11. Reference Types

Reference Types: Definition and Initialization, Pass By Value, Pass by Reference, Temporary Objects, Constants, Const-References

Swap!

```
// POST: values of x and y are exchanged
void swap (int& x, int& y) {
 int t = x;
 x = y;
 y = t;
}
int main(){
    int a = 2;
    int b = 1;
    swap (a, b);
    assert (a == 1 && b == 2); // ok!  ☺
}
```

Reference Types

- We can make functions change the values of the call arguments
- no new concept for functions, but a new class of types

↑
Reference Types

Reference Types: Definition

T& read as "*T*-reference"

↑
underlying type

- *T&* has the same range of values and functionality as *T*, ...
- but initialization and assignment work differently.

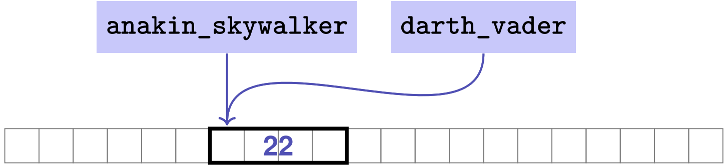
Anakin Skywalker alias Darth Vader

Anakin Skywalker alias Darth Vader

```
int anakin_skywalker = 9;
int& darth_vader = anakin_skywalker; //  alias
darth_vader = 22;
```

assignment to the L-value behind the alias

```
std::cout << anakin_skywalker; // 22
```



Reference Types: Intialization and Assignment

```
int& darth_vader = anakin_skywalker;
darth_vader = 22; // anakin_skywalker = 22
```

- A variable of reference type (a *reference*) can only be initialized with an L-Value .
- The variable is becoming an *alias* of the L-value (a different name for the referenced object).
- Assignment to the reference is to the object behind the alias.

Reference Types: Implementation

Internally, a value of type *T&* is represented by the address of an object of type *T*.

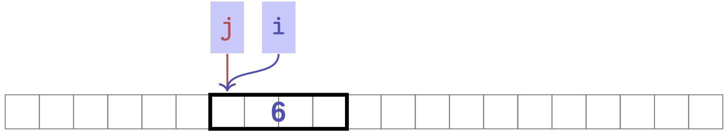
```
int& j;  // Error: j must be an alias of something

int& k = 5;  // Error: the literal 5 has no address
```

Pass by Reference

Reference types make it possible that functions modify the value of the call arguments:

```
void increment (int& i)
{ // i becomes an alias of the call argument
    ++i;
}
...
int j = 5;
increment (j);
std::cout << j << "\n"; // 6
```

← initialization of the formal arguments



Pass by Reference

Formal argument has reference type:

⇒ **Pass by Reference**

Formal argument is (internally) initialized with the *address* of the call argument (L-value) and thus becomes an *alias*.

Pass by Value

Formal argument does not have a reference type:

⇒ **Pass by Value**

Formal argument is initialized with the *value* of the actual parameter (R-Value) and thus becomes a *copy*.

References in the Context of intervals_intersect

```
// PRE:  [a1, b1], [a2, b2] are (generalized) intervals,
// POST: returns true if [a1, b1], [a2, b2] intersect, in which case
//       [l, h] contains the intersection of [a1, b1], [a2, b2]
bool intervals_intersect (int& l, int& h,
                          int a1, int b1, int a2, int b2) {
  sort (a1, b1);
  sort (a2, b2);
  l = std::max (a1, a2); // Assignments
  h = std::min (b1, b2); // via references
  return l <= h;
}
...
int lo = 0; int hi = 0;
if (intervals_intersect (lo, hi, 0, 2, 1, 3)) // Initialization
   std::cout << "[" << lo << "," << hi << "]" << "\n"; // [1,2]
```

