C++ Course 12 : Move semantics.

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Copy operations (C++ 98), Move operations (C++ 11+)

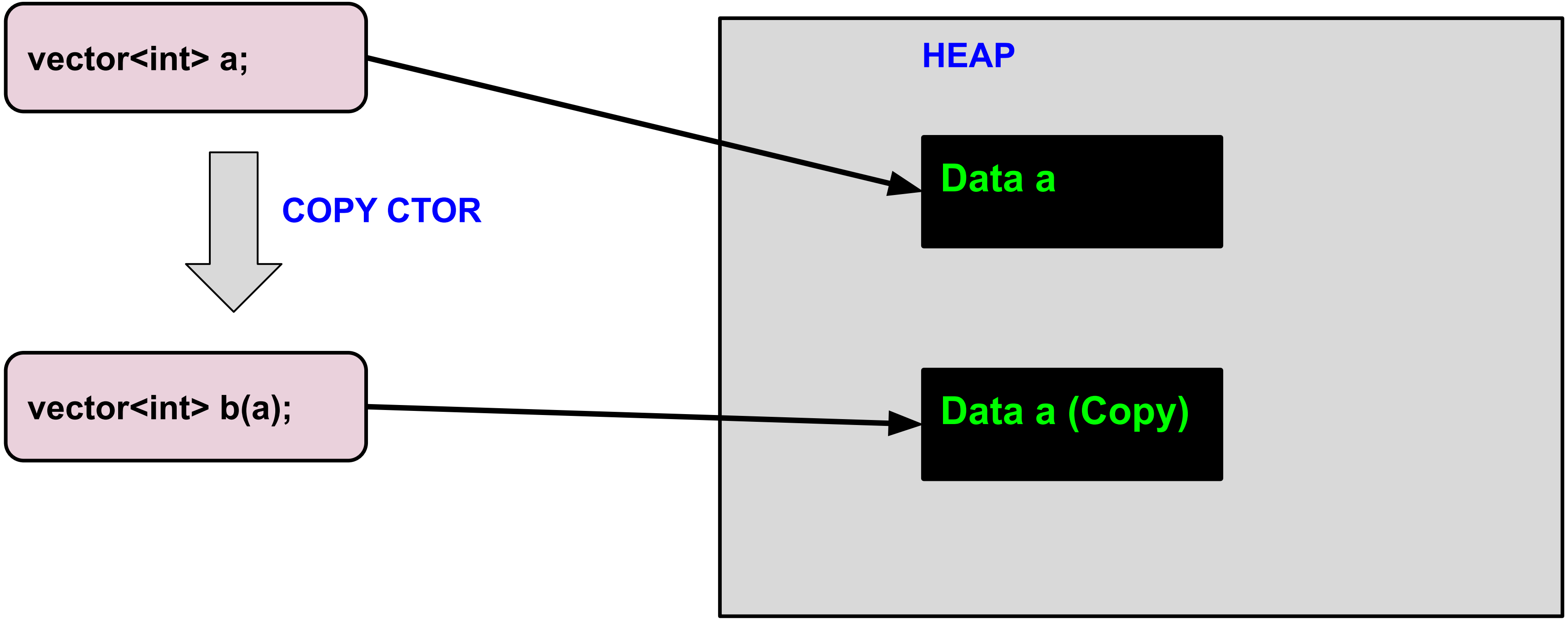
String a("Mickey mouse");
String b(a); // Copy Ctor
String c;
String c = a; // Copy Assignment

b = string("Cinderella"); // Copy assignment in C++ 98, Move assignment in C++ 11+
c = move(b); // Move assignment in C++ 11+, **b** is now empty string !
String d(move(a)); // Move ctor in C++ 11+, **a** is now empty string !

Copy is easy to understand: we clone our object.

