cppyy

CaaS monthly meeting – 09/02/21

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cppyy: Yet another Python – C++ binder?!

- Yes, but it has its niche: *bindings are runtime*
  - Python is all runtime, so runtime is more natural
  - C++-side runtime-ness is provided by Cling
- Very complete feature-set (not just "C with classes")
- Good performance on CPython; great with PyPy✷

pip: https://pypi.org/project/cppyy/
conda: https://anaconda.org/conda-forge/cppyy
git: https://github.com/wlav/cppyy
docs: https://cppyy.readthedocs.io/en/latest/

For HEP users: *cppyy in ROOT is an old fork. It won't run all the examples here, doesn't work with PyPy, and has worse performance.*

(✷) PyPy support lags CPython

Examples of Runtime Behavior

Runtime Template Instantiations

- **Cling instantiates templates at runtime**
  - No pre-instantiation/compilation necessary
  - Prevent duplication of standard classes (e.g. STL)
  - No combinatorial explosion (esp. with numeric types)
  - Support for templates of user classes

Runtime Template Instantiations

```cpp
struct MyClass {
  MyClass(int i) : fData(i) {}
  virtual ~MyClass() {}
  virtual int add(int i) {
    return fData + i;
  }
  int fData;
};
```

```python
>>> import cppyy.gbl as CC
>>> v = \
...   CC.std.vector[CC.MyClass]()
...
>>> for i in range(10):
...    v.emplace_back(i)
...
>>> len(v)
10
>>> for m in v:
...    print(m.fData, end=' ')
...
0 1 2 3 4 5 6 7 8 9
>>>
```

Runtime Cross-Inheritance

- **Cling's JIT compiles generated trampolines**
  - All proper C++ base classes can be inherited from
    - No need to select a subset of likely base classes
  - Only trampoline methods actually overridden
  - No overhead added to bound base class
  - Memory managed (copy, move, assign, destruct)

Runtime Cross-Inheritance

```cpp
struct MyClass {
  MyClass(int i) : fData(i) {}
  virtual ~MyClass() {}
  virtual int add(int i) {
    return fData + i;
  }
  int fData;
};
```

```python
>>> import cppyy.gbl as CC
>>> class PyMyClass(CC.MyClass):
...   def add(self, i):
...     return self.fData + 2*i
...
>>> m = PyMyClass(1)
>>> CC.callb(m, 2)
5
>>>
```

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The obvious next step …

- Cross-inheritance allows Python classes in C++
  - Uniquely identifiable, memory managed
- C++ classes can be used as template argument
- Emergent property: *Python classes in templates!*

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Thus obvious next step …

```cpp
struct MyClass {
  MyClass(int i) : fData(i) {}
  virtual ~MyClass() {}
  virtual int add(int i) {
    return fData + i;
  }
  int fData;
};
```

```python
>>> import cppyy.gbl as CC
>>> class PyMyClass(CC.MyClass):
...   def __init__(self, d, extra):
...     super(PyMyClass, self).__init__(d)
...     self.extra = extra
...   def add(self, i):
...     return self.fData + \
...            self.extra + 2*i
...
>>> v = \
...   CC.std.vector[PyMyClass]()
...
>>> v.push_back(PyMyClass(4, 42))
>>> v.back().add(17)
80
>>>
```

Runtime Automatic Fallbacks

- Cling instantiates templates at runtime
- But Python types do no map uniquely, example:

Python	C++
type int	`int8_t, uint8_t, short, unsigned short, int, unsigned int, long, unsigned long, long long, unsigned long long, int64_t, uint64_t, …`

- Solution: automatically fallback as needed

Runtime Automatic Fallbacks

```
template<typename T>
T passT(T t) {
    return t;
}
```

```
>>> import cppyy.gbl as CC
>>> type(1)
<class 'int'>
>>> CC.passT(1)
1
>>> CC.passT.__doc__
'int ::passT(int t)'
>>> type(2**64-1)
<class 'int'>
>>> CC.passT(2**64-1)
18446744073709551615
>>> CC.passT.__doc__
'unsigned long long ::passT(
          unsigned long long t)'
>>>
```

Runtime Callbacks

- **Cling's JIT compiles generated wrappers**
  - Type checked and memory managed
    - Errors (exceptions) can trace through both Python and C++
    - Python manages lifetime, C++ manages resources
      - Note: manage manually if C++ stores the function ptr
  - Supports C++ function pointers and `std::function`
- **Python can pass any callable**
  - Functions, lambda's, objects implementing `__call__`
  - Bound C++ functions and methods (w/o wrapper)