References in the Context of intervals_intersect

```
// POST: a <= b
void sort (int& a, int& b) {
   if (a > b)
     std::swap (a, b); // Initialization ("passing through" a, b
}

bool intervals_intersect (int& l, int& h,
                          int a1, int b1, int a2, int b2) {
  sort (a1, b1); // Initialization
  sort (a2, b2); // Initialization
  l = std::max (a1, a2);
  h = std::min (b1, b2);
  return l <= h;
}
```

Return by Value / Reference

- Even the return type of a function can be a reference type (return by reference)
- In this case the function call itself is an L-value

```
int& increment (int& i)
{
     return ++i;
}
```

exactly the semantics of the pre-increment

Temporary Objects

What is wrong here?

```
int& foo (int i)
{
     return i;
}
```

Return value of type `int&` becomes an alias of the formal argument. But the memory lifetime of i ends after the call!

```
int k = 3;
int& j = foo (k); // j is an alias of a zombie
std::cout << j << "\n";  // undefined behavior
```

The Reference Guidline

Reference Guideline

When a reference is created, the object referred to must “stay alive” at least as long as the reference.

Const-References

- have type `const` *T* `&`
- type can be interpreted as “(`const` *T*) `&`”
- can be initialized with R-Values (compiler generates a temporary object with sufficient lifetime)

`const` *T*`&` `r` = *lvalue*;

r is initialized with the address of *lvalue* (efficient)

`const` *T*`&` `r` = *rvalue*;

r is initialized with the address of a temporary object with the value of the *rvalue* (pragmatic)

When `const` *T*`&` ?

Rule

Argument type `const` *T* `&` (pass by *read-only* reference) is used for efficiency reasons instead of *T* (pass by value), if the type *T* requires large memory. For fundamental types (`int`, `double`,...) it does not pay off.

Examples will follow later in the course

What exactly does Constant Mean?

Consider an L-value with type `const` *T*

- Case 1: *T* is no reference type

Then the L-value is a constant.

```
const int n = 5;
int& i = n; // error: const-qualification is discarded
i = 6;
```

The compiler detects our attempt to cheat

What exactly does Constant Mean?

Consider L-value of type `const` *T*

- Case 2: *T* is reference type.

Then the L-value is a read-only alias which cannot be used to change the value

```
int n = 5;
const int& i = n;// i: read-only alias of n
int& j = n;      // j: read-write alias
i = 6;           // Error: i is a read-only alias
j = 6;           // ok: n takes on value 6
```

12. Vectors and Strings I

Vector Types, Sieve of Erathostenes, Memory Layout, Iteration, Characters and Texts, ASCII, UTF-8, Caesar-Code

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Vectors: Motivation

- Now we can iterate over numbers

```
for (int i=0; i<n ; ++i) ...
```

- Often we have to iterate over *data*. (Example: find a cinema in Zurich that shows “C++ Runner 2049” today)
- Vectors allow to store *homogeneous* data (example: schedules of all cinemas in Zurich)

Vectors: a first Application

The Sieve of Erathostenes

- computes all prime numbers $< n$
- method: cross out all non-prime numbers

2	3	~~4~~	5	~~6~~	7	~~8~~	~~9~~	~~10~~	11	~~12~~	13	~~14~~	~~15~~	~~16~~	17	~~18~~	19	~~20~~	~~21~~	~~22~~	23

at the end of the crossing out process, only prime numbers remain.

- Question: how do we cross out numbers ??
- Answer: with a *vector*.

