INTERACTIVE C++ CODE DEVELOPMENT USING C++EXPLORER AND GITHUB CLASSROOM FOR EDUCATIONAL PURPOSES

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ABSTRACT

Teaching C++ programming to non-computer science majors comes with the burden of setting up an integrated development environment, a struggle for most students. Therefore, we present the open source tool, C++Explorer, a Jupyterhub deployment for interactively developing C++ code. Students can connect to the server without installing anything, and, almost instantly, they can begin to engage with code using the notebooks. Another aspect of code development is remote communication with co-workers or the community. To develop this skill, we use GitHub classroom to provide feedback on the assignments and practice remote communication. C++Explorer was used in the fall of 2019 and 2020 to teach parallel computation to mathematics students. At the end of the class, we gather student's feedback. This data will be used to continue improving the course. In addition, we present a Telegram[®] bot for the communication with the server using smartphones or tablets. However, this tool was not used in the course and will be explored in future teaching.

Keywords GitHub[®] ; GitHub Classroom; C++; HPX, Jupyterhub ; Cling, Telegram[®]

1 Introduction

Teaching C++ programming to non-computer science students comes with the burden of setting up an integrated development environment (IDE). Most students struggle to install Visual Studio[®] on Windows[®] or Xcode[®] on macOS[®] to compile the first assignment. Jupyterhub provides a solution to address this problem for the Python ecosystem. Thus, students can access the web server, use the notebooks, and work on their assignments without dealing with the installation of any IDE. This paper shows how to extend Jupyterhub using the cling interpreter (cling is the interpreted version of clang), and Pybind11, to compile C++ code within a Python notebook, freeing students from installing any IDE and allowing them to focus on writing code. A second goal for the teaching environment we have created is to enable students to play with C++ code interactively, to more rapidly experiment with different ideas and algorithmic designs.

Another aspect of code development is communication within the open source community or the company. The major issue here is remote communication while creating tickets, pull requests, or in commenting on these. Git is one of the most widely used tools for software development, and GitHub[®] is one of the largest platforms in this space. GitHub[®] Classroom extends GitHub[®] 's functionality for teaching. By using this platform, students can improve their remote communication skills by adding comments to the commit messages, generating pull requests on the semester-long project, and reacting to instructor comments on their source code.

The C++Explorer was used in the fall of 2019 and 2020 to teach parallel computation to mathematics students. The course is composed of three modules. In the first module, the basic concepts of C++, *e.g.* classes, access modifiers, lambda functions, containers, and the standard library algorithms. In the second module, the recently introduced

parallel algorithms, *e.g.* executors, in the C++ 17 standard and asynchronous programming, *e.g.* `std::future` and `std::future`, are showcased as possibilities for shared memory parallelism. In the third module, the additional features of the parallel algorithms and distributed capabilities provided by the C++ standard library for parallelism and concurrency (HPX) are introduced. All these features are used to implement simple applied mathematical problems, *e.g.* Monte Carlo method, N-body simulation, stencil-based one dimensional heat equation in single threaded and multithreaded. Some of these are extended for distributed memory parallelism. The course is offered for undergraduate students in the mathematics program. However, students from mechanical engineering and physics attended the course. For each of the two iterations, graduate students attended the course and some audited the course. The feedback among these students were conducted at the end of each course to analyze these tools for educational purposes.

The paper’s outline is structured as follows: Section 2 discusses related work. Section 3 lists the tools. Section 4 provides some implementation details of the C++ Explorer. The results of the student’s feedback was administered and are shown in Section 5. Finally, conclusions are drawn in Section 6.

2 Related work

The usage of GitHub® Classroom has been studied in several disciplines [1, 24, 15, 16, 10, 12]. In the majority of cases, the courses were related to programming, *e.g.* computer science, engineering, and statistics. Hisng and Gennarelli recently did a survey among teachers and students on the usage of GitHub® Classroom [12]. We summarized their findings related to the author’s work:

- “[...] found that students who used GitHub in the classroom [...] felt more prepared for a future internship or career than students who did not use GitHub in the classroom.”
- “[...] found that students who used GitHub in the classroom [...] felt more prepared for developing a portfolio of their work than students who did not use GitHub in the classroom.”

