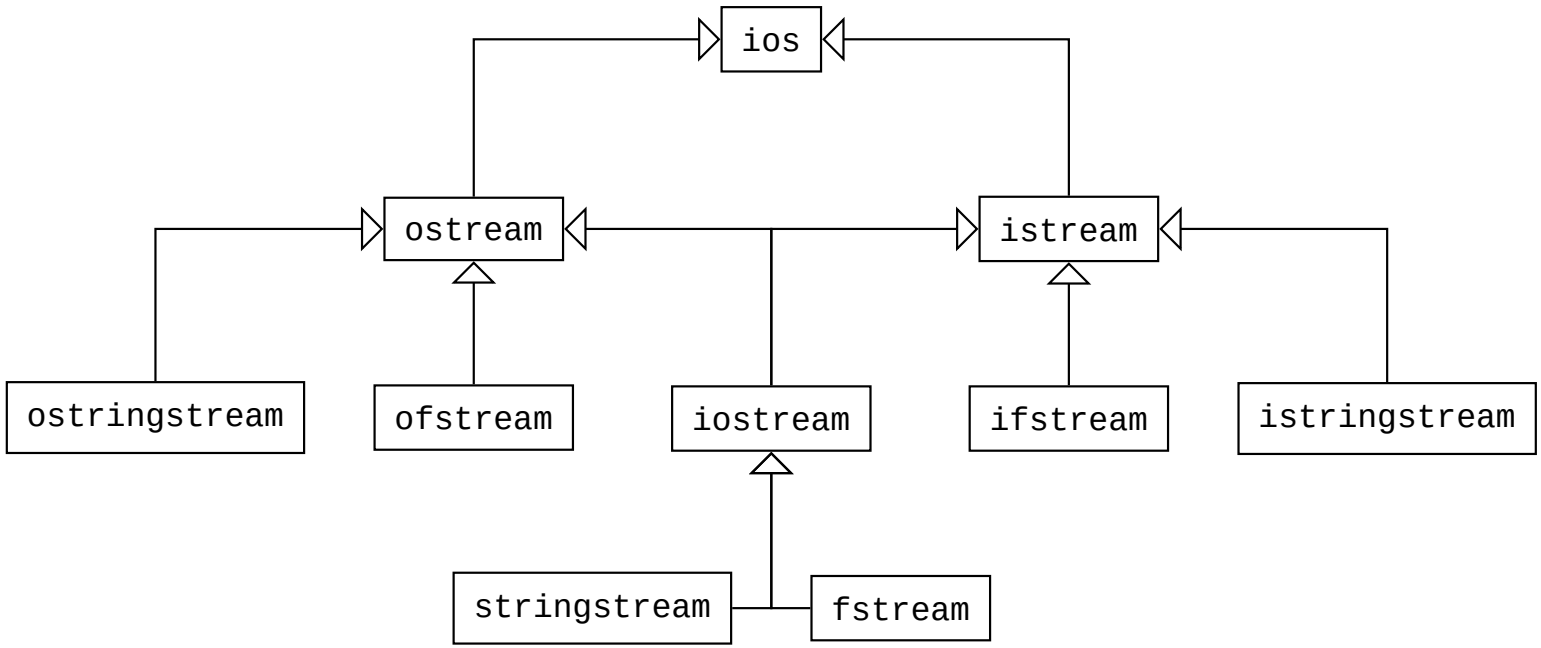
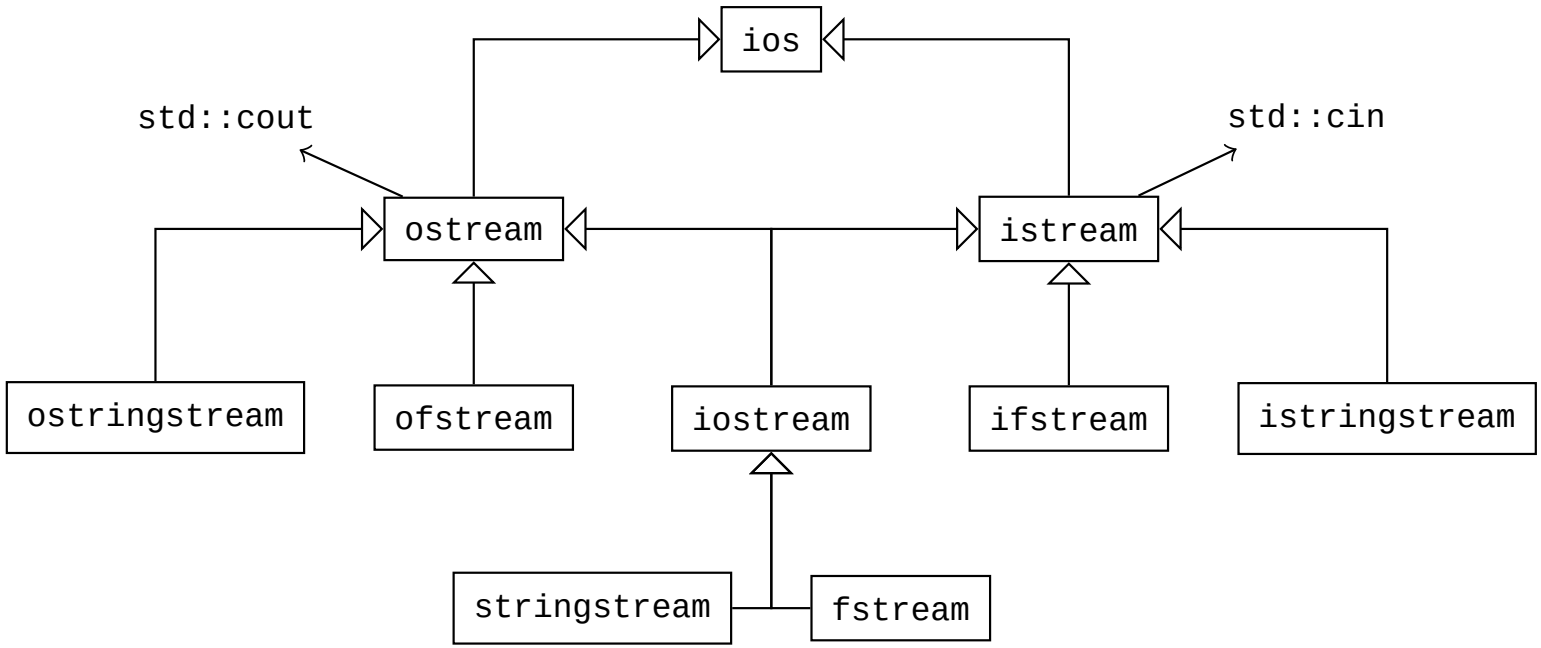
IO

Streams


ios
ostream
istream
ostringstream
ofstream
iostream
ifstream
istringstream
stringstream
fstream

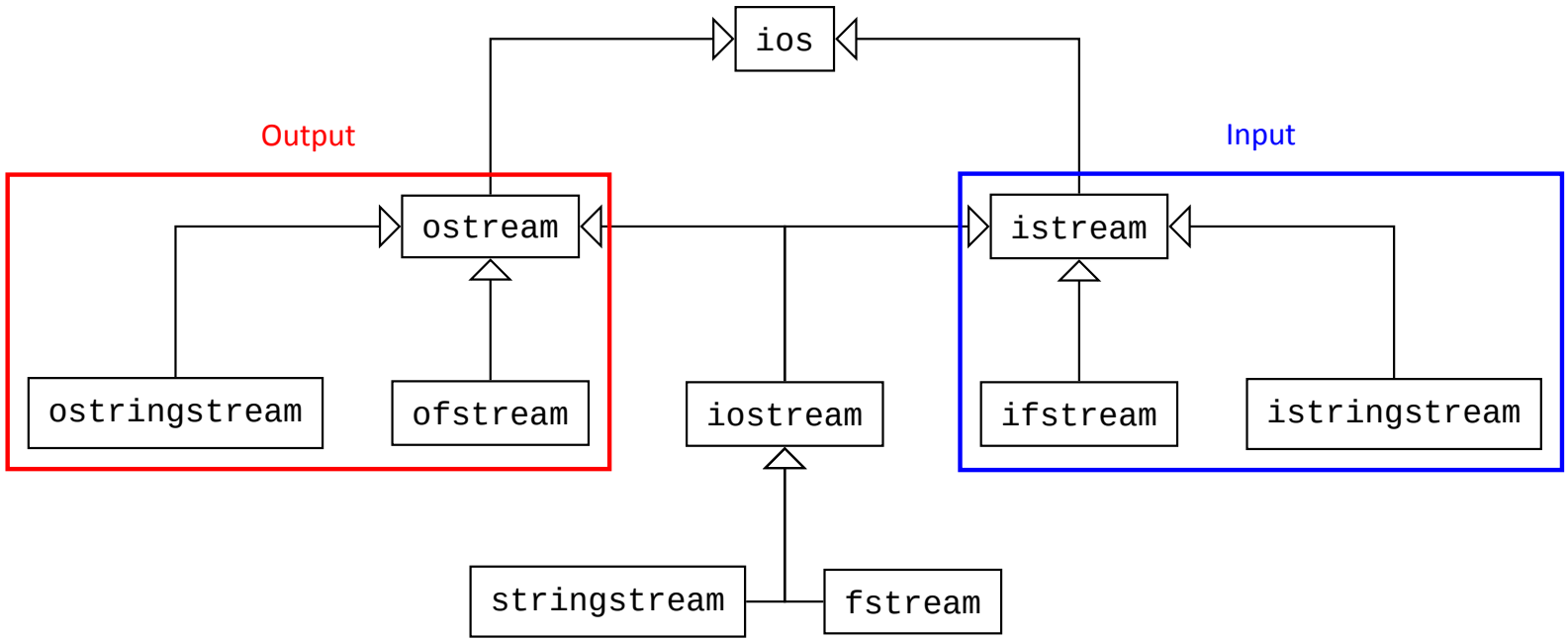
IO

Streams


ios
std::cout
std::cin
ostream
istream
ostringstream
ofstream
iostream
ifstream
istringstream
stringstream
fstream

IO

Streams


ios
Output
Input
ostream
istream
ostringstream
ofstream
iostream
ifstream
istringstream
stringstream
fstream

IO

Streams

- Represent reading and writing data to some *device*
- Example of devices;
  - a terminal
  - a file
  - a chunk of memory
  - sockets
- `operator>>` to read
- `operator<<` to write

IO

Stream operators

```
template <typename T>
ostream& operator<<(ostream& os, T&& data)
{
  // write data to the device
  return os;
}
// ...
cout << 1 << 2;
```

IO

Stream operators

```
ostream& operator<<(ostream& os, T&& data);
```

```
cout << 1 << 2;
```

IO

Stream operators

```
ostream& operator<<(ostream& os, T&& data);
```

```
(cout << 1) << 2;
```

IO

Stream operators

```
ostream& operator<<(ostream& os, T&& data);
```

```
operator<<(cout, 1) << 2;
```

IO

Stream operators

```
ostream& operator<<(ostream& os, T&& data);
```

```
cout << 2;
```

IO

Stream operators

```
ostream& operator<<(ostream& os, T&& data);
```

```
(cout << 2);
```

IO

Stream operators

```
ostream& operator<<(ostream& os, T&& data);
```

```
cout;
```

IO

Chaining operators

- Stream operators return a reference to the stream
- This is done to enable *chaining*
- Since << and >> are *left associative* this will allow us to make several calls to the stream in one expression

IO

Devices

```
ostream& operator<<(ostream& os, T&& data);

int main()
{
  ostringstream oss{};
  ofstream ofs{"my_file.txt"};
  cout << 1; // write to terminal
  oss  << 1; // write to string
  ofs  << 1; // write to file
  oss.str(); // access string
}
```

IO

Devices

```
istream& operator>>(istream& is, T& data);

int main()
{
  int x;
  istringstream iss{"1"};
  ifstream ofs{"my_file.txt"};
  cin >> x; // read from terminal
  oss >> x; // read from string
  ofs >> x; // read from file
}
```

IO

Devices

- The interface of streams are general
- Underlying devices are abstracted away
- all streams are within a (polymorphic) hierarchy
- so we can write general code that operates on arbitrary streams if we take `ostream&` or `istream&`

IO

Error handling

```
int x;
ifstream ifs{"file"};
while (ifs >> x)
{
  // do stuff
}
```

Exits loop if:

IO

Error handling

```
int x;
ifstream ifs{"file"};
while (ifs >> x)
{
  // do stuff
}
```

Exits loop if:

unable to read as `int`

IO

Error handling

```
int x;
ifstream ifs{"file"};
while (ifs >> x)
{
  // do stuff
}
```

Exits loop if:

- unable to read as `int`
- found end of file character

IO

Error handling

```
int x;
ifstream ifs{"file"};
while (ifs >> x)
{
  // do stuff
}
```

Exits loop if:

- unable to read as `int`
- found end of file character
- file is corrupt

IO

Error handling

```
int x;
ifstream ifs{"file"};
while (ifs >> x)
{
  // do stuff
}
```

Exits loop if:

`fail:` unable to read as `int`

found end of file character

file is corrupt

IO

Error handling

```
int x;
ifstream ifs{"file"};
while (ifs >> x)
{
  // do stuff
}
```

Exits loop if:

`fail:` unable to read as `int`

`eof:` found end of file character

file is corrupt

IO

Error handling

```
int x;
ifstream ifs{"file"};
while (ifs >> x)
{
  // do stuff
}
```

Exits loop if:

