Python/C++ Homogeneous Containers

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CHAPTER ONE

INTRODUCTION

Python is well known for it's ability to handle *heterogeneous* data in containers such as lists. But what if you need to interact with C++ containers such as `std::vector<T>` that require *homogeneous* data types?

This project is about converting Python containers (`list`, `dict`, `set`, `tuple`) containing homogeneous types to and from their C++ equivalent.

1.1 A Problematic Example

Suppose that you have a Python list of floats and need to pass it to a C++ library that expects a `std::vector<double>`. If the result of that call modifies the C++ vector, or creates a new one, you need to return a Python list of floats from the result.

Your code might look like this:

```
PyObject *example(PyObject *op) {
    std::vector<double> vec;
    // Populate the vector, function to be defined...
    write_to_vector(op, vec);
    // Do something in C++ with the vector
    // ...
    // Convert the vector back to a Python list.
    // Function to be defined...
    return read_from_vector(vec);
}
```

What should the implementation of `write_to_vector()` and `read_from_vector()` look like?

The answer seems fairly simple; firstly `write_to_vector` converting a Python list to a C++ `std::vector<double>`:

```
void write_to_vector(PyObject *op, std::vector<double> &vec) {
    vec.clear();
    for (Py_ssize_t i = 0; i < PyList_Size(op); ++i) {
        vec.push_back(PyFloat_AsDouble(PyList_GET_ITEM(op, i)));
    }
}
```

And the inverse, `read_from_vector` creating a new Python list from a C++ `std::vector<double>`:

```
PyObject *read_from_vector(const std::vector<double> &vec) {
    PyObject *ret = PyList_New(vec.size());
    for (size_t i = 0; i < vec.size(); ++i) {
```

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```
        PyList_SET_ITEM(ret, i, PyFloat_FromDouble(vec[i]));
    }
    return ret;
}
```

There is no error handling here and all errors are runtime errors.

However if you need to support other object types, say lists of `int`, `bytes` then each one needs a pair of hand written functions. It gets worse when you want to support other containers such as (`tuple`, `set`, `dict`). Then you have to write individual conversion functions for all the combinations of object types *and* containers. This is tedious and error prone.

1.2 Why This Project

This project makes extensive use of C++ templates, partial template specialisation and code generation to reduce dramatically the amount of hand maintained code. It also converts many runtime errors to compile time errors.

If we want to support a fairly basic set of types:

Table 1: Supported Object types.

Python Type	C++ Type
`True`, `False`	`bool`
`int`	`long`
`float`	`double`
`bytes`	`std::string`

And a basic set of containers:

Table 2: Supported Containers.

Python Type	C++ Type
`tuple`	`std::vector`
`list`	`std::vector`
`set`	`std::unordered_set`
`frozenset`	`std::unordered_set`
`dict`	`std::unordered_map`

The number of conversion functions is worse than the cartesian product of the types and containers as in the case of a dict the types can appear as either a key or a value.

The tables above would normally require 64 conversion functions to be written, tested and documented[1] . The project uses a mix of C++ templates and code generators to reduce this number to six hand written functions.

- Two C++ templates for Python `tuple` / `list` two way conversions for all types.
- Two C++ templates for Python `set` / `frozenset` two way conversions for all types.
- Two C++ templates for Python `dict` two way conversions for all types combinations.

[1] There are four unary containers (`tuple`, `list`, `set`, `frozenset`). Each container/type combination requires two functions to give two way conversion from Python to C++ and back. Thus 4 (containers) * 4 (types) * 2 (way conversion) = 32 required functions. For `dict` there are four types but the key and the value can be either so 16 possible variations (any 2 out of 4). With two way conversion this means another 32 functions. This is a total of 64 functions.

These templates are fairly simple and comprehensible and, for simplicity, code generation via a Python script is used to create the extensive number of final functions.

1.3 Hand Written Functions

There are only six non-trivial hand written functions along with a much larger of generated functions that successively specialise these functions.

As an example, here how the function is developed that converts a Python list of `float` to a C++ `std::vector<double>`.

1.3.1 Converting a Python tuple or list to a C++ `std::vector<T>`

This generic function that converts unary Python indexed containers (`tuple` and `list`) to a C++ `std::vector<T>` for any type has this signature:

```
template<typename T,
        int (*PyObject_Check)(PyObject *),
        T (*PyObject_Convert)(PyObject *),
        int(*PyUnaryContainer_Check)(PyObject *),
        Py_ssize_t(*PyUnaryContainer_Size)(PyObject *),
        PyObject *(*PyUnaryContainer_Get)(PyObject *, size_t)>
int
generic_py_unary_to_cpp_std_vector(PyObject *op, std::vector<T> &vec);
```

This template has these parameters:

Table 3: `generic_py_unary_to_cpp_std_vector()` template parameters.

Template Parameter	Notes
`T`	The C++ type of the objects in the target C++ container.
`PyObject_Check`	A pointer to a function that checks that any `PyObject *` in the Python container is the correct type, for example that it is a `bytes` object.
`PyObject_Convert`	A pointer to a function that converts any `PyObject *` in the Python container to the C++ type, for example from `bytes` -> `std::string`.
`PyUnaryContainer_Check`	A pointer to a function that checks that the `PyObject *` argument is the correct container type, for example a `tuple`.
`PyUnaryContainer_Size`	A pointer to a function that returns the size of the Python container.
`PyUnaryContainer_Get`	A pointer to a function that gets a `PyObject *` from the Python container at a given index.

The function has the following parameters.

Table 4: `generic_py_unary_to_cpp_std_vector()` parameters.

Type	Name	Notes
`PyObject *`	`op`	The Python container to read from.
`std::vector<T>`	`vec`	The C++ to write to.

The return value is zero on success or non zero if there is a runtime error. These errors could be:

- `PyObject *op` is not a container of the required type.

- An member of the Python container can not be converted to the C++ type `T` (`PyObject_Check` fails).

1.3.2 Partial Specialisation to Convert a Python list to a C++ `std::vector<T>`

This template can be partially specialised for converting Python *lists* of any type to C++ `std::vector<T>`. This is hand written code but it is trivial by wrapping a single function call.

Note the use of the function pointers to `py_list_check`, `py_list_len` and `py_list_get`. These are thin wrappers around existing functions or macros in `"Python.h"`.

