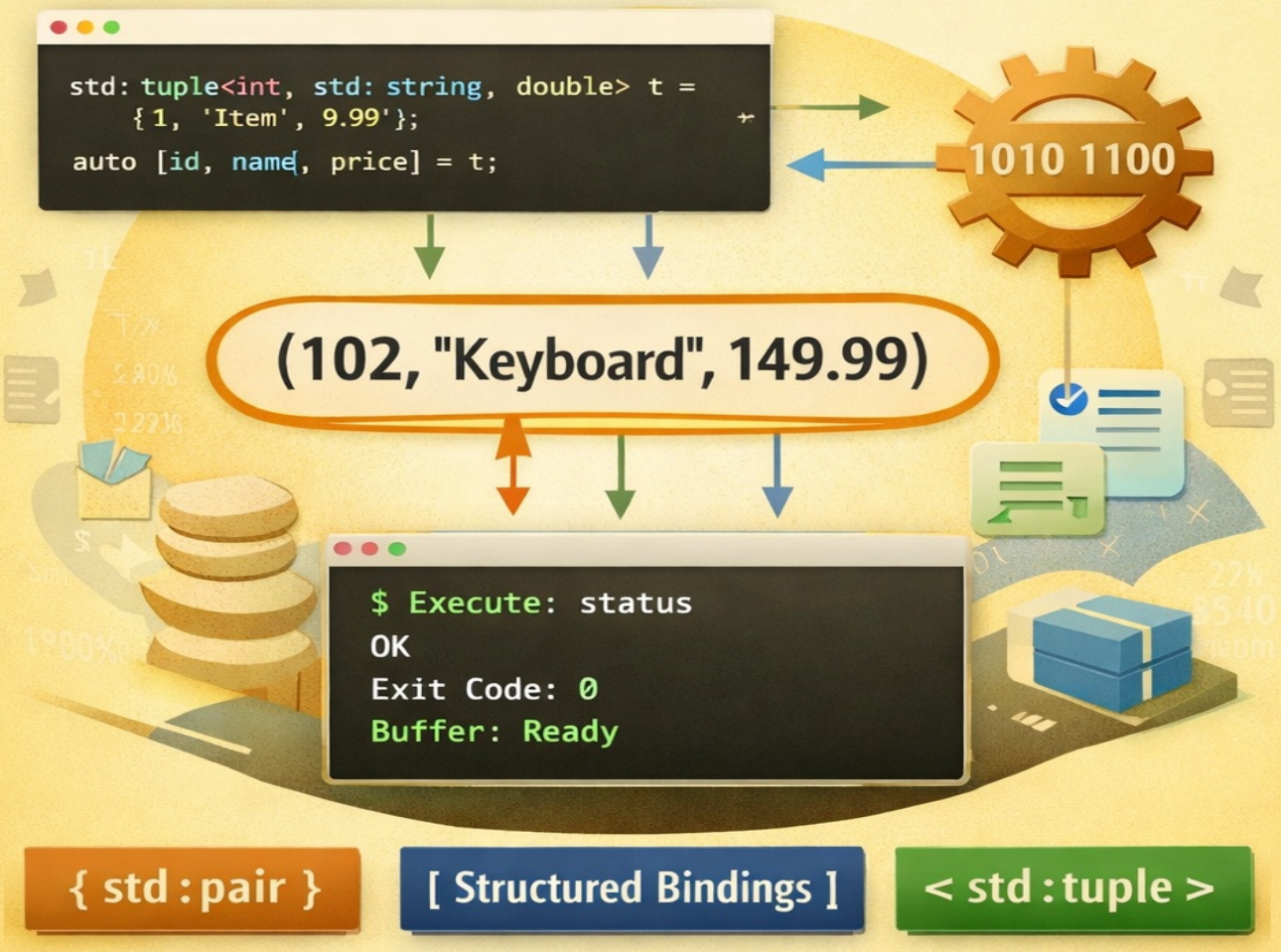
Modern C++

Multi-Value Abstractions

*Designing Efficient and Expressive Data Grouping with **std:tuple***



{ std : pair } [Structured Bindings] < std : tuple >

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Modern C++ Multi-Value Abstractions

Designing Efficient and Expressive Data Grouping with std::tuple

Some drafting assistance and idea exploration were supported by modern AI tools, with full supervision, verification, correction, and authorship.