The usage of Jupyter notebooks and Jupyterhub for teaching has been studied in several disciplines [4, 22, 20, 3], *e.g.* meteorology, physics, and data science. However, all of them used Python. To the best of our knowledge, this is the first publication describing the interactive teaching of C++ programming using Jupyter notebooks. The usage of Telegram® bots for teaching purposes has been studied for medical education [14], teaching English language pronunciation [23], and effectiveness of Telegram®-based virtual education versus in person education [9], however not for learning a programming language.

The difficulties of setting up the C++ development environment have not yet been studied much. Recently, in the C++ developer survey 2020 conducted by ISOcpp.org, C++ developers were asked what frustrated them most about C++ development. One option was setting up the C++ IDE from scratch. Out of 1032 responses, 25.71% mentioned that setting up an IDE from scratch is a major point for them. For 43.11% it was a minor point and for 31.18% it was not significant. Similar results can be found in the 2021 survey. These survey results indicated that setting up the C++ IDE can be frustrating for various kinds of C++ developers. While these surveys included all C++ developers, this implies similar difficulties in an educational environment.

3 Methodology

3.1 GitHub and GitHub Classroom

GitHub® is a widely used platform for the community-based development of open source software. The web-based platform uses git for version control and provides collaborative features, like a ticketing system, discussion for pull requests, and a Wiki for documentation purposes. GitHub® Classroom [24] is a downsized version of GitHub® in a private setup designed for teaching. The instructor can assign homework to an individual student or a group of students using a git repository. Students can commit the code until a specified deadline by the instructor. The instructor can use the collaborative features to provide feedback to the student’s submission.

3.2 jupyterhub with git login

JupyterHub [17] comes with an OAuth plugin for GitHub®, enabling any user with a git login to use the server. While this is convenient, it is possibly too permissive. For this purpose, we customized the authentication system to require that a code word be used in addition to GitHub® credentials, for the first login. The instructor can write this code word

```

In [1]:
#include <vector>
#include <iostream>

Out[1]:

In [2]:
std::vector<int> values = {1,2,3};

Out[2]:

In [3]:
for( auto v : values )
    std::cout << v << std::endl;

1
2
3

```

(a) Example of a C++17 notebook using cling to compile the C++ code in each cell.

```

In [1]:
from cling import cling
foo = "world"

In [2]:
%%cling
#include <iostream>

In [3]:
%%cling
// Note that "baz" is not defined by
// Python, but "foo" is.
std::cout << "Hello {foo} {baz}" << std::endl;

Hello world {baz}

(std::basic_ostream<char, std::char_traits<char> >::__ostream_type &) @0x7f3a6425440

```

(b) Example of a Python notebook using the `%%cling` magic cells. In the example, the variable `foo` is substituted in the cell where the sequence `{foo}` is found.

Figure 1: Examples for the usage of C++ code within the Jupyter notebook (a) and the usage of the `%%cling` magic cells (b).

on the board and deactivate it after class. This provides a simple method for the instructor to permit users to login to the system.

3.3 Python/C++ interface

We have provided a number of mechanisms by which the students can interface with C++ through the notebook. Each has different strengths and different places in which it is appropriate for use.

1. `cling` - Cling is a C++ interpreter [21], part of the ROOT project developed in Switzerland. Cling comes with its own Jupyter interface, enabling users to run C++ directly in notebook cells. See Fig. 1a. While this is convenient, we extend the notebook with “magics,” bits of code introduced by the sequence `%%` that cause a cell to be interpreted differently. The three magics that we are particularly interested in are `%%load`, which loads file content into the cell for editing and inserts a `%%writefile` magic at the top; `%%writefile`, which allows the user to save the contents of the cell in the named file; and `%%bash`, allowing the user to run one or more bash commands. These capabilities allow students to save their code to disk and compile it using `gcc` directly from the command line.