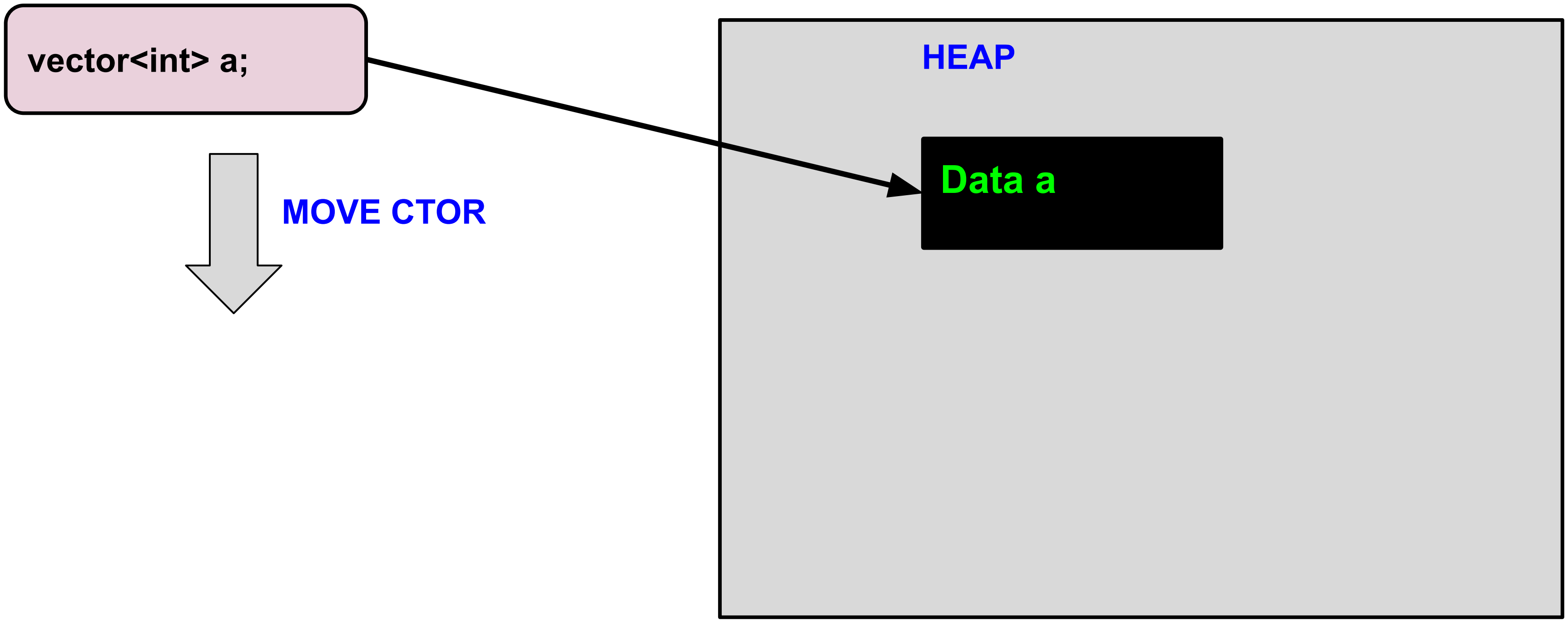
But what is MOVE ?
DATA is moved, NOT OBJECT !!!

Copy constructor : std::vector copies data in the heap

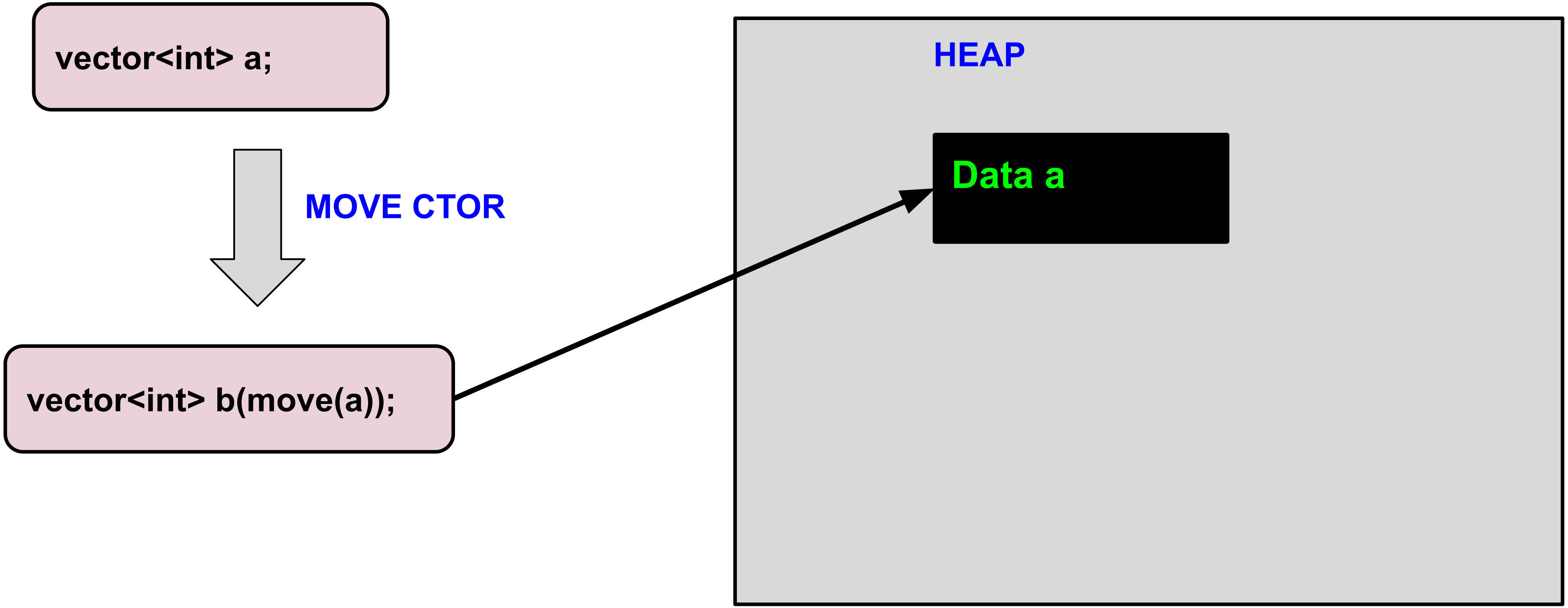


A new vector **b** is created. The data of vector **a** is COPIED in the heap to **b**.
Copying class objects is often EXPENSIVE.