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Tuple in Modern C++

1.1 Overview

`std::tuple` is one of the most useful utility types in Modern C++. It provides a way to group multiple values of possibly different types into a single object. Unlike arrays or vectors, which normally hold many values of the same type, a tuple can hold an `int`, a `std::string`, a `double`, a `bool`, and many other types together in a fixed structure.

A tuple is a **fixed-size heterogeneous container**. The term fixed-size means that the number of elements is determined at compile time and does not change at runtime. The term heterogeneous means that the stored elements may have different types.

In real software, tuples are commonly used when:

- a function needs to return more than one value,
- temporary grouped data is needed without designing a dedicated `struct`,
- generic library code must handle collections of values with different types,
- algorithms need to associate several related values together,
- internal helper code needs compact grouping without creating a full class.

Although tuples are powerful, they should be used with care. A tuple is ideal for temporary, local, or generic programming tasks. However, if the grouped values have clear semantic meaning, a named `struct` is usually more readable and more maintainable.

1.2 Header

```
#include <tuple>
```

In many practical examples, tuples are also used together with other headers such as:

```
#include <string>
#include <vector>
#include <iostream>
#include <utility>
#include <algorithm>
```

1.3 Why `std::tuple` Exists

Before `std::tuple`, programmers often used:

- output parameters,
- custom `struct` types,
- arrays with weak type meaning,
- `std::pair` even when two values were not enough.

`std::tuple` solves the problem of grouping multiple values in a strongly typed and efficient way. It is especially useful when the grouped values are not meant to define a long-lived domain model, but rather represent a temporary bundle of results.
For example, a function that analyzes a file may need to return:

- whether the operation succeeded,
- the number of lines,
- the number of words,
- an error message.

Using a tuple makes this possible without creating a dedicated data type every time.

1.4 Key Characteristics

- The number of elements is fixed at compile time.
- Each element may have a completely different type.

- Access is type-safe.
- Access is normally done by compile-time index using `std::get`.
- Tuples integrate well with structured bindings.
- Tuples are efficient and do not introduce hidden runtime overhead beyond the stored objects themselves.
- Tuples support comparison operations when their element types support comparison.
- Tuples work well in generic programming and template metaprogramming.

1.5 Basic Syntax

1.5.1 Direct Construction

```
std::tuple<int, std::string, double> t(10, "Hello", 3.14);
```

This tuple contains:

- element 0: `int`
- element 1: `std::string`
- element 2: `double`

1.5.2 Using `std::make_tuple`

```
auto t = std::make_tuple(42, std::string("World"), 2.71);
```

`std::make_tuple` is convenient because the compiler deduces the tuple type automatically.

1.5.3 A First Complete Example

```
#include <iostream>
#include <tuple>
#include <string>

int main() {
    std::tuple<int, std::string, double> product(1001, "Keyboard", 149.95);
```

```
    std::cout << "ID    : " << std::get<0>(product) << '\n';
    std::cout << "Name  : " << std::get<1>(product) << '\n';
    std::cout << "Price : " << std::get<2>(product) << '\n';
}
```

1.5.4 Explanation

In this example, the tuple stores three related values:

- the product identifier,
- the product name,
- the product price.

This is acceptable for small internal logic, but if product data becomes central to the application, a dedicated `struct Product` would be better.

1.6 Accessing Elements

1.6.1 Access by Index

Tuple elements are accessed with `std::get<index>(tuple)`.

```
auto t = std::make_tuple(7, std::string("Ali"), 88.5);

std::cout << std::get<0>(t) << '\n';
std::cout << std::get<1>(t) << '\n';
std::cout << std::get<2>(t) << '\n';
```

The index is a compile-time constant, not a runtime variable.