Runtime Callbacks

```cpp
typedef int (*P)(int);

int callPtr(P f, int i) {
  return f(i);
}

typedef std::function<int(int)> F;

int callFun(const F& f, int i) {
  return f(i);
}
```

```python
>>> import cppyy.gbl as CC
>>> def f(val):
...   return 2*val
...
>>> CC.callPtr(f, 2)
4
>>> CC.callFun(f, 3)
6
>>> CC.callPtr(lambda i: 5*i, 4)
20
>>> CC.callFun(lambda i: 6*i, 4)
24
>>>
```

Runtime Templated Callbacks

- **Modern Python3 supports “annotations”**
  - Very commonly used in any modern Python project
  - Type information used by IDEs, static checkers, etc.
    - Unused by (and mostly irrelevant to) the interpreter
  - Dictionary of (strings of) argument and return types
    - Strings are necessary for compound C++ types
- **Annotated functions can instantiate templates**
  - Incl. bound C++ functions (by definition “annotated”)

Runtime Templated Callbacks

```cpp
template<typename R,
         typename... U,
         typename... A>
R callT(R(*f)(U...), A&&... a) {
    return f(a...);
}
```

```python
>>> import cppyy.gbl as CC
>>> def f(a: 'int') -> 'double':
...     return 3.1415*a
...
>>> CC.callT(f, 2)
6.283
>>> def f(a: 'int', b: 'int') \
                          -> 'int':
...     return 3*a*b
...
>>> CC.callT(f, 6, 7)
126
>>>
```


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Runtime Auto-downcast and Object Identity

- **Always cast to the most derived C++ type**
  - Involves a fake base and retrieving C++ RTTI
  - Custom RTTI implementation on MS Windows 64b
- **Preserve identity Python proxy ⇔ C++ instance**
  - Eases resource management / prevents dangling ptrs
  - Guarantees equal hashes for dictionary lookups
    - Alternative: specialize `std::hash` or `__hash__`
  - Enables cctor and assignment of cross-derived classes

Runtime Auto-downcast and Object Identity

```cpp
struct Base {
  virtual ~Base() {}
};

struct Derived : public Base {};

Base* passB(Base* b) {
  return b;
}
```

```python
>>> import cppyy.gbl as CC
>>> d = CC.Derived()
>>> b = CC.passB(d)
>>> type(b) == CC.Derived
True
>>> d is b
True
>>>
```

Runtime Exceptions

- **Map exceptions derived from `std::exception`**
  - Python exceptions are not `object` instances
  - Python exception classes do not match C++ ones
- **Preserves C++ exception types**
  - Allows crossing multiple language layers
    - Provides trace showing full call stack

Note: can't mix compiled & JITed on all platforms

- To be fixed in a future version of Clang?

Runtime Exceptions

```cpp
class MyException :
    public std::exception {
public:
  const char* what() const throw() {
    return "C++ failed";
  }
};

void throw_error() {
  throw MyException{};
}
```

```python
>>> import cppyy.gbl as CC
>>> try:
...    CC.throw_error()
... except CC.MyException as e:
...    print(e)
...
void ::throw_error() =>
    MyException: C++ failed
>>>
```

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Runtime Unicode

- **Python unicode encapsulates code points + codec**
  - Defaults to UTF-8 (with BOM check)
- **C++ is just all over the place, for example:**
  - Byte-encoded w/o codec (e.g. `std::string`)
  - Code points w/o codec (e.g. `std::u16string`)
  - Wide char types w/ assumed codec (platform-specific)
- **Python's `type str` != C++'s `std::string`**
  - Developers still want interchangeable use by default …

Runtime Unicode

```cpp
template<class T>
std::string to_str(const T& chars) {
  char buf[12]; int n = 0;
  for (auto c : chars)
    buf[n++] = char(c);
  return std::string(buf, n-1);
}

std::string utf8_chinese() {
  auto chars = {0xe4, 0xb8, 0xad,
    0xe6, 0x96, 0x87, 0};
  return to_str(chars);
}
std::string gbk_chinese() {
  auto chars = {0xd6, 0xd0, 0xce,
    0xc4, 0};
  return to_str(chars);
}
```

```python
>>> import cppyy.gbl as CC
>>> CC.utf8_chinese()
中文
>>> CC.gbk_chinese()
b'\xd6\xd0\xce\xc4'
>>> CC.gbk_chinese().decode('gbk')
中文
>>>
```