`fail:` unable to read as `int`

`eof:` found end of file character

`bad:` file is corrupt

IO

Error handling

```
int x;
ifstream ifs{"file"};
ifs >> x;
if (ifs.fail())     // unable to read as int
// ...
else if (ifs.eof()) // reached end of file
// ...
else if (ifs.bad()) // device is corrupt
// ...
```

IO

Error flags

```
istream& operator>>(istream& is, T& t)
{
  // try to read from is
  if (/* unable to read as T */)
  {
    is.setstate(ios::failbit);
  }
  return is;
}
```

IO

Error flags

`ios::failbit`	stream operation failed
`ios::eofbit`	device has reached the end
`ios::badbit`	irrecoverable stream error
`ios::goodbit`	no error

IO

Error flags

- Multiple flags can be set at once
- except `goodbit`; it is set when no other flag is set
- This means that several errors can occur at once
- Do note that these flags are set *after* a stream operation failed
- The stream does not magically detect an error if no operation has been performed

IO

Converting from strings

```
int main(int argc, char* argv[])
{
  int x;
  istringstream iss{argv[1]};
  if (!(iss >> x))
  {
    // error

    // reset flags
    iss.clear();
  }
  // continue
}
```

```
int main(int argc, char* argv[])
{
  int x;
  try
  {
    x = stoi(argv[1]);
  }
  catch (invalid_argument& e)
  {
    // error
  }
  // continue
}
```

IO

Converting from strings

`istringstream` version

- \+ More general
- \+ Cheaper error path
- − Requires a stream
- − Must check flags

`stoi` version

- \+ No extra objects
- \+ Easier error handling
- − Expensive error path
- − Only works for `int`

Prefer the `istringstream` version because of generality, but as always; there are no universal solutions

IO

What will be printed?

```
#include <sstream>
#include <iostream>
#include <string>
using namespace std;
int main()
{
  stringstream ss{};
  ss << "123a bc hello";
  int    n{};
  char   c{};
  string str{};

  if (ss >> n >> n >> c) cout << n << " ";
  ss.clear();
  if (ss >> c >> c) cout << c << " ";
  ss.clear();
  if (ss >> str) cout << str << " ";
}
```

1 Introduction
2 IO
3 Sequential Containers

Containers

Containers

- Sequential Containers
- Associative Containers
- Container Adaptors

Sequential Containers

Important concepts

- Memory allocations
  - Different containers have different models of allocation.
  - Calling `new` is **very** slow,
  - So the number of memory allocations is an important factor in the effectiveness of a container
- CPU caching
- Pointer invalidation

Sequential Containers

Important concepts

- Memory allocations
- CPU caching
  - Modern CPU:s perform what is known as caching.
  - Whenever the CPU fetch data from the RAM it will fetch a block of data and store that in the cache.
  - Accessing data in the CPU cache is several magnitudes faster than accessing data in the RAM.
- Pointer invalidation

Sequential Containers

Important concepts

- Memory allocations
- CPU caching
  - We always read data in blocks, so we know that the element after the data we just read is almost guaranteed to be in the cache.
  - So containers that read data in sequence is a lot faster than those that do not.
- Pointer invalidation

Sequential Containers

Important concepts

- Memory allocations
- CPU caching
  - On the flip side: if the elements of a container is spread all around the RAM, then it will be a lot slower since we almost always have to read the data from RAM rather than cache.
  - Usually we talk about the *cache locality* of a container: how much of the cache it can leverage for speedups.

Sequential Containers

Important concepts

- Memory allocations
- CPU caching
- Pointer invalidation
  - If we have pointers or references to data in containers we have to know whenever these gets *invalidated*.
  - A pointer (or reference) points to a specific address in memory,

Sequential Containers

Important concepts

- Memory allocations
- CPU caching
- Pointer invalidation
  - So if the container for some reason moves the element to another address in memory, then the pointer doesn't refer to the same element (and chances are it doesn't even point to a valid object)
  - This can prove to be a big impact in how we use containers.

Sequential Containers

What is a sequential container?

- Data stored in sequence
- Accessed with indices
- Ordered but not (necessarily) sorted

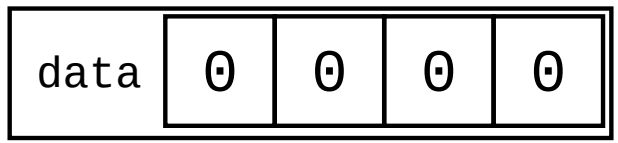
Sequential Containers

Which sequential containers are there?

- `std::array`
- `std::vector`
- `std::list`
- `std::forward_list`
- `std::deque`

Sequential Containers

`std::array`

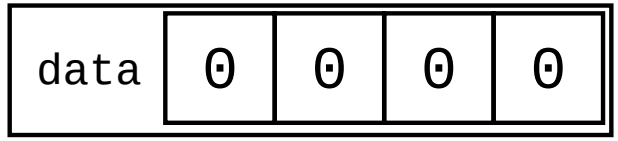


`std::array<int, 4>`

```
std::array<int, 4> array{};
```

Sequential Containers

`std::array`

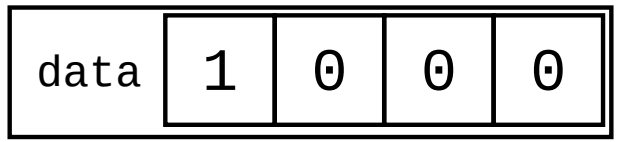


`std::array<int, 4>`

```
array[0] = 1;
```

Sequential Containers

`std::array`



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Sequential Containers

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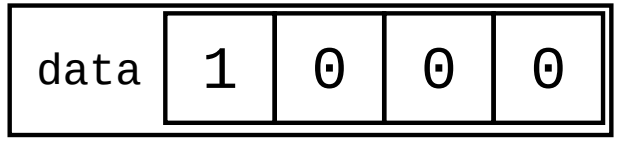
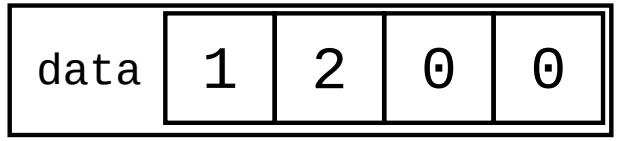


`std::array<int, 4>`

```
array[1] = 2;
```

Sequential Containers

`std::array`



`std::array<int, 4>`

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array[1] = 2;
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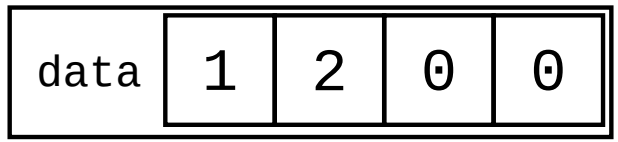
Sequential Containers

`std::array`

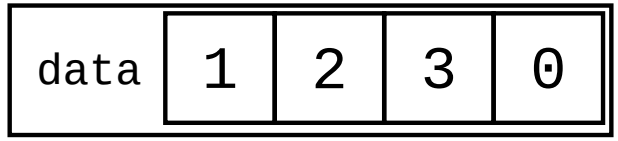


`std::array<int, 4>`

```
array[2] = 3;
```

Sequential Containers

`std::array`



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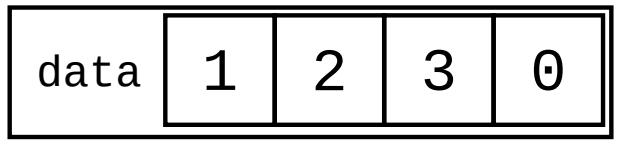
Sequential Containers

`std::array`



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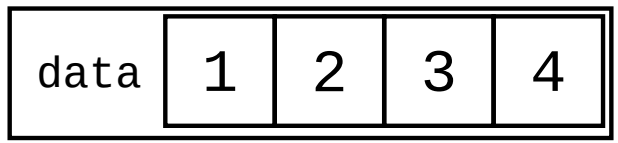
Sequential Containers

`std::array`



`std::array<int, 4>`

```
array[3] = 4;
```

Sequential Containers

`std::array`

- insertion: *not applicable*
- deletion: *not applicable*
- lookup: $O(1)$

Sequential Containers

`std::array`

- \+ No memory allocations
- \+ Data never move in memory
- – Fixed size
- – Size must be known during compilation

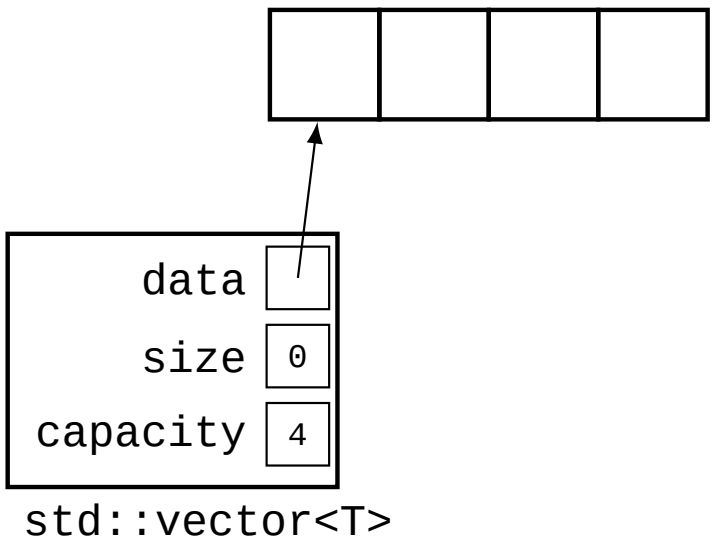
Sequential Containers

Example

```
#include <array>
// ...
int main()
{
  std::array<int, 5> data{};
  for (unsigned i{}; i < data.size(); ++i)
  {
    cin >> data.at(i);
  }
  for (auto&& i : data)
  {
    cout << i << endl;
  }
}
```

Sequential Containers

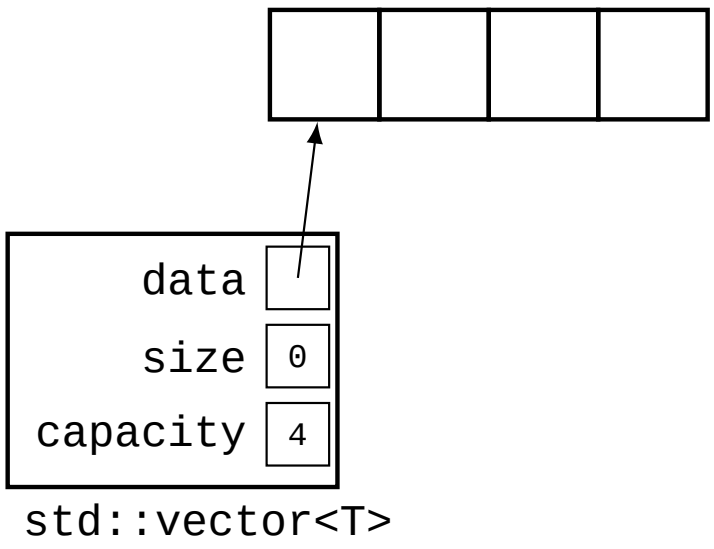
`std::vector`




```
std::vector<int> vector{};
```

Sequential Containers

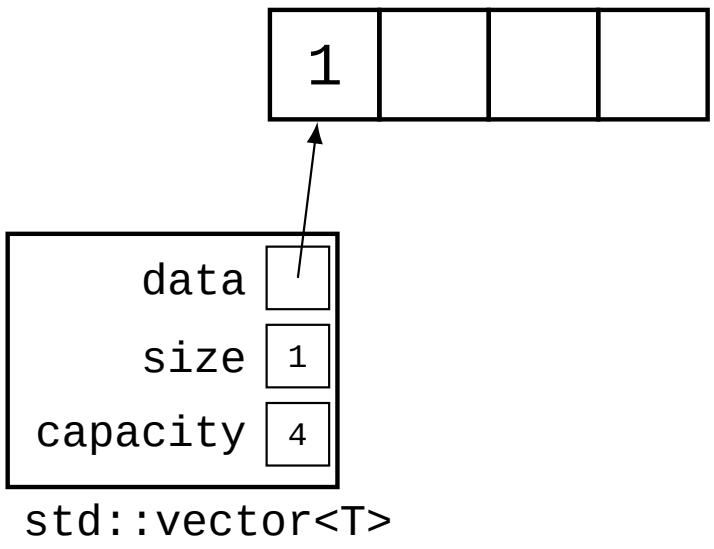
`std::vector`




```
vector.push_back(1);
```