```
template<typename T, int (*PyObject_Check)(PyObject *), T (*PyObject_Convert)(PyObject␣
↪*)>
int generic_py_list_to_cpp_std_vector(PyObject *op, std::vector<T> &vec) {
    return generic_py_unary_to_cpp_std_vector<T, PyObject_Check, PyObject_Convert,
        &py_list_check, &py_list_len, &py_list_get>(op, vec);
}
```

1.4 Generated Functions

These are created by a script that takes the cartesian product of object types and container types and creates functions for each container/object. For example, to convert a Python `list` of `float` to a C++ `std::vector<double>` the following are created:

A base declaration in *auto_py_convert_internal.h*:

```
template<typename T>
int
py_list_to_cpp_std_vector(PyObject *op, std::vector<T> &container);
```

And a concrete declaration for each C++ target type `T` in *auto_py_convert_internal.h*:

```
template <>
int
py_list_to_cpp_std_vector<double>(PyObject *op, std::vector<double> &container);
```

And the concrete definition is in *auto_py_convert_internal.cpp*:

```
template <>
int
py_list_to_cpp_std_vector<double>(PyObject *op, std::vector<double> &container) {
    return generic_py_list_to_cpp_std_vector<double, &py_float_check, &py_float_to_cpp_
↪double>(
        op, container
    );
}
```

This is the function hierarchy for the code that converts Python lists and tuples to C++ `std::vector<T>` for all object types. Here is the function hierarchy for converting lists to C++ `std::vector<T>`:

```
                                py_unary_to_cpp_vector       <--- Hand written
                                          |
                         /--------------------------\
```

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```
                        |                          |             Hand written partial
        generic_py_list_to_cpp_std_vector       tuples...    <-- specialisation
                        |                          |             (one liners).
                        |                          |
            py_list_to_cpp_std_vector<T>          ...        <-- Generated
                        |                          |
        /-------------------------------\      /-------\
        |                               |      |       |         Generated declaration
py_list_to_cpp_std_vector<double>      ...    ...     ...    <-- and implementation
                                                                 (one liners)
```

1.4.1 Usage

Using the concrete function is as simple as this:

```
using namespace Python_Cpp_Containers;
// Create a PyObject* representing a list of Python floats.
PyObject *op = PyList_New(3);
PyList_SetItem(op, 0, PyFloat_FromDouble(21.0));
PyList_SetItem(op, 1, PyFloat_FromDouble(42.0));
PyList_SetItem(op, 2, PyFloat_FromDouble(3.0));

// Create the output vector...
std::vector<double> cpp_vector;

// Template specialisation will automatically invoke the appropriate
// function call.
// It will be a compile time error if the container/type function
// is not available.
// At run time this will return zero on success, non-zero on failure,
// for example if op is not a Python tuple or members of op can not be
// converted to C++ doubles.
int err = py_list_to_cpp_std_vector(op, cpp_vector);
// Handle error checking...

// Now convert back.
// Again this will be a compile time error if the C++ type is not supported.
PyObject *new_op  = cpp_std_vector_to_py_list(cpp_vector);
// new_op is a Python list of floats.
// new_op will be null on failure and a Python exception will have been set.
```

1.4.2 Converting a C++ `std::vector<T>` to a Python tuple or list

The generic function signature looks like this:

```
template<typename T,
        PyObject *(*ConvertCppToPy)(const T &),
        PyObject *(*PyUnaryContainer_New)(size_t),
        int(*PyUnaryContainer_Set)(PyObject *, size_t, PyObject *)>
PyObject *
generic_cpp_std_vector_to_py_unary(const std::vector<T> &vec);
```

1.4.3 Alternatives

Buffer protocol

multiprocessing.shared_memory

numpy is a common example.

CHAPTER

TWO

USING THIS LIBRARY IN YOUR C++ CODE

2.1 The Basics

2.1.1 Code Generation

If necessary run the code generator:

```
cd src/py
python code_gen.py
```

Which should give you something like:

```
Target directory "src/cpy"
Writing declarations to "src/cpy/auto_py_convert_internal.h"
Wrote 910 lines of code with 66 declarations.
Writing definitions to  "src/cpy/auto_py_convert_internal.cpp"
Wrote 653 lines of code with 64 definitions.

Process finished with exit code 0
```

2.1.2 Build Configuration

You need to compile the following C++ files by adding them to your makefile or CMakeLists.txt:

```
src/cpy/auto_py_convert_internal.cpp
src/cpy/python_container_convert.cpp
src/cpy/python_object_convert.cpp
```

2.1.3 Source Inclusion

Your pre-processor needs access to the header files with the compiler flag:

```
-I src/cpy
```

Then in your Python extension include the line:

```
#include "python_convert.h"
```

An this gives you access to the whole API.