Moreover, to assist in plotting output, we have added a `%png` magic that will display a PNG file type. In principle, this could be made to happen using a code cell and a `<img src=...>` tag, but this option will try to cache images and make it difficult to see updates. (Note that because this magic reads the line it is on and not the notebook cell, it only uses a single `%` character)

2. `magic cling cells` - As an alternative to using the `cling` notebook, students can use a Python 3 notebook and run `cling` code using a `%%cling` magic. This magic starts a `cling` server in the background and sends commands to that server. An advantage of the `%%cling` magic is that the notebook does not halt if a segfault occurs (a problem for the `cling` notebook). In addition, magic provides mechanisms to transfer data between the C++ code and Python. See Fig. 1b.
3. `pybind11 + decorators` - `Pybind11` provides a relatively simple yet powerful way to interface between C++ and Python. Building on that framework, we developed a Python decorator, `@py11`. The user writes a Python function and decorates it with `@py11` and adds type annotations (see PEP 484, “Type Hints”). In the function’s doc comment, the student can provide C++ code. Figure 2 illustrates how to write a basic function in this framework.

```

In [6]: @py11()
        def sumi(a : int,b : int)->int:
            """
            // add 2 args
            return a+b;
            """

In [7]: sumi(20,22)

Out[7]: 42

```

Figure 2: Example using pybind11 and decorators for a powerful way to interface between C++ and Python. The students provide the C++ code within the function’s doc comment (highlighted in red) and decorate the function with the @py11 decorator to annotate it.

When the above definition is read by the interpreter, the source code for the `sumi()` function is written to a temporary file, compiled, and made available to be called (with arguments) directly from Python. One can specify additional headers and other information as arguments to the @py11 decorator.

There are two advantages to running code through @py11 rather than cling. First, cling does not allow users to redefine symbols. Once the `sumi()` function is defined in cling, its definition cannot be changed. Second, cling has a number of bugs relative to the more mature gcc compiler (cling works with the 5.0.0 clang compiler). If a student wishes to do something cling does not support, it may be possible using @py11. Finally, of the methods discussed, it is the most convenient for sending data to and from Python, since data structures such as lists and dicts will be serialized and translated. This is an advantage for students who wish to write a hybrid code.

3.4 C++ packages

1. HPX is a C++ Standard Library for Concurrency and Parallelism [11, ?]. It implements all corresponding facilities defined by the C++ Standard. Additionally, it implements some functionality proposed as part of the ongoing C++ standardization process, which is our primary reason for including it in this teaching environment.

Another advantage to using HPX for C++ parallelism is that cling is unable to support `std::async` because the Low Level Virtual Machine (LLVM) on which it is based does not support thread local data [19]. Thus, by using `hpx::async` instead of `std::async`, students are able to explore the benefits of working with standard futures in an interactive environment.

2. Blaze [13] is an open-source, high-performance C++ math library for dense and sparse arithmetic. Blaze provides several shared memory implementations, and one of them is HPX’s parallel algorithm. One essential ingredient for mathematical computations are matrices and vector operations. Thus, it is essential to introduce some linear algebra library to the students. Since Blaze is a heavily template-based library capable of using different backends for threading (e.g. HPX), it is an ideal candidate for this course. One aspect which is rather challenging is to plot simulation results in C++ without any additional libraries. Here, the Matplotlib [?] is an easy tool for plotting simulation results in Python. We added some magic %data to convert Blaze’s data structure to Python objects. In Figure 3 a Blaze vector is generated and filled in Cell 2. In the Cell 4 the magic is used to pass the Blaze vector `x` to Python and in the Output Cell 4 the corresponding Python array is shown. In Cell, 5 the magic %%plot is used to plot `np.sin(x)`. The plot is shown in the Output cell 5. This is one small example to transfer the simulation results from C++ to Python for plotting.

3.5 Docker image

Docker [18] is a service which can package an application and all dependencies within a so-called virtual container. This container can be executed on any server. We packaged Jupyterhub and all dependencies described above in an image which we hosted on a server at our institute. Alternatively, the container can be downloaded and run as a notebook. A separate `docker-compose.yml` file is provided for each usage. Note that if the server instance is not supplied with the tokens needed for GitHub, it runs with the “Create Your Own Login Authenticator” [2], which allows

```
In [1]: #include <blaze/Math.h>
#include <numeric>
```

```
Out[1]:
```

```
In [2]: .expr size_t N = 100;
auto x = blaze::DynamicVector<double>(N,0);
for(size_t i = 0 ; i < N ; i++)
    x[i] = i*0.1;
```

```
Out[2]:
```

```
In [3]: // Passing Blaze vectors to Python arrays
```

```
Out[3]:
```

```
In [4]: %data x
```

```
Out[4]: x shape is (100,)
```

```
In [5]: %%plot
import numpy as np
plt.xlabel("x-Label")
plt.ylabel("y-label")
plt.plot(x,np.sin(x),label="Data")
plt.grid()
plt.legend()
```

```
Out[5]:
```

Figure 3: A small example to use the magic %data to transfer the Blaze vector x to the corresponding Python array x . The transferred data can now be used within the magic %%data to generate plots using Matplotlib[?].

users to create their own login and password if they know a code word. Using the docker containers, we can have an instance for each course with different dependencies.