Sequential Containers

`std::vector`




```
vector.push_back(1);
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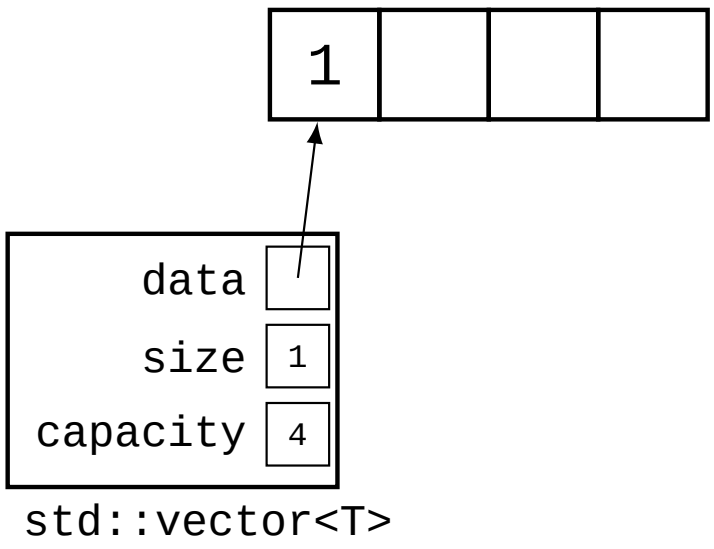
Sequential Containers

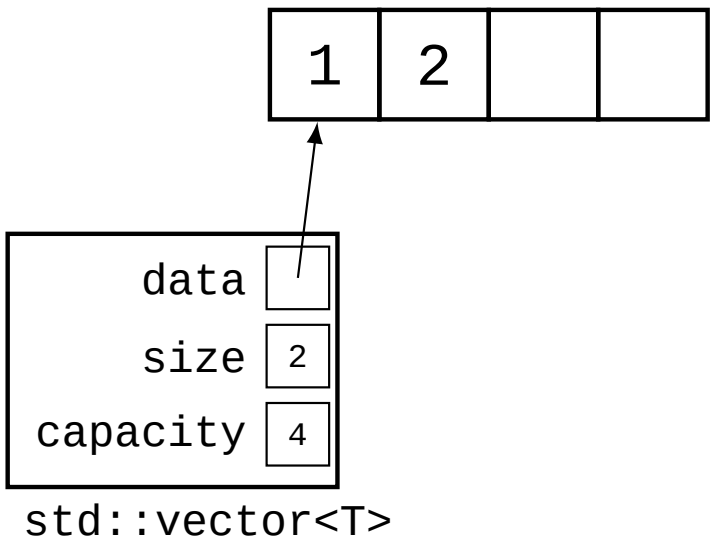
`std::vector`




```
vector.push_back(2);
```

Sequential Containers

`std::vector`

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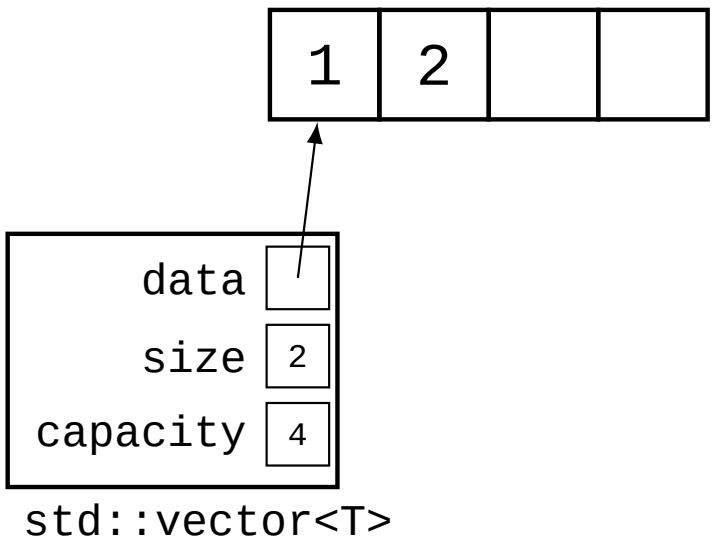
Sequential Containers

`std::vector`

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Sequential Containers

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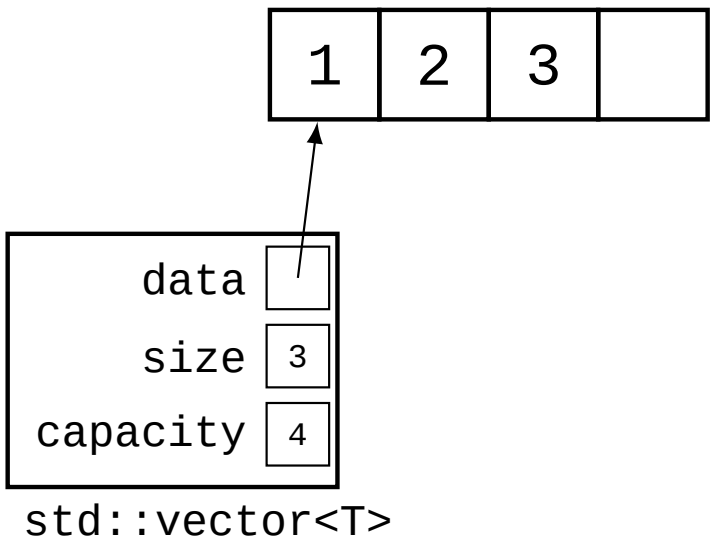


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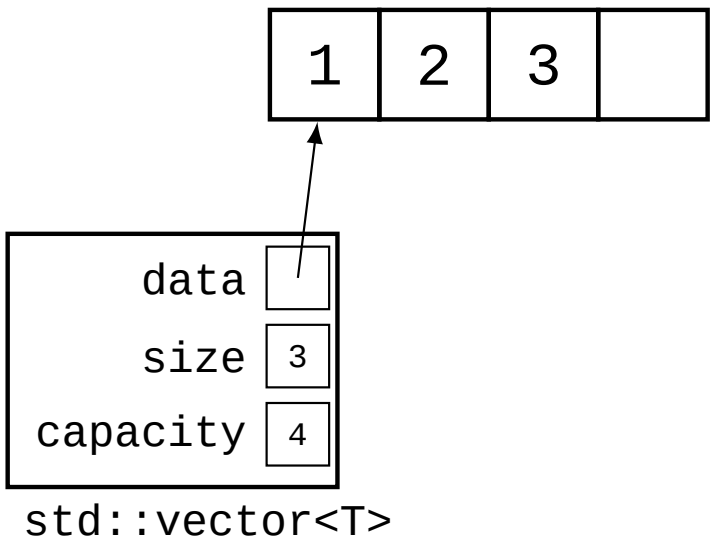
Sequential Containers

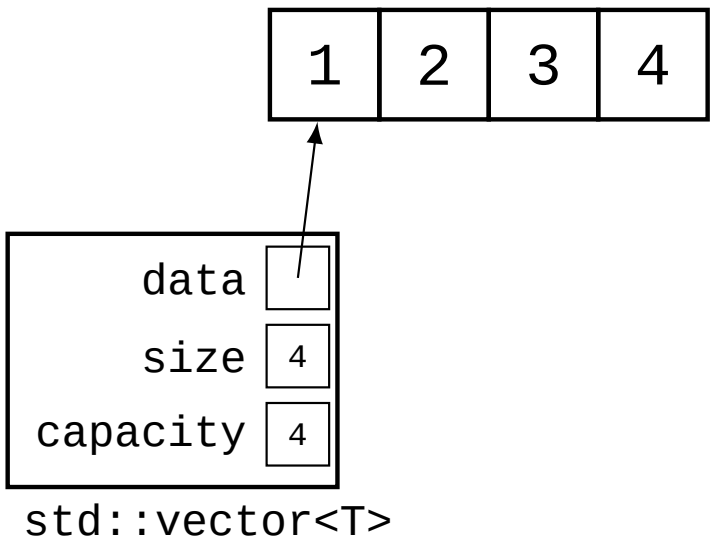
`std::vector`




```
vector.push_back(4);
```

Sequential Containers

`std::vector`

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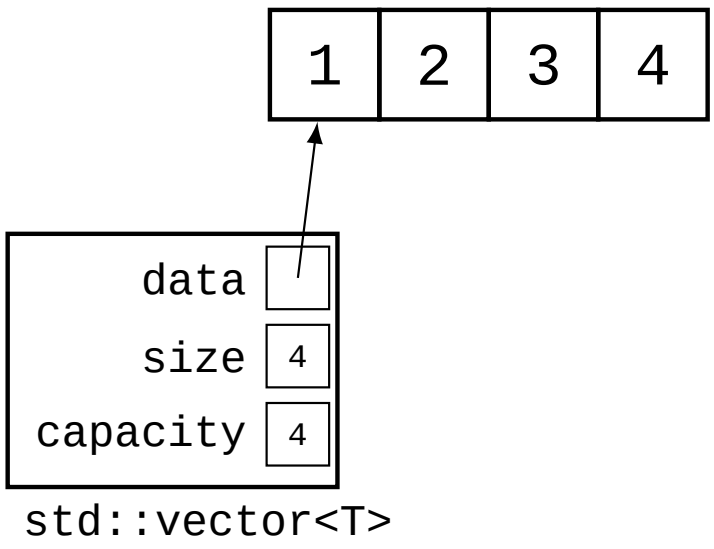
Sequential Containers

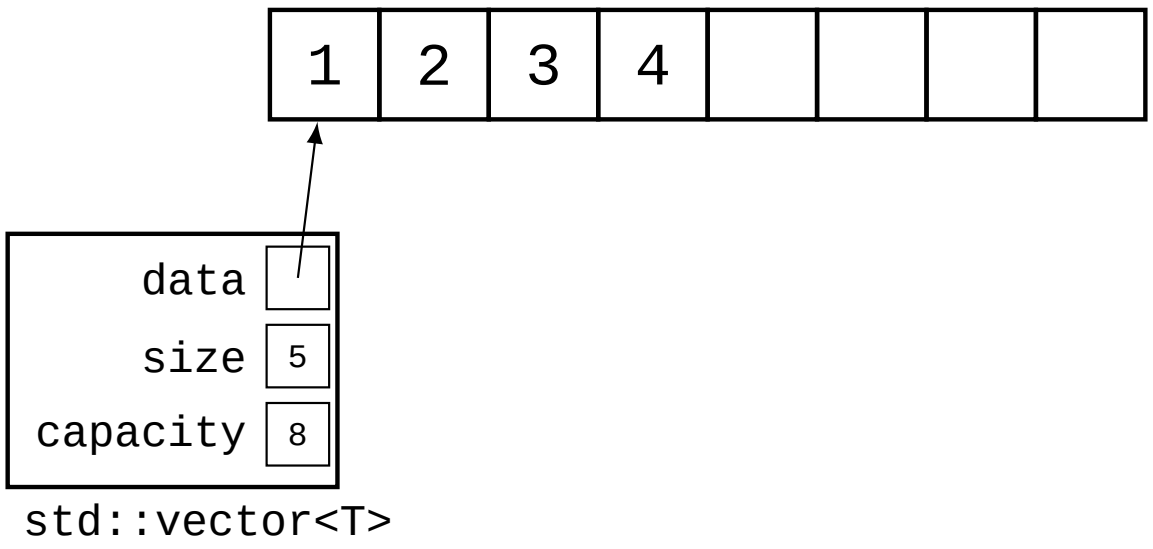
`std::vector`