Move constructor : data is moved to another vector object



Move constructor : data is moved to another vector object

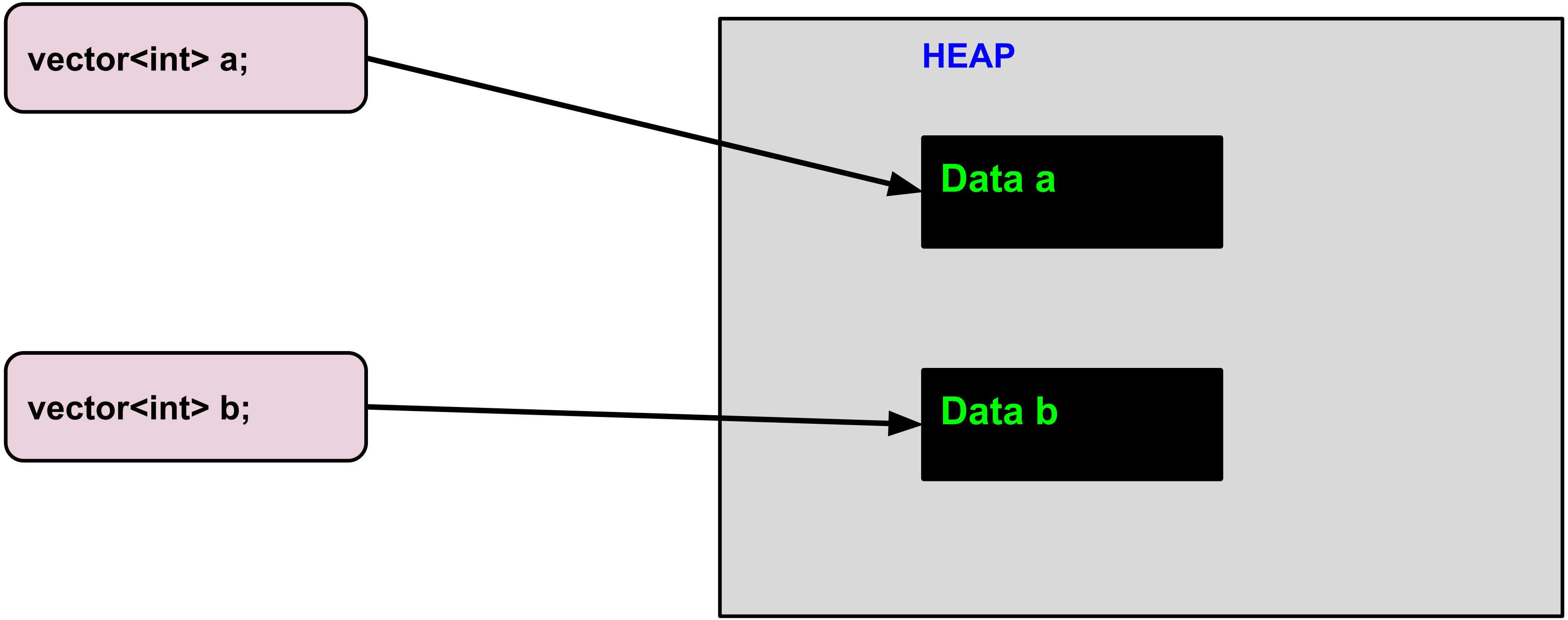


The data is moved from object **a** to the new vector **b**.

Vector **a** is now empty (**size == 0, capacity == 0**), but NOT destroyed !