1.6.2 Modifying Elements

```
auto t = std::make_tuple(7, std::string("Ali"), 88.5);

std::get<0>(t) = 10;
std::get<1>(t) = "Omar";
std::get<2>(t) = 91.25;
```

This shows an important difference from Python tuples. In C++, tuple elements are modifiable if the tuple object itself is non-const and the element type supports assignment.

1.6.3 Access by Type

If a tuple contains a type only once, it is possible to access by type:

```
std::tuple<int, std::string, double> t(1, "Book", 55.0);

std::cout << std::get<std::string>(t) << '\n';
```

However, this works only when the type appears exactly once. If the same type appears multiple times, access by type is ambiguous and not allowed.

1.7 Tuple Construction Techniques

1.7.1 Using Direct Initialization

```
std::tuple<int, char, bool> t(5, 'A', true);
```

1.7.2 Using Brace Initialization

```
std::tuple<int, char, bool> t{5, 'A', true};
```

1.7.3 Using `std::make_tuple`

```
auto t = std::make_tuple(5, 'A', true);
```

1.7.4 Using Class Template Argument Deduction

In newer C++ standards, class template argument deduction can simplify code:

```
std::tuple t(5, std::string("Hello"), 9.5);
```

The compiler deduces the tuple type automatically.

1.8 Structured Bindings

Structured bindings, introduced in C++17, make tuples much easier to use.

1.8.1 Basic Example

```
auto t = std::make_tuple(1, std::string("Item"), 9.99);

auto [id, name, price] = t;

std::cout << id << ' ' << name << ' ' << price << '\n';
```

1.8.2 Why Structured Bindings Matter

Without structured bindings, tuple code often becomes less readable because of repeated `std::get<>()` calls. Structured bindings assign meaningful variable names to each element.

1.8.3 Binding by Reference

```
auto t = std::make_tuple(1, std::string("Mouse"), 50.0);

auto& [id, name, price] = t;

id = 2;
name = "Monitor";
price = 399.0;

std::cout << std::get<0>(t) << '\n';
std::cout << std::get<1>(t) << '\n';
std::cout << std::get<2>(t) << '\n';
```

Because the bindings are references, modifications affect the original tuple.

1.8.4 Binding from a Const Tuple

```
const auto t = std::make_tuple(10, std::string("Readonly"), 15.5);

const auto& [id, name, value] = t;

std::cout << id << ' ' << name << ' ' << value << '\n';
```

1.9 Returning Multiple Values

One of the most common uses of tuples is returning multiple values from a function.

1.9.1 Simple Example

```
std::tuple<int, int> divideWithRemainder(int a, int b) {
    return {a / b, a % b};
}

int main() {
    auto [quotient, remainder] = divideWithRemainder(17, 5);

    std::cout << "Quotient  = " << quotient << '\n';
    std::cout << "Remainder = " << remainder << '\n';
}
```

1.9.2 Why This Is Better Than Output Parameters

Without tuple return, code often becomes:

```
void divideWithRemainder(int a, int b, int& q, int& r) {
    q = a / b;
    r = a % b;
}
```

That style is valid, but tuple return is often cleaner because:

- the function clearly expresses that it produces a grouped result,
- the caller receives values directly,
- structured bindings make the result easy to read.

1.9.3 Real Case Example: File Analysis Result

```
#include <tuple>
#include <string>
#include <fstream>
#include <sstream>

std::tuple<bool, std::size_t, std::size_t, std::string>
analyzeFile(const std::string& filename) {
    std::ifstream file(filename);
    if (!file) {
        return {false, 0, 0, "Cannot open file"};
```

```
    }

    std::size_t lineCount = 0;
    std::size_t wordCount = 0;
    std::string line;

    while (std::getline(file, line)) {
        ++lineCount;
        std::istringstream iss(line);
        std::string word;
        while (iss >> word) {
            ++wordCount;
        }
    }

    return {true, lineCount, wordCount, ""};
}
```

```
#include <iostream>

int main() {
    auto [ok, lines, words, error] = analyzeFile("report.txt");

    if (!ok) {
        std::cout << "Error: " << error << '\n';
        return 1;
    }

    std::cout << "Lines: " << lines << '\n';
    std::cout << "Words: " << words << '\n';
}
```

1.9.4 Discussion

This is a realistic and useful tuple example because the function returns several related pieces of information:

- success state,
- number of lines,
- number of words,
- error text.