2.1.4 Errors

If using this library in C++ there will be a linker error if you specify a template type that is not supported. For example here is some code that tries to copy a Python list of unsigned integers. The two conversion functions are not defined for `unsigned int`.

```
static PyObject *
new_list_unsigned_int(PyObject *Py_UNUSED(module), PyObject *arg) {
    std::vector<unsigned int> vec;
    if (!py_list_to_cpp_std_vector(arg, vec)) {
        return cpp_std_vector_to_py_list(vec);
    }
    return NULL;
}
```

A C++ tool chain will complain with a linker error such as:

```
Undefined symbols for architecture x86_64:
  "_object* Python_Cpp_Containers::cpp_std_vector_to_py_list<unsigned int>(std::__
↪1::vector<unsigned int, std::__1::allocator<unsigned int> > const&)", referenced from:
      new_list_unsigned_int(_object*, _object*) in cPyCppContainers.cpp.o
  "int Python_Cpp_Containers::py_list_to_cpp_std_vector<unsigned int>(_object*, std::__
↪1::vector<unsigned int, std::__1::allocator<unsigned int> >&)", referenced from:
      new_list_unsigned_int(_object*, _object*) in cPyCppContainers.cpp.o
ld: symbol(s) not found for architecture x86_64
```

If you are building a Python extension this will, most likely, build but importing the extension will fail immediately with something like:

```
>>> import cPyCppContainers
Traceback (most recent call last):
  File "<stdin>", line 1, in <module>
ImportError: dlopen(cPyCppContainers.cpython-39-darwin.so, 2): Symbol not found: __
↪ZN21Python_Cpp_Containers25cpp_std_vector_to_py_listIjEEP7_objectRKNSt3__16vectorIT_
↪NS3_9allocatorIS5_EEEE
  Referenced from: cPyCppContainers.cpython-39-darwin.so
  Expected in: flat namespace
 in cPyCppContainers.cpython-39-darwin.so
```

2.2 Examples

There are some examples of using this library in *src/ext/cPyCppContainers.cpp*. This extension is built by *setup.py* and tested with *tests/unit/test_cPyCppContainers.py*.

To build this extension:

```
$ python setup.py develop
```

And to use it:

```
import cPyCppContainer
```

2.2.1 Using C++ to Double the Values in a Python List of `float`

Here is one of those examples in detail; doubling the values of a Python list of floats.

At the beginning of the extension C/C++ code we have:

```
#include "cpy/python_convert.h"
```

For convenience we use the namespace that the conversion code is within:

```
using namespace Python_Cpp_Containers;
```

Here is the C++ function that we want to call that multiplies the values of a `std::vector<double>` in-place by 2.0:

```
/** Double the values of a vector in-place. */
static void
vector_double_x2(std::vector<double> &vec) {
    for (size_t i = 0; i < vec.size(); ++i) {
        vec[i] *= 2.0;
    }
}
```

And here is the code that takes a Python list of floats, then calls the C++ function and finally converts the C++ `std::vector<double>` back to a new Python list of floats:

```
/** Create a new list of floats with doubled values. */
static PyObject *
list_x2(PyObject *Py_UNUSED(module), PyObject *arg) {
    std::vector<double> vec;
    // py_list_to_cpp_std_vector() will return non-zero if the Python
    // argument can not be converted to a std::vector<double>
    // and a Python exception will be set.
    if (!py_list_to_cpp_std_vector(arg, vec)) {
        // Double the values in pure C++ code.
        vector_double_x2(vec);
        // cpp_std_vector_to_py_list() returns NULL on failure
        // and a Python exception will be set.
        return cpp_std_vector_to_py_list(vec);
    }
    return NULL;
}
```

The vital piece of code is the declaration `std::vector<double> vec;` and that means:

- If a `py_list_to_cpp_std_vector()` implementation does not exist for `double` there will be a compile time error.
- Giving `py_list_to_cpp_std_vector()` anything other than a list of floats will create a Python runtime error.
- If `cpp_std_vector_to_py_list()` fails for any reason there will be a Python runtime error.

Using the Extension

Once the extension is built you can use it thus:

```
>>> import cPyCppContainers
>>> cPyCppContainers.list_x2([1.0, 2.0, 4.0])
[2.0, 4.0, 8.0]
```

You can verify that the returned list is a new one rather than modifying the input in-place: .. code-block:: python

```
>>> a = [1.0, 2.0, 4.0]
>>> b = cPyCppContainers.list_x2(a)
>>> hex(id(a))
'0x1017150c0'
>>> hex(id(b))
'0x101810dc0'
```

If the values are not floats or the container is not a list a `ValueError` is raised:

```
>>> cPyCppContainers.list_x2([1, 2, 4])
Traceback (most recent call last):
  File "<stdin>", line 1, in <module>
ValueError: Python value of type int can not be converted
>>> cPyCppContainers.list_x2((1.0, 2.0, 4.0))
Traceback (most recent call last):
  File "<stdin>", line 1, in <module>
ValueError: Can not convert Python container of type tuple
```

2.2.2 Reversing a `tuple` of `bytes` in C++

Here is another example, suppose that we have a function to to reverse a `tuple` of `bytes` in C++:

```
/** Returns a new vector reversed. */
template<typename T>
static std::vector<T>
reverse_vector(const std::vector<T> &input){
    std::vector<T> output;
    for (size_t i = input.size(); i-- > 0;) {
        output.push_back(input[i]);
    }
    return output;
}
```

Here is the extension code that call this:

```
/** Reverse a tuple of bytes in C++. */
static PyObject *
tuple_reverse(PyObject *Py_UNUSED(module), PyObject *arg) {
    std::vector<std::string> vec;
    if (!py_tuple_to_cpp_std_vector(arg, vec)) {
        return cpp_std_vector_to_py_tuple(reverse_vector(vec));
    }
```

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```
    return NULL;
}
```

Once again the declaration `std::vector<std::string> vec;` ensures that the correct instantiations of conversion functions are called.

When the extension is built it can be used like this:

```
>>> import cPyCppContainers
>>> cPyCppContainers.tuple_reverse((b'ABC', b'XYZ'))
(b'XYZ', b'ABC')
```

2.2.3 Incrementing `dict` values in C++

Here is an example of taking a Python `dict` of `[bytes, int]` and creating a new `dict` with the values increased by one. The C++ code in the extension is this:

```
/** Creates a new dict[bytes, int] with the values incremented by 1 in C++ */
static PyObject *
dict_inc(PyObject *Py_UNUSED(module), PyObject *arg) {
    std::unordered_map<std::string, long> dict;
    /* Copy the Python structure to the C++ one. */
    if (!py_dict_to_cpp_std_unordered_map(arg, dict)) {
        /* Increment. */
        for(auto &key_value: dict) {
            key_value.second += 1;
        }
        /* Copy the C++ structure to a new Python dict. */
        return cpp_std_unordered_map_to_py_dict(dict);
    }
    return NULL;
}
```

Once the extension is built this can be used thus:

```
>>> import cPyCppContainers
>>> cPyCppContainers.dict_inc({b'A' : 65, b'Z' : 90})
{b'Z': 91, b'A': 66}
```

There are several other examples in *src/ext/cPyCppContainers.cpp* with tests in *tests/unit/test_cPyCppContainers.py*.

CHAPTER

THREE

EXAMPLES BY CONTAINER

3.1 Python Tuples

3.1.1 Converting a Python Tuple to a C++ std::vector

Here is some demonstration code that takes a Python tuple of floats then converts that to C++ vector of doubles with a single function call:

```
#include "python_convert.h"

// Demonstration code.
void test_example_py_tuple_to_vector_double(PyObject *op) {
    // Create the vector of the appropriate type.
    std::vector<double> cpp_vector;
    // Copy the tuple to a vector
    int err = Python_Cpp_Containers::py_tuple_to_cpp_std_vector(op, cpp_vector);
    if (err != 0) {
        // Handle error
        // ...
    } else {
        // Use C++ vector.
        // ...
    }
}
```

`Python_Cpp_Containers::py_tuple_to_cpp_std_vector` has implementations for vectors of `bool`, `long`, `double` and `std::string`.

3.1.2 Converting a C++ std::vector to a Python Tuple

Here is some demonstration code that creates a C++ vector of doubles then converts that to a Python tuple with a single function call:

```
#include "python_convert.h"

PyObject *test_example_vector_to_py_tuple_double() {
    // An imaginary function that creates a C++ std::vector<double>
    std::vector<double> cpp_vector = get_cpp_vector_doubles();
    // Convert to a Python tuple that contains floats
    // This might return NULL in which case a Python error will be set.
```

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```
    // Otherwise it will return a new reference, it is for the caller to decrement this.
    return Python_Cpp_Containers::cpp_std_vector_to_py_tuple(cpp_vector);
}
```

`Python_Cpp_Containers::cpp_std_vector_to_py_tuple` has implementations for vectors of `bool`, `long`, `double` and `std::string`.

3.2 Python Lists

3.2.1 Converting a Python List to a C++ `std::vector`

This is done with `Python_Cpp_Containers::cpp_std_vector_to_py_list` which is very similar to the code for tuples. `Python_Cpp_Containers::cpp_std_vector_to_py_list` has implementations for vectors of `bool`, `long`, `double` and `std::string`.

3.2.2 Converting a C++ `std::vector` to a Python List

This is done with `Python_Cpp_Containers::py_list_to_cpp_std_vector` which is very similar to the code for tuples. `Python_Cpp_Containers::py_list_to_cpp_std_vector` has implementations for vectors of `bool`, `long`, `double` and `std::string`.

3.3 Python Sets

3.3.1 Converting a Python Set to a C++ `std::unordered_set`

This is done with `Python_Cpp_Containers::cpp_std_unordered_set_to_py_set` which is very similar to the code for tuples and lists. `Python_Cpp_Containers::cpp_std_unordered_set_to_py_set` has implementations for the C++ types of `bool`, `long`, `double` and `std::string`.

3.3.2 Converting a C++ `std::unordered_set` to a Python Set

This is done with `Python_Cpp_Containers::py_list_to_cpp_std_unordered_set` which is very similar to the code for tuples and lists. `Python_Cpp_Containers::py_list_to_cpp_std_unordered_set` has implementations for C++ types of `bool`, `long`, `double` and `std::string`.

3.4 Python Dicts

3.4.1 Converting a Python `dict` to a C++ `std::unordered_map`

This is done with `Python_Cpp_Containers::py_dict_to_cpp_std_unordered_map`. This has implementations for all the combinations of C++ types of `bool`, `long`, `double` and `std::string` as keys and values so there are 16 combinations.

Here is an example of converting a Python dict of `[int, bytes]` to a C++ `std::unordered_map<long, std::string>`:

```
#include "python_convert.h"

void test_example_py_dict_to_cpp_std_unordered_map(PyObject *op) {
    std::unordered_map<long, std::string> cpp_map;
    int err = Python_Cpp_Containers::py_dict_to_cpp_std_unordered_map(op, cpp_map);
    if (err != 0) {
        // Handle error.
        // ...
    } else {
        // Do something with cpp_map
        // ...
    }
}
```

3.4.2 Converting a C++ `std::unordered_map` to a Python `dict`

This is done with `Python_Cpp_Containers::cpp_std_unordered_map_to_py_dict`. This has implementations for all the combinations of C++ types of `bool`, `long`, `double` and `std::string` as keys and values so there are 16 combinations.

Here is an example of converting a C++ `std::unordered_map<long, std::string>` to a Python dict of `[int, bytes]`:

```
#include "python_convert.h"

PyObject *test_example_cpp_std_unordered_map_to_py_dict() {
    // An imaginary function that creates a C++ std::unordered_map<long, std::string>
    std::unordered_map<long, std::string> cpp_map = get_cpp_map();
    // Convert to a Python dict.
    // This might return NULL in which case a Python error will be set.
    // Otherwise it will return a new reference, it is for the caller to decrement this.
    return Python_Cpp_Containers::cpp_std_unordered_map_to_py_dict(cpp_map);
}
```

3.5 Matrix Example

Supposing there is a C++ library that provides matrix support for a `std::vector<std::vector<double>>` type and you want it to work on a Python tuple of tuples of floats.

Firstly creating the C++ matrix from Python.