3.6 Telegram bot

Figure 4 shows the usage of the Telegram[®] bot to access the class server and experiment with Jupyterhub interactively. A Telegram[®] bot is a third-party application within Telegram[®] which users can send messages and commands. The Bot API is an HTTP-based interface created using the hypertext preprocessor (PHP) scripting language. In order to configure a Telegram[®] bot, you must interact with a special telegram account called BotFather. Use the BotFather to create a bot and get an access token. Set the CXXBOT.TOKEN environment variable with this token and your bot will be enabled through telegram. The Telegram[®] bot is written in Python and has to implement some provided functions to handle the user requests. The Python script for the Telegram[®] bot is available here¹ and for further details, we refer to the documentation².

To initiate a session with the C++Explorer bot, the bot asks for a password to prevent arbitrary people from executing code. For security reasons, the name of the bot was erased from the following pictures. Figure 4a shows how to compile a simple “hello world” program. The first message sends the C++ code `#include <iostream>` to the Telegram[®] bot. The first answer shows the code in the cell, and the second message that the code was successfully compiled. The second message sends the C++ code `std :: cout << "Hello_World"<< std::endl;` to the bot. The second to last answer shows the printed string, and finally the last answer shows the output of the cell. Figure 4b shows a simple plotting functionality, see the first message. The first answer shows the content of the cell, the third answer is the rendered content, and the last answer is the cling output.

4 C++ Explorer’s implementation details

Compiling the complete notebook system and making it function as intended presented a number of technical challenges. Many relate to limitations of the cling interpreter. The ease with which it can die (due to syntax errors or segfaults) is particularly challenging.

To overcome these issues, we created an alternate version of the `Kernel.cpp` source file which runs the commands. The modification uses a child process to run each update to the notebook. Before the child process executes a command, it calls `fork()`. If the evaluation succeeds, the grandchild process takes over the duties of the child, and the child exits. If the evaluation fails, the grandchild process exits.

The result is that the notebook is stable against both segfaults and syntax errors. Of course, memory problems that create the potential for segfaults cannot be caught or stopped in this way.

An odd side effect of this mechanism is that calls to `getpid()` within the notebook will constantly return new results.

Cling comes with Jupyter integration. The `clingkernel.py` source file provides an instance of the code for linking between Python and Cling. We leveraged this code to write the `%%cling` magics as well as the Telegram[®] bot.

5 User feedback

A brief questionnaire was sent to the students at the end of both semesters. The synthetic datasets without the timestamp or IP address provided by Survey Monkey and Qualtrics are available here [7] for the fall semester in 2019 and for the fall semester 2020 here [8], respectively. Note that for the fall semester of 2019, we had four responses out of five students, and for the fall semester of 2020 we had 11 responses out of 13 students. For simplicity, we report the answer for the fall of 2019 first and for the fall of 2020 second. First, we focus on the usage of git, see Figure 5. We asked if students used git before (a) and ³/₄ and ⁹/₁₁ had. Thus, most had no difficulty setting up git, see Figure 5b. A few needed some assistance in office hours; however, this was mostly related to how to use the bash terminal, since some students never used it before. Moreover, most students agreed that the bash terminal in the notebook was convenient, see Figure 5c. In general, most of the students agreed that git is a valuable skill for their future career, see Figure 5d. This relates to the survey results in [12].

¹<https://github.com/stevenrbrandt/CxxExplorer/blob/master/bot/cxxbot.py>

²<https://core.telegram.org/bots>

(a) Simple Hello World program within Telegram®.

(b) Simple plot within Telegram®.

Figure 4: Usage of the Telegram® bot to communicate with Jupyterhub using a smartphone or a tablet. Note that for simplicity of capture the screen, we used the App on macOS, however, the functionality on the portable device is exactly the same.