This is a valid tuple usage because the result is compact, temporary, and internal.

1.10 `std::tie`

`std::tie` creates a tuple of references. It is useful for assigning tuple elements into already existing variables.

1.10.1 Basic Example

```
int id;
std::string name;
double salary;

std::tie(id, name, salary) =
    std::make_tuple(101, std::string("Ayman"), 8500.0);
```

1.10.2 Ignoring Unneeded Values

```
int id;
double salary;

std::tie(id, std::ignore, salary) =
    std::make_tuple(101, std::string("Ayman"), 8500.0);
```

1.10.3 Real Case Example: Parsing a Record

```
#include <tuple>
#include <string>
#include <sstream>

std::tuple<int, std::string, double> parseEmployeeLine(const std::string& line) {
    std::istringstream iss(line);

    int id;
    std::string name;
    double salary;

    iss >> id >> name >> salary;
    return {id, name, salary};
}
```

```
#include <iostream>

int main() {
    int employeeId;
    std::string employeeName;
    double employeeSalary;

    std::tie(employeeId, employeeName, employeeSalary) =
        parseEmployeeLine("2001 Omar 7200.5");

    std::cout << employeeId << '\n';
    std::cout << employeeName << '\n';
    std::cout << employeeSalary << '\n';
}
```

1.11 Tuple Utilities

1.11.1 `std::tuple_size`

This utility gives the number of elements in a tuple type.

```
auto t = std::make_tuple(1, 2.5, std::string("Test"));

constexpr std::size_t n = std::tuple_size<decltype(t)>::value;
```

1.11.2 `std::tuple_element`

This utility gives the type of the element at a specific index.

```
using T = std::tuple_element<1, std::tuple<int, double, char>>::type;
```

Here, `T` is `double`.

1.11.3 Checking Types

```
#include <type_traits>
#include <tuple>

using MyTuple = std::tuple<int, double, char>;
using SecondType = std::tuple_element<1, MyTuple>::type;

static_assert(std::is_same_v<SecondType, double>);
```

1.12 Comparing Tuples

Tuples support comparisons if their element types support comparisons.

1.12.1 Example

```
#include <tuple>
#include <iostream>

int main() {
    auto a = std::make_tuple(1, std::string("Ali"), 80.0);
    auto b = std::make_tuple(1, std::string("Ali"), 90.0);

    if (a < b) {
        std::cout << "a is less than b\n";
    }
}
```

Tuple comparison is lexicographical:

- compare first elements,
- if equal, compare second elements,
- continue until a difference is found.

1.12.2 Real Case Example: Sorting Records

```
#include <iostream>
#include <tuple>
#include <vector>
#include <algorithm>
#include <string>

int main() {
    std::vector<std::tuple<int, std::string, double>> employees = {
        {1003, "Nora", 6400.0},
        {1001, "Ayman", 9000.0},
        {1002, "Omar", 7200.0}
    };
```

```
    std::sort(employees.begin(), employees.end());

    for (const auto& [id, name, salary] : employees) {
        std::cout << id << " | " << name << " | " << salary << '\n';
    }
}
```

Because tuples compare lexicographically, this sorts first by ID, then by name, then by salary.

1.13 Tuple and `std::pair`

`std::pair` is a special case of `std::tuple` containing exactly two elements.