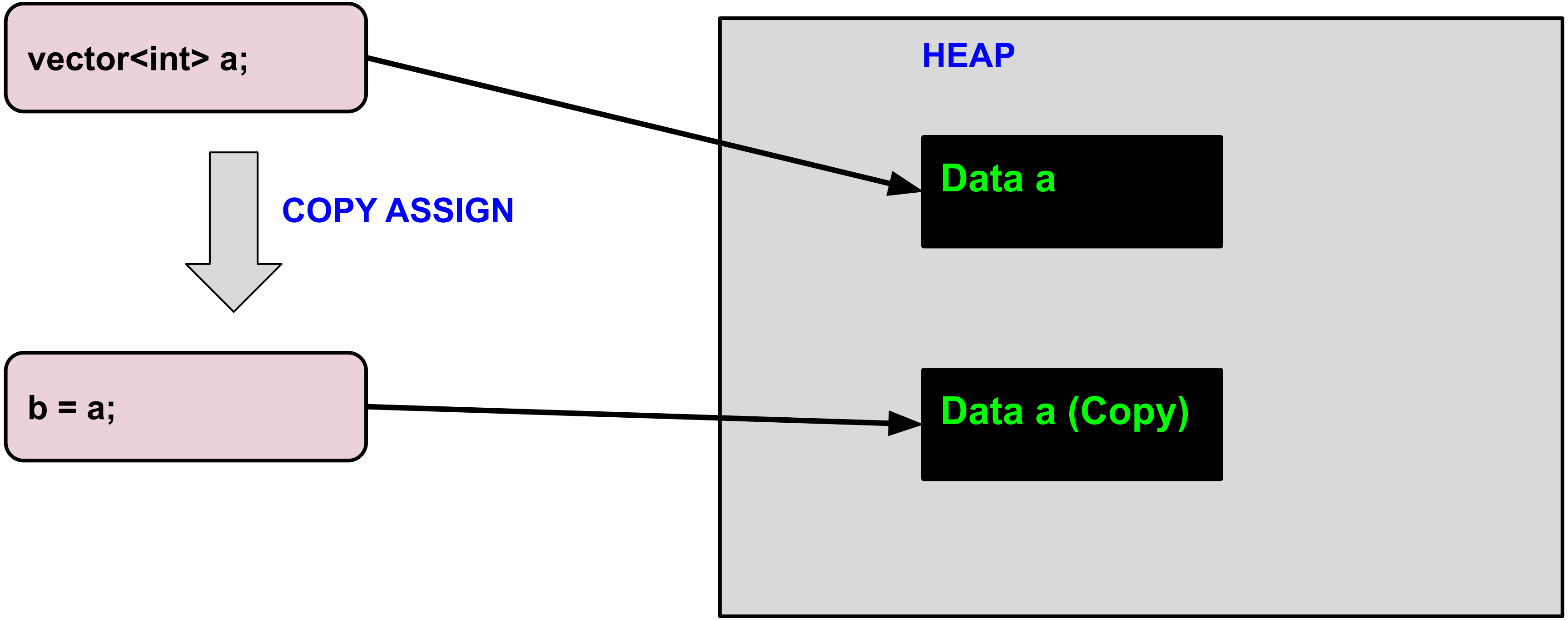
Data is moved, not objects !

Before Copy or Move assignment



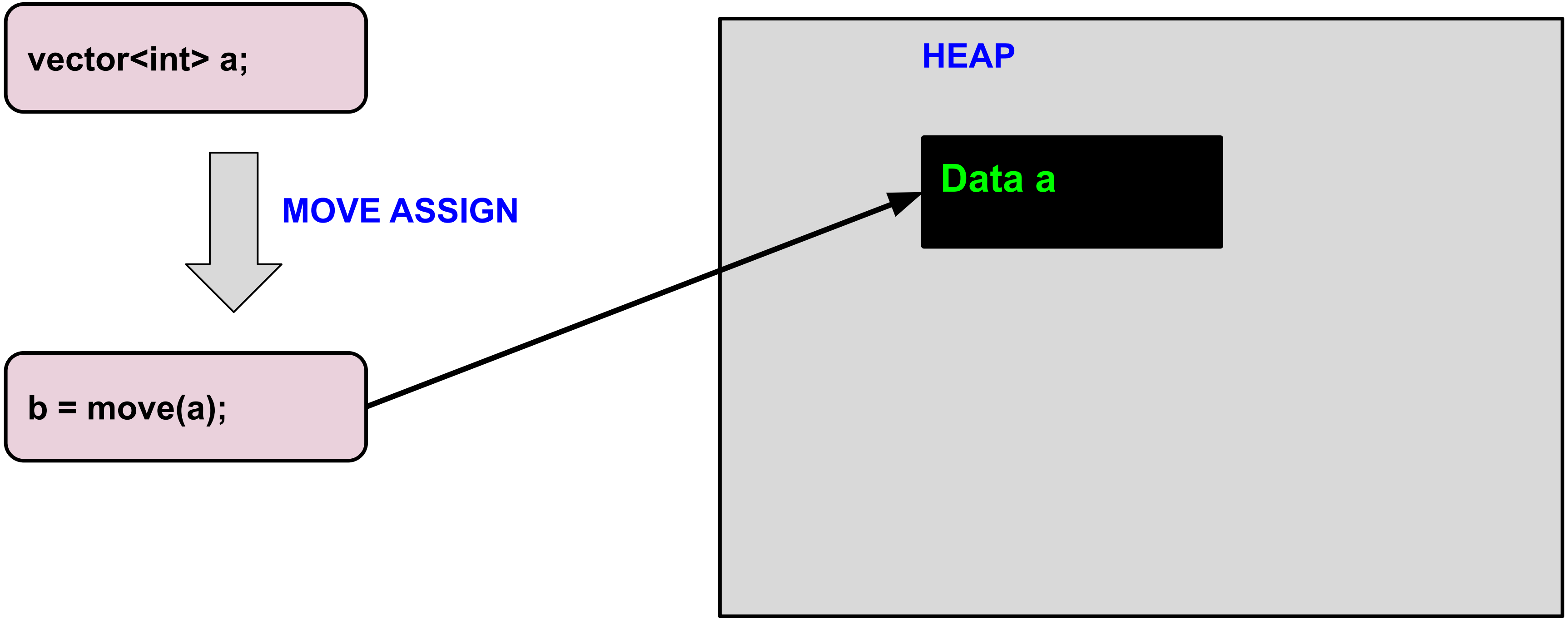
Vectors **a** and **b** both exist and keep their own heap data.

