

PyQBench: a Python library for benchmarking gate-based quantum computers

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Abstract

We introduce PyQBench, an innovative open-source framework for benchmarking gate-based quantum computers. PyQBench can benchmark NISQ devices by verifying their capability of discriminating between two von Neumann measurements. PyQBench offers a simplified, ready-to-use, command line interface (CLI) for running benchmarks using a predefined family of measurements. For more advanced scenarios, PyQBench offers a way of employing user-defined measurements instead of predefined ones.

Keywords: Quantum computing, Benchmarking quantum computers, Discrimination of quantum measurements, Discrimination of von Neumann measurements, Open-source, Python programming

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Current code version

C1	Current code version	0.1.1
C2	Permanent link to code/repository used for this code version	https://github.com/iitis/PyQBench
C3	Code Ocean compute capsule	https://codeocean.com/capsule/89088992-9a27-4712-8525-d92a9b23060f/tree
C4	Legal Code License	Apache License 2.0
C5	Code versioning system used	git
C6	Software code languages, tools, and services used	Python, Qiskit, AWS Braket
C7	Compilation requirements, operating environments & dependencies	<code>Python >= 3.8</code> <code>numpy ~= 1.22.0</code> <code>scipy ~= 1.7.0</code> <code>pandas ~= 1.5.0</code> <code>amazon-braket-sdk >= 1.11.1</code> <code>pydantic ~= 1.9.1</code> <code>qiskit ~= 0.37.2</code> <code>mthree ~= 1.1.0</code> <code>tqdm ~= 4.64.1</code> <code>pyyaml ~= 6.0</code> <code>qiskit-braket-provider ~= 0.0.3</code>
C8	If available Link to developer documentation/manual	https://pyqbench.readthedocs.io/en/latest/
C9	Support email for questions	dexter2206@gmail.com

Table 1: Code metadata

1. Motivation and significance

Noisy Intermediate-Scale Quantum (NISQ) [1] devices are storming the market, with a wide selection of devices based on different architectures and accompanying software solutions. Among hardware providers offering public access to their gate-based devices, one could mention Rigetti [2], IBM [3], Oxford Quantum Group [4], IonQ [5] or Xanadu [6]. Other vendors offer devices operating in different paradigms. Notably, one could mention D-Wave [7] and their quantum annealers, or QuEra devices [8] based on neutral atoms. Most vendors provide their own software stack and application programming interface for accessing their devices. To name a few, Rigetti’s computers are available through their Forest SDK [9] and PyQuil library [10] and IBM Q [3]

12 computers can be accessed through Qiskit [11] or IBM Quantum Experience
13 web interface [12]. Some cloud services, like Amazon Braket [13], offer ac-
14 cess to several quantum devices under a unified API. On top of that, several
15 libraries and frameworks can integrate with multiple hardware vendors. Ex-
16 amples of such frameworks include IBM Q’s Qiskit or Zapata Computing’s
17 Orquestra [14].

18 It is well known that NISQ devices have their limitations [15]. The ques-
19 tion is to what extent those devices can perform meaningful computations?
20 To answer this question, one has to devise a methodology for benchmarking
21 them. For gate-based computers, on which this paper focuses, there al-
22 ready exist several approaches. One could mention randomized benchmark-
23 ing [16, 17, 18, 19, 20], benchmarks based on the quantum volume [21, 22, 23].

24 In this paper, we introduce a different approach to benchmarking gate-
25 based devices with a simple operational interpretation. In our method, we
26 test how well the given device is at guessing which of the two known von
27 Neumann measurements were performed during the experiment. We imple-
28 mented our approach in an open-source Python library called PyQBench.
29 The library supports any device available through the Qiskit library, and
30 thus can be used with providers such as IBM Q or Amazon Braket. Along
31 with the library, the PyQBench package contains a command line tool for
32 running most common benchmarking scenarios.

33 2. Existing benchmarking methodologies and software

34 Unsurprisingly, PyQBench is not the only software package for bench-
35 marking gate-based devices. While we believe that our approach has signif-
36 icant benefits over other benchmarking techniques, for completeness, in this
37 section we discuss some of the currently available similar software.

38 Probably the simplest benchmarking method one could devise is simply
39 running known algorithms and comparing outputs with the expected ones.
40 Analyzing the frequency of the correct outputs, or the deviation between
41 actual and expected outputs distribution provides then a metric of the per-
42 formance of a given device. Libraries such as Munich Quantum Toolkit
43 (MQT) [24, 25] or SupermarQ [26, 27] contain benchmarks leveraging mul-
44 tiple algorithms, such as Shor’s algorithm or Grover’s algorithm. Despite
45 being intuitive and easily interpretable, such benchmarks may have some
46 problems. Most importantly, they assess the usefulness of a quantum device
47 only for a very particular algorithm, and it might be hard to extrapolate
48 their results to other algorithms and applications. For instance, the inability
49 of a device to consistently find factorizations using Shor’s algorithms does
50 not tell anything about its usefulness in Variational Quantum Algorithm’s.