```
vector.push_back(5);
```

Sequential Containers

`std::vector`

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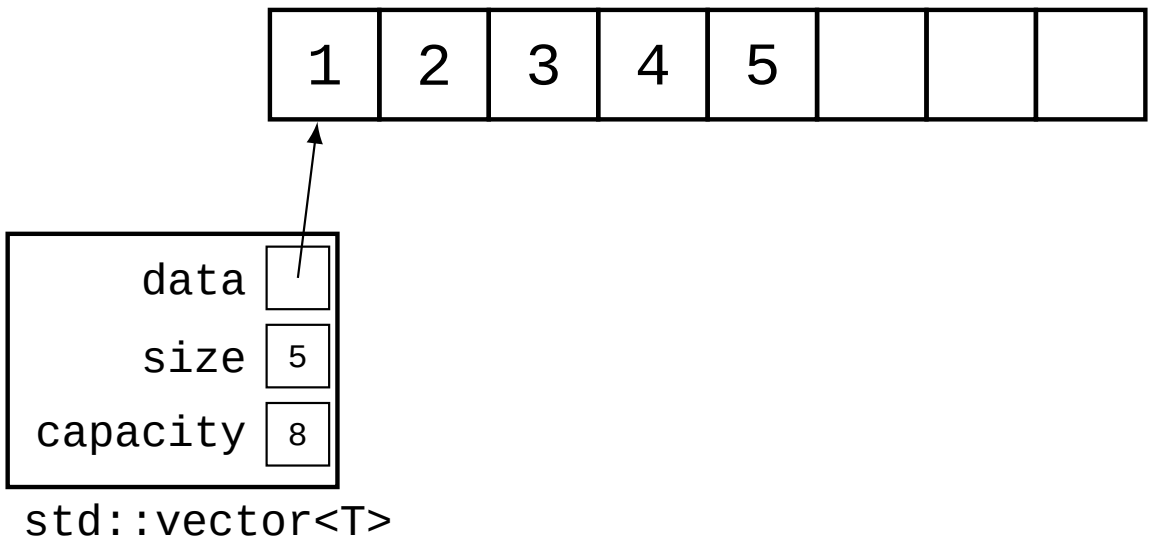
Sequential Containers

`std::vector`

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vector.push_back(5);
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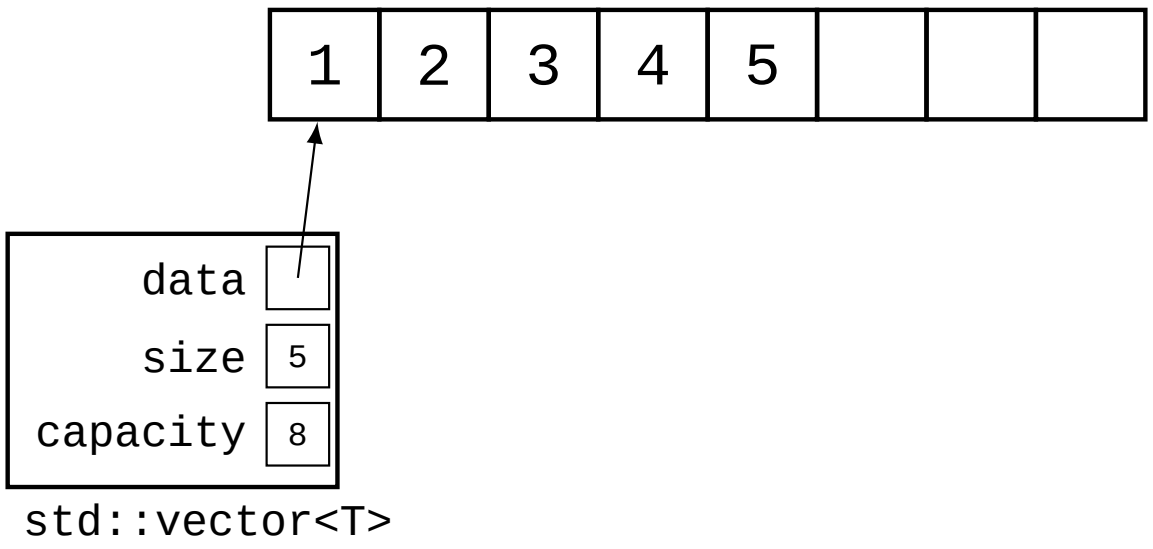
Sequential Containers

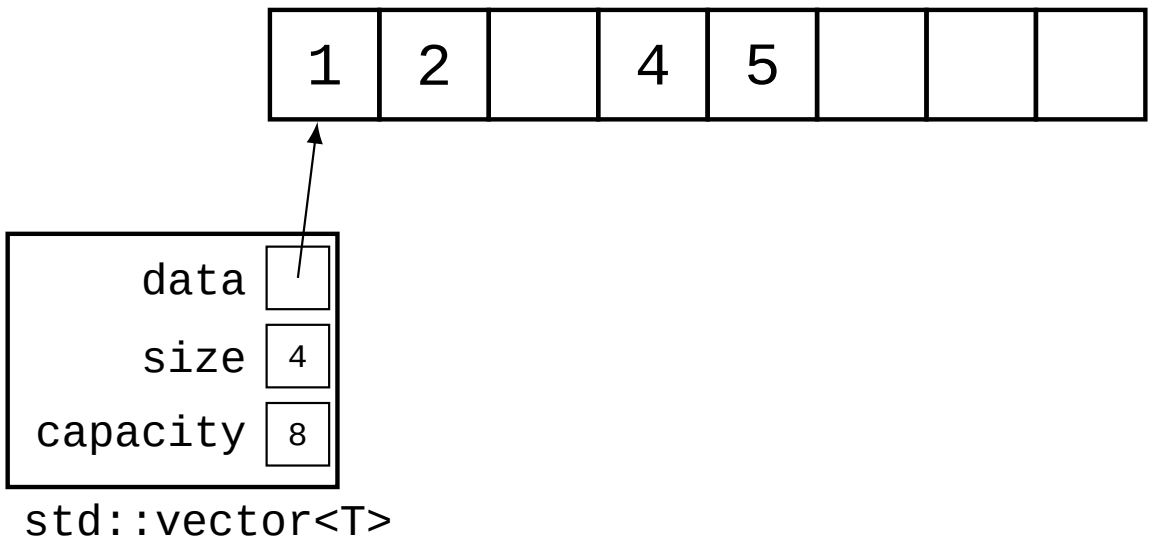
`std::vector`




```
vector.erase(vector.begin() + 2);
```

Sequential Containers

`std::vector`

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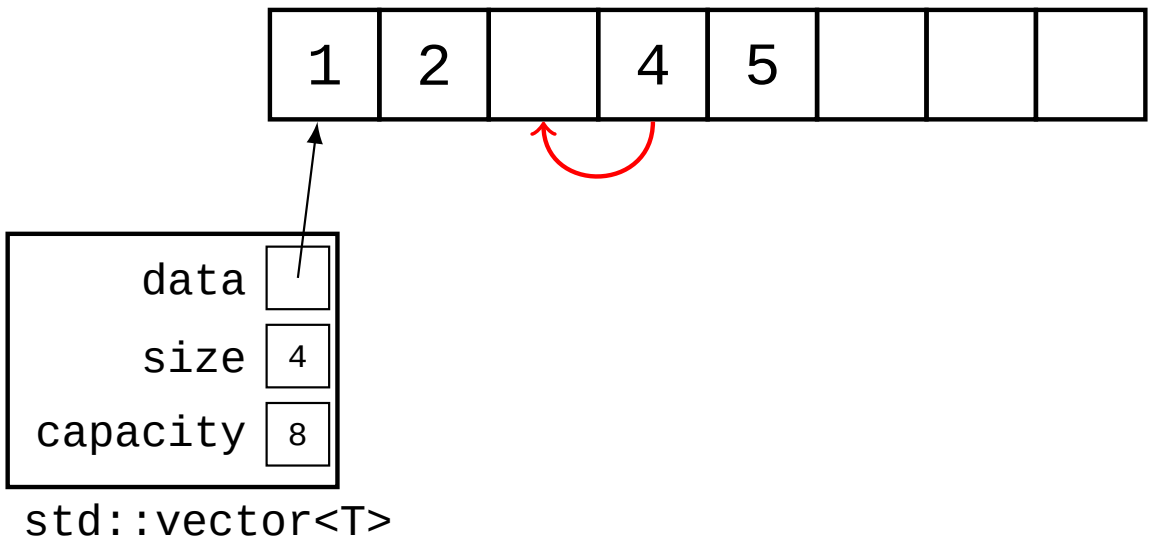
Sequential Containers

`std::vector`

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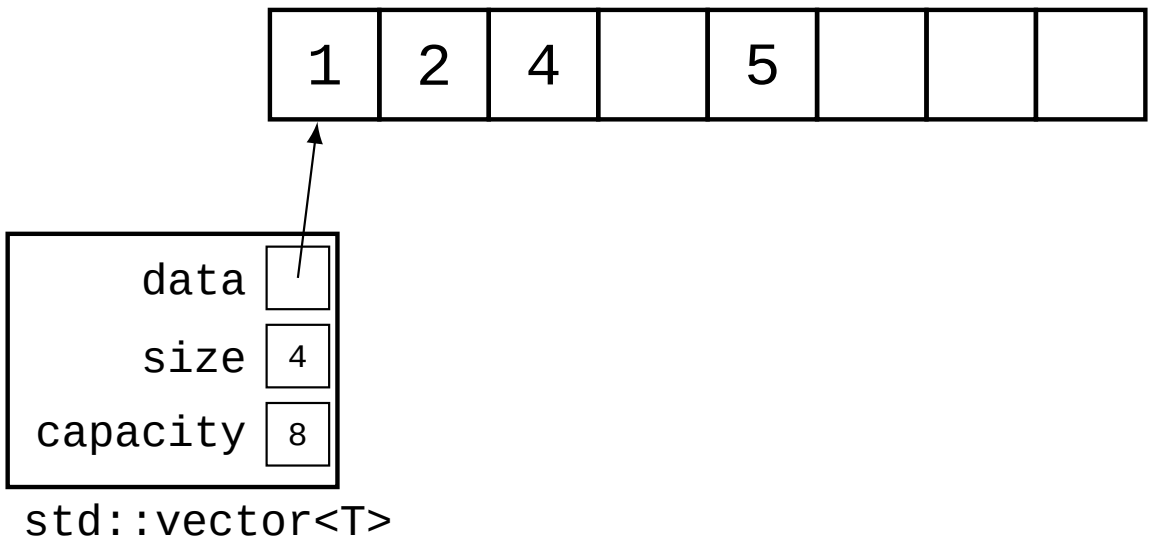
Sequential Containers

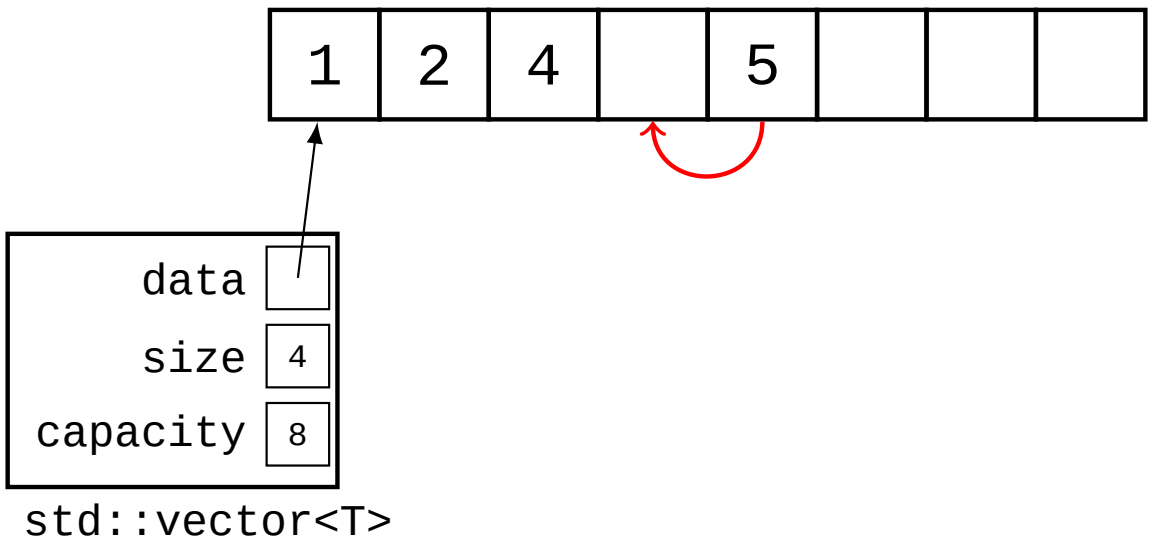
`std::vector`




```
vector.erase(vector.begin() + 2);
```

Sequential Containers

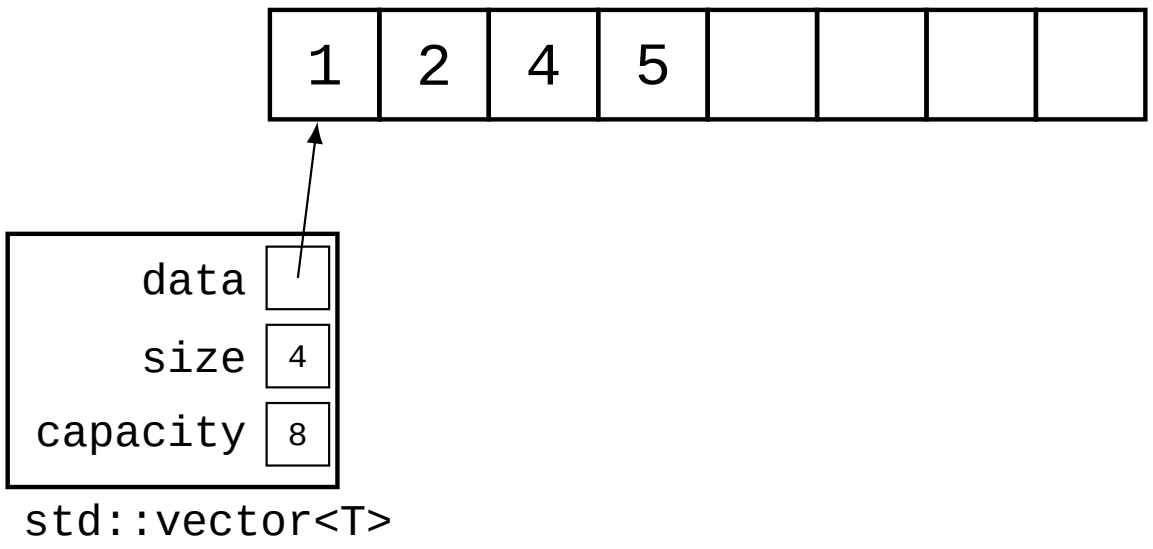
`std::vector`




```
vector.erase(vector.begin() + 2);
```

Sequential Containers

`std::vector`




```
vector.erase(vector.begin() + 2);
```

Sequential Containers

`std::vector`

- insertion:
  - at end: $O(1)$
  - otherwise: $O(n)$
- deletion:
  - last element: $O(1)$
  - otherwise: $O(n)$
- lookup: $O(1)$

Sequential Containers

`std::vector`

+ Data is sequential in memory
+ Dynamic size
– Entire data range can move in memory
– Dynamic allocations are slow

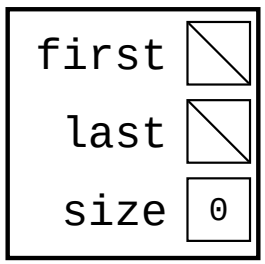
Sequential Containers

Example

```
#include <vector>
// ...
int main()
{
  std::vector<int> data{};
  int x{};
  while (cin >> x)
  {
    data.push_back(x);
  }
  for (auto&& i : data)
    cout << i << endl;
}
```

Sequential Containers

`std::list`

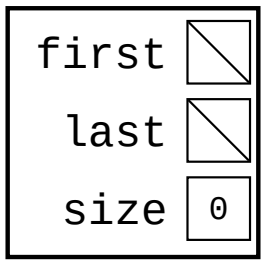


`std::list<T>`

```
std::list<int> list{};
```

Sequential Containers

`std::list`

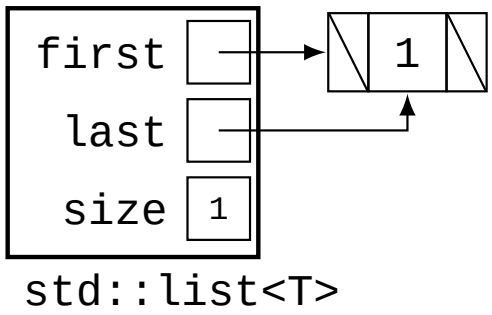


`std::list<T>`