Copy assignment



Data **b** is lost (and destroyed on the heap), Data **a** is copied in the heap to vector **b**.

Move assignment



Data **b** is lost (and destroyed on the heap), Data **a** is moved to vector **b**.

Vector **a** is now empty (**size == 0, capacity == 0**), but NOT destroyed !

Data is moved, not objects !

In a move operation the victim is NOT destroyed !!!

Move is a robbery, not murder !

```
{
    string a("Sword");
    string b(move(a));
    // Now b == "Sword", a == "" (Empty, Not destroyed !)
    cout << "a = " << a << endl;  // OK, Empty
    cout << "b = " << b << endl;  // OK, Sword
    a = "Spear";    // a can be assigned again
}  // Now a, b run out of scope and are destroyed !
```

Move victim is never destroyed only robbed of data (becomes empty/null).

Data is moved, not objects !

When is MOVE useful?

1. Classes with data in heap : **vector**, **string**, most other containers.
2. Classes which cannot be copied : **unique_ptr**, **ifstream**, **thread**, **future**.

Rvalue vs lvalue

Move operations are implemented with the help of RVALUE REFERENCES.

The terminology LVALUE, RVALUE comes from the early days of C.
The assignment statement:
LVALUE = RVALUE;
LVALUE (left value) can be assigned. Variable, array element **arr[i]**, etc.
RVALUE (right value) cannot be assigned. Temporary: literal, expression result etc.

However, in modern sense of the word:
const a = 17;
a is an LVALUE (every variable is LVALUE), but cannot be assigned!
Confusing!
We need a better definition of LVALUE, RVALUE !

BOOK: Scott Meyers, Effective Modern C++, chapter 5

Rvalue vs lvalue: Better definition

LVALUE is something you can take the address of with the **&** operator:

string s("Mouse");

string * pS1 = & s; // OK, **s** in an LVALUE

string * pS2 = & string("Rat"); // ERROR, **string("Rat")** in an RVALUE

LVALUE examples:

1. Variable, or constant variable: **int a = 17;**
2. Function/method return by LVALUE ref : **arr.at(j)**
3. Operator return by LVALUE ref : **arr[i], *ptr**

RVALUE examples:

1. Literal : **17, "Mouse"**
2. Temporary object : **string("Rat")**
3. Expression result: **2*a + b**
4. Function return by value : **cos(alpha)**

LVALUE vs RVALUE references

C++ 98 : Non-const (LVALUE) reference binds to LVALUE only.

```
string s("Guinea Pig");
string & lrS1 = s;  // OK, ref to variable s
string & lrS2 = string("Marmot");  // ERROR !!!
```

C++ 98 : Const (LVALUE) reference binds to LVALUE, but also RVALUE.

```
string s("Guinea Pig");
const string & clrS1 = s;  // OK, const ref to variable s
const string & clrS2 = string("Marmot");  // OK, const ref to a temporary
```

C++ 11+ : RVALUE reference binds to RVALUE (temporary object) only.

```
string s("Guinea Pig");
string && rrS1 = s;          // ERROR rvalue ref to lvalue !
string && rrS2 = string("Marmot");  // OK, rvalue ref to a temporary
```

Note: The lifetime of TEMPORARY is extended until **}** for **clrS2** and **rrS2** !

Copy and move constructors and assignment operators

```
Tjej(const Tjej & rhs) noexcept : name(rhs.name){}             // Copy Ctor

Tjej(Tjej && rhs) noexcept : name(std::move(rhs.name)){}       // Move Ctor

Tjej & operator= (const Tjej & rhs) noexcept{              // Copy assignment
     if (this != &rhs)     // Check for self-assignment
          name = rhs.name;
     return *this;
}

Tjej & operator= (Tjej && rhs) noexcept{                  // Move assignment
     if (this != &rhs)     // Check for self-assignment
          name = std::move(rhs.name);
     return *this;
}
```

Tjej && is an *RVALUE* reference.**const Tjej &** is a const *LVALUE* reference.
The actual MOVE operation is implemented in move Ctor and Assignment.
move() does not move anything, it selects the *RVALUE* overload.

Copy (LVALUEs) and Move (RVALUEs)

How are COPY or MOVE overloads selected ?

```
String a("Mickey mouse");
String b(a);        // Copy Ctor, a is a LVALUE
String c;
String c = a;       // Copy Assignment, a is a LVALUE

b = string("Cinderella");    // Move assignment, string("Cinderella")  is a RVALUE
c = static_cast<string &&>(b);           // Move assignment, cast to RVALUE !
c = move(b);             // The same
String d(static_cast<string &&>(a));     // Move ctor, cast to RVALUE !
String d(move(a));      // The same
```

move() does not move anything, it casts to *RVALUE* !