Fall 2019

Fall 2019

(a) Have you used git before?

(b) How difficult was it to set up git?

(c) The bash terminal in the notebook was convenient.

(d) Do you feel Git is a valuable skill?

Figure 5: Survey results from the fall semester of 2019 (left) and the fall semester of 2020 (right) for the usage of git. Additional results and the raw data is available here [7, 8].

Fall 2019

Fall 2020

Figure 6: Student’s feedback results from the fall semester 2019 (left) and the fall semester 2020 (right) for the usage of Python and Jupyterhub : Additional results and the raw data is available here [7, 8].

Second, we looked at the experience with Python and Jupyterhub , see Figure 6. The majority of the students had some experience with the Python programming language, see Figure 6a, which helped them to understand the pybind and pycling examples more easily. In addition, the majority of the students did not have experience using Jupyterhub , see Figure 6b. Only few of the students had experience with Jupyter notebooks in the fall semester of 2019 and the fall semester of 2020.

Third, we asked for the usage of the C++ feature of the notebooks, see Figure 7. For the following questions we have fewer answers from the fall 2020 class since something went wrong in the transition from Survey Monkey to Qualmetrics and some questions were missing in the first survey. We again sent the questionnaire to all students, however, only four answered the missing questions. First, we asked if they used the server/notebook often. For the fall 2019 semester, the majority of the students agreed or strongly agreed. However, all students strongly agreed for the fall 2020. see Figure 7a. Second, we asked if the students liked the notebook as an editor, see Figure 7b. We had an increasing amount of student’s agreement in the semester of fall 2019. However, in the fall of 2020 we had one student strongly disagreeing. Third, we asked how convenient the Docker setup was, see Figure 7c. Over half of the student agreed for both semesters. The remaining students had a neutral opinion. Lastly, we asked if the students would be interested in running the docker/notebook on their laptop, see Figure 7d. The majority of the students showed interest. For the fall 2020 course, only one student was neutral.

Lastly, students were asked for any issues they had with the notebooks and what features were missing. One student in the fall 2019 semester mentioned to both questions that he would like to be able to run a debugger in the notebook. For the fall 2020 semester, two students complained that `std::cin` didn’t work in the notebook. One student reported that it was odd that there can be only one function definition per cell, and lambda functions showed odd behavior. One student was bothered by the output of the C++ compiler, but found it useful after he understood the C++ compiler specific output.

Fall 2019

Fall 2020

(a) I used the server/notebook often.

(b) I liked the notebook as an editor.

(c) How convenient was the Docker setup.

(d) Would you be interested in running the docker/notebook on your laptop.

Figure 7: Student's feedback results from the fall semester 2019 (left) and the fall semester 2020 (right) for the usage of Python and Jupyterhub : Additional results and the raw data is available here [7, 8].

6 Conclusion

We have presented a novel environment adapted to teaching parallel C++ programming and source code management. We have made use of a fusion of existing technologies including GitHub[®], Jupyterhub, the OAuth facility of Jupyterhub, pybind11, and cling. We have provided extensions to many of these tools to make the notebooks richer and the interactive experience more complete. After teaching parallel C++ in 2019 and 2020, we analyzed the student’s feedback. Results of the math course have, so far, been mostly positive. Students have found the tools useful. Therefore, in the fall of 2021, we intend to use this setup again and continue to update the server, hopefully with a larger class size. In addition, we hope to broaden the usage of the C++Explorer in different courses within our university. As a next step, we intend to use the C++Explorer at tutorials and short courses at various conferences to teach modern C++ programming and parallel and distributed implementations using HPX. One example is the short course at the 16th U.S. National Congress on Computational Mechanics. In addition, we would like to build an open source community around the C++Explorer to discuss further applications and acquire new contributors to implement features faster.

The Telegram[®] bot was only tested within our research group and not used in the classroom yet. Next, the plotting functionality is very limited in the current version, and we intend to make it more sophisticated. *e.g.* the integration of Python’s Matplotlib.

Supplementary material

The lecture slides [6] and the exercises [5] of the course are available on Zenodo. The source code for the C++Explorer is available on GitHub³. Some Jupyter notebooks with some example course exercises are available on GitHub⁴. The complete results of the surveys are available on Zenodo [7, 8].

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³<https://github.com/stevenrbrandt/CxxExplorer>

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