1.13.1 Example

```
std::pair<int, std::string> p{1, "One"};
std::tuple<int, std::string> t{1, "One"};
```

1.13.2 When to Use Each

Use `std::pair` when:

- exactly two values are grouped,
- the pair meaning is simple,
- API conventions already use pair.

Use `std::tuple` when:

- there are three or more values,
- generic programming needs arbitrary element counts,
- a richer grouped return is needed.

1.14 Real Case Example: Student Exam Processing

This example demonstrates a more realistic use of tuples in data processing code.

1.14.1 Goal

We want to process exam results where each record contains:

- student ID,
- student name,
- math score,
- physics score,
- chemistry score.

We will store records in tuples, compute total and average, and report status.

1.14.2 Implementation

```
#include <iostream>
#include <tuple>
#include <vector>
#include <string>
#include <iomanip>

using StudentRecord = std::tuple<
    int,
    std::string,
    double,
    double,
    double
>;

std::tuple<double, double, bool> analyzeScores(
    double math,
    double physics,
    double chemistry
) {
    double total = math + physics + chemistry;
    double average = total / 3.0;
    bool passed = average >= 60.0;
    return {total, average, passed};
}
```

```cpp
int main() {
    std::vector<StudentRecord> students = {
        {1001, "Ayman", 82.5, 77.0, 91.0},
        {1002, "Omar", 55.0, 63.5, 58.0},
        {1003, "Lina", 95.0, 88.5, 92.0},
        {1004, "Nora", 61.0, 59.0, 62.0}
    };

    for (const auto& [id, name, math, physics, chemistry] : students) {
        auto [total, average, passed] =
            analyzeScores(math, physics, chemistry);

        std::cout << "Student ID : " << id << '\n';
        std::cout << "Name       : " << name << '\n';
        std::cout << "Math       : " << math << '\n';
        std::cout << "Physics    : " << physics << '\n';
        std::cout << "Chemistry  : " << chemistry << '\n';
        std::cout << "Total      : " << total << '\n';
        std::cout << "Average    : " << average << '\n';
        std::cout << "Status     : " << (passed ? "Passed" : "Failed") << '\n';
        std::cout << "----------------------------\n";
    }
}
```

1.14.3 Why This Example Is Useful

This example demonstrates several important tuple uses:

- storing heterogeneous records,
- unpacking records with structured bindings,
- returning multiple computed values from a helper function,
- keeping temporary grouped data concise.

1.14.4 Important Observation

This style is useful for internal educational examples and smaller processing tasks. However, if student records become part of a large system, a dedicated `struct Student` would likely be a better design.

1.15 Real Case Example: Inventory and Sales Summary

This example models a small inventory report.

1.15.1 Problem

Suppose a store needs to store:

- product code,
- product name,
- unit price,
- quantity sold.

Then the system should compute:

- total sales amount,
- tax amount,
- final amount after tax.

1.15.2 Implementation

```
#include <iostream>
#include <tuple>
#include <vector>
#include <string>
#include <iomanip>

using ProductSale = std::tuple<int, std::string, double, int>;

std::tuple<double, double, double> calculateAmounts(
    double unitPrice,
    int quantity
) {
    double subtotal = unitPrice * quantity;
    double tax = subtotal * 0.15;
    double total = subtotal + tax;
    return {subtotal, tax, total};
```

```
}

int main() {
    std::vector<ProductSale> sales = {
        {501, "Keyboard", 120.0, 3},
        {502, "Mouse", 80.0, 5},
        {503, "Monitor", 950.0, 2},
        {504, "USB_Cable", 35.0, 10}
    };

    double grandTotal = 0.0;

    for (const auto& [code, name, unitPrice, qty] : sales) {
        auto [subtotal, tax, total] = calculateAmounts(unitPrice, qty);

        grandTotal += total;

        std::cout << "Code      : " << code << '\n';
        std::cout << "Product   : " << name << '\n';
        std::cout << "Unit Price: " << unitPrice << '\n';
        std::cout << "Quantity  : " << qty << '\n';
        std::cout << "Subtotal  : " << subtotal << '\n';
        std::cout << "Tax       : " << tax << '\n';
        std::cout << "Total     : " << total << '\n';
        std::cout << "-----------------------------\n";
    }

    std::cout << "Grand Total: " << grandTotal << '\n';
}
```

1.15.3 Discussion

This is a realistic business-style example showing tuples in:

- transactional calculations,
- grouped return values,
- tuple-based iteration.