Copy Ctor/assignment is selected for LVALUEs.

Move Ctor/assignment is selected for RVALUEs.

Source (factory) : creates a new object

Return by value, no MOVE !

```
Tjej source1(const string & s){
    Tjej t(s);
    return t;
}
...
Tjej t1 = source1("Karen Koenig");
```

Return Value Optimization : No copy or move (but not guaranteed until C++ 17) !

We can even make source within source:

```
Tjej source2(const string & s){
    return source1(s);
}
Tjej t2 = source2("Alice Elliot");
```

Still no copy or move, only 1 object created !

Is RVALUE reference VARIABLE an RVALUE? NO !!!

```
void doSomething(Tjej && rrT){        // rrS is an RVALUE parameter
        string && rrS = string("Maria Traydor");        // rrS is an RVALUE variable
        // rrT and rrS are RVALUE refs, but not RVALUES !
        Tjej t(rrT);    // Copy, NOT MOVE !
        string s(rrS);     // Copy, NOT MOVE !
        ...
}
```

All variables and parameters are LVALUES by definition !

If we want move, we must cast them to rvalue refs as usual :

```
void doSomething2(Tjej && rrT){
        string && rrS = string("Maria Traydor");
        Tjej t(move(rrT));    // MOVE !
        string s(move(rrS));     // MOVE !
        ...
}
```

Writing a sink (consumer)

A sink consumes an object by MOVE and lets it die.

```
void sink(Tjej && t0) {        // By rvalue ref
        Tjej t(move(t0));           // Move to a local var
        cout << "sink : " << t.getName() << endl;
}  // t dies here
```

A copy of a ref parameter? Better to pass by value !

```
void sink1(Tjej t) {        // By value (move), local that dies !
        cout << "sink1 : " << t.getName() << endl;
}  // t dies here
...
Tjej t3("Lucia");
sink1(move(t3));  // 1 move, 0 copy, Move ctor is selected for the parameter t
```

Writing a sink (consumer)

A copy of a ref parameter? Better to pass by value !

```
void sink1(Tjej t) {        // By value (move), local that dies !
        cout << "sink1 : " << t.getName() << endl;
}  // t dies here
...
Tjej t3("Lucia");
sink1(move(t3));  // 1 move, 0 copy, Move ctor is selected for the parameter t
```

Chain sinks :

```
void sink2(Tjej t) {  // By value (move), local that dies !
    sink1(move(t));    // The correct way, move to die !
} // t dies here
...
Tjej t4("Margarete Gertrude Zelle");
sink2(move(t4));  //  2 moves, 0 copy, Move ctor is selected for the parameter t
```

In Move Ctor/assign use move() for :

Class fields:

```
Tjej(Tjej && rhs) noexcept : name(std::move(rhs.name)){}     // Move Ctor
Tjej & operator= (Tjej && rhs) noexcept{             // Move assignment
        if (this != &rhs)    // Check for self-assignment
                name= std::move(rhs.name);
        return *this;
}
```

Parent class:

```
class LilTjej : public Tjej{
        ...
        // Move Ctor
        LilTjej(LilTjej && rhs) noexcept : Tjej(std::move(rhs)){}
};
```

Remember ! Move ctor must be **noexcept** to work in **std::vector** !

Move summary

1. MOVE operations are only useful for classes with heap memory (containers) and the ones which cannot be copied (**unique_ptr**, **thread**, **ostream**).

2. C++ does not move anything, the move ctor/operator= does!

3. Move ctor/assign is selected for RVALUES, copy ctor/assign is selected for LVALUES.

4. **std::move()** does not move anything, it casts to RVALUE.

5. Sources return by value, sinks get parameter by value.

6. RVALUE reference is itself LVALUE, not RVALUE ! Use **std::move()** to move it!

7. The victim of MOVE is not destroyed, it becomes empty.

Universal references

Universal ref can bind to both LVALUES and RVALUES:

```
template <typename T>
void fun(T && t){ ...}    // Universal REF !

auto && t = ...;     // Universal REF !
```

Only **T &&** or **auto &&** is universal ref, everything else with **&&** is RVALUE ref:

```
template <typename T>
void fun(vector<T> && t){ ...}    // Rvalue REF !

template <typename T>
void fun(T::type && t){ ...}    // Rvalue REF !

void fun(string && t){ ...}    // Rvalue REF !
```

How does it work ???

Normally *REFERENCE to REFERENCE* is forbidden in C++:

int & & a = i;   // ERROR !

But in template type deduction and **auto** the rules are different.

Reference collapse rules :

& &   -> &

&& &   -> &

& &&   -> &

&& && -> &&

In reality THERE IS NO UNIVERSAL REFERENCES.

They are special RVALUE references.

It is all about type deduction + reference collapsing.

How does it work ???

Template with a universal ref :

template <typename T>

void fun(T && t){ ...} // Universal REF !