3.5.1 Converting a Python Tuple[Tuple[float]] to a C++ std::vector<std::vector<double>>

```
#include "python_convert.h"

// Demonstration code.
void py_matrix_to_cpp_matrix(PyObject *op) {
    // Create the matrix of the appropriate type.
    std::vector<std::vector<double>> cpp_matrix;
    for (Py_ssize_t i = 0; i < Python_Cpp_Containers::py_tuple_len(op), ++i) {
        std::vector<double> cpp_vector;
        PyObject *row = Python_Cpp_Containers::py_tuple_get(op, i);
        int err = Python_Cpp_Containers::py_tuple_to_cpp_std_vector(row, cpp_vector);
        if (err != 0) {
            // Handle error
            // ...
            return;
        } else {
            cpp_matrix.push_back(cpp_vector);
        }
    }
    // Use the matrix
    some_function_that_uses_a_matrix(cpp_matrix);
}
```

Note: Some error checking omitted.

3.5.2 Converting a C++ std::vector<std::vector<double>> to a Python Tuple[Tuple[float]]

And the reverse, given a C++ matrix this converts that to a Python tuple of tuples with a single function call:

```
#include "python_convert.h"

PyObject *
cpp_matrix_to_py_matrix() {
    // An imaginary function that creates a C++ std::vector<double>
    std::vector<std::vector<double>> cpp_matrix = get_cpp_matrix();
    PyObject *op = Python_Cpp_Containers::py_tuple_new(cpp_matrix.size());
    if (op) {
        for (size_t i = 0; i < cpp_matrix.size(); ++i) {
            PyObject *row = Python_Cpp_Containers::cpp_std_vector_to_py_tuple(cpp_
↪matrix[i]);
            if (! row) {
                // Handle error condition.
                // ...
                return NULL;
            }
            int err = Python_Cpp_Containers::py_tuple_set(op, i, row)
            if (err != 0) {
```

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```
                // Handle error
                // ...
                return;
            }
        }
    }
    return op;
}
```

Note: Some error checking omitted.

CHAPTER

FOUR

DESIGN

4.1 python_object_convert.h and python_object_convert.cpp

This is a hand written file that contains implementations of functions to convert Python types to their C++ equivalent. There are three functions to each type:

- Convert a C++ value to a new Python object.
- Convert a Python object to a C++ value.
- Check that a Python object is of the expected type.

For example here are the three functions for Python `int` and C++ `long`:

```
PyObject *cpp_long_to_py_long(const long &l);

long py_long_to_cpp_long(PyObject *op);

int py_long_check(PyObject *op);
```

The implementations of these are just one line wrappers around functions or macros in the Python C API.

4.2 python_container_convert.h and python_container_convert.cpp

This is a hand written file that contains implementations of functions to create and access Python unary containers (`list`, `tuple`, `set`). There are a number off functions to each container, for example a list:

- Check that a Python object is of the expected type.
- Create a new Python container.
- Find the length of a Python container.
- Set a value in a Python container.
- Get a value from a Python container.

For example here are the three functions for Python lists:

```
int py_list_check(PyObject *op);

PyObject *py_list_new(size_t len);

Py_ssize_t py_list_len(PyObject *op);
```

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```
int py_list_set(PyObject *list_p, size_t pos, PyObject *op);

PyObject *py_list_get(PyObject *list_p, size_t pos);
```

The implementations of these are just one line wrappers around functions or macros in the Python C API.

4.3 `python_convert.h`

This is a hand written file that contains templates that convert containers to and fro between Python and C++. It includes `python_object_convert.h` and `python_container_convert.h`, declares the templates then includes `auto_py_convert_internal.h`.

4.4 Conversion Templates

4.5 Python Lists and Tuples

4.5.1 Conversion From a `std::vector<T>` to a Python List or Tuple

```
template<typename T,
        PyObject *(*Convert)(const T &),
        PyObject *(*PyUnary_New)(size_t),
        int(*PyUnary_Set)(PyObject *, size_t, PyObject *)>
PyObject *
generic_cpp_std_vector_to_py_unary(const std::vector<T> &vec);
```

Table 1: Convert a `std::vector` to a Python Tuple or List.

Type	Description
`typename T`	The C++ type of the object.
`PyObject *(*Convert)(const T &)`	A pointer to a function that takes a type T and returns a new Python object.
`PyObject *(*PyUnary_New)(size_t)`	A pointer to a function that returns a new Python container of the given length.
`int(*PyUnary_Set)(PyObject *, size_t, PyObject *)>`	Sets a Python object in the Python container at the given position.

This template is then partially specified for both tuples and lists of type `T`:

```
template<typename T, PyObject *(*Convert)(const T &)>
PyObject *
generic_cpp_std_vector_to_py_tuple(const std::vector<T> &vec) {
    return generic_cpp_std_vector_to_py_unary<T,
                                              Convert,
                                              &py_tuple_new,
                                              &py_tuple_set>(vec);
}
```

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```
template<typename T, PyObject *(*Convert)(const T &)>
PyObject *
generic_cpp_std_vector_to_py_list(const std::vector<T> &vec) {
    return generic_cpp_std_vector_to_py_unary<T,
                                              Convert,
                                              &py_list_new,
                                              &py_list_set>(vec);
}
```

Then these are specialised by auto-generated in `auto_py_convert_internal.h` code for the types `bool`, `long`, `double` and `sts::string`. Their declarations are:

```
// Base declaration
template<typename T>
PyObject *
cpp_std_vector_to_py_tuple(const std::vector<T> &container);

// Instantiations
template <>
PyObject *
cpp_std_vector_to_py_tuple<bool>(const std::vector<bool> &container);

template <>
PyObject *
cpp_std_vector_to_py_tuple<long>(const std::vector<long> &container);

template <>
PyObject *
cpp_std_vector_to_py_tuple<double>(const std::vector<double> &container);

template <>
PyObject *
cpp_std_vector_to_py_tuple<std::string>(const std::vector<std::string> &container);
```

Their declarations are auto-generated in `auto_py_convert_internal.cpp`:

```
template <>
PyObject *
cpp_std_vector_to_py_tuple<bool>(const std::vector<bool> &container) {
    return generic_cpp_std_vector_to_py_tuple<bool, &cpp_bool_to_py_bool>(container);
}

template <>
PyObject *
cpp_std_vector_to_py_tuple<long>(const std::vector<long> &container) {
    return generic_cpp_std_vector_to_py_tuple<long, &cpp_long_to_py_long>(container);
}

template <>
PyObject *
cpp_std_vector_to_py_tuple<double>(const std::vector<double> &container) {
```

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```
    return generic_cpp_std_vector_to_py_tuple<double, &cpp_double_to_py_float>
↪(container);
}

template <>
PyObject *
cpp_std_vector_to_py_tuple<std::string>(const std::vector<std::string> &container) {
    return generic_cpp_std_vector_to_py_tuple<std::string, &cpp_string_to_py_bytes>
↪(container);
}
```

4.5.2 Conversion From a Python List or Tuple to a `std::vector<T>`

```
template<typename T,
        int (*Check)(PyObject *),
        T (*Convert)(PyObject *),
        int(*PyUnary_Check)(PyObject *),
        Py_ssize_t(*PyUnary_Size)(PyObject *),
        PyObject *(*PyUnary_Get)(PyObject *, size_t)>
int generic_py_unary_to_cpp_std_vector(PyObject *op, std::vector<T> &vec);
```

Table 2: Convert a `std::vector` to a Python Tuple or List.

Type	Description
`typename T`	The C++ type of the object.
`int (*Check)(PyObject *)`	A pointer to a function returns true if Python object can be converted to type T.
`int(*PyUnary_Check)(PyObject *)`	A pointer to a function that returns true if the given Python container of the correct type (list or tuple respectively).
`Py_ssize_t(*PyUnary_Size)(PyObject *)`	A pointer to a function that returns the size of the Python container.
`PyObject *(*PyUnary_Get)(PyObject *, size_t)`	Gets a Python object in the Python container at the given position.

This template is then partially specified for both tuples and lists of type `T`:

```
template<typename T, int (*Check)(PyObject *), T (*Convert)(PyObject *)>
int generic_py_tuple_to_cpp_std_vector(PyObject *op, std::vector<T> &vec) {
    return generic_py_unary_to_cpp_std_vector<T,
                                              Check,
                                              Convert,
                                              &py_tuple_check,
                                              &py_tuple_len,
                                              &py_tuple_get>(op, vec);
}

template<typename T, int (*Check)(PyObject *), T (*Convert)(PyObject *)>
int generic_py_list_to_cpp_std_vector(PyObject *op, std::vector<T> &vec) {
    return generic_py_unary_to_cpp_std_vector<T,
```

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```
                                    Check,
                                    Convert,
                                    &py_list_check,
                                    &py_list_len,
                                    &py_list_get>(op, vec);
}
```

Then these are specialised by auto-generated in `auto_py_convert_internal.h` code for the types `bool`, `long`, `double` and `sts::string`. Their declarations for tuple are (similarly for lists):

```
// Base declaration
template<typename T>
int
py_tuple_to_cpp_std_vector(PyObject *tuple, std::vector<T> &container);

// Instantiations
template <>
int
py_tuple_to_cpp_std_vector<bool>(PyObject *tuple, std::vector<bool> &container);

template <>
int
py_tuple_to_cpp_std_vector<long>(PyObject *tuple, std::vector<long> &container);

template <>
int
py_tuple_to_cpp_std_vector<double>(PyObject *tuple, std::vector<double> &container);

template <>
int
py_tuple_to_cpp_std_vector<std::string>(PyObject *tuple, std::vector<std::string> &
↪container);
```

Their definitions for tuple are are auto-generated in `auto_py_convert_internal.cpp` (similarly for lists):

```
template <>
int
py_tuple_to_cpp_std_vector<bool>(PyObject *op, std::vector<bool> &container) {
    return generic_py_tuple_to_cpp_std_vector<bool, &py_bool_check, &py_bool_to_cpp_bool>
↪(op, container);
}

template <>
int
py_tuple_to_cpp_std_vector<long>(PyObject *op, std::vector<long> &container) {
    return generic_py_tuple_to_cpp_std_vector<long, &py_long_check, &py_long_to_cpp_long>
↪(op, container);
}

template <>
int
py_tuple_to_cpp_std_vector<double>(PyObject *op, std::vector<double> &container) {
```

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```
    return generic_py_tuple_to_cpp_std_vector<double, &py_float_check, &py_float_to_cpp_
→double>(op, container);
}

template <>
int
py_tuple_to_cpp_std_vector<std::string>(PyObject *op, std::vector<std::string> &
→container) {
    return generic_py_tuple_to_cpp_std_vector<std::string, &py_bytes_check, &py_bytes_to_
→cpp_string>(op, container);
}
```

CHAPTER

FIVE

PERFORMANCE

Here are some benchmarks for converting Python containers to and from their C++ equivalents.

The C++ code was compiled with `-O3` and run on the following hardware:

```
Model Name:                 MacBook Pro
Model Identifier:           MacBookPro15,2
Processor Name:                 Intel Core i7
Processor Speed:            2.7 GHz
Number of Processors:       1
Total Number of Cores:          4
L2 Cache (per Core):            256 KB
L3 Cache:                   8 MB
Hyper-Threading Technology: Enabled
Memory:                         16 GB

System Version:                 macOS 10.14.6 (18G9323)
Kernel Version:                 Darwin 18.7.0
```

5.1 Summary

- Sequences of fundamental types are converted at around 100m objects/sec.
- Sequences of strings are converted at a memory rate of around 4000 Mb/sec.
- Dicts are about 8-10x slower. Why this should be so different from the expected 2x is a mystery at the moment.