```
list.push_back(1);
```

Sequential Containers

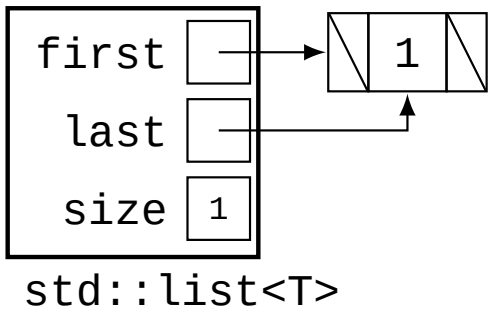
`std::list`




```
list.push_back(1);
```

Sequential Containers

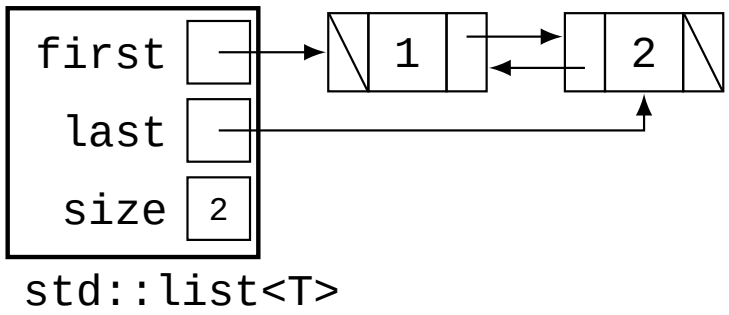
`std::list`




```
list.push_back(2);
```

Sequential Containers

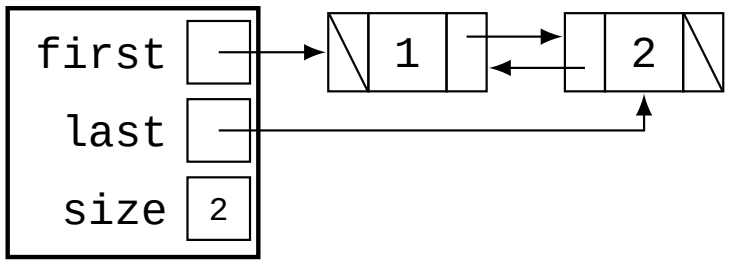
`std::list`




```
list.push_back(2);
```

Sequential Containers

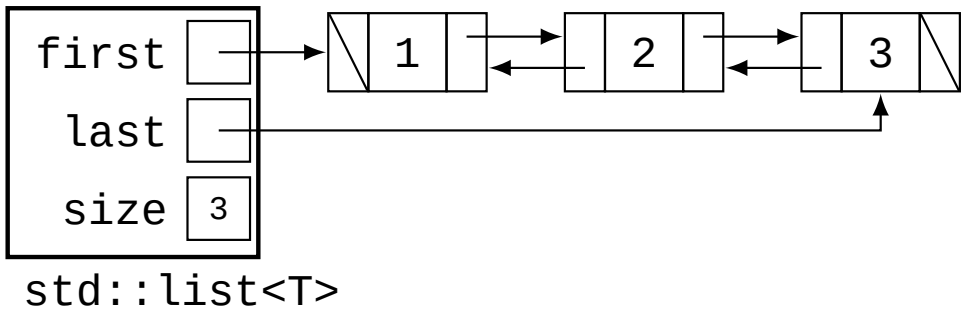
`std::list`




```
list.push_back(3);
```

Sequential Containers

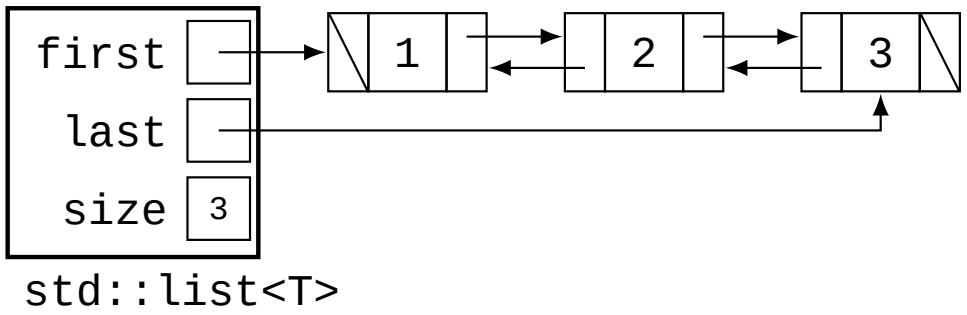
`std::list`




```
list.push_back(3);
```

Sequential Containers

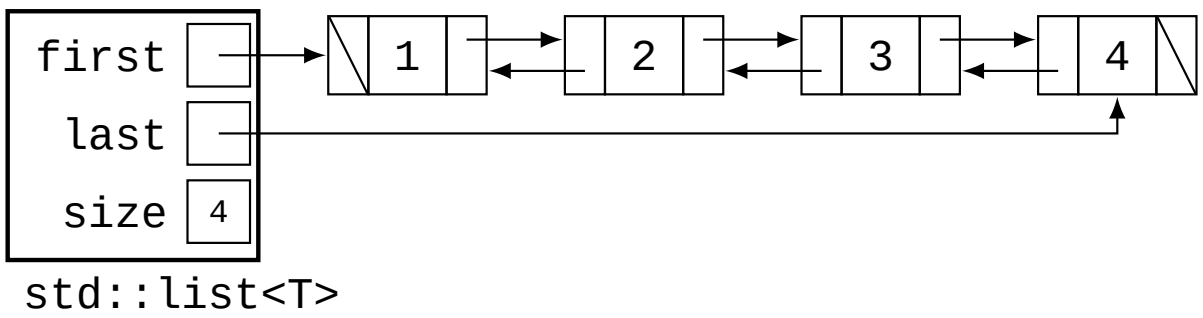
`std::list`




```
list.push_back(4);
```

Sequential Containers

`std::list`




```
list.push_back(4);
```

Sequential Containers

`std::list`

- insertion:
  - at the ends: $O(1)$
  - otherwise: $O(n)$
- deletion:
  - first or last element: $O(1)$
  - otherwise: $O(n)$
- lookup: $O(n)$

Sequential Containers

`std::list`

- \+ elements never move in memory
- \+ Operations around a specific element is $O(1)$
- − Many allocations (one for each element)
- − Linear lookup

Sequential Containers

`std::list`

- \+ elements never move in memory
- \+ Operations around a specific element is $O(1)$
- − Many allocations (one for each element)
- − Linear lookup
- − Makes the CPU cache very sad :(

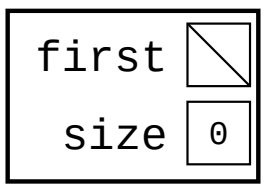
Sequential Containers

Example

```
#include <list>
#include <vector>
// ...
int main()
{
  std::list<int> data{};
  std::vector<int*> order{};
  int x;
  while (cin >> x)
  {
    data.push_back(x);
    order.push_back(&data.back());
  }
  data.sort();
  int i{0};
  for (auto&& val : data)
  {
    cout << val << ", " << *order[i++] << endl;
  }
}
```

Sequential Containers

`std::forward_list`

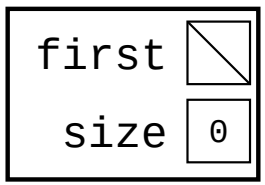


`std::forward_list<T>`

```
std::forward_list<int> list{};
```

Sequential Containers

`std::forward_list`

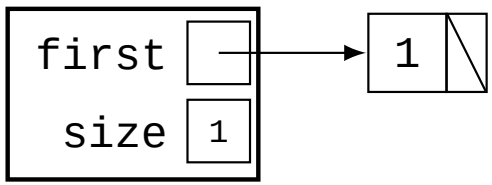


`std::forward_list<T>`

```
list.push_front(1);
```

Sequential Containers

`std::forward_list`

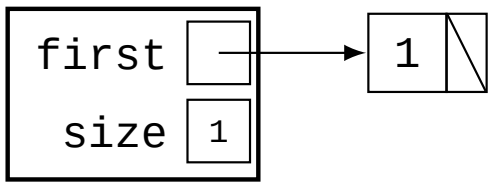


`std::forward_list<T>`

```
list.push_front(1);
```

Sequential Containers

`std::forward_list`

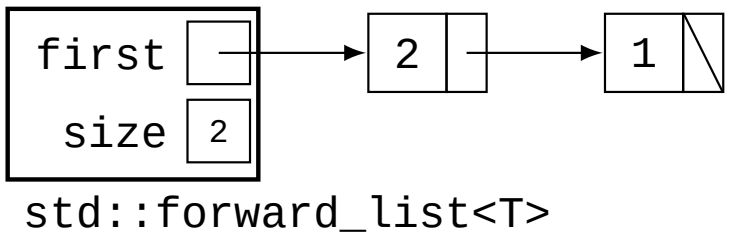


`std::forward_list<T>`

```
list.push_front(2);
```

Sequential Containers

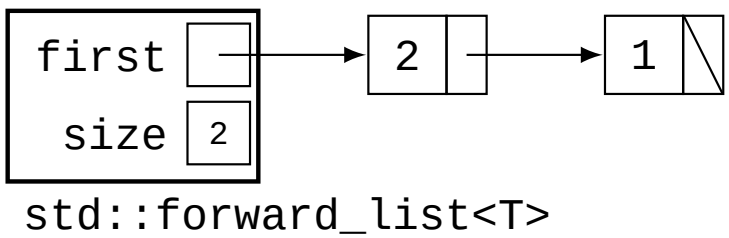
`std::forward_list`




```
list.push_front(2);
```

Sequential Containers

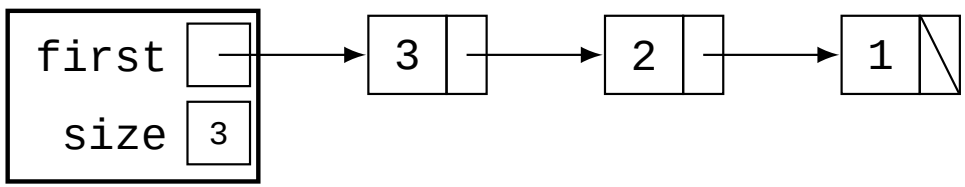
`std::forward_list`




```
list.push_front(3);
```

Sequential Containers

`std::forward_list`

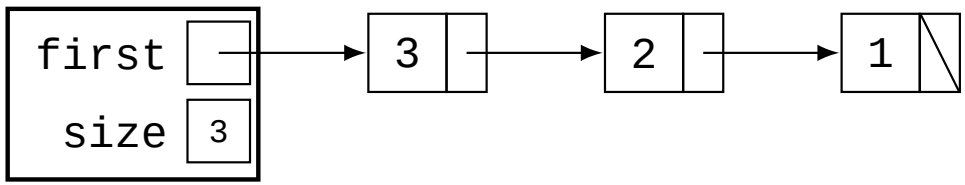


`std::forward_list<T>`

```
list.push_front(3);
```

Sequential Containers

`std::forward_list`

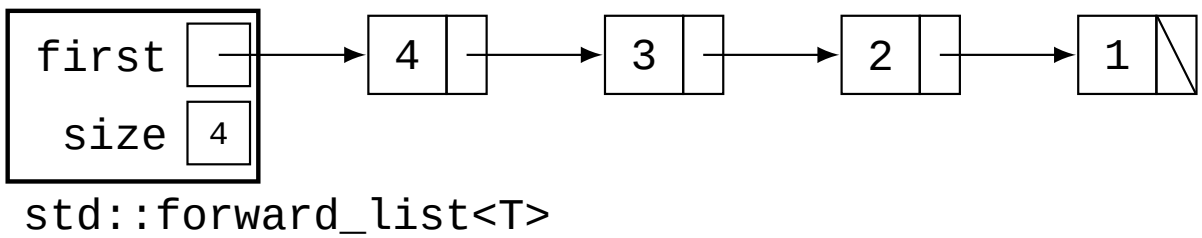


`std::forward_list<T>`