For LVALUE:

string s("Mickey Mouse");

fun(s);

T is deduced as **string &**, and we get : **fun(string & && s);**

Which means **fun(string & s);**

For RVALUE:

string s("Mickey Mouse");

fun(move(s));

T is deduced as **string** , and we get : **fun(string && s);**

std::move possible implementation

In C++ 11:

```
template<typename T>
typename remove_reference<T>::type && move(T  && param){
        using ReturnType = typename remove_reference<T>::type &&;
        return static_cast<ReturnType>(param);  // Cast to RVALUE ref
}
```

In C++ 14:

```
template<typename T>
decltype(auto) move(T  && param){
        using ReturnType = typename remove_reference<T>::type &&;
        return static_cast<ReturnType>(param);  // Cast to RVALUE ref
}
```

But how does it work ?

std::move for LVALUES

```
template<typename T>
typename remove_reference<T>::type && move(T  && param){
        using ReturnType = typename remove_reference<T>::type &&;
        return static_cast<ReturnType>(param);  // Cast to RVALUE ref
}
```

For **string** LVALUE: **T = string &** :

```
typename remove_reference<string &>::type && move(string & && param){
        using ReturnType = typename remove_reference<string &>::type &&;
        return static_cast<ReturnType>(param);  // Cast to RVALUE ref
}
```

or

```
string && move(string & param){
        using ReturnType = string &&;
        return static_cast<ReturnType>(param);  // Cast to RVALUE ref
}
```

std::move for RVALUES

```
template<typename T>
typename remove_reference<T>::type && move(T  && param){
        using ReturnType = typename remove_reference<T>::type &&;
        return static_cast<ReturnType>(param);  // Cast to RVALUE ref
}
```

For **string** RVALUE: **T = string** :

```
typename remove_reference<string>::type && move(string && param){
        using ReturnType = typename remove_reference<string>::type &&;
        return static_cast<ReturnType>(param);  // Cast to RVALUE ref
}
```

or

```
string && move(string && param){
        using ReturnType = string &&;
        return static_cast<ReturnType>(param);  // Cast to RVALUE ref
}
```

Perfect forwarding. Problem :

We want to write a template which adds element to a **vector** :

```
template<typename V, typename T>
void addToVec(V & v, const T & t){
    v.push_back(t);
}
```

Is it good ? Not exactly !

```
vector<Tjej> v;
v.reserve(10);
Tjej t1("Clair Lasbard");
addToVec(v, t1); // Add a LVALUE, 1 copy, OK

addToVec(v, Tjej("Nel Zelpher"));   // RVALUE is copied instead of MOVE !!!
```

Solution : Perfect forwarding + universal reference

We *perfect forward* the argument :

```
template<typename V, typename T>
void addToVec(V & v, T && t){
    v.push_back(forward<T>(t));
}
```

std::forward() always needs type argument : **forward<T>(...)**

Is it good ? YES !

```
vector<Tjej> v;
v.reserve(10);
Tjej t1("Clair Lasbard");
addToVec(v, t1); // Add a LVALUE, 1 copy, OK

addToVec(v, Tjej("Nel Zelpher"));   // Add a RVALUE, 1 move, OK
```

How does std::forward work ? Possible implementation.

```
template<typename T>
T && forward(typename remove_reference<T>::type & param){
        return static_cast<T &&>(param);
}
```

Type T is not deduced, but fixed by universal ref in e.g. **addToVec()**.

For **string** RVALUE: **T = string** : Similar to **move** :

```
string && forward(string & param){
        return static_cast<string  &&>(param);
}
```

For **string** LVALUE: **T = string &** :

```
string & forward(string & param){
        return static_cast<string  &>(param);
}
```

Perfect forwarding variadic version

We want to write a template which adds element to a **vector** using **emplace_back()**:

```
template <typename V, typename ... Args>
void addToVec2(V & v, Args && ... args){
        v.emplace_back(forward<Args>(args)...);
}
```

We perfect-forward all arguments to **emplace_back()**.

```
addToVec2(v, string("Maria Traydor"));       // Construct in-place
```

Linear algebra libraries in C++

- BLAS/LAPACK: classical Fortran libraries
- Eigen: header-only OR optionally can use BLAS/LAPACK for speed
- GNU Scientific Library (GSL): Copyleft, uses BLAS
- Armadillo: Nice C++ classes, uses BLAS/LAPACK
- OpenCV : Not really linear algebra, efficient linear algebra only with BLAS/LAPACK

Other languages:

- Python: numpy/scipy : uses BLAS/LAPACK
- Matlab : uses BLAS/LAPACK

Do you see any common theme here?

Library of the day: CBLAS + LAPACKE (or BLAS/LAPACK)

BLAS (Basic Linear Algebra Subprograms) :

Very low-level operations (up to matrix*matrix)

Original *Reference BLAS* : FORTRAN, slow

Modern BLAS is super-optimized for modern CPUs (SIMD etc.)