5.1.1 Fundamental Types

Converting and copying of `int/long` and `float/double` takes about 0.01 µs per object (100m objects per second) for large containers. This corresponds to around 800 Mb/s. `boolean/bool` is around 2x to 5x faster.

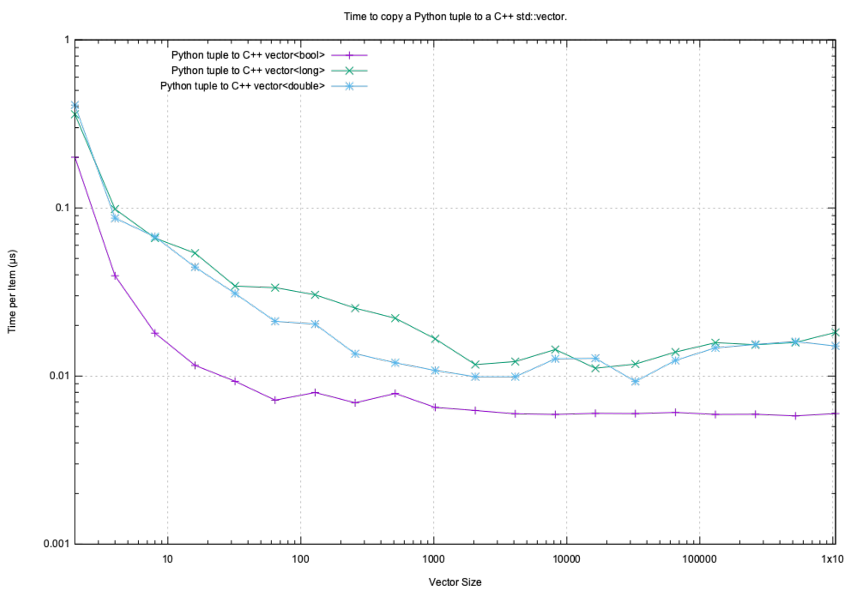
5.1.2 Strings of Different Lengths

With `bytes/std::string` converting and conversion takes about the following. The performance appears appears linear (with some latency for small strings):

String size	~Time per object (µs)	~Rate, million per second	~Rate x Size Mb/s
8	0.02	50	400
64	0.03	30	2000
512	0.1	10	5000
4096	1.0	1	4000

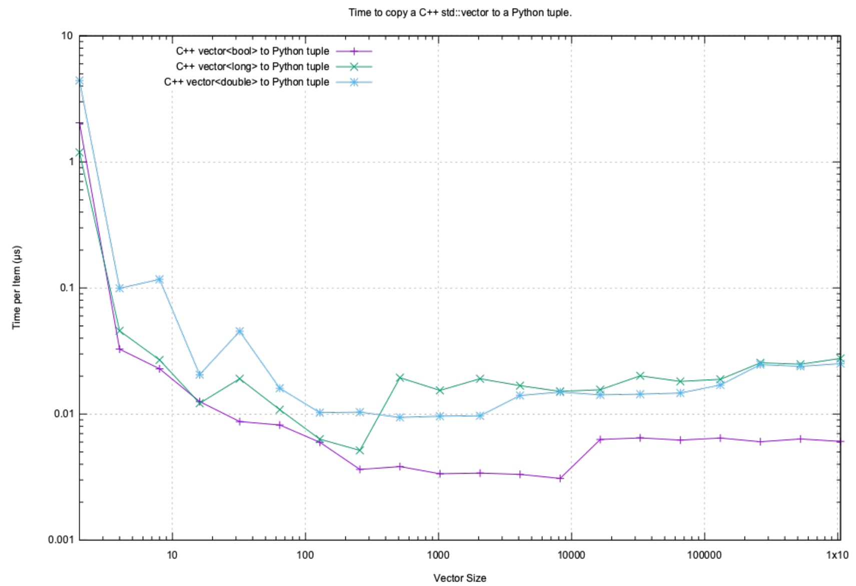
5.2 Python Tuple to a C++ `std::vector`

Here is an example of converting a Python tuple to a C++ `std::vector<T>` for up to 1m `bool`, `long` and `double` types. Time is per-object in µs. So 1m float/long conversion takes about 10 to 20 ms.



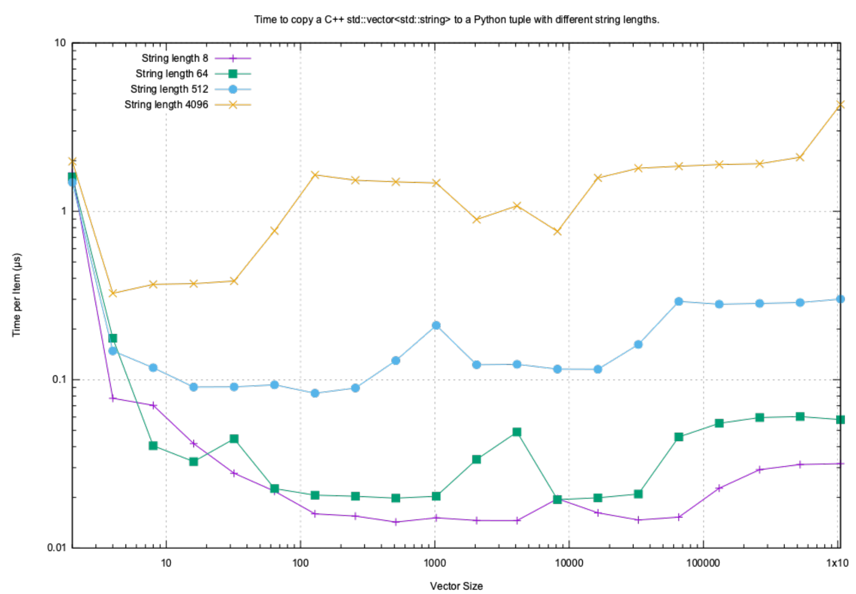
5.3 C++ `std::vector` to a Python Tuple

This is the reverse of the above, the time to convert a C++ `std::vector<T>` to a Python `tuple` for up to 1m `bool`, `long` and `double` types.