```
list.push_front(4);
```

Sequential Containers

`std::forward_list`




```
list.push_front(4);
```

Sequential Containers

`std::forward_list`

- insertion:
  - in beginning: $O(1)$
  - otherwise: $O(n)$
- deletion:
  - first element: $O(1)$
  - otherwise: $O(n)$
- lookup: $O(n)$

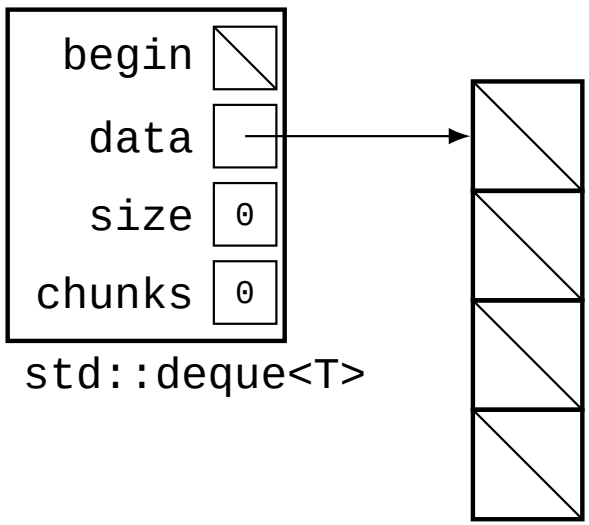
Sequential Containers

`std::forward_list`

- \+ Less memory per element compared to `std::list`
- − No $O(1)$ operations on last element
- − Unable to go backwards

Sequential Containers

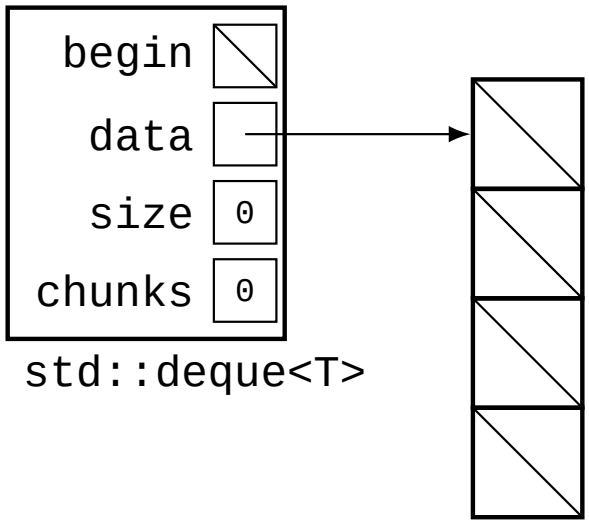
`std::deque`




```
std::deque<int> deque{};
```

Sequential Containers

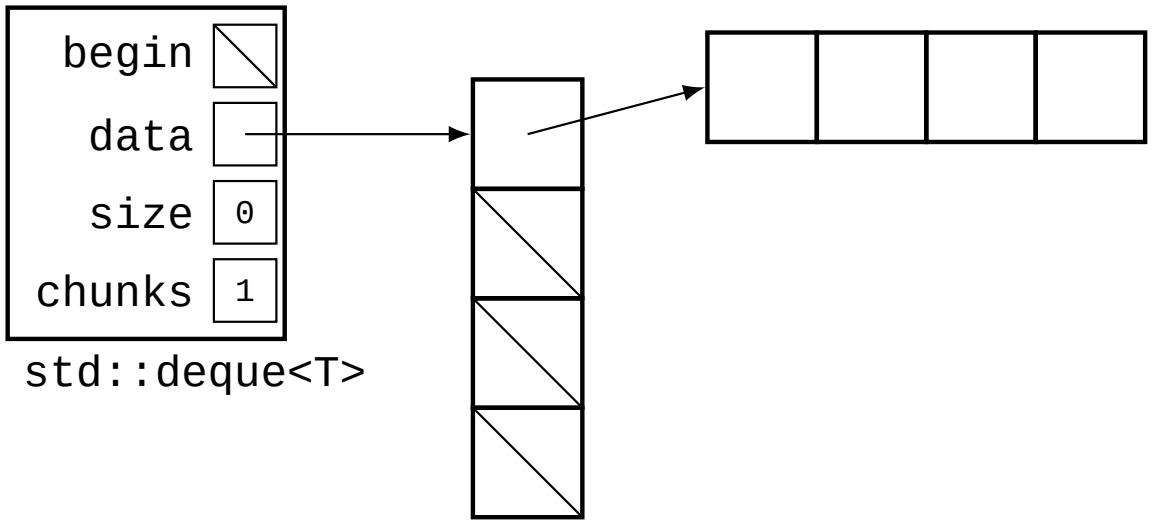
`std::deque`




```
deque.push_back(1);
```

Sequential Containers

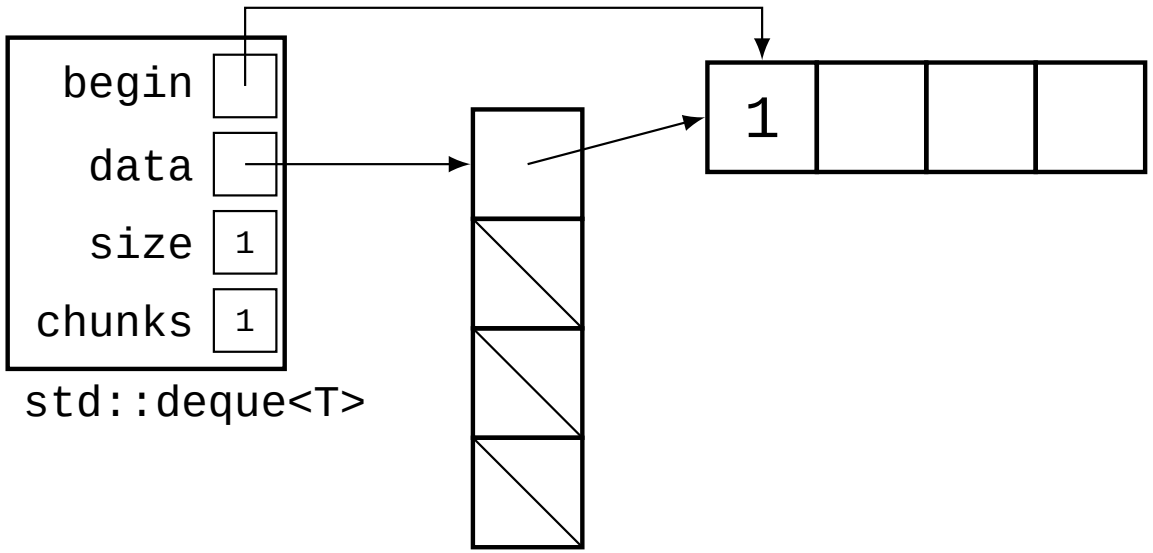
`std::deque`




```
deque.push_back(1);
```

Sequential Containers

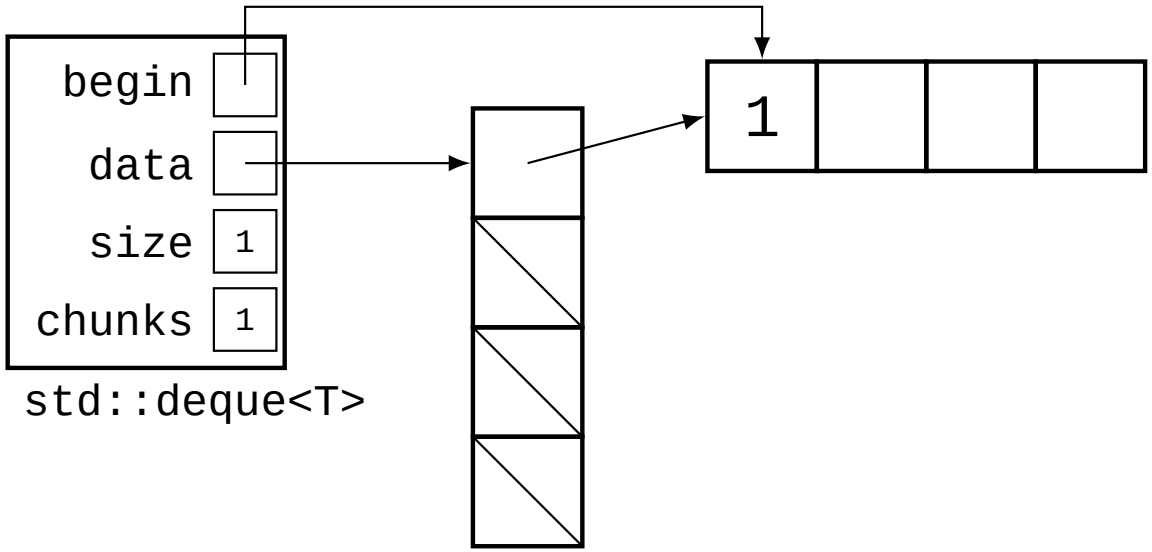
`std::deque`




```
deque.push_back(1);
```

Sequential Containers

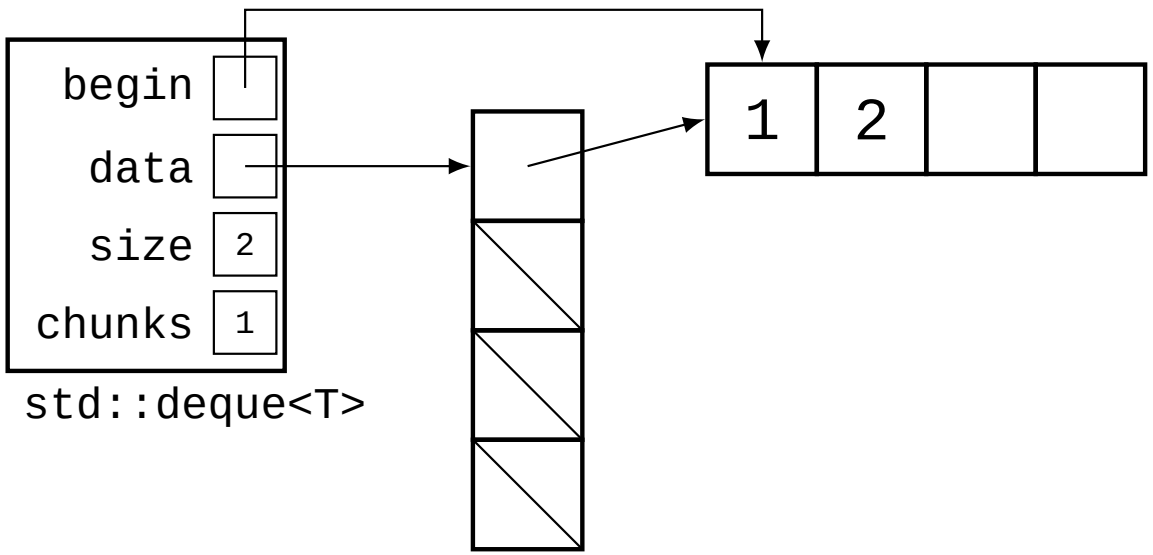
`std::deque`




```
deque.push_back(2);
```

Sequential Containers

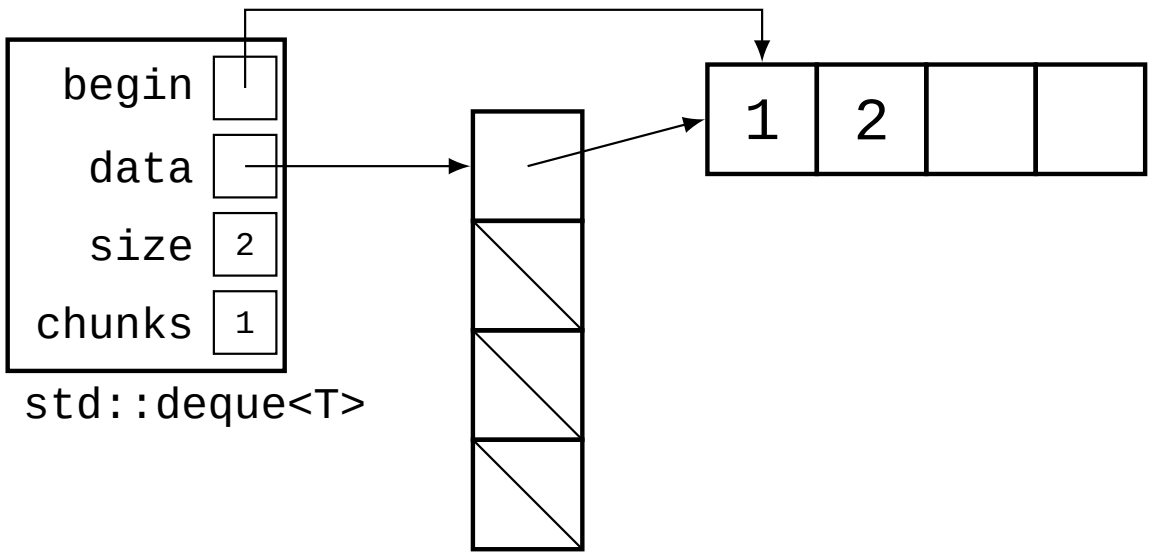
`std::deque`




```
deque.push_back(2);
```

Sequential Containers

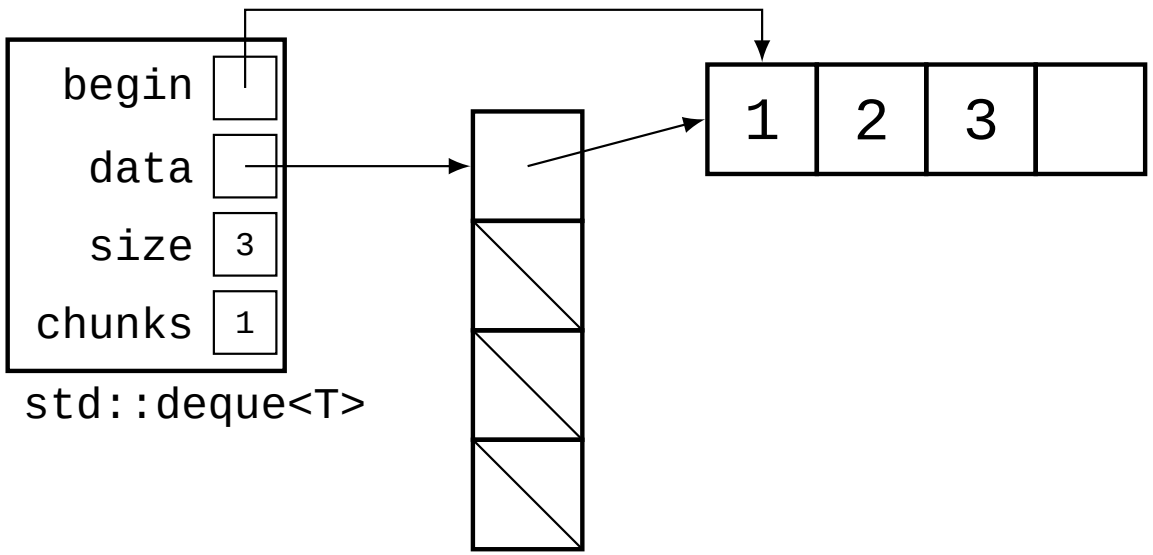
`std::deque`