1.16 Real Case Example: Parsing Command Results

In systems programming and tooling, it is common to run a process and return multiple outputs such as:

- exit code,
- standard output text,
- standard error text,
- execution success flag.

A tuple is a good short internal result carrier for this case.

1.16.1 Example Design

```
#include <tuple>
#include <string>

std::tuple<bool, int, std::string, std::string>
simulateCommandExecution(const std::string& command) {
    if (command == "version") {
        return {true, 0, "Tool version 1.2.0", ""};
    }

    if (command == "help") {
        return {true, 0, "Usage: tool [options]", ""};
    }

    return {false, 1, "", "Unknown command"};
}
```

```
#include <iostream>

int main() {
    auto [ok, exitCode, outText, errText] =
        simulateCommandExecution("version");

    if (ok) {
        std::cout << "Exit code: " << exitCode << '\n';
        std::cout << "Output   : " << outText << '\n';
    } else {
```

```
        std::cout << "Exit code: " << exitCode << '\n';
        std::cout << "Error    : " << errText << '\n';
    }
}
```

1.16.2 Why Tuple Fits Here

This kind of result is temporary, local, and operational. It is often not necessary to define a dedicated class just to pass a short-lived collection of outputs.

1.17 Tuple in Containers

Tuples can be stored in standard containers such as `std::vector`, `std::list`, or `std::deque`.

1.17.1 Example

```
#include <vector>
#include <tuple>
#include <string>

std::vector<std::tuple<int, std::string, double>> employees = {
    {1, "Ali", 7000.0},
    {2, "Sara", 8200.5},
    {3, "Mona", 7600.0}
};
```

1.17.2 Iterating with Structured Bindings

```
for (const auto& [id, name, salary] : employees) {
    std::cout << id << " | " << name << " | " << salary << '\n';
}
```

1.18 Tuple and Function Results in Search Logic

A very practical scenario is returning the result of a search operation.

1.18.1 Example

```cpp
#include <tuple>
#include <vector>
#include <string>

std::tuple<bool, std::size_t, std::string>
findUserById(
    const std::vector<std::tuple<int, std::string>>& users,
    int targetId
) {
    for (std::size_t i = 0; i < users.size(); ++i) {
        const auto& [id, name] = users[i];
        if (id == targetId) {
            return {true, i, name};
        }
    }
    return {false, 0, ""};
}
```

```cpp
#include <iostream>

int main() {
    std::vector<std::tuple<int, std::string>> users = {
        {1, "Ayman"},
        {2, "Omar"},
        {3, "Lina"}
    };

    auto [found, index, name] = findUserById(users, 2);

    if (found) {
        std::cout << "User found at index " << index
                  << " with name " << name << '\n';
    } else {
        std::cout << "User not found\n";
    }
}
```

1.19 Tuple Concatenation

It is possible to combine tuples using `std::tuple_cat`.

1.19.1 Example

```
#include <tuple>
#include <string>
#include <iostream>

int main() {
    auto a = std::make_tuple(1, 2.5);
    auto b = std::make_tuple(std::string("Hello"), true);

    auto c = std::tuple_cat(a, b);

    std::cout << std::get<0>(c) << '\n';
    std::cout << std::get<1>(c) << '\n';
    std::cout << std::get<2>(c) << '\n';
    std::cout << std::get<3>(c) << '\n';
}
```

1.20 Using Tuples with Generic Code

Tuple is especially important in generic code because templates can work with arbitrary types grouped together.