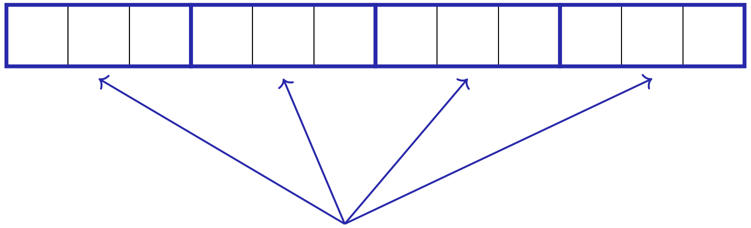
Sieve of Erathostenes with Vectors

```
#include <iostream>
#include <vector> // standard containers with vector functionality
int main() {
  // input
  std::cout << "Compute prime numbers in {2,...,n−1} for n =? ";
  unsigned int n;
  std::cin >> n;

  // definition and initialization: provides us with Booleans
  // crossed_out[0],..., crossed_out[n−1], initialized to false
  std::vector<bool> crossed_out (n, false);

  // computation and output
  std::cout << "Prime numbers in {2,...," << n−1 << "}:\n";
  for (unsigned int i = 2; i < n; ++i)
    if (!crossed_out[i]) { // i is prime
      std::cout << i << " ";
      // cross out all proper multiples of i
      for (unsigned int m = 2∗i; m < n; m += i)
        crossed_out[m] = true;
    }
  std::cout << "\n";
  return 0;
```

Memory Layout of a Vector

- A vector occupies a *contiguous* memory area

example: a vector with 4 elements



memory cells for a value of type `T` each

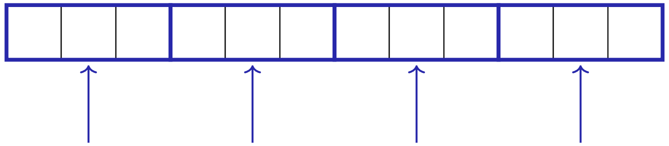
Random Access

The L-value

value i

a [*expr*]

has type *T* and refers to the i-th element of the vector *a* (counting from 0!)



a[0] a[1] a[2] a[3]

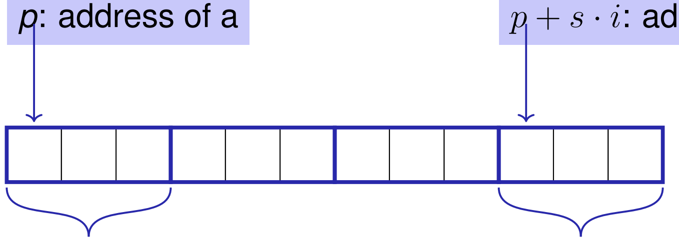
Random Access

a [*expr*]

The value i of *expr* is called *index*.
`[]`: subscript operator

Random Access

- Random access is very efficient:



p: address of a

$p + s \cdot i$: address of a[i]

s: memory consumption of *T* (in cells)

a[i]

Vector Initialization

- `std::vector<int> a (5);`
  The five elements of `a` are zero intialized)
- `std::vector<int> a (5, 2);`
  the 5 elements of `a` are initialized with 2.
- `std::vector<int> a {4, 3, 5, 2, 1};`
  the vector is initialized with an *initialization list*.
- `std::vector<int> a;`
  An initially empty vector is created.

Attention

- Accessing elements outside the valid bounds of a vector leads to undefined behavior.

```
std::vector arr (10);
for (int i=0; i<=10; ++i)
  arr[i] = 30; // runtime error: access to arr[10]!
```

Attention

Bound Checks

When using a subscript operator on a vector, it is the sole *responsibility of the programmer* to check the validity of element accesses.

Vectors are Comfortable

```
std::vector<int> v (10);
v.at(5) = 3; // with bound check
v.push_back(8); // 8 is appended
std::vector<int> w = v; // w is initialized with v
int sz = v.size(); // sz = 11
```

Characters and Texts

- We have seen texts before:

```
std::cout << "Prime numbers in {2,...,999}:\n";
```

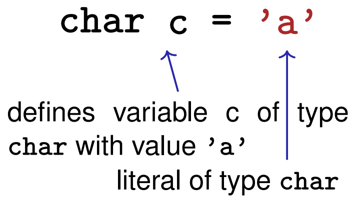
$\underbrace{\texttt{"Prime numbers in \{2,...,999\}:\textbackslash n"}}_{\text{String-Literal}}$

- can we really work with texts? Yes:

Character:	Value of the fundamental type **`char`**
Text:	**`std::string`** ≈ vector of **`char`** elements

The type `char` (“character”)