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And much more, not directly runtime …

- Classes, functions, (static) methods, operators, iterators, enums, single/multiple inheritance, shared/unique_ptr, STL pythonizations, …
- Low-level C support (memory, arrays, ptr math, …)
- Debug support (e.g. segfault ->Python exception)
- Customize with pythonizations, “freeze” binary distributions, cmake fragments for projects, …
- See: https://cppyy.readthedocs.io/en/latest/

Yes, okay, runtime is great … but what about performance?

Performance Compared to Static Approaches

- No fundamental CPU performance difference

Note carefully that *everything* in Python is runtime: compile-time just means that the bindings *recipe* is compiled, not the actual bindings themselves!

- But heavy Cling/LLVM dependency:
  - ~25MB download cost; ~100MB memory overhead
  - Complex installation (and worse build)

Basic Performance Tests

```
void empty_call() {}

class Overload {
public:
  double add(int a, int b);
  double add(short a);
  double add(long a);
  double add(int a, int b, int c);
  double add(double a);
  double add(float a);
  double add(int a);
};

// benchmark example:
Overload obj;
for (size_t i=0; i < N; ++i)
   obj.add((double)i);
```

```
System:
  Ubuntu 20.04.2 LTS
  AMD EPYC 7702P 64-Core CPU
  1TB of RAM

Setup:
  gcc            9.3.0 (system)
  pytest         6.2.4 (pypi)
  benchmark:     3.4.1 (pypi)

Comparison:
  cppyy          2.1.0 (pypi)
  pybind11       2.7.1 (pypi)
  swig           4.0.1 (system)
  pypy-c         3.7.1 (system)
```

Basic Performance Test: empty call

Tool	Execution time (ns/call)✷
C++ (Cling w/ -O2; out-of-line)	1.5
cppyy / pypy-c	16
swig (builtin)	27
cppyy / CPython	68
pybind11	68
swig (default)	104

⇒ Empty global function call is a pure overhead measure (zero work)
⇒ pypy-c slower than C++ b/c of global interpreter lock (GIL) release
⇒ "Builtin" swig trades functionality for speed
⇒ There is no obvious benefit to "static" over runtime bindings

(✷) lower is better

Basic Performance Test: overload

Tool	Execution time (ms/call)✷
C++ (Cling w/ -O2; out-of-line)	1.8E-6
cppyy / pypy-c	0.50
cppyy / CPython	1.25
swig (builtin)	1.29
swig (default)	4.23
pybind11	6.97

⇒ C++ overload is resolved at compile time, not based on dynamic type
⇒ Largest overhead: Python instance type checking (avoidable, but clumsy)
⇒ There is no obvious benefit to “static” over runtime bindings

(✷) lower is better

Implementation: Bird's Eye View

Implementation

- **Python offers hooks for C++ entity lookups, e.g.:**
  - meta-classes for class creation
  - `__getattr__` for resolving attributes
  - `__getitem__`/`__call__` for template instantations
- **The hooks call into Cling for name lookup**
  - All initial lookups are always *string-based*
- **Access provided by address or through wrappers**
  - Wrappers are C++ code to easily cover esoteric uses
  - Generalized interfaces to simplify downstream code

