Let's Move

The Hidden Features and Traps of C++ Move Semantics

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6/20

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IT communication

Nicolai M. Josuttis

- **Independent consultant**
  - Continuously learning since 1962
- **C++:**
  - since 1990
  - ISO Standard Committee since 1997
- **Other Topics:**
  - Systems Architect
  - Technical Manager
  - SOA
  - X and OSF/Motif

The C++ Standard Library A Tutorial and Reference
C++11
Die C++-Standardbibliothek
Objektorientiertes Programmieren in C++
C++ Templates The Complete Guide
The C++ Standard Library Second Edition A Tutorial and Reference
C++17 The Complete Guide
Nicolai M. Josuttis
C++ Move Semantics The Complete Guide
C++ Templates The Complete Guide Second Edition

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Agenda

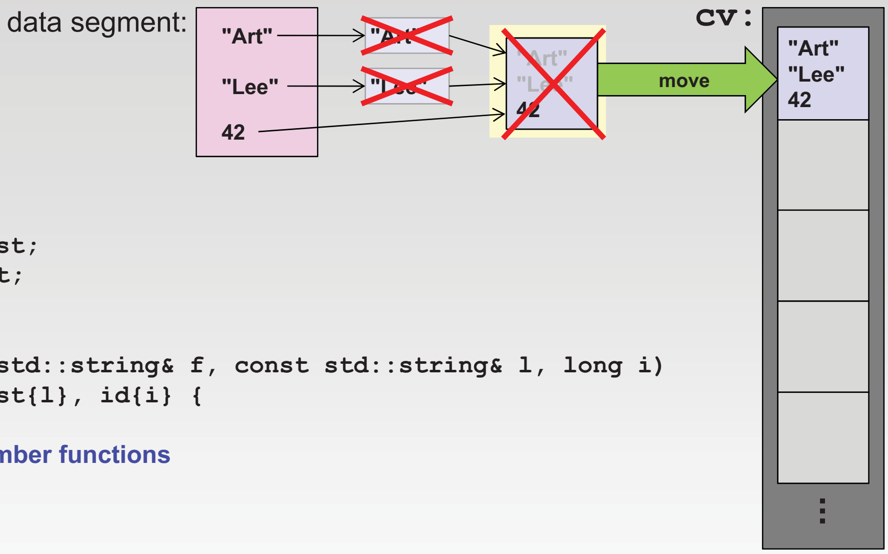
Implement and test a

`class Email`

representing email addresses

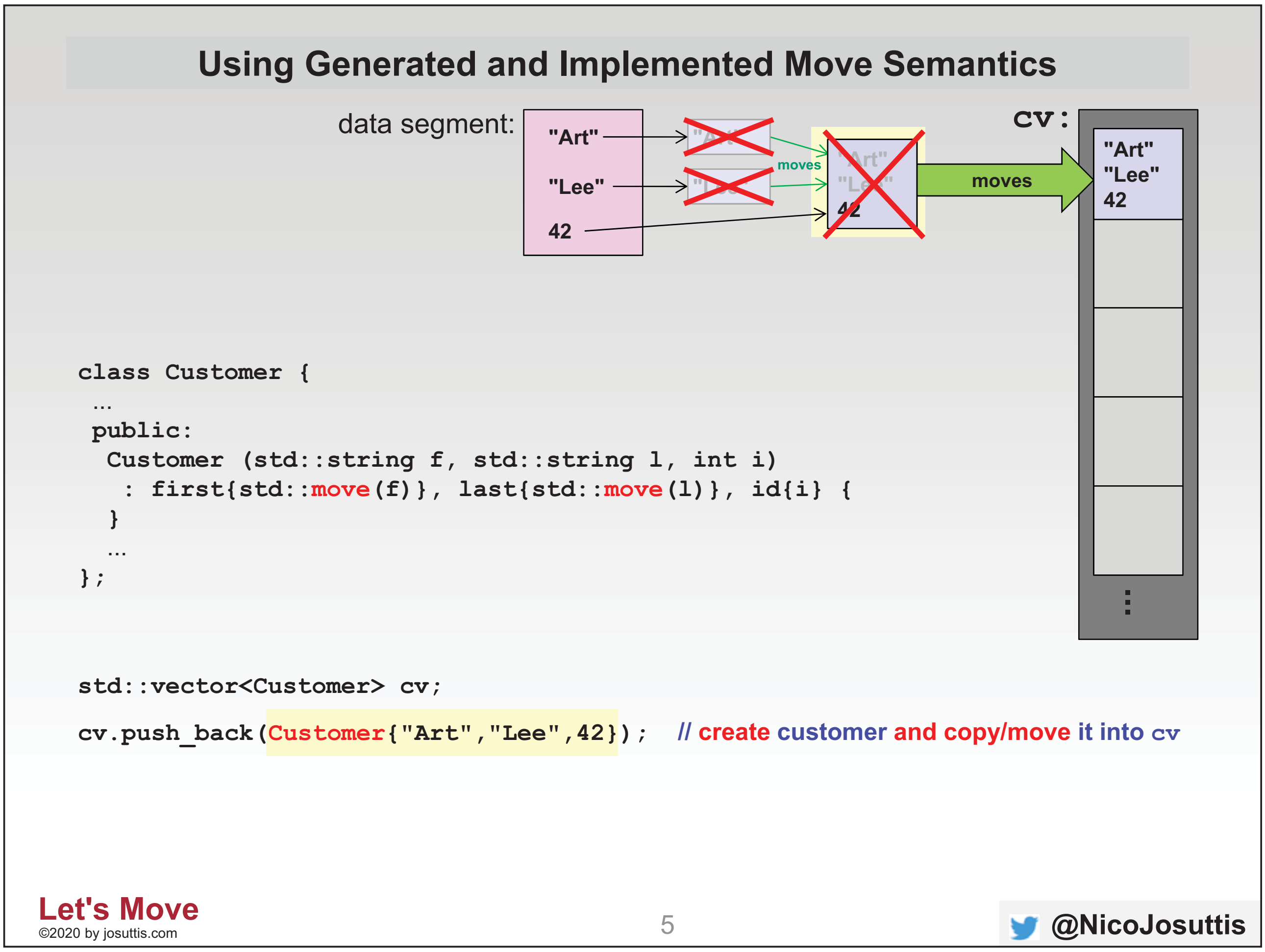
having good performance

Using Generated Move Semantics



```
class Customer {
 private:
  std::string first;
  std::string last;
  long        id;
 public:
  Customer(const std::string& f, const std::string& l, long i)
   : first{f}, last{l}, id{i} {
  }
  ... // no special member functions
};
```

```
std::vector<Customer> cv;
…
cv.push_back(Customer{"Art","Lee",42});   // create customer and copy/move it into cv
```

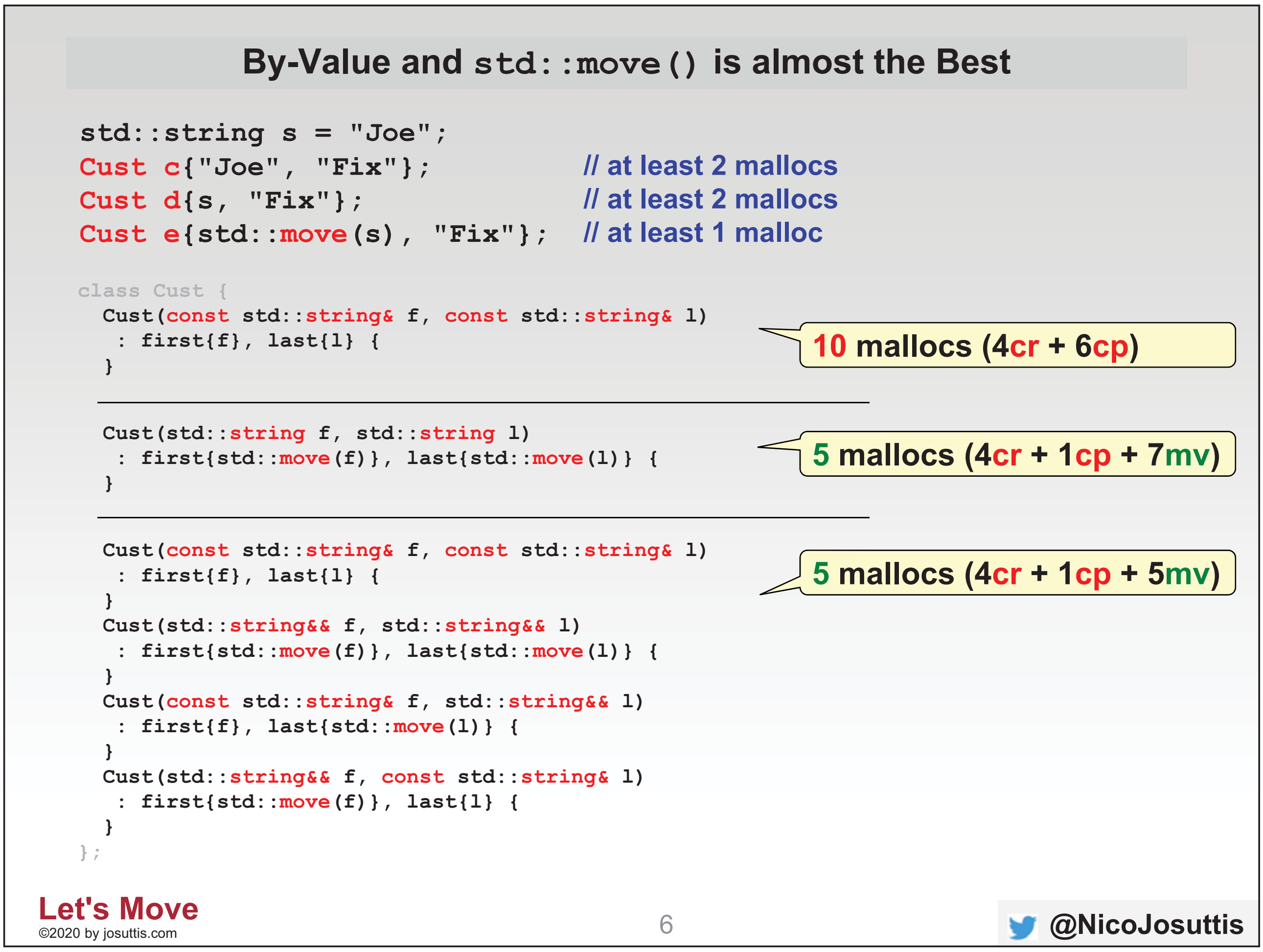


Using Generated and Implemented Move Semantics

```
class Customer {
 …
 public:
  Customer (std::string f, std::string l, int i)
   : first{std::move(f)}, last{std::move(l)}, id{i} {
  }
  …
};
```

```
std::vector<Customer> cv;

cv.push_back(Customer{"Art","Lee",42});    // create customer and copy/move it into cv
```