- represents printable characters (e.g. **`'a'`**) and *control characters* (e.g. **`'\n'`**)



```
char c = 'a'
```

defines variable c of type **`char`** with value **`'a'`**

literal of type **`char`**

The type `char` (“character”)

is formally an integer type

- values convertible to **`int`** / **`unsigned int`**
- all arithmetic operators are available (with dubious use: what is **`'a'/'b'`** ?)
- values typically occupy 8 Bit

domain:
$\{-128, \ldots, 127\}$ or $\{0, \ldots, 255\}$

The ASCII-Code

- defines concrete conversion rules
  `char` $\longrightarrow$ **`int / unsigned int`**
- is supported on nearly all platforms

Zeichen $\longrightarrow \{0, \ldots, 127\}$
`'A', 'B', ... , 'Z'` $\longrightarrow 65, 66, ..., 90$
`'a', 'b', ... , 'z'` $\longrightarrow 97, 98, ..., 122$
`'0', '1', ... , '9'` $\longrightarrow 48, 49, ..., 57$

-
  ```
  for (char c = 'a'; c <= 'z'; ++c)
      std::cout << c;
  ```

```
abcdefghijklmnopqrstuvwxyz
```

Extension of ASCII: UTF-8

- Internationalization of Software ⇒ large character sets required. Common today: unicode, 100 symbol sets, 110000 characters.
- ASCII can be encoded with 7 bits. An eighth bit can be used to indicate the appearance of further bits.

Bits	Encoding
7	`0xxxxxxx`
11	`110xxxxx 10xxxxxx`
16	`1110xxxx 10xxxxxx 10xxxxxx`
21	`11110xxx 10xxxxxx 10xxxxxx 10xxxxxx`
26	`111110xx 10xxxxxx 10xxxxxx 10xxxxxx 10xxxxxx`
31	`1111110x 10xxxxxx 10xxxxxx 10xxxxxx 10xxxxxx 10xxxxxx`

Interesting property: for each byte you can decide if a new UTF8 character begins.

Einige Zeichen in UTF-8

Symbol	Codierung (jeweils 16 Bit)
ﯹ	`11101111 10101111 10111001`
☠	`11100010 10011000 10100000`
☃	`11100010 10011000 10000011`
☙	`11100010 10011000 10011001`
A	`01000001`

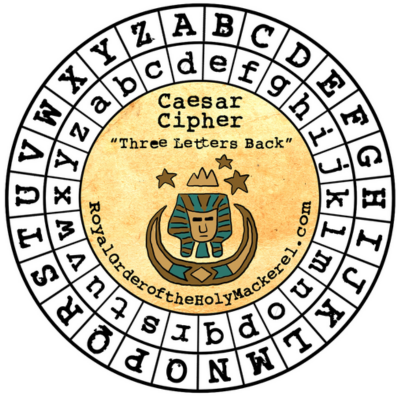
P.S.: Search for `apple "unicode of death"`

http://t-a-w.blogspot.ch/2008/12/funny-characters-in-unicode.html

Caesar-Code

Replace every printable character in a text by its pre-pre-predecessor.

’ ’	(32)	→	’|’	(124)
’!’	(33)	→	’}’	(125)
		...		
’D’	(68)	→	’A’	(65)
’E’	(69)	→	’B’	(66)
		...		
∼	(126)	→	’{’	(123)



Caesar-Code: `shift`-Function

```
// pre: divisor > 0
// post: return the remainder of dividend / divisor
//       with 0 <= result < divisor
int mod(int dividend, int divisor);

// POST: if c is one of the 95 printable ASCII characters, c is
//       cyclically shifted s printable characters to the right
char shift(char c, int s) {
   if (c >= 32 && c <= 126) { // c printable
     c = 32 + mod(c − 32 + s,95)};
   }
   return c;
}
```

"- 32" transforms interval $[32, 126]$ to $[0, 94]$
"32 +" transforms interval $[0, 94]$ back to $[32, 126]$
mod(x,95) is the representative of $x(\mathrm{mod} 95)$ in interval $[0, 94]$