Implementation Flow: Lookup Example

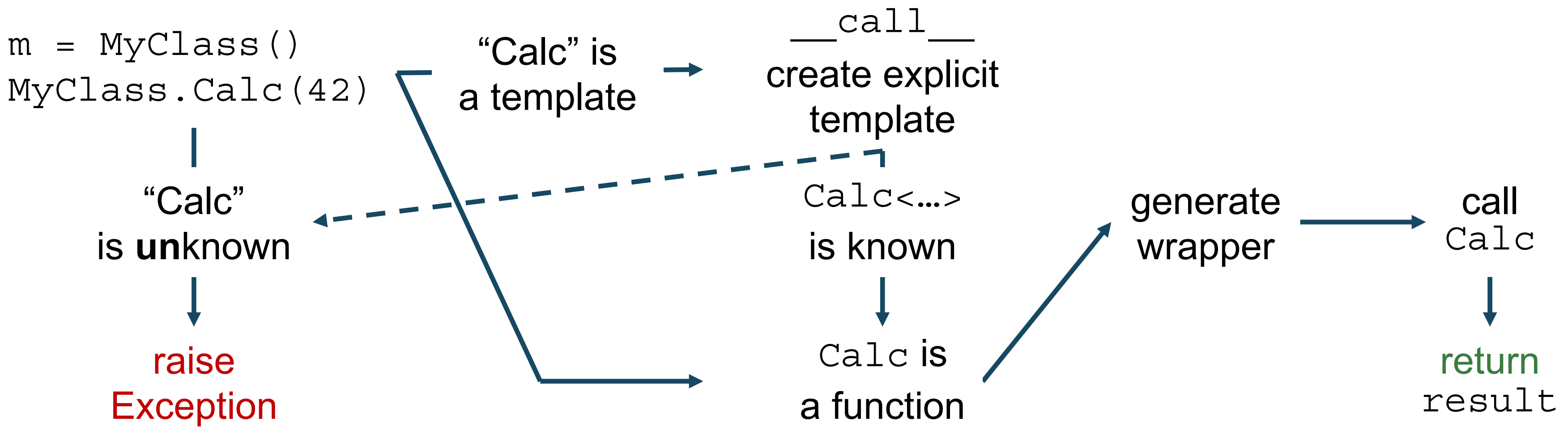
`cppyy.gbl.MyClass` — "MyClass" is **un**known → `__getattr__` to Cling's lookup — "MyClass" is known → Create Proxy `MyClass` → return `MyClass`

`cppyy.gbl.MyClass` — "MyClass" is known → return `MyClass`

`__getattr__` to Cling's lookup — "MyClass" is **un**known → raise Exception

Templates additionally use either `__getitem__` (explicit instantiation) or `__call__` (implicit).
Proxy creation calls into Cling for reflection information; wrappers are created on first use.

Implementation Flow: Call Example



Wrappers of generated (and JITted) C++ are used to easily cover a range of C++isms, such as linkage of `inline` functions, overloaded `operator new`, default arguments, `operator` lookup, etc., etc. For simple cases in PyPy, direct FFI is used, for improved performance.

Conclusions

Current Limitations

- Complex and heavy Cling/LLVM dependency
- All C++ code enters single, global, translation unit
  - Significant slowdown for templates (Eigen, PCL, …)
- PyPy/cppyy is significantly behind CPython/cppyy
- No MS Windows port for conda
- Significant Clang JIT limitations on MS Windows

Current Focus

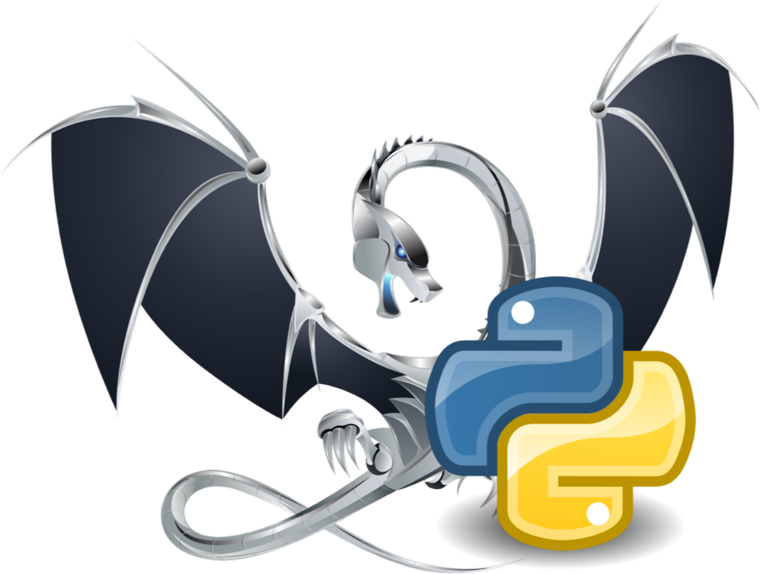
- Add GPU (`cuda`) support to cppyy
- Bring PyPy / cppyy on par with CPython / cppyy
- Simplify installation / distribution

Conclusion

Runtime Python-C++ bindings are much more functional than similar static approaches

(and without loss in performance✷)

(✷) memory overhead is higher



That's all Folks!