By-Value and `std::move()` is almost the Best

```
std::string s = "Joe";
Cust c{"Joe", "Fix"};           // at least 2 mallocs
Cust d{s, "Fix"};               // at least 2 mallocs
Cust e{std::move(s), "Fix"};    // at least 1 malloc
```

```
class Cust {
  Cust(const std::string& f, const std::string& l)
   : first{f}, last{l} {
  }
```

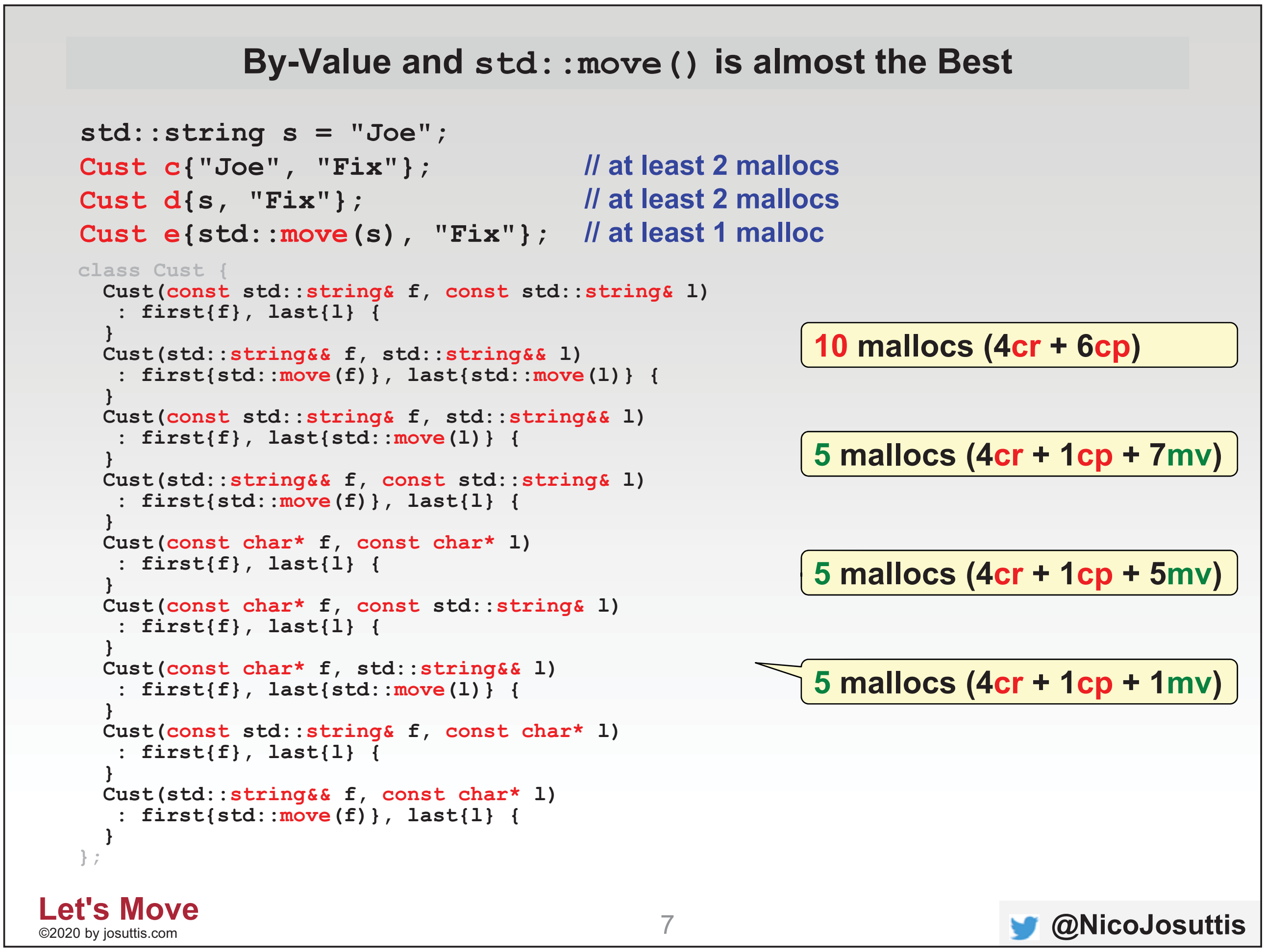
10 mallocs (4cr + 6cp)

```
  Cust(std::string f, std::string l)
   : first{std::move(f)}, last{std::move(l)} {
  }
```

5 mallocs (4cr + 1cp + 7mv)

```
  Cust(const std::string& f, const std::string& l)
   : first{f}, last{l} {
  }
  Cust(std::string&& f, std::string&& l)
   : first{std::move(f)}, last{std::move(l)} {
  }
  Cust(const std::string& f, std::string&& l)
   : first{f}, last{std::move(l)} {
  }
  Cust(std::string&& f, const std::string& l)
   : first{std::move(f)}, last{l} {
  }
};
```

5 mallocs (4cr + 1cp + 5mv)



By-Value and `std::move()` is almost the Best

```
std::string s = "Joe";
Cust c{"Joe", "Fix"};            // at least 2 mallocs
Cust d{s, "Fix"};                // at least 2 mallocs
Cust e{std::move(s), "Fix"};     // at least 1 malloc
```

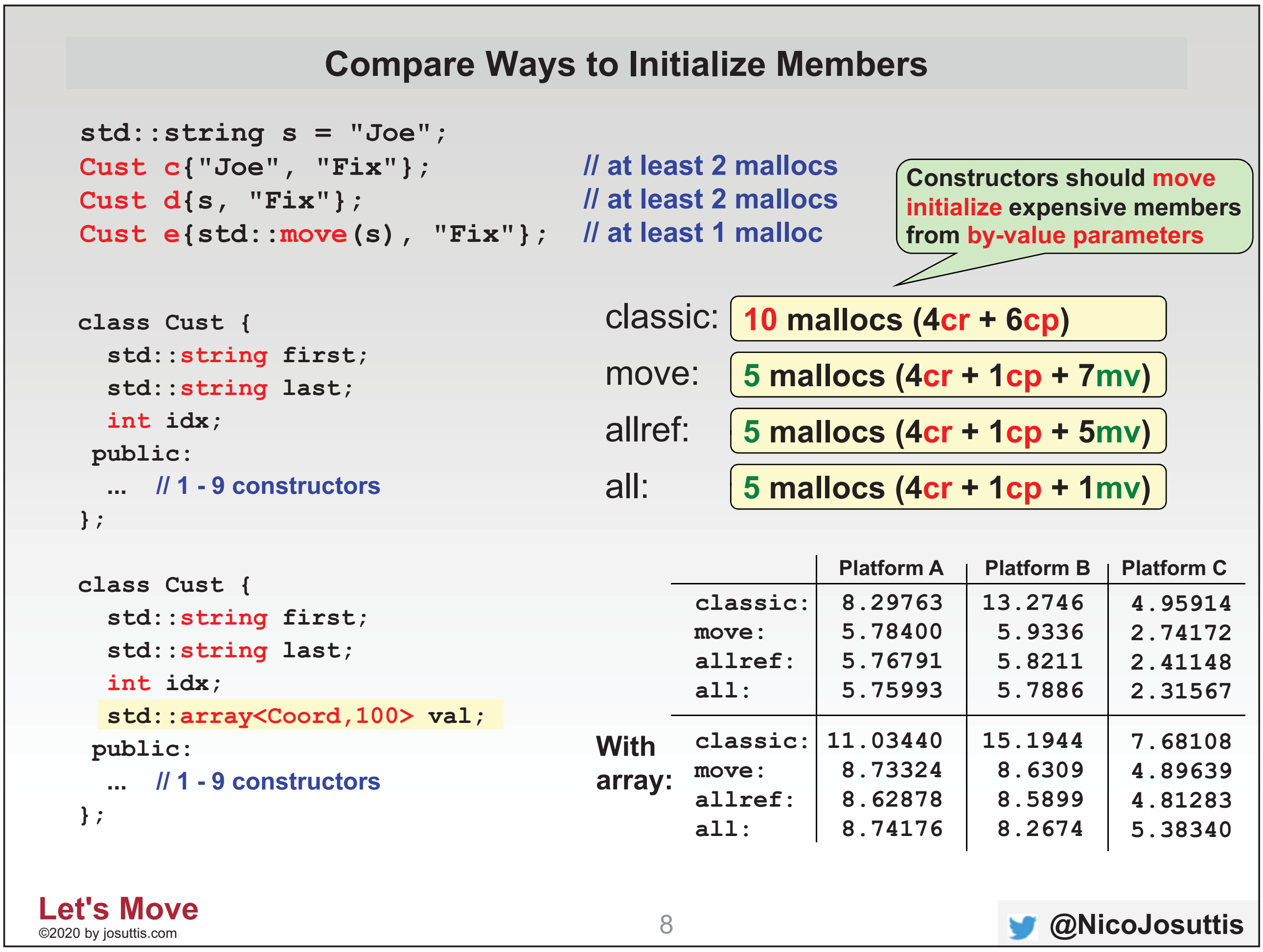
```
class Cust {
  Cust(const std::string& f, const std::string& l)
   : first{f}, last{l} {
  }
  Cust(std::string&& f, std::string&& l)
   : first{std::move(f)}, last{std::move(l)} {
  }
  Cust(const std::string& f, std::string&& l)
   : first{f}, last{std::move(l)} {
  }
  Cust(std::string&& f, const std::string& l)
   : first{std::move(f)}, last{l} {
  }
  Cust(const char* f, const char* l)
   : first{f}, last{l} {
  }
  Cust(const char* f, const std::string& l)
   : first{f}, last{l} {
  }
  Cust(const char* f, std::string&& l)
   : first{f}, last{std::move(l)} {
  }
  Cust(const std::string& f, const char* l)
   : first{f}, last{l} {
  }
  Cust(std::string&& f, const char* l)
   : first{std::move(f)}, last{l} {
  }
};
```

10 mallocs (4cr + 6cp)

5 mallocs (4cr + 1cp + 7mv)

5 mallocs (4cr + 1cp + 5mv)

5 mallocs (4cr + 1cp + 1mv)