```
deque.push_back(3);
```

Sequential Containers

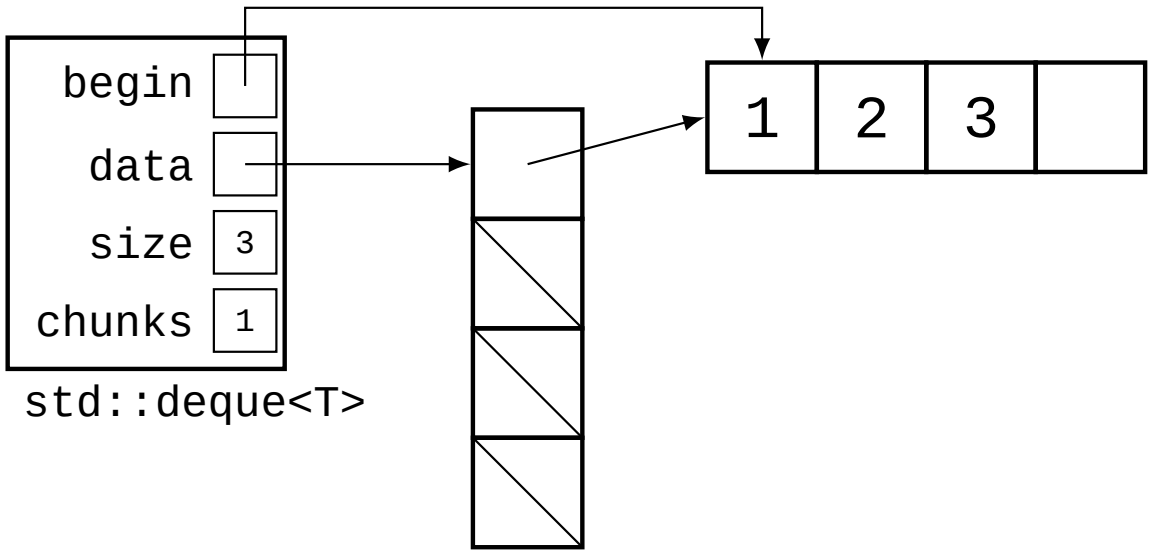
`std::deque`




```
deque.push_back(3);
```

Sequential Containers

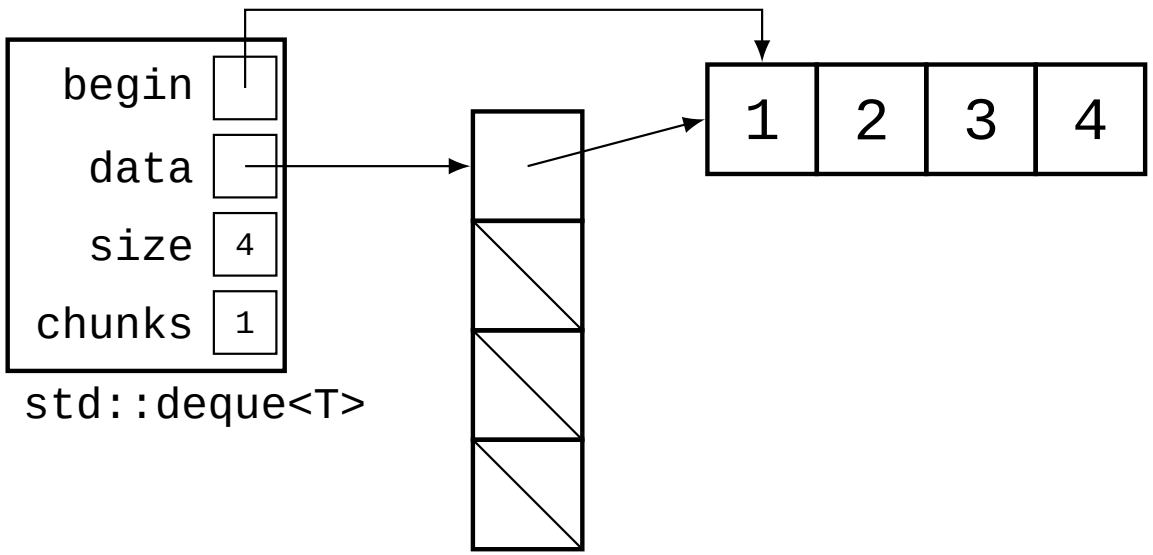
`std::deque`




```
deque.push_back(4);
```

Sequential Containers

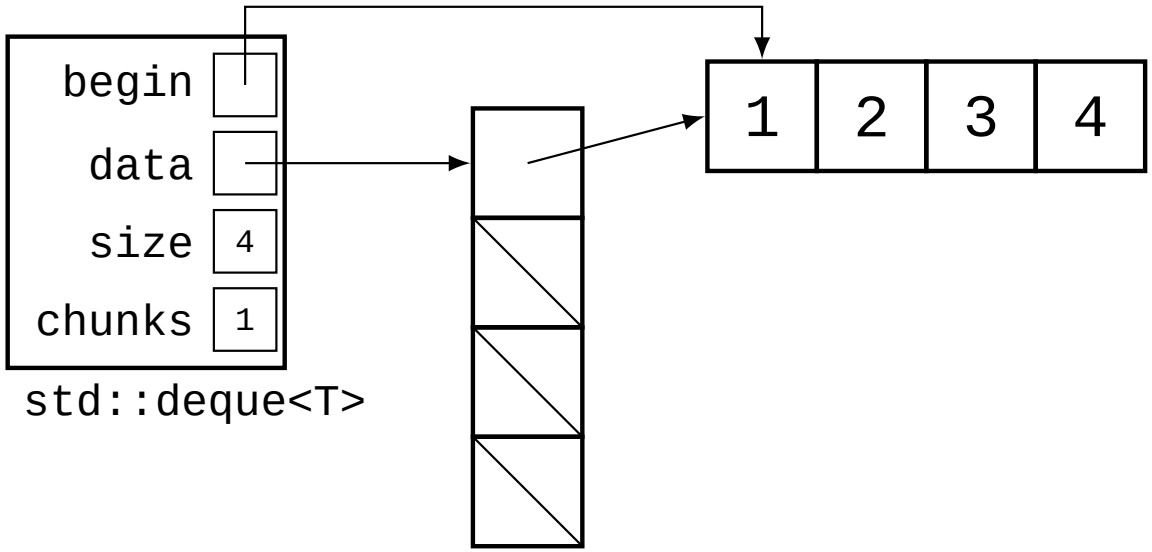
`std::deque`




```
deque.push_back(4);
```

Sequential Containers

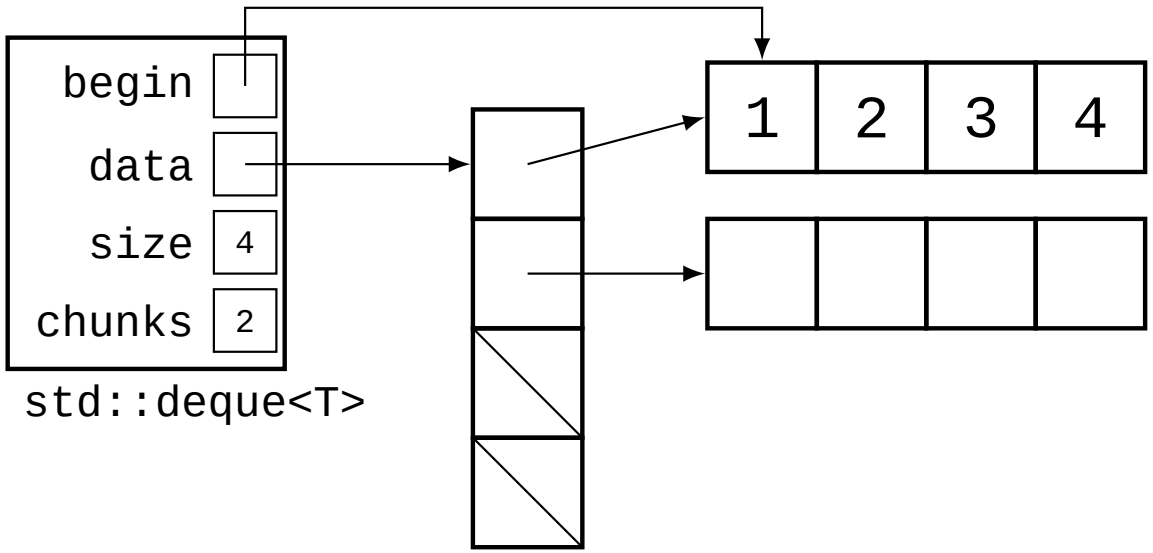
`std::deque`




```
deque.push_back(5);
```

Sequential Containers

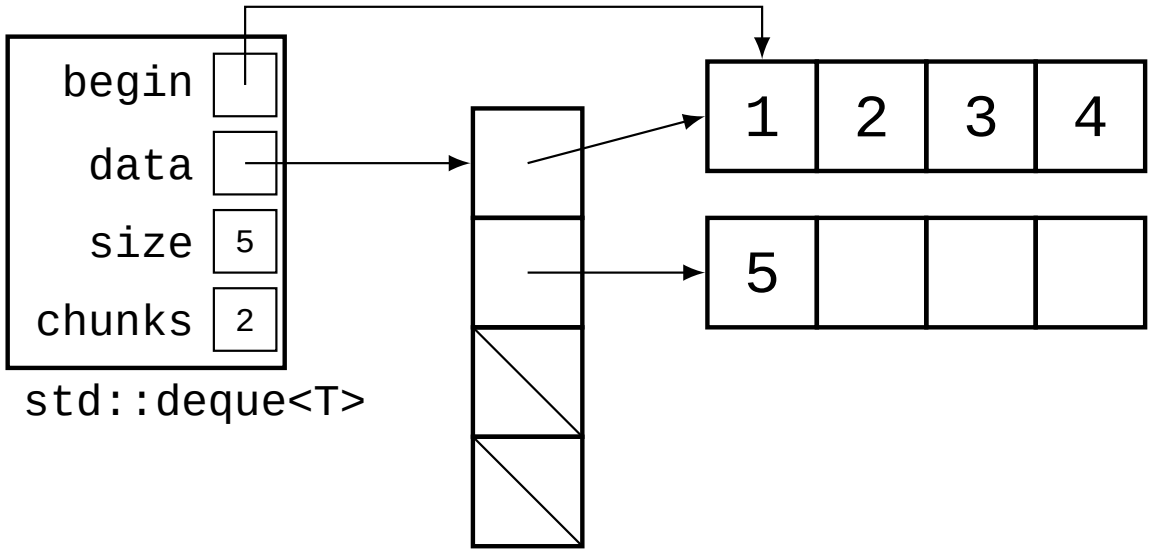
`std::deque`




```
deque.push_back(5);
```

Sequential Containers

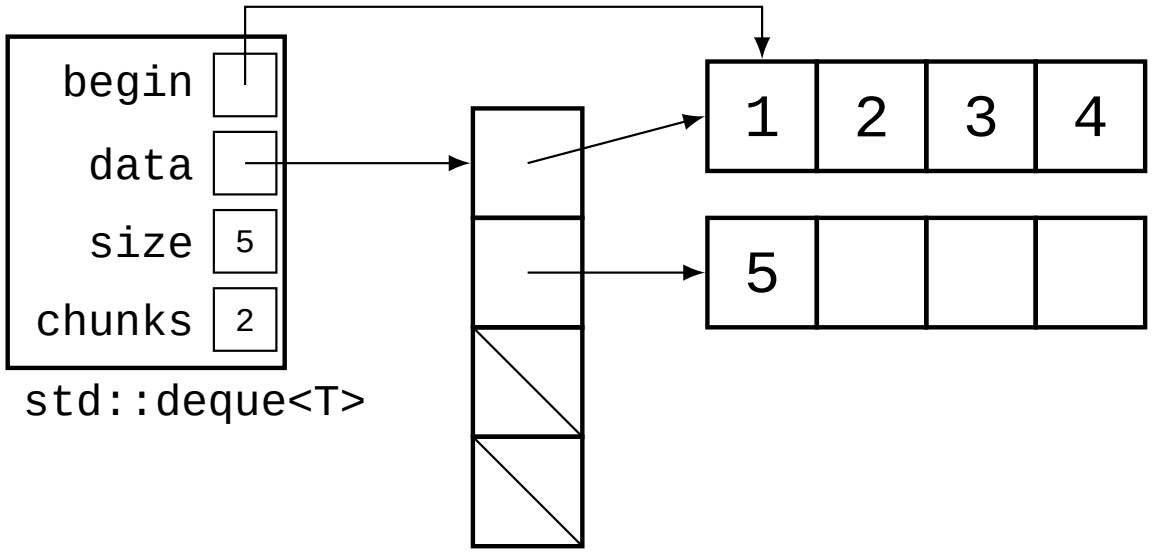
`std::deque`