1.20.1 Example: Generic Return of Three Different Values

```
template<typename T>
std::tuple<T, T, T> duplicateThreeTimes(const T& value) {
    return {value, value, value};
}
```

```
auto [a, b, c] = duplicateThreeTimes<std::string>("C++");
```

1.21 Tuple vs `struct`

This is one of the most important design discussions.

1.21.1 Tuple Version

```
std::tuple<int, std::string, double> employee = {101, "Ayman", 9000.0};
```

1.21.2 Struct Version

```
struct Employee {
    int id;
    std::string name;
    double salary;
};

Employee employee{101, "Ayman", 9000.0};
```

1.21.3 Why the Struct Is Often Better

The struct version is usually better for domain objects because:

- field names carry meaning,
- code becomes self-documenting,
- maintenance is easier,
- later extension is more natural,
- member functions can be added if needed.

1.21.4 Rule of Thumb

Use a tuple when:

- the grouping is temporary,
- the code is local and simple,
- the data has no strong domain identity,
- generic programming benefits from tuple form.

Use a struct when:

- the data represents a real object in the domain,

- readability matters strongly,
- the type is shared across modules,
- the object may evolve with behavior and invariants.

1.22 C++ Tuple vs Python Tuple

Although the names are similar, C++ tuples and Python tuples differ in major ways.

1.22.1 Python Example

```
t = (10, "Hello", 3.14)

print(t[0])
print(t[1])
print(t[2])

x, y, z = t
```

1.22.2 Important Differences

- Python tuple access uses runtime indexing such as `t[0]`.
- C++ tuple access usually uses compile-time indexing such as `std::get<0>(t)`.
- Python tuples are immutable.
- C++ tuple elements can be modified if the tuple itself is not const.
- Python is dynamically typed.
- C++ is statically typed.
- In Python, tuple operations are flexible and very common in daily scripting.
- In C++, tuples are more formal and are often used in utility code, generic code, and multi-value returns.

1.22.3 Python Style

In Python, tuples are lightweight and convenient for quick packing and unpacking.

1.22.4 C++ Style

In C++, tuples fit the language philosophy of strong typing, compile-time knowledge, and zero-overhead abstraction.

1.22.5 Comparison Table

Aspect	**C++ `std::tuple`**	**Python tuple**
Typing	Static, compile-time checked	Dynamic, runtime checked
Mutability	Modifiable if non-const	Immutable
Access style	`std::get<>()` or structured bindings	Indexing and unpacking
Performance model	Native compiled efficiency	Interpreted or VM-based runtime
Main usage style	Utility, generic code, multi-return	Daily scripting and lightweight grouping

1.23 Common Mistakes

1.23.1 Using Tuple Where Meaningful Names Are Needed

```
std::tuple<int, std::string, double, bool> x;
```

This is legal, but unclear. A reader must remember the meaning of each position.

1.23.2 Better Alternative

```
struct EmployeeStatus {
    int id;
    std::string name;
    double salary;
    bool active;
};
```

1.23.3 Overusing `std::get`

```
std::cout << std::get<0>(t) << '\n';
std::cout << std::get<1>(t) << '\n';
std::cout << std::get<2>(t) << '\n';
```

Too much repeated positional access hurts readability. Structured bindings are often better.

1.23.4 Using Runtime Variable as Tuple Index

This does not work:

```
int i = 1;
// std::cout << std::get<i>(t); // Error
```

Tuple indices must be compile-time constants.

1.23.5 Choosing Tuple for Public API Design Without Care

If an API returns a tuple with many unnamed positions, users of the API may find it difficult to understand what each value means.

1.24 Best Practices

- Use tuples for short-lived grouped results.
- Prefer structured bindings for readability.
- Use `std::tie` when assigning to existing variables.
- Prefer a named `struct` when the values represent a meaningful domain object.
- Avoid large tuples with too many unrelated elements.
- Document tuple meaning clearly when the tuple has more than two or three elements.
- Use type aliases to improve readability for longer tuple types.

1.24.1 Type Alias Example

```
using EmployeeTuple = std::tuple<int, std::string, double>;
```

This is better than repeating the full type everywhere.