Compare Ways to Initialize Members

```
std::string s = "Joe";
Cust c{"Joe", "Fix"};            // at least 2 mallocs
Cust d{s, "Fix"};                // at least 2 mallocs
Cust e{std::move(s), "Fix"};     // at least 1 malloc
```

Constructors should move initialize expensive members from by-value parameters

```
class Cust {
  std::string first;
  std::string last;
  int idx;
 public:
  ...   // 1 - 9 constructors
};
```

classic: 10 mallocs (4cr + 6cp)

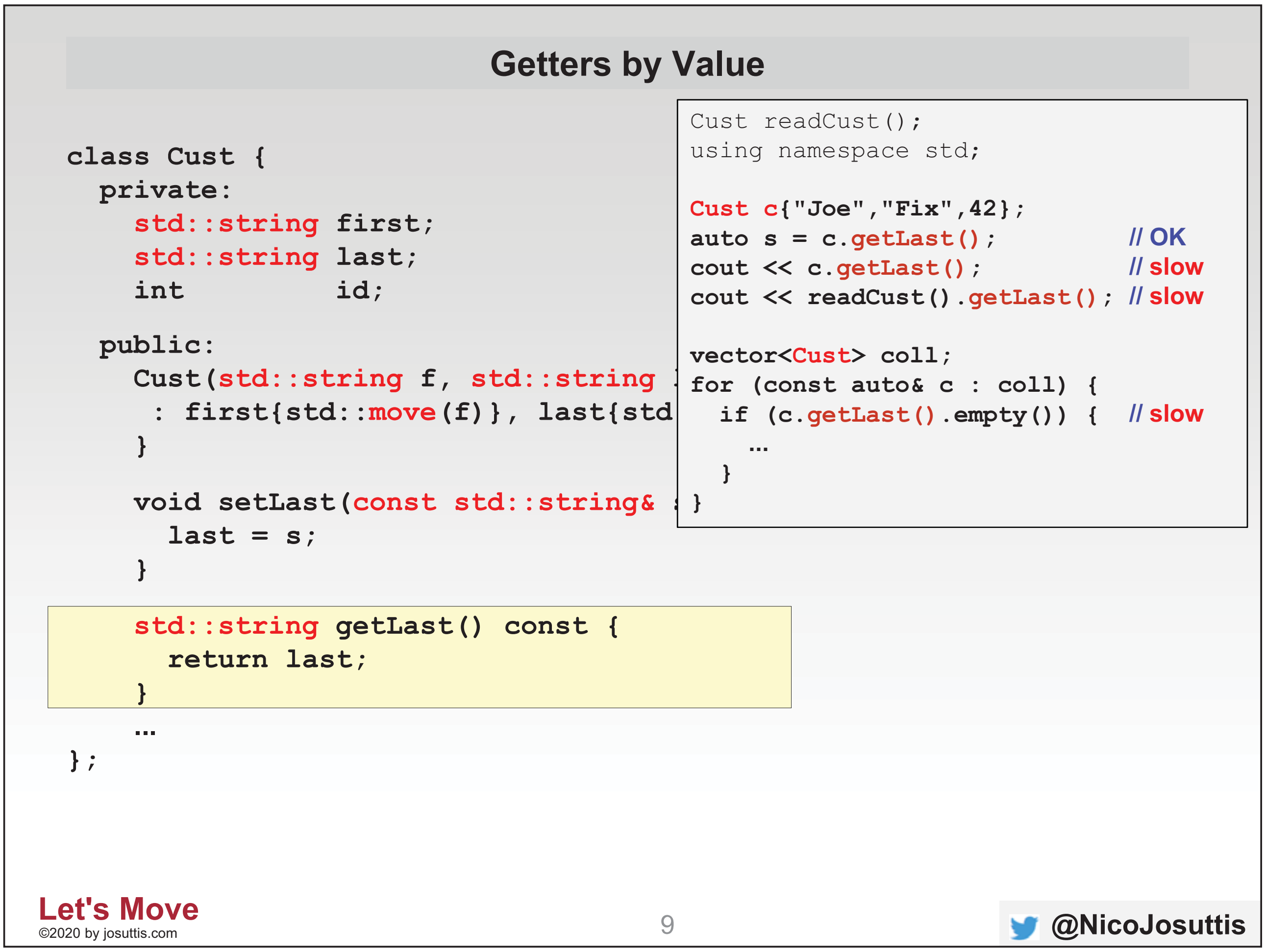
move: 5 mallocs (4cr + 1cp + 7mv)

allref: 5 mallocs (4cr + 1cp + 5mv)

all: 5 mallocs (4cr + 1cp + 1mv)

```
class Cust {
  std::string first;
  std::string last;
  int idx;
  std::array<Coord,100> val;
 public:
  ...   // 1 - 9 constructors
};
```

		Platform A	Platform B	Platform C
	classic:	8.29763	13.2746	4.95914
	move:	5.78400	5.9336	2.74172
	allref:	5.76791	5.8211	2.41148
	all:	5.75993	5.7886	2.31567
With array:	classic:	11.03440	15.1944	7.68108
	move:	8.73324	8.6309	4.89639
	allref:	8.62878	8.5899	4.81283
	all:	8.74176	8.2674	5.38340



Getters by Value

```
class Cust {
  private:
    std::string first;
    std::string last;
    int         id;

  public:
    Cust(std::string f, std::string
     : first{std::move(f)}, last{std
    }

    void setLast(const std::string&
      last = s;
    }

    std::string getLast() const {
      return last;
    }
    …
};
```

```
Cust readCust();
using namespace std;

Cust c{"Joe","Fix",42};
auto s = c.getLast();              // OK
cout << c.getLast();               // slow
cout << readCust().getLast();      // slow

vector<Cust> coll;
for (const auto& c : coll) {
  if (c.getLast().empty()) {       // slow
    …
  }
}
```

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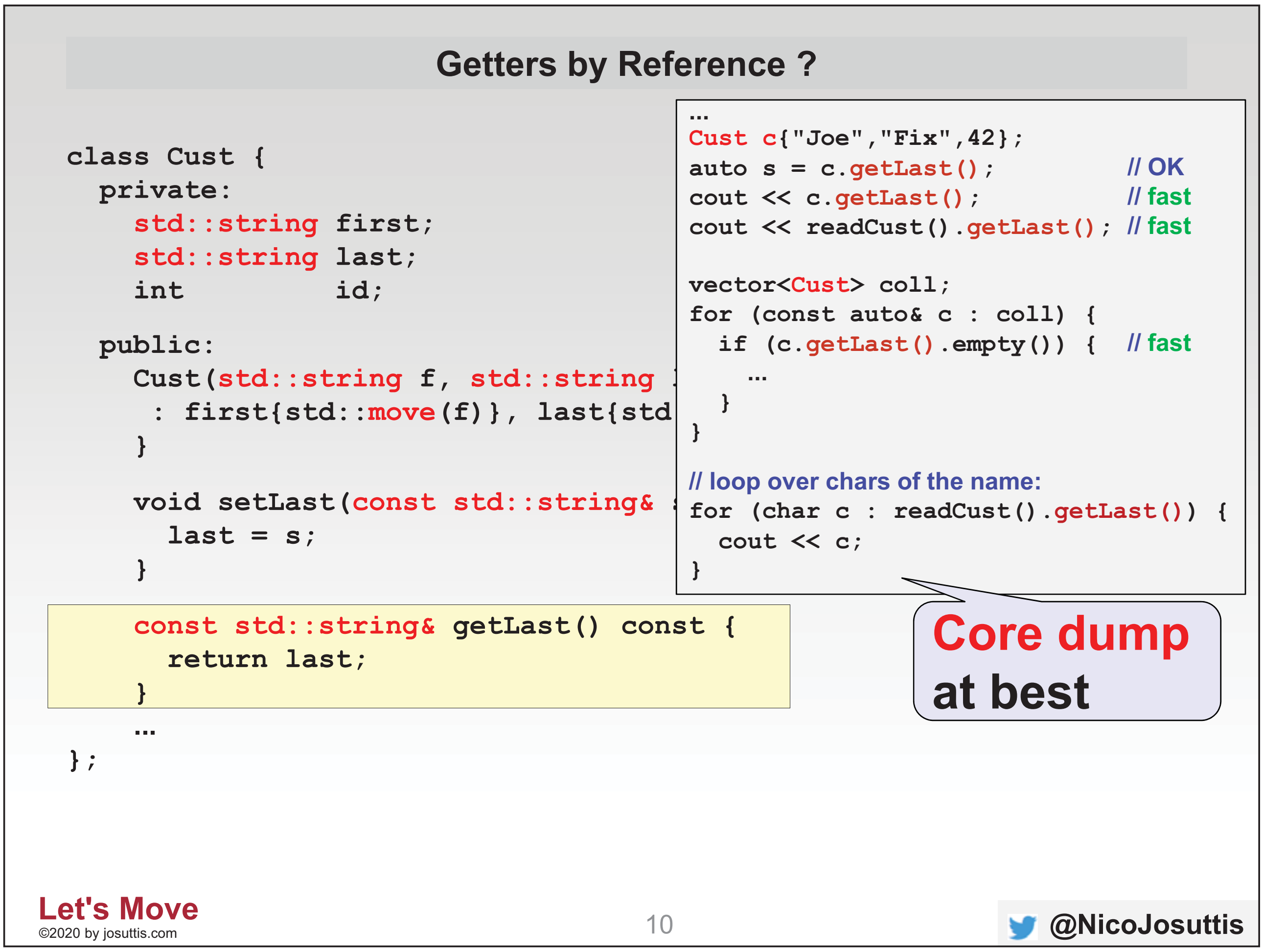

Getters by Reference ?

```
class Cust {
  private:
    std::string first;
    std::string last;
    int         id;

  public:
    Cust(std::string f, std::string
     : first{std::move(f)}, last{std
    }

    void setLast(const std::string&
      last = s;
    }

    const std::string& getLast() const {
      return last;
    }
    …
};
```

```
…
Cust c{"Joe","Fix",42};
auto s = c.getLast();              // OK
cout << c.getLast();               // fast
cout << readCust().getLast();      // fast

vector<Cust> coll;
for (const auto& c : coll) {
  if (c.getLast().empty()) {       // fast
    …
  }
}

// loop over chars of the name:
for (char c : readCust().getLast()) {
  cout << c;
}
```