It is very important to use recent versions for modern CPUs !

OpenBlas : various architectures (Intel, AMD, ARM), open source

Intel MKL : Intel CPUs only, very slow on AMD, proprietary

LAPACK (Linear Algebra Package) :

Higher-level operations (eigenvalues etc.)

Usually generic FORTRAN LAPACK is used

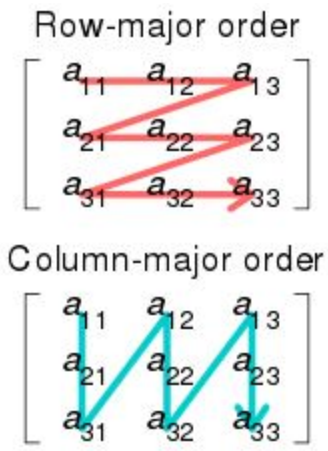
Intel MKL has an own modified LAPACK version

Fortran : BLAS + LAPACK

C/C++ wrappers : CBLAS+LAPACKE (or you can use fortran libraries directly)

BLAS+LAPACK

- Blas level 1: Vector-vector operations (vec+vec, vec.vec)
- Blas level 2: Matrix-vector operations (mat*vec)
- Blas level 3: Matrix-matrix operations (mat*mat)
- Lapack *computational routines*: QR-factorization etc.
- Lapack *driver routines*: Highest levels (eigenvalues+eigenvectors)



BLAS+LAPACK facts:

- BLAS-LAPACK uses *column-major* matrices (Opposite to C/C++)!
- Support for special matrices (symmetric, band, triangular, sparse)
- Lapack has different algorithms to choose from for some operations
- Vectors and matrices can have strides ("increment" or "leading dimension")
- Uses low-level C (or Fortran), no C++ classes

Other libraries: FFTW (Fastest Fourier Transform in the West), ScaLapack (multi-CPU)
Documentation : https://software.intel.com/en-us/mkl-developer-reference-c

Blas levels 1, 2 :

Blas level 1 example: vector-vector: dot product of two vectors (Note : C API, uses *pointers*)

```
vector<double> a{2., 3., 7., 2.}; // We can use vector
double b[] = {1., -1., 1., -2.};   // Or array
int n = 4;                         // Vector size
int inca = 1, incb = 1;            // Strides of a, b
double result = cblas_ddot(n, a.data(), inca, b, incb);    // Double DOT
```

Blas level 2 example: matrix-vector: operation **dgemv** **alpha*A*x + beta*y**

Double **GE**neral matrix **M**atrix-**V**ector product

```
double a[]{1, 2, 3, 6, 5, 4};
double x[]{1, -1};
double y[]{2, 1, -1};
int m = 3, n = 2;          // Dimensions of A
int incx = 1, incy = 1;    // Strides of x, y
int lda = m;               // "Leading dimensions" (matrix strides)
double alpha = -1., beta = -2.;
cblas_dgemv(CblasColMajor, CblasNoTrans, m, n, alpha,
            a, lda, x, incx, beta, y, incy);
```

Blas levels 3 :

Blas level 3 example: matrix-matrix: operation **dgemm** (**alpha*A*B + beta*C**)

Double **GE**neral matrix **M**atrix-**M**atrix product

```
double a[]{1, 2, 3, 6, 5, 4};   // 3x2
double b[]{1, -1, 2, 0, 0, 2, 1, 1};   // 2x4
double c[]{0.5, 0.5, 0.5, 0.5, 0.5, 0.5, 0.5, 0.5, 0.5, 0.5, 0.5, 0.5};  // 3x4

int m = 3, k = 2;                  // Dimensions of A
int n = 4;                         // Columns of B
int lda = m, ldb = k, ldc = m;     // "Leading dimensions" (matrix strides)
double alpha = 0.5, beta = 2.0;

cblas_dgemm(CblasColMajor, CblasNoTrans, CblasNoTrans, m, n, k,
            alpha, a, lda, b, ldb, beta, c, ldc);
```

Lapack

Lapack example: matrix-matrix: diagonalize a real symmetric matrix : operation **dsyevr**

Double **SY**mmetric **E**igen**V**alues with Relatively **R**obust Representations

This is a high-level driver routine!

```
double a[2][2] = {0., 1., 1, 0.};
int n = 2;                   // Dimension of a
int lda = 2;                 // Leading dimension of z
char jobz = 'V';             // Compute e-values + e-vectors
char range = 'A';            // Compute all e-values
char uplo = 'U';             // Upper triangular part of a

double z[2][2];              // Output eigenvectors
int ldz = 2;                 // Leading dimension of z
double w[2] {-3.14, -3.14};  // Output eigenvalues
int m = -1;                  // Output: number of e-values found
int isuppz[4];               // "Support output"

LAPACKE_dsyevr(LAPACK_COL_MAJOR, jobz, range, uplo, n, (double *)a, lda, 0, 0,
               0, 0, 0, &m, w, (double *)z, ldz, isuppz);
```

title

text

Thank you for your attention !

THE END