1.25 Extended Practical Example: Mini Employee Reporting System

This final example combines many tuple concepts in a realistic small application.

1.25.1 Requirements

We want to:

- store employees in a container,
- calculate annual salary and bonus,
- search by employee ID,
- print a formatted report,
- return multiple values from helper functions.

1.25.2 Implementation

```
#include <iostream>
#include <tuple>
#include <vector>
#include <string>
#include <iomanip>

using Employee = std::tuple<int, std::string, double, int>;
// id, name, monthly salary, years of service

std::tuple<double, double, double> calculateCompensation(
    double monthlySalary,
    int yearsOfService
) {
    double annualSalary = monthlySalary * 12.0;

    double bonusRate = 0.05;
    if (yearsOfService >= 10) {
        bonusRate = 0.20;
    } else if (yearsOfService >= 5) {
        bonusRate = 0.10;
    }
```

```
    double bonus = annualSalary * bonusRate;
    double totalCompensation = annualSalary + bonus;

    return {annualSalary, bonus, totalCompensation};
}

std::tuple<bool, Employee> findEmployeeById(
    const std::vector<Employee>& employees,
    int targetId
) {
    for (const auto& employee : employees) {
        if (std::get<0>(employee) == targetId) {
            return {true, employee};
        }
    }

    return {false, Employee{}};
}

void printEmployeeReport(const Employee& employee) {
    const auto& [id, name, monthlySalary, yearsOfService] = employee;

    auto [annualSalary, bonus, totalCompensation] =
        calculateCompensation(monthlySalary, yearsOfService);

    std::cout << "Employee ID         : " << id << '\n';
    std::cout << "Name                : " << name << '\n';
    std::cout << "Monthly Salary      : " << monthlySalary << '\n';
    std::cout << "Years of Service    : " << yearsOfService << '\n';
    std::cout << "Annual Salary       : " << annualSalary << '\n';
    std::cout << "Bonus               : " << bonus << '\n';
    std::cout << "Total Compensation  : " << totalCompensation << '\n';
    std::cout << "----------------------------------------\n";
}

int main() {
    std::vector<Employee> employees = {
        {1001, "Ayman", 9000.0, 12},
        {1002, "Omar", 7200.0, 6},
        {1003, "Lina", 8300.0, 3},
        {1004, "Nora", 7600.0, 9}
```

```
    };

    std::cout << "=== Employee Reports ===\n\n";

    for (const auto& employee : employees) {
        printEmployeeReport(employee);
    }

    std::cout << "\n=== Search Result ===\n\n";

    auto [found, employee] = findEmployeeById(employees, 1002);

    if (found) {
        printEmployeeReport(employee);
    } else {
        std::cout << "Employee not found\n";
    }
}
```

1.25.3 What This Example Demonstrates

This example shows:

- tuple aliases,
- tuples stored in containers,
- structured bindings,
- helper functions returning multiple values,
- tuple-based search results,
- practical reporting logic.

1.25.4 Final Design Reflection

This example is educational and realistic. For a production business system, a named `Employee` class or `struct` would probably be the better long-term choice. Still, this example clearly demonstrates how tuples can simplify many internal tasks and function interactions.

1.26 Summary

`std::tuple` is a powerful and important utility in Modern C++. It allows multiple heterogeneous values to be grouped together efficiently and safely. It is especially useful for returning several values from a function, internal helper logic, temporary grouped data, and generic programming.
Its greatest strengths are:

- flexibility in grouping unlike types,
- compile-time type safety,
- good integration with structured bindings,
- zero-overhead abstraction style.

Its main weakness is readability when overused. A tuple does not give names to its positions, so code may become difficult to understand if tuples are used where a proper named data type is more appropriate.
In practice, a very good rule is this:

- use `std::tuple` for temporary grouped results and utility logic,
- use `struct` or `class` for meaningful long-lived data models.

When used correctly, tuples are an elegant and highly practical part of Modern C++.