Core dump
at best

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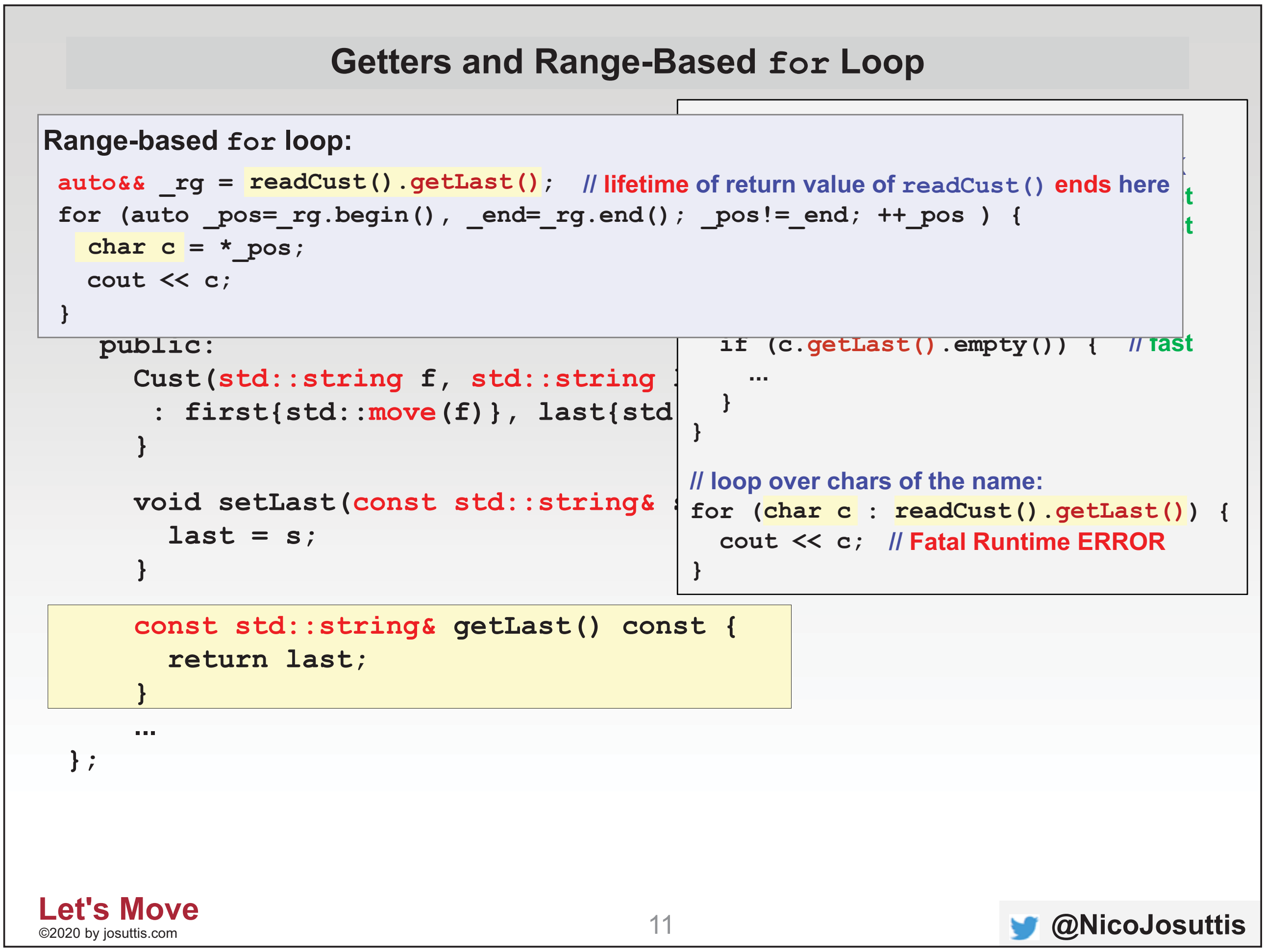

Getters and Range-Based for Loop

Range-based for loop:

```
auto&& _rg = readCust().getLast();   // lifetime of return value of readCust() ends here
for (auto _pos=_rg.begin(), _end=_rg.end(); _pos!=_end; ++_pos ) {
  char c = *_pos;
  cout << c;
}
```

```
  public:
    Cust(std::string f, std::string
      : first{std::move(f)}, last{std
    }

    void setLast(const std::string&
      last = s;
    }

    const std::string& getLast() const {
      return last;
    }
    ...
};
```

```
  if (c.getLast().empty()) {   // fast
    ...
  }
}

// loop over chars of the name:
for (char c : readCust().getLast()) {
  cout << c;   // Fatal Runtime ERROR
}
```

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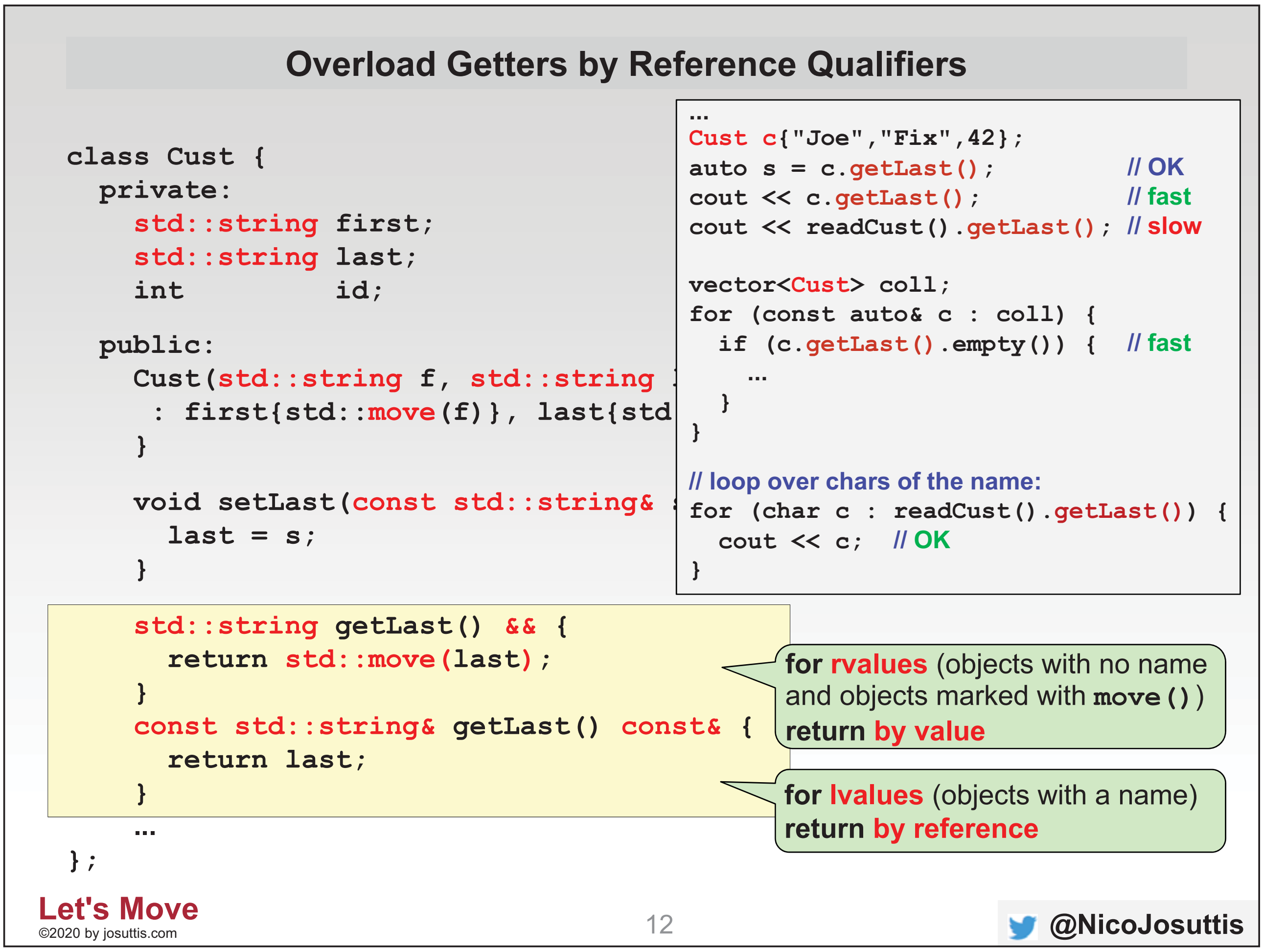

Overload Getters by Reference Qualifiers

```
class Cust {
  private:
    std::string first;
    std::string last;
    int         id;

  public:
    Cust(std::string f, std::string
      : first{std::move(f)}, last{std
    }

    void setLast(const std::string&
      last = s;
    }

    std::string getLast() && {
      return std::move(last);
    }
    const std::string& getLast() const& {
      return last;
    }
    ...
};
```

```
...
Cust c{"Joe","Fix",42};
auto s = c.getLast();            // OK
cout << c.getLast();             // fast
cout << readCust().getLast();    // slow

vector<Cust> coll;
for (const auto& c : coll) {
  if (c.getLast().empty()) {     // fast
    ...
  }
}

// loop over chars of the name:
for (char c : readCust().getLast()) {
  cout << c;   // OK
}
```

for rvalues (objects with no name and objects marked with **move()**) **return by value**

for lvalues (objects with a name) **return by reference**

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Moved-from States

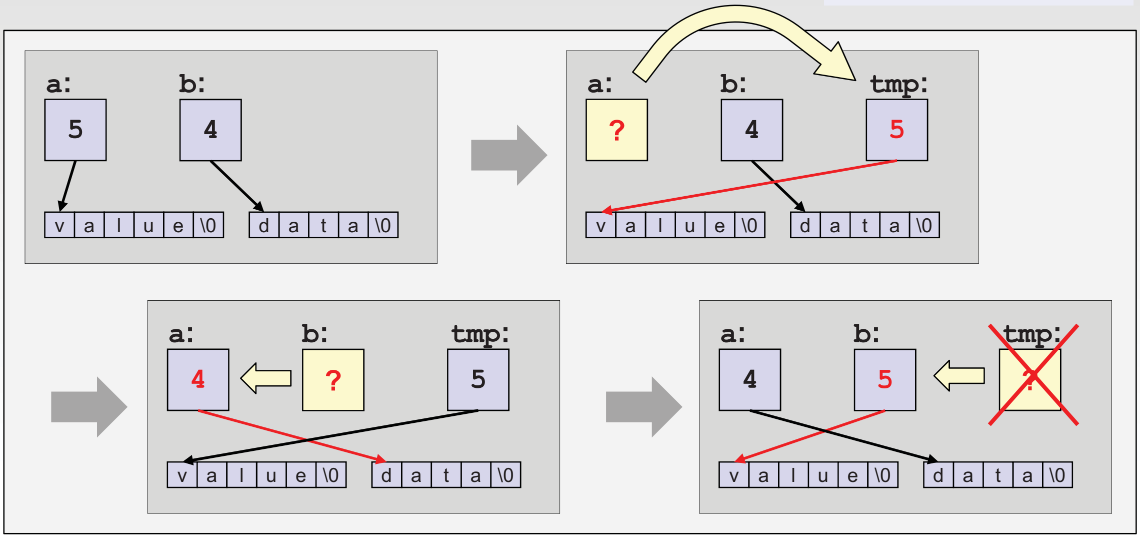
- **Requirements by the C++ Standard Library**
  - A moved-from object is nothing special
  - All requirements also apply to moved-from objects
    - Usually: destruction and assignment
    - But `sort()` might call < for a moved-from object
  - Moved-from objects should also support all requirements
- **Guarantees by the C++ Standard Library**
  - Moved-from objects are in a *valid but unspecified state*
    - No invariants broken
    - All operations work as expected
  - These guarantees fulfill the requirements
- **Ideally you give the same guarantees for your types**

under discussion
by the C++ committee

Requirements According to Swap

- **Assign new values to moved-from objects**
  - Note: self-swap should work
- **Destroy moved-from objects**

```
void swap(T& a, T& b) {
  tmp = std::move(a);
  a = std::move(b);
  b = std::move(tmp);
}
```