Caesar-Code: `caesar`-Function

```
// POST: Each character read from std::cin was shifted cyclically
//       by s characters and afterwards written to std::cout
void caesar(int s) {
  std::cin >> std::noskipws; // #include <ios>

  char next;
  while (std::cin >> next) {
    std::cout << shift(next, s);
  }
}
```

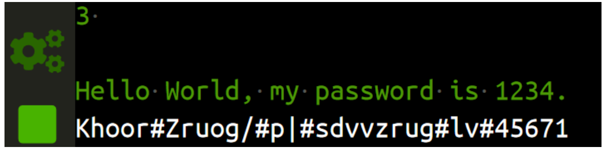
Conversion to `bool`: returns *false* if and only if the input is empty.

shifts only printable characters.

Caesar-Code: Main Program

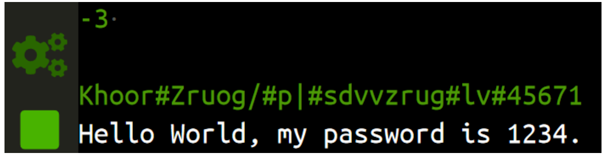
```
int main() {
  int s;
  std::cin >> s;

  // Shift input by s
  caesar(s);

  return 0;
}
```

Encode: shift by n (here: 3)



```
3·
Hello·World,·my·password·is·1234.
Khoor#Zruog/#p|#sdvvzrug#lv#45671
```

Encode: shift by $-n$ (here: -3)

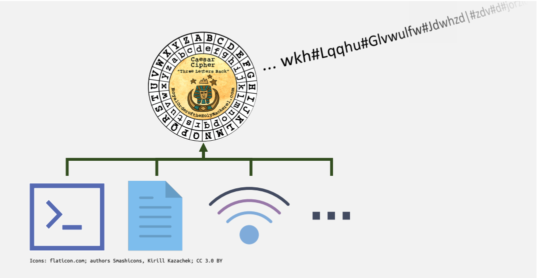


```
-3·
Khoor#Zruog/#p|#sdvvzrug#lv#45671
Hello World, my password is 1234.
```

Caesar-Code: Generalisation

```
void caesar(int s) {
  std::cin >> std::noskipws;

  char next;
  while (std::cin >> next) {
    std::cout << shift(next, s);
  }
}
```

- Currently only from `std::cin` to `std::cout`
- Better: from arbitrary character source (console, file, ...) to arbitrary character sink (console, ...)



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Caesar-Code: Generalisation

```
void caesar(std::istream& in,
            std::ostream& out,
            int s) {

  in >> std::noskipws;

  char next;
  while (in >> next) {
    out << shift(next, s);
  }
}
```

- `std::istream`/`std::ostream` is an *generic input/output stream* of `char`s
- Function is called with *specific streams*, e.g.: Console (`std::cin/cout`), Files (`std::i/ofstream`), Strings (`std::i/ostringstream`)

Caesar-Code: Generalisation, Example 1

```
#include <iostream>
...

// in void main():
caesar(std::cin, std::cout, s);
```

Calling the generalised `caesar` function: from `std::cin` to `std::cout`

Caesar-Code: Generalisation, Example 2

```
#include <iostream>
#include <fstream>
...

// in void main():
std::string from_file_name = ...; // Name of file to read from
std::string to_file_name = ...; // Name of file to write to
std::ifstream from(from_file_name); // Input file stream
std::ofstream to(to_file_name); // Output file stream

caesar(from, to, s);
```

Calling the generalised `caesar` function: from file to file

Caesar-Code: Generalisation, Example 3

```
#include <iostream>
#include <sstream>
...

// in void main():
std::string plaintext = "My password is 1234";
std::istringstream from(plaintext);

caesar(from, std::cout, s);
```

Calling the generalised `caesar` function: from a string to `std::cout`