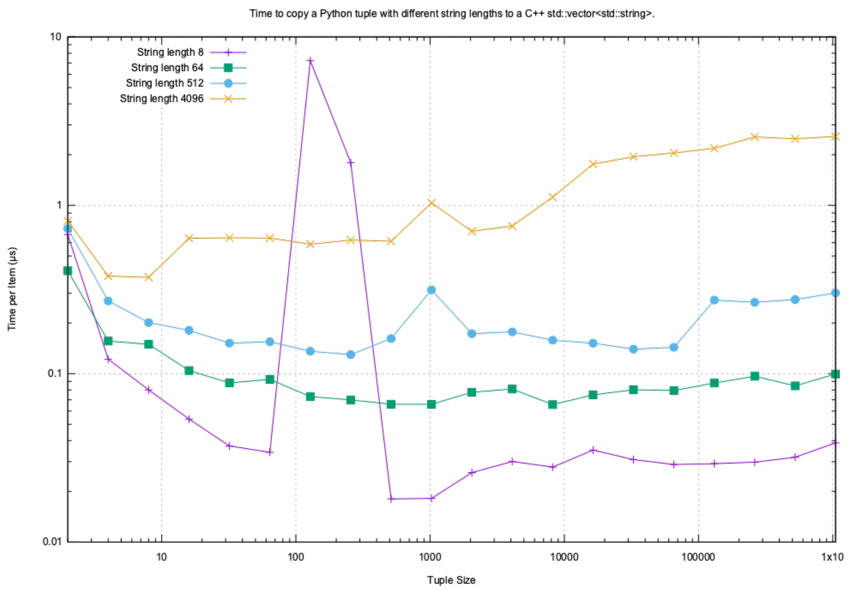
5.4 Python Tuple of `bytes` to a C++ `std::vector<std::string>>`

This shows the conversion cost of various length strings.



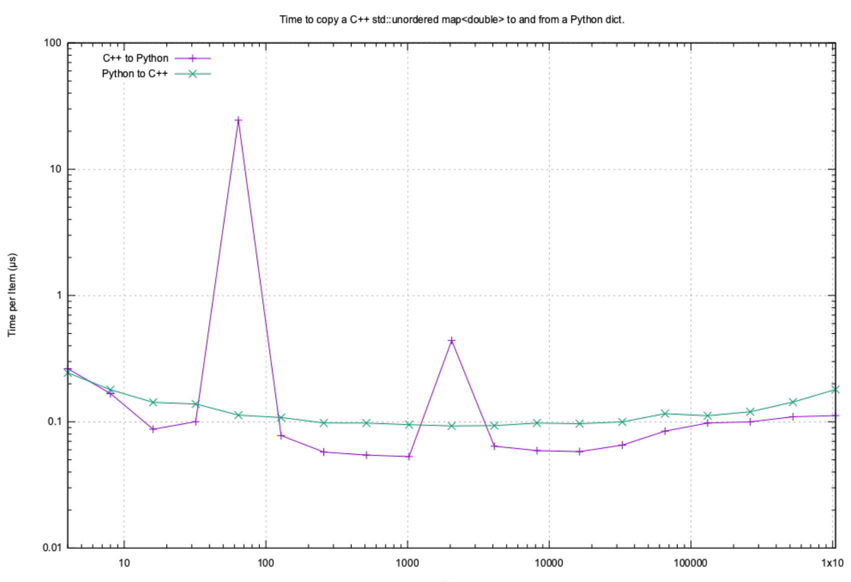
5.5 C++ `std::vector<std::string>>` to a Python Tuple of `bytes`

This is the reverse of the above.



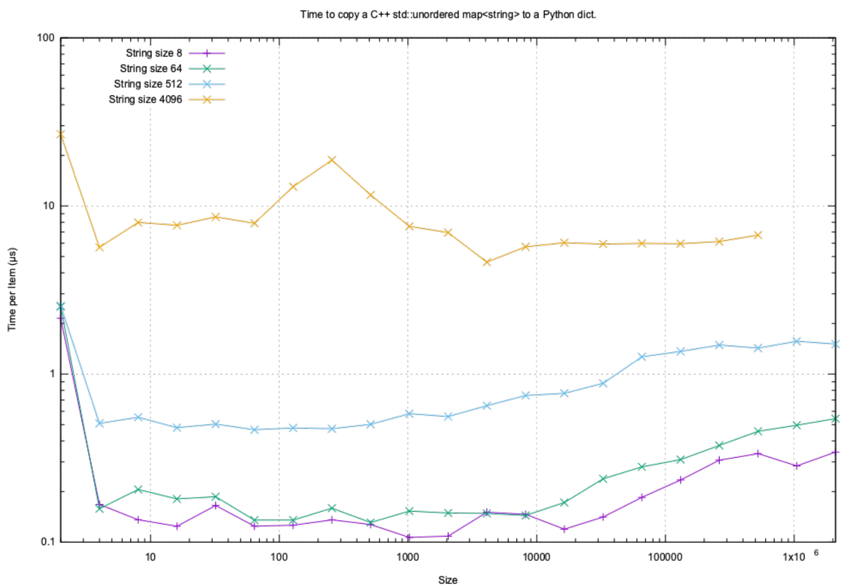
5.6 Python Dict of [float, float] to a C++ `std::unordered_map<double, double>`

This shows the conversion rate of a dict of floats to and from Python. At 0.1 µs per item (10m objects/s) this rate is about one-tenth of the rate of converting a sequence.



5.7 Python Dict of [bytes, bytes] to a C++ std::unordered_map<std::string, std::string>

Similarly for dicts of bytes. This corresponds, roughly, to a data rate of around 500 Mb/s.



CHAPTER

SIX

INDICES AND TABLES

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