Using the Guarantees for Moved-from Objects

```
std::vector<std::string> coll;
...
std::string row;
while (std::getline(myStream, row)) {
  coll.push_back(std::move(row));    // move the line into the vector
}
```

```
std::stack<int> stk;
...
foo(std::move(stk));     // stk gets unspecified state
stk.push(42);
...   // do something else without using stk
int i = stk.top();
assert(i == 42);         // should never fail
```

Invariants Broken by Move Semantics

```
class Email {
 private:
  std::string value;
 public:
  Email(const std::string& val)
   : value{val} {
    assert(value.find('@') != std::string::npos);
  }
  void setValue(const std::string& val) {
    value = val;
    assert(value.find('@') != std::string::npos);
  }
  std::string getValue() const {
    return value;
  }
  ...
};
```

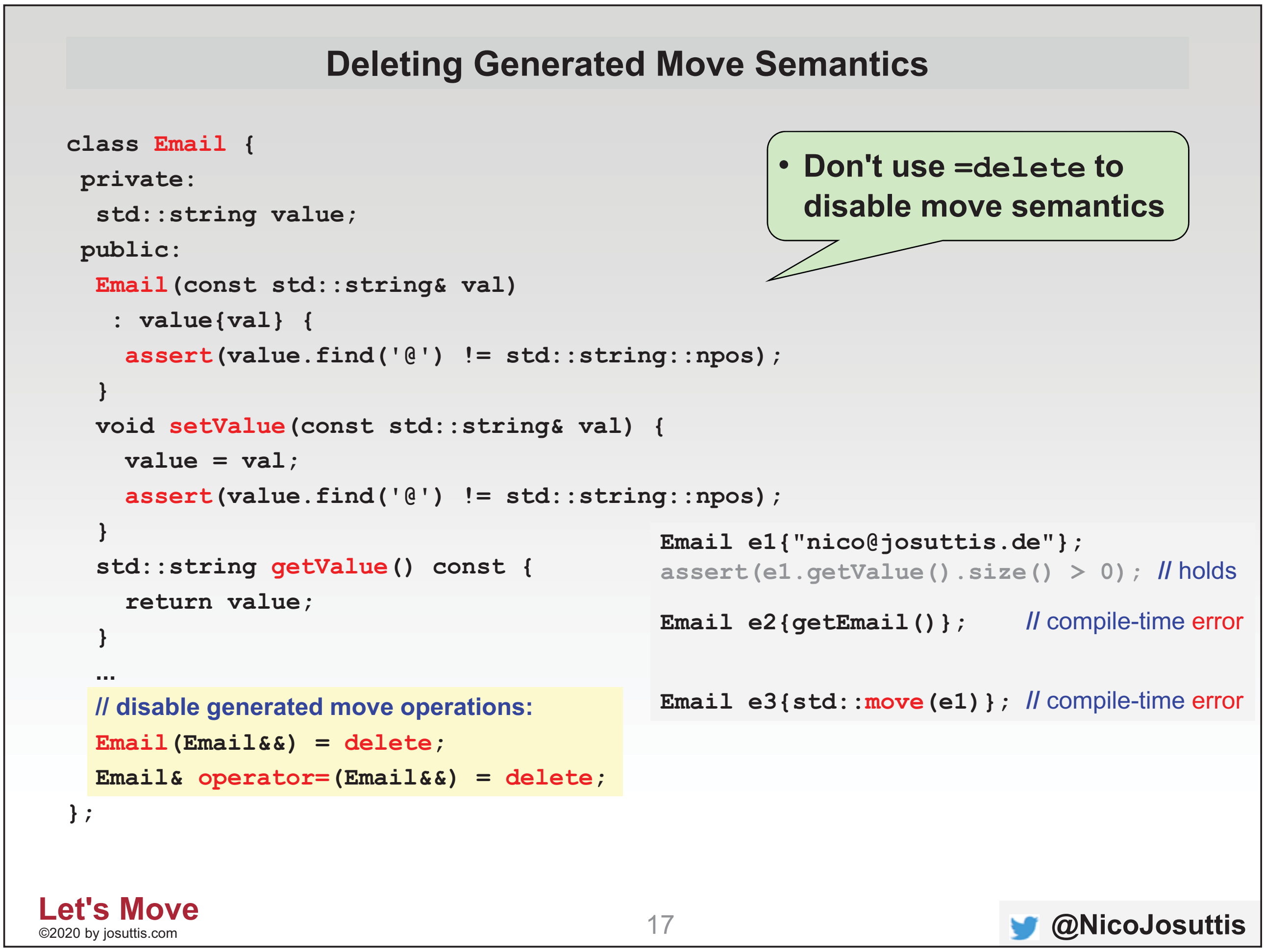
Invariant:
Objects always have an email address (`getValue()` has a string with a @)

```
Email e1{"nico@josuttis.de"};
assert(e1.getValue().size() > 0);  // holds

Email e2{getEmail()};              // moves
assert(e2.getValue().size() > 0);  // holds

Email e3{std::move(e1)};           // moves
assert(e1.getValue().size() > 0);  // fails
```

- **Moved-from objects can be in invalid/inconsistent states**
- **Only a problem when using objects after `std::move()`**



Deleting Generated Move Semantics

```
class Email {
 private:
  std::string value;
 public:
  Email(const std::string& val)
   : value{val} {
    assert(value.find('@') != std::string::npos);
  }
  void setValue(const std::string& val) {
    value = val;
    assert(value.find('@') != std::string::npos);
  }
  std::string getValue() const {
    return value;
  }
  ...
  // disable generated move operations:
  Email(Email&&) = delete;
  Email& operator=(Email&&) = delete;
};
```

- Don't use =delete to disable move semantics

```
Email e1{"nico@josuttis.de"};
assert(e1.getValue().size() > 0);  // holds

Email e2{getEmail()};      // compile-time error

Email e3{std::move(e1)};   // compile-time error
```

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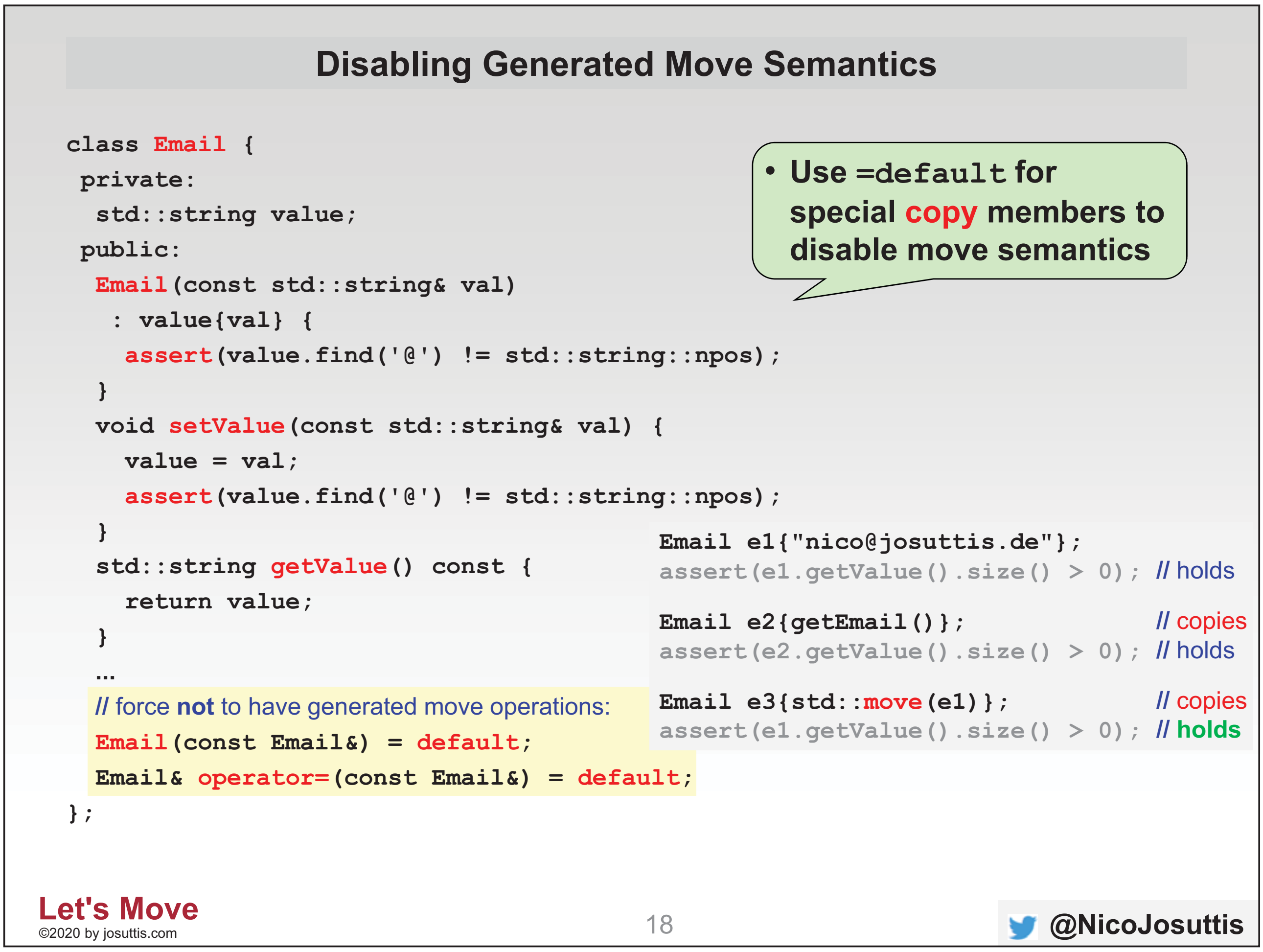