```
deque.push_back(5);
```

Sequential Containers

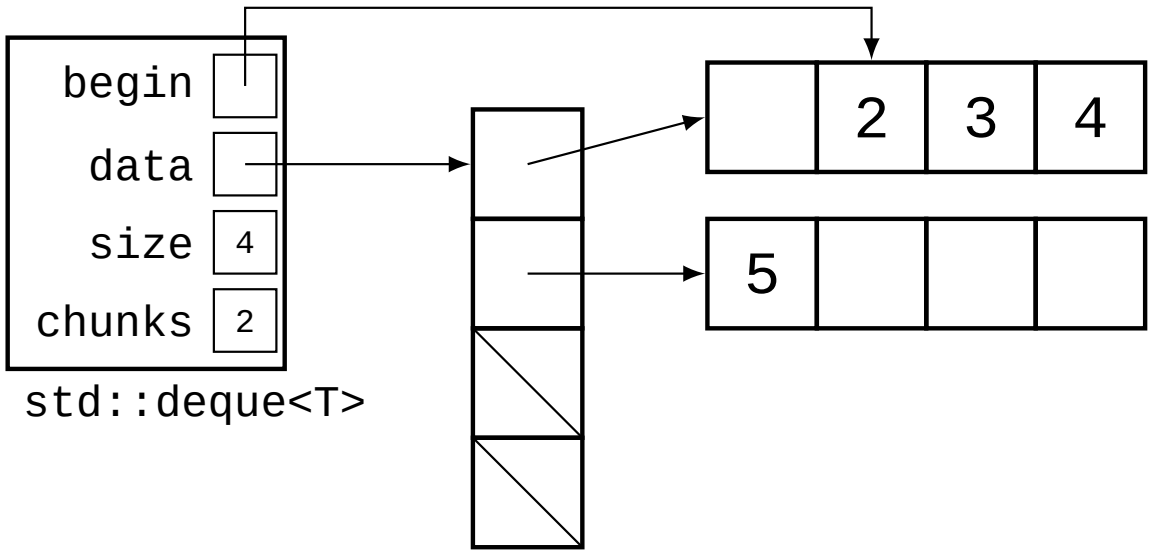
`std::deque`




```
deque.pop_front();
```

Sequential Containers

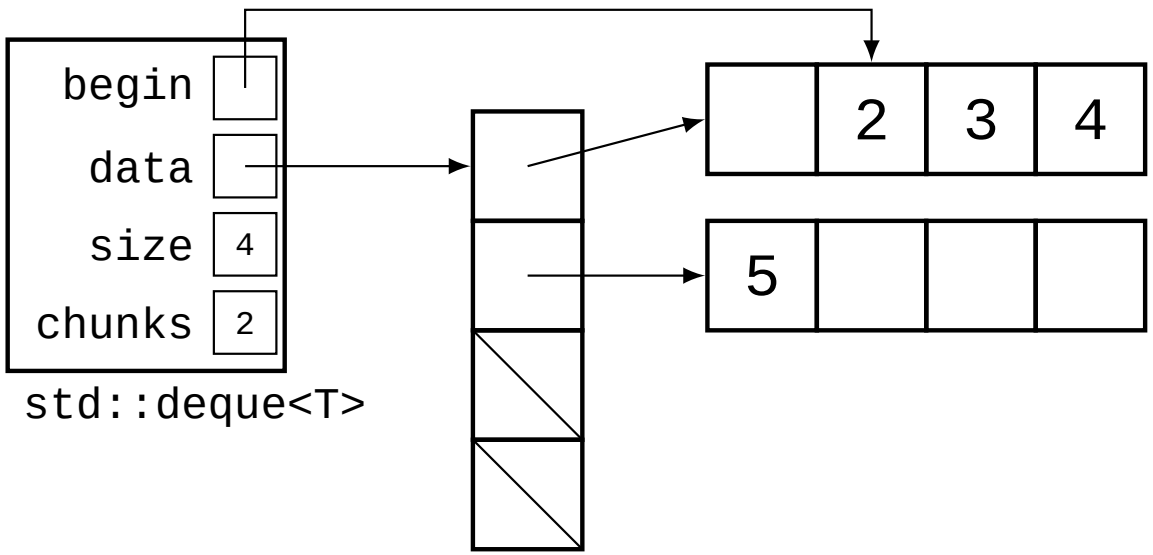
`std::deque`




```
deque.pop_front();
```

Sequential Containers

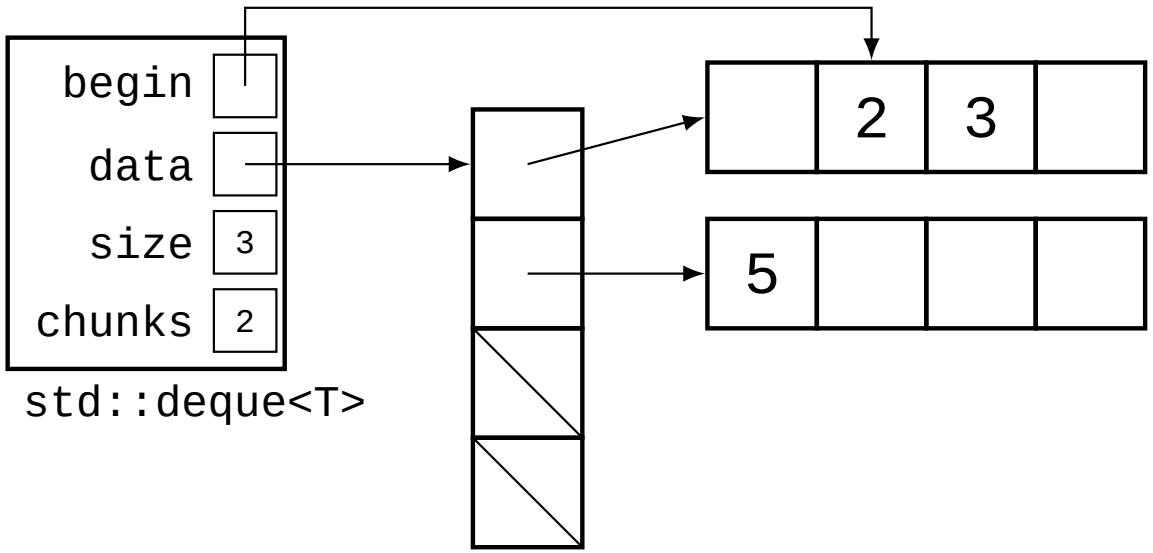
`std::deque`




```
deque.erase(deque.begin() + 2);
```

Sequential Containers

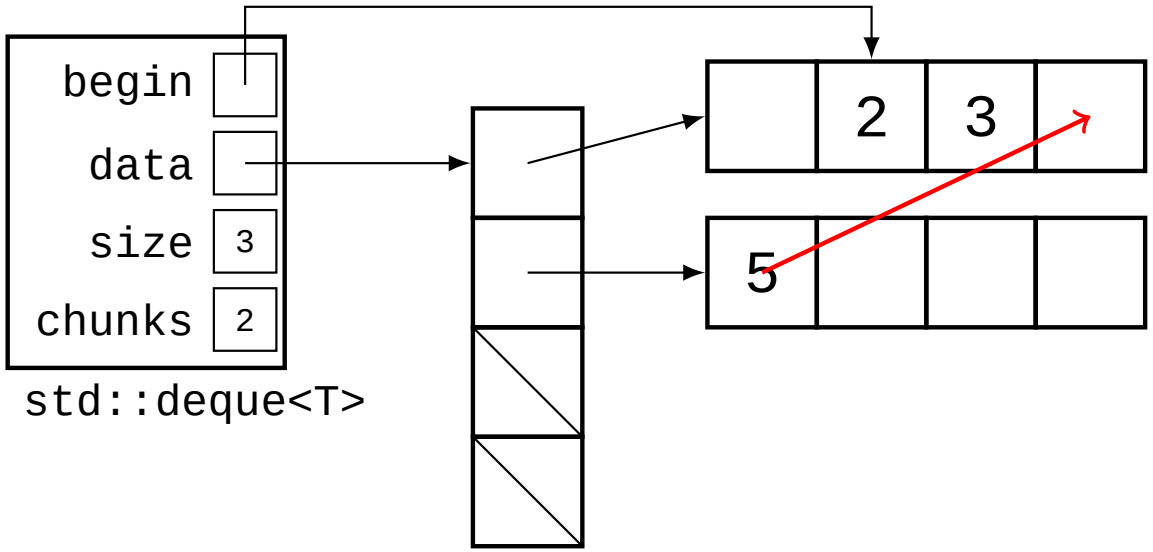
`std::deque`




```
deque.erase(deque.begin() + 2);
```

Sequential Containers

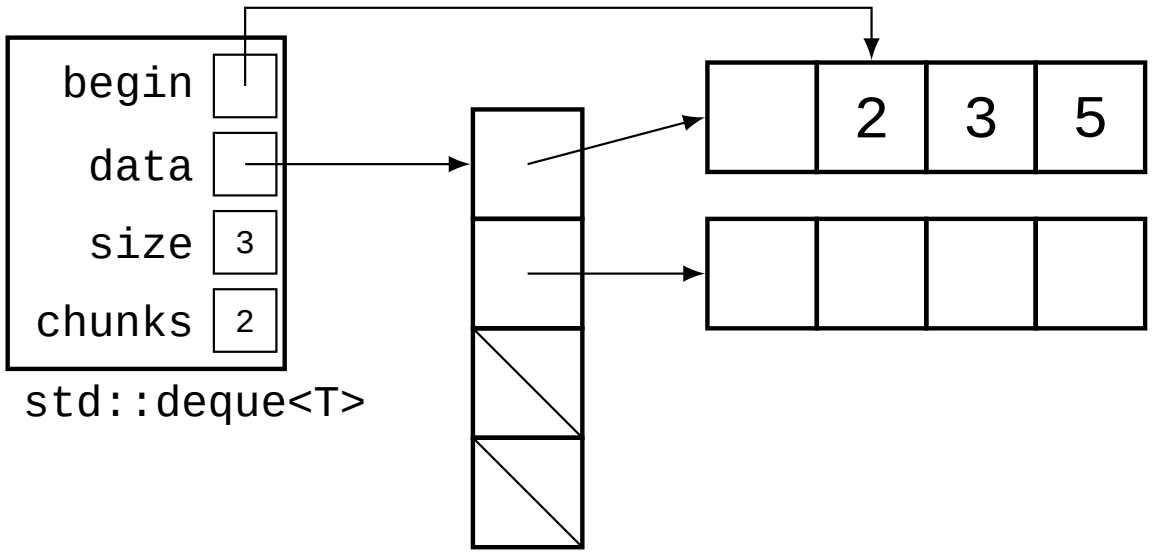
`std::deque`




```
deque.erase(deque.begin() + 2);
```

Sequential Containers

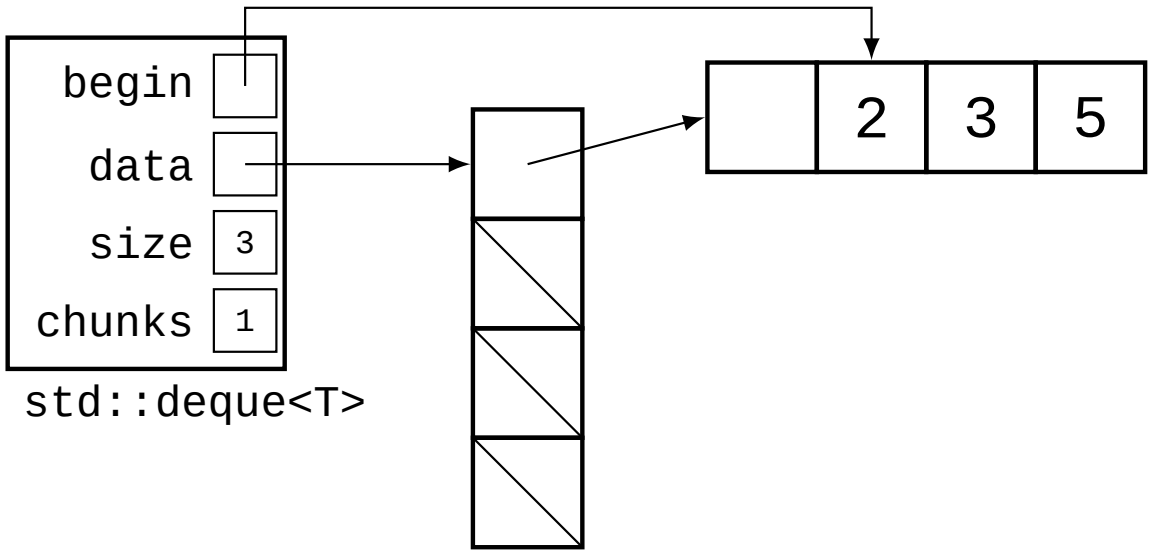
`std::deque`




```
deque.erase(deque.begin() + 2);
```

Sequential Containers

`std::deque`




```
deque.erase(deque.begin() + 2);
```

Sequential Containers

`std::deque`

- insertion:
  - at ends: $O(1)$
  - otherwise: $O(n)$
- deletion:
  - at ends: $O(1)$
  - otherwise: $O(n)$
- lookup: $O(1)$

Sequential Containers

`std::deque`

- \+ Elements rarely move in memory
- \+ Fast operations at ends
- \+ More cache friendly than `std::list`
- – Not contigous in memory
- – Additional complexity gives slighly worse performance

Sequential Containers

Uses

- Great for queues and stacks!
- Will automatically shrink the container so use it when there are a lot of insertions and deletions

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