Disabling Generated Move Semantics

```
class Email {
 private:
  std::string value;
 public:
  Email(const std::string& val)
   : value{val} {
    assert(value.find('@') != std::string::npos);
  }
  void setValue(const std::string& val) {
    value = val;
    assert(value.find('@') != std::string::npos);
  }
  std::string getValue() const {
    return value;
  }
  ...
  // force not to have generated move operations:
  Email(const Email&) = default;
  Email& operator=(const Email&) = default;
};
```

- Use =default for special copy members to disable move semantics

```
Email e1{"nico@josuttis.de"};
assert(e1.getValue().size() > 0);  // holds

Email e2{getEmail()};                // copies
assert(e2.getValue().size() > 0);  // holds

Email e3{std::move(e1)};             // copies
assert(e1.getValue().size() > 0);  // holds
```

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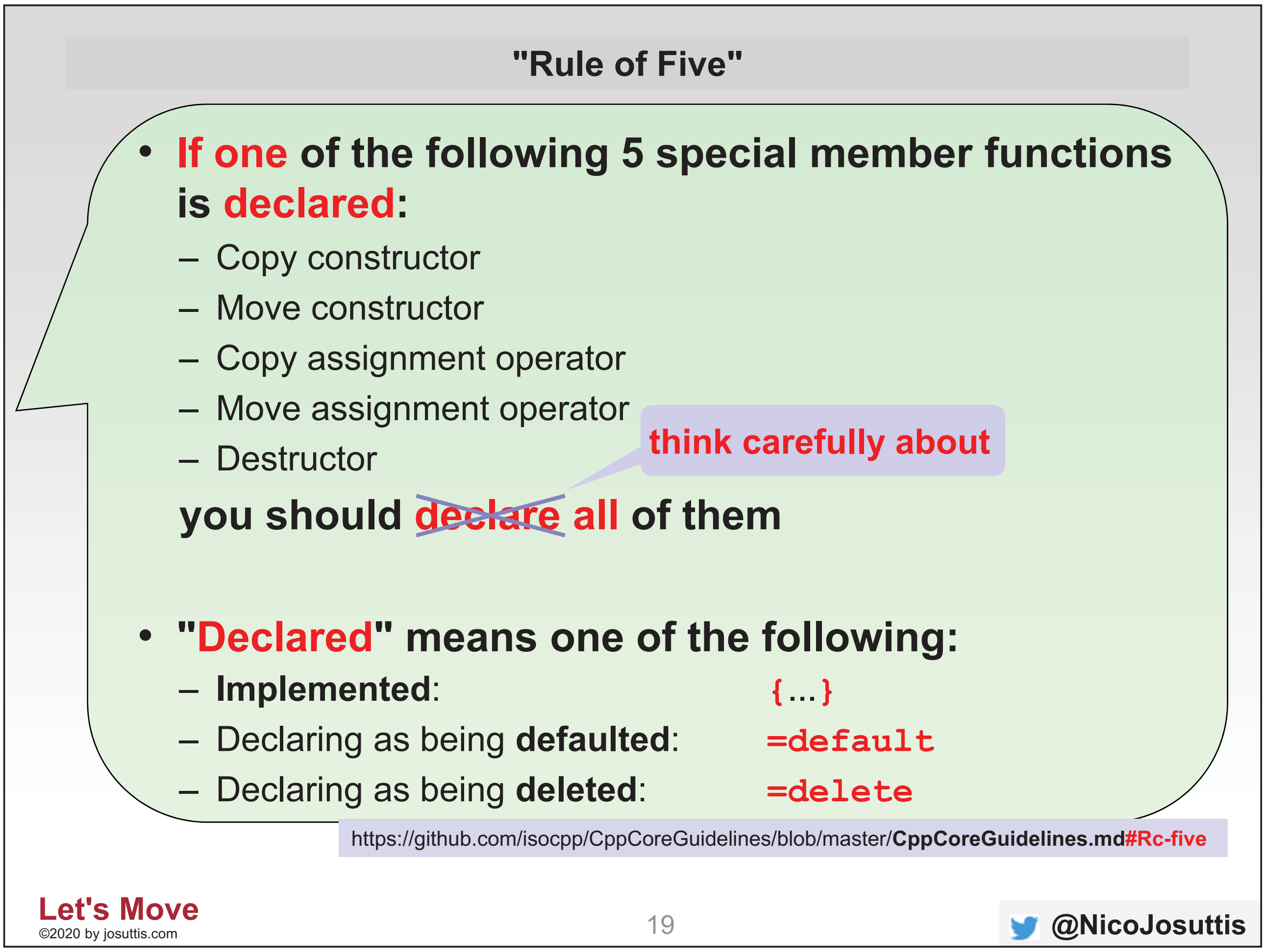


"Rule of Five"

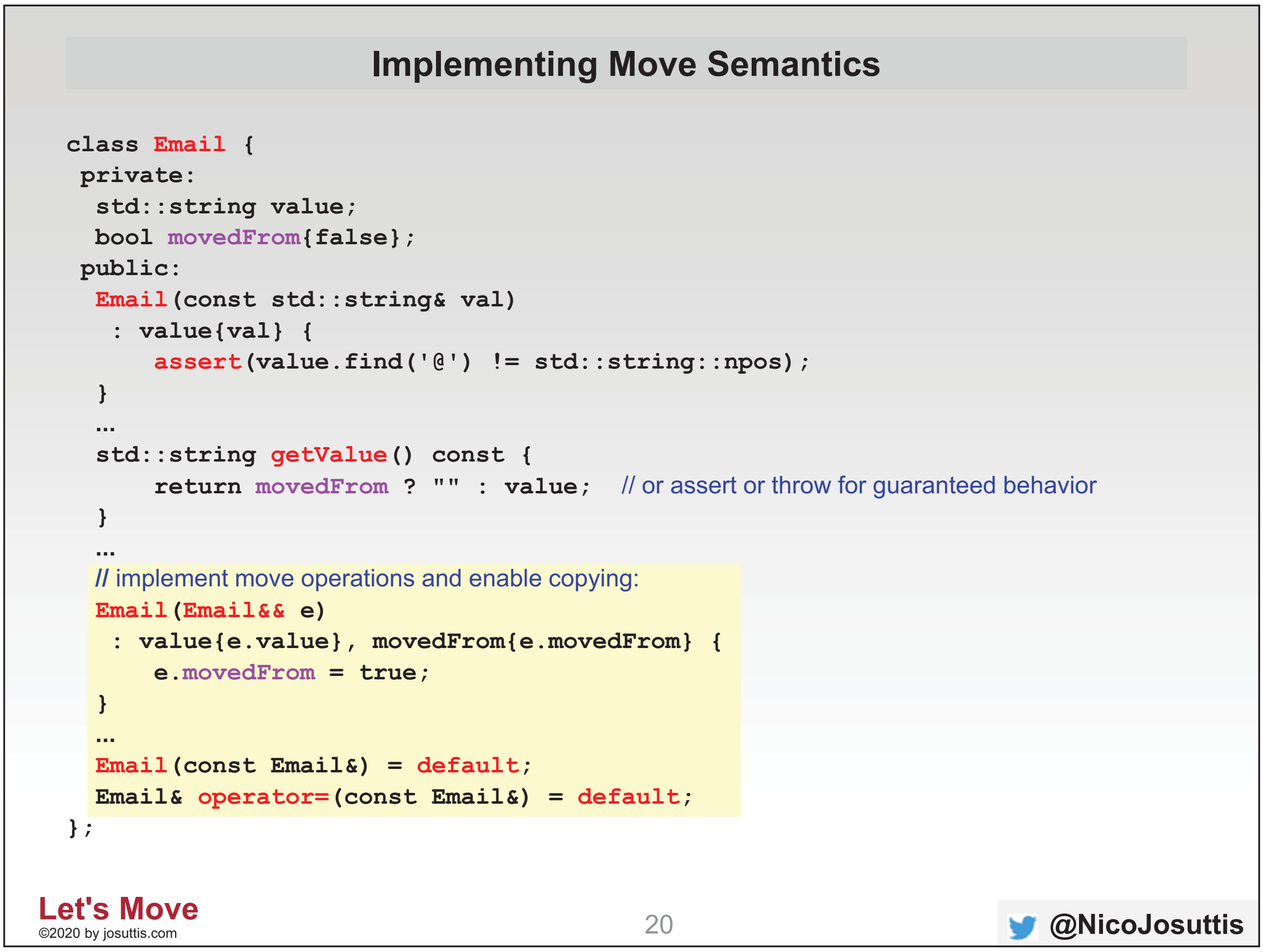
- **If one of the following 5 special member functions is declared:**
  - Copy constructor
  - Move constructor
  - Copy assignment operator
  - Move assignment operator
  - Destructor

  you should ~~declare~~ all of them

  think carefully about

- **"Declared" means one of the following:**
  - **Implemented**: `{...}`
  - Declaring as being **defaulted**: `=default`
  - Declaring as being **deleted**: `=delete`

https://github.com/isocpp/CppCoreGuidelines/blob/master/**CppCoreGuidelines.md**#Rc-five



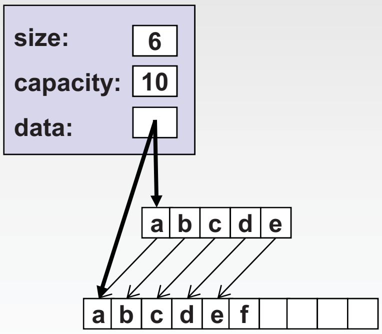
Implementing Move Semantics

```
class Email {
 private:
  std::string value;
  bool movedFrom{false};
 public:
  Email(const std::string& val)
   : value{val} {
      assert(value.find('@') != std::string::npos);
  }
  ...
  std::string getValue() const {
      return movedFrom ? "" : value;    // or assert or throw for guaranteed behavior
  }
  ...
  // implement move operations and enable copying:
  Email(Email&& e)
   : value{e.value}, movedFrom{e.movedFrom} {
      e.movedFrom = true;
  }
  ...
  Email(const Email&) = default;
  Email& operator=(const Email&) = default;
};
```

Exception Safety Guarantee for Vector's push_back()

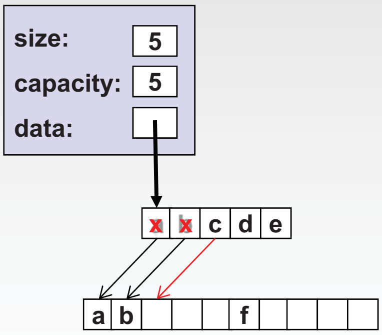
- **In C++98/C++03 the guarantee is possible because:**
  - Reallocation is done by the following steps:
    - allocate new memory
    - assign new value
    - copy old elements (element by element)

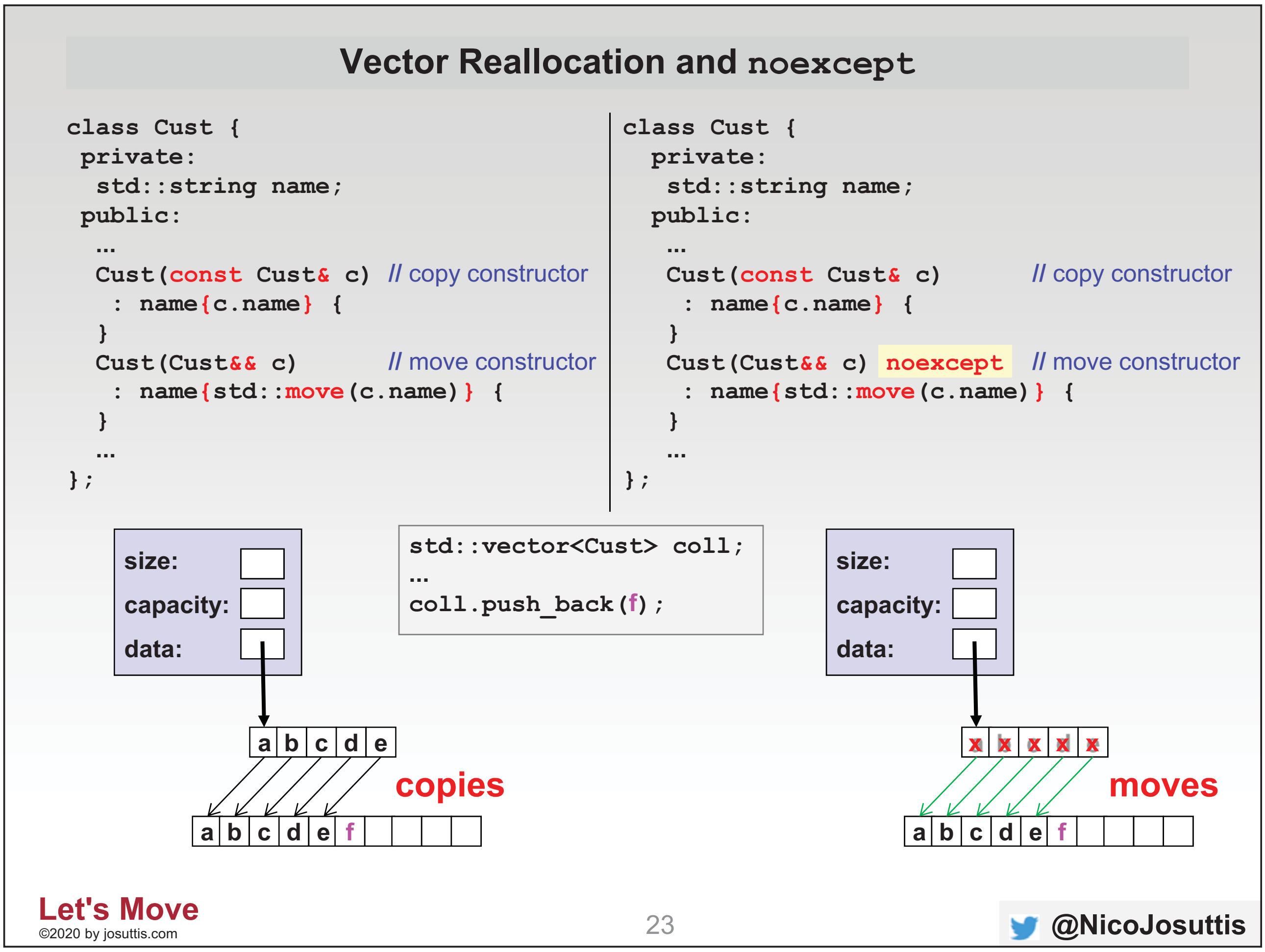
    ------ point of no rollback ------
    - assign new memory to internal pointer
    - delete old elements and free old memory
    - update size and capacity



Exception Safety Guarantee for Vector's push_back()

- **Reallocation with move semantics breaks the strong exception guarantee**
  - Moving elements might throw but we can't always roll back
- **We can't**
  - silently break the strong exception guarantee
    - Existing code would be broken
  - replace `push_back()` by something new
    - Too much use
  - require that move constructors don't throw
    - Even the moved-from state (valid but unspecified) might need memory
- **So:**
  std::vector<> moves only if it's safe
  - with guarantee that the move constructor does not throw





Vector Reallocation and `noexcept`

```
class Cust {
 private:
  std::string name;
 public:
  ...
  Cust(const Cust& c)  // copy constructor
   : name{c.name} {
  }
  Cust(Cust&& c)       // move constructor
   : name{std::move(c.name)} {
  }
  ...
};
```

```
class Cust {
  private:
   std::string name;
  public:
   ...
   Cust(const Cust& c)            // copy constructor
    : name{c.name} {
   }
   Cust(Cust&& c) noexcept        // move constructor
    : name{std::move(c.name)} {
   }
   ...
};
```

```
std::vector<Cust> coll;
...
coll.push_back(f);
```

size:
capacity:
data:
a b c d e
a b c d e f
copies
size:
capacity:
data:
x x x x x
a b c d e f
moves

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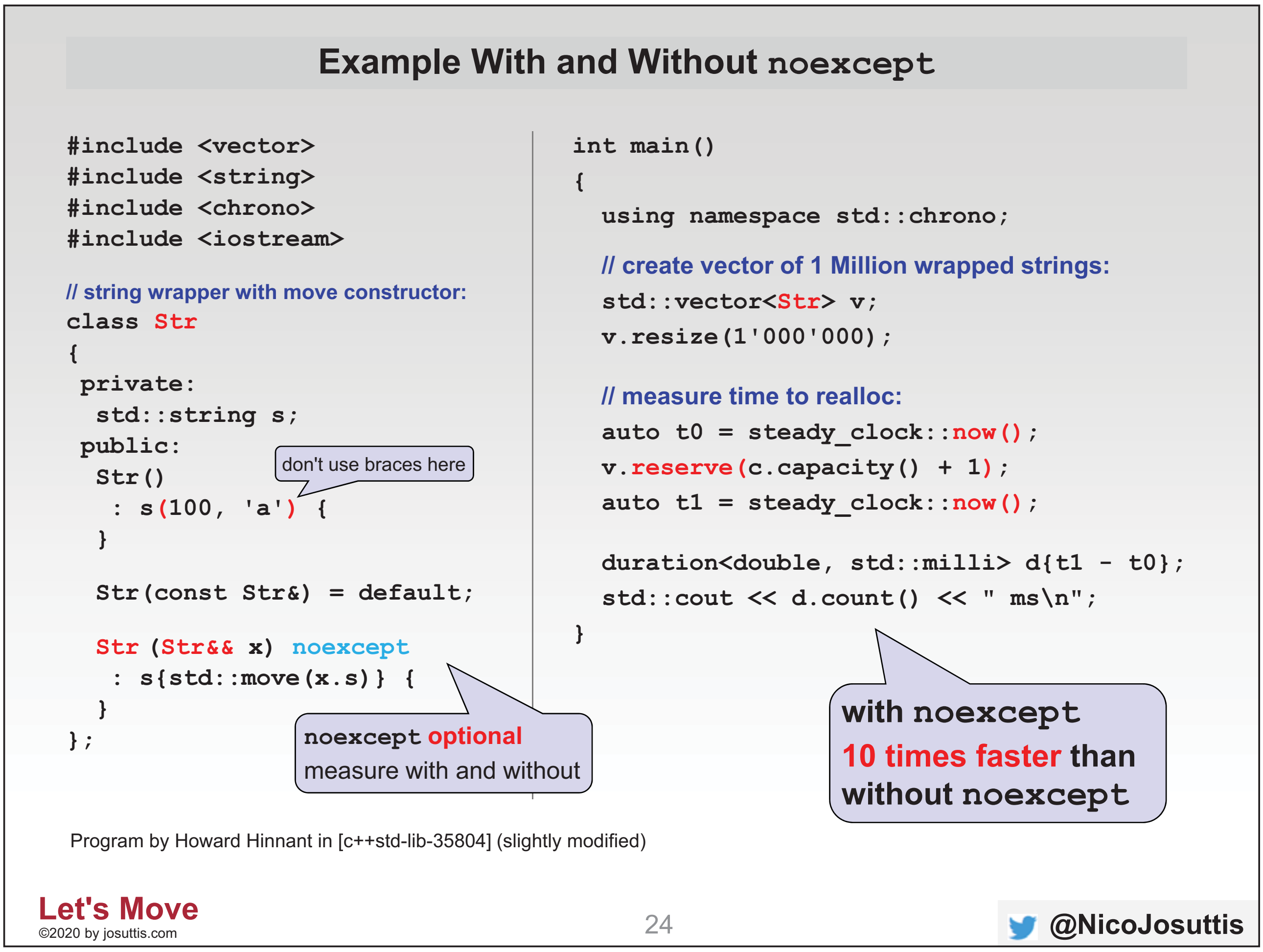

Example With and Without `noexcept`

```
#include <vector>
#include <string>
#include <chrono>
#include <iostream>

// string wrapper with move constructor:
class Str
{
 private:
  std::string s;
 public:
  Str()
   : s(100, 'a') {
  }

  Str(const Str&) = default;

  Str (Str&& x) noexcept
   : s{std::move(x.s)} {
  }
};
```

don't use braces here

`noexcept` optional
measure with and without

```
int main()
{
  using namespace std::chrono;

  // create vector of 1 Million wrapped strings:
  std::vector<Str> v;
  v.resize(1'000'000);

  // measure time to realloc:
  auto t0 = steady_clock::now();
  v.reserve(c.capacity() + 1);
  auto t1 = steady_clock::now();

  duration<double, std::milli> d{t1 - t0};
  std::cout << d.count() << " ms\n";
}
```

with `noexcept`
10 times faster than
without `noexcept`

Program by Howard Hinnant in [c++std-lib-35804] (slightly modified)

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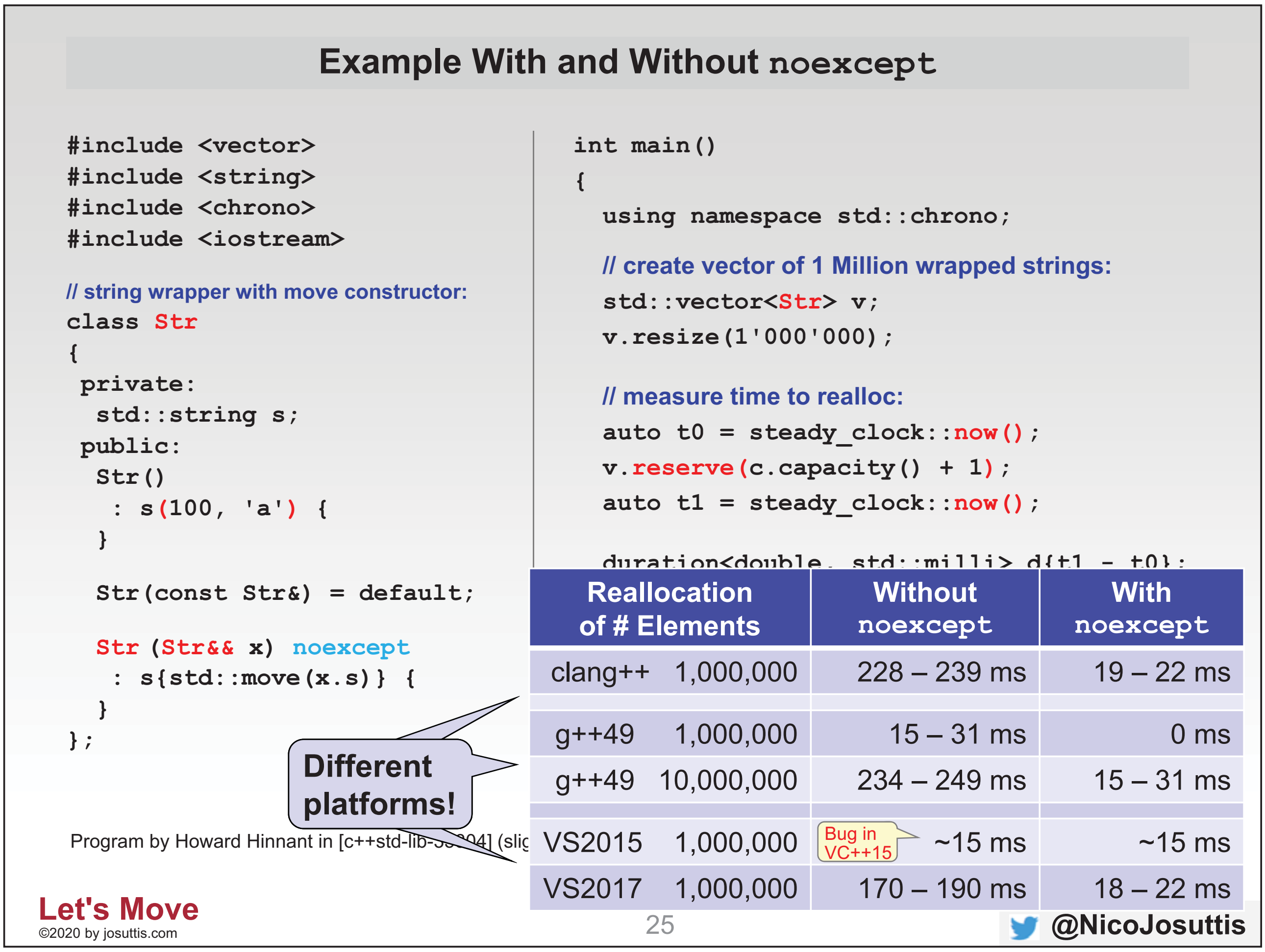


Example With and Without noexcept

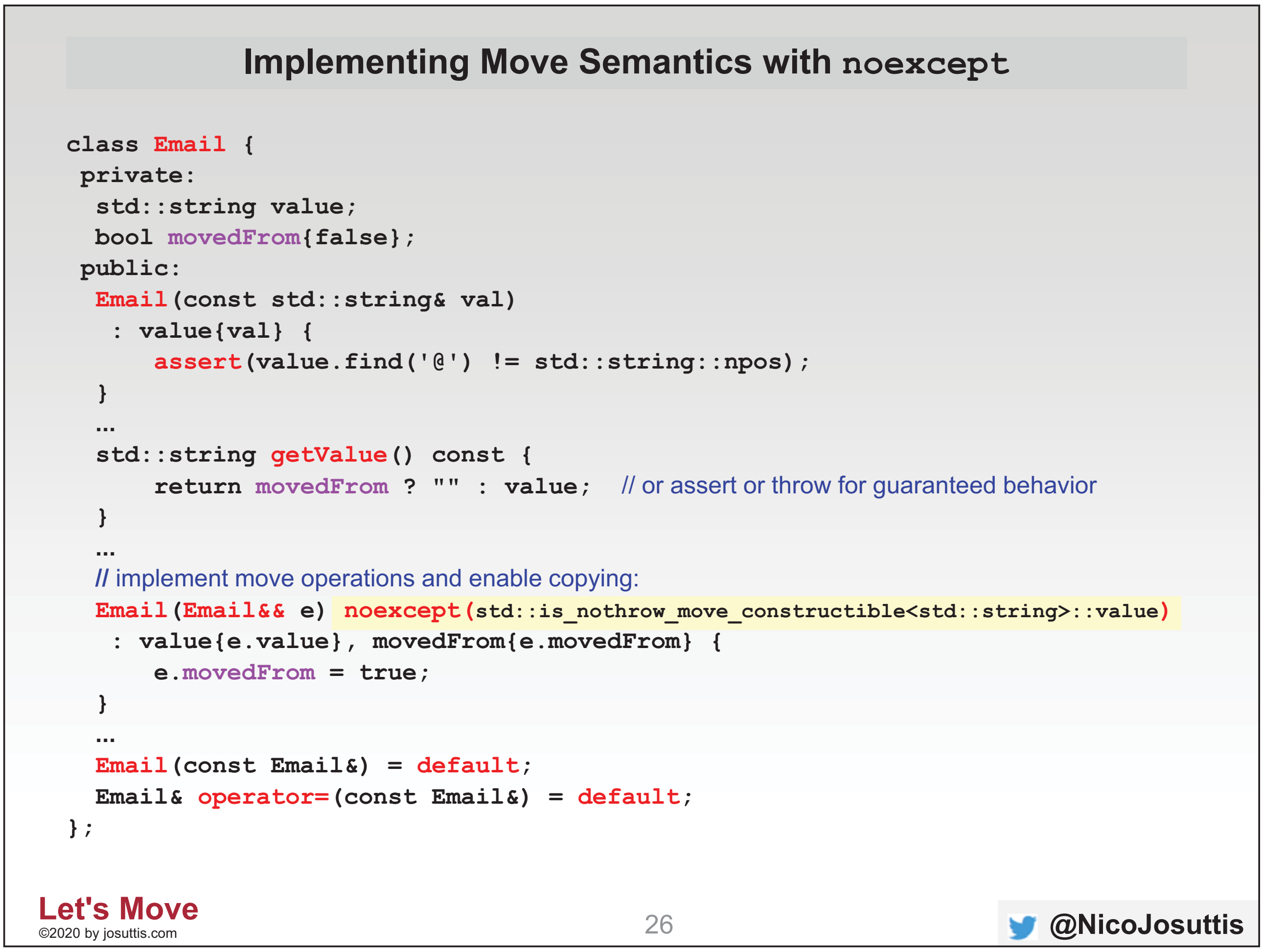
```
#include <vector>
#include <string>
#include <chrono>
#include <iostream>

// string wrapper with move constructor:
class Str
{
 private:
  std::string s;
 public:
  Str()
   : s(100, 'a') {
  }

  Str(const Str&) = default;

  Str (Str&& x) noexcept
   : s{std::move(x.s)} {
  }
};
```

```
int main()
{
  using namespace std::chrono;

  // create vector of 1 Million wrapped strings:
  std::vector<Str> v;
  v.resize(1'000'000);

  // measure time to realloc:
  auto t0 = steady_clock::now();
  v.reserve(c.capacity() + 1);
  auto t1 = steady_clock::now();

  duration<double, std::milli> d{t1 - t0};
```

Program by Howard Hinnant in [c++std-lib-3[illegible]04] (slig

Reallocation of # Elements		Without noexcept	With noexcept
clang++	1,000,000	228 – 239 ms	19 – 22 ms
g++49	1,000,000	15 – 31 ms	0 ms
g++49	10,000,000	234 – 249 ms	15 – 31 ms
VS2015	1,000,000	Bug in VC++15 ~15 ms	~15 ms
VS2017	1,000,000	170 – 190 ms	18 – 22 ms

Different platforms!



Implementing Move Semantics with noexcept

```
class Email {
 private:
  std::string value;
  bool movedFrom{false};
 public:
  Email(const std::string& val)
   : value{val} {
      assert(value.find('@') != std::string::npos);
  }
  ...
  std::string getValue() const {
      return movedFrom ? "" : value;    // or assert or throw for guaranteed behavior
  }
  ...
  // implement move operations and enable copying:
  Email(Email&& e) noexcept(std::is_nothrow_move_constructible<std::string>::value)
   : value{e.value}, movedFrom{e.movedFrom} {
      e.movedFrom = true;
  }
  ...
  Email(const Email&) = default;
  Email& operator=(const Email&) = default;
};
```

Lessons Learned

- **Your types automatically provide move semantics**
- **For expensive members**
  - Initializing constructors take by value and `move()`
  - Overload getters for `&&` and `const&`
- **Moved-from objects**
  - are nothing special for the C++ standard library
    - Functions expect all requirements also to work for moved-from objects
  - should not break invariants
    - Ideally in a "valid but unspecified state"
- **To disable move semantics `=default` other special members**
  - breaks "*Rule of 5*"
- **Use `noexcept` when implementing special move members**

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