Another possible approach to benchmarking quantum computers is randomized benchmarking. In this approach, one samples circuits to be run from some predefined set of gates (e.g. from the Clifford group) and tests how much the output distribution obtained from the device running these circuits differs from the ideal one. It is also common to concatenate randomly chosen circuits with their inverses (which should yield the identity circuit) and run those concatenated circuits on the device. Libraries implementing this approach include Qiskit [28] or PyQuil [29].

Another quantity used for benchmarking NISQ devices is quantum volume. The quantum volume characterizes capacity of a device for solving computational problems. It takes into account multiple factors like number of qubits, connectivity and measurement errors. The Qiskit library allows one to measure quantum volume of a device by using its `qiskit.ignis.verification.quantum_volume`. Other implementations of Quantum Volume can be found as well, see e.g. [30].

3. Preliminaries and discrimination scheme approach

In this section, we describe how the benchmarking process in PyQBench works. We start by discussing necessary mathematical preliminaries. Then, we present the general form of the discrimination scheme used in PyQBench and practical considerations on how to implement it taking into account the limitations of the current NISQ devices. We encourage the readers interested in a more in-depth discussion of the mathematical foundations behind our discrimination scheme to read Section 1 in the supplemental materials.

3.1. Von Neumann Measurements

A von Neumann measurement \mathcal{P} is a collection of rank-one projectors $\{|u_0\rangle\langle u_0|, \dots, |u_{d-1}\rangle\langle u_{d-1}|\}$, called effects, that sum up to the identity operator, i.e. $\sum_{i=0}^{d-1} |u_i\rangle\langle u_i| = \mathbb{1}$. If U is a unitary matrix of size d , one can construct a von Neumann measurement \mathcal{P}_U by taking projectors onto its columns. In this case we say that \mathcal{P}_U is described by the matrix U .

Typically, NISQ devices can only perform measurements in computational Z -basis, i.e. $U = \mathbb{1}$. To implement an arbitrary von Neumann measurement \mathcal{P}_U , one has to first apply U^\dagger to the measured system and then follow with Z -basis measurement. This process, depicted in Fig. 1, can be viewed as performing a change of basis in which measurement is performed prior to measurement in the computational basis.

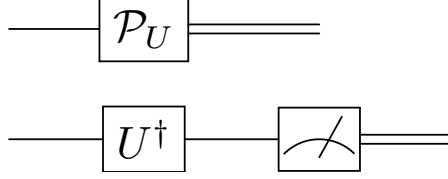


Figure 1: Implementation of a von Neumann measurement using measurement in computational basis. The upper circuit shows a symbolic representation of a von Neumann measurement \mathcal{P}_U . The bottom, equivalent circuit depicts its decomposition into a change of basis followed by measurement in the Z basis.

86 3.2. Discrimination scheme

87 Benchmarks in PyQBench work by experimentally determining the prob-
 88 ability of correct discrimination between two von Neumann measurements
 89 by the device under test and comparing the result with the ideal, theoretical
 90 predictions.

91 Without loss of generality¹, we consider discrimination task between sin-
 92 gle qubit measurements \mathcal{P}_1 , performed in the computational Z -basis, and an
 93 alternative measurement \mathcal{P}_U performed in the basis U . Note, however, that
 94 the discrimination scheme described below can work regardless of dimension-
 95 ality of the system, see [31] for details.

96 The discrimination scheme presented in Fig. 2 requires an auxiliary qubit.
 97 First, the joint system is prepared in some state $|\psi_0\rangle$. Then, one of the
 98 measurements, either \mathcal{P}_U or \mathcal{P}_1 , is performed on the first part of the system.
 99 Based on its outcome i , we choose another measurement \mathcal{P}_{V_i} and perform
 100 it on the second qubit, obtaining the outcome j . Finally, if $j = 0$, we say
 101 that the performed measurement is \mathcal{P}_U , otherwise we say that it was \mathcal{P}_1 .
 102 Naturally, we need to repeat the same procedure multiple times for both
 103 measurements to obtain a reliable estimate of the underlying probability
 104 distribution. In PyQBench, we assume that the experiment is repeated the
 105 same number of times for both \mathcal{P}_U and \mathcal{P}_1 .

106 In principle, our discrimination scheme could be used with any choice of
 107 $|\psi_0\rangle$ and final measurements \mathcal{P}_{V_i} . However, we argue that it is best to choose
 108 those components so that they maximize the probability of correct discrim-
 109 ination. To see that, suppose that some choice of $|\psi_0\rangle, \mathcal{P}_{V_0}, \mathcal{P}_{V_1}$ allows for
 110 correctly discriminating between two measurements with probability equal
 111 to one, i.e. on a perfect quantum computer you will always make a cor-
 112 rect guess. Then, on real hardware, we might obtain any empirical value in

¹Explaining why we can consider only discrimination scheme between \mathcal{P}_1 and \mathcal{P}_U is beyond the scope of this paper. See [31] for a in depth explanation.

113 range $[\frac{1}{2}, 1]$. On the other hand, if we choose the components of our scheme
 114 such that the successful discrimination probability is $\frac{3}{5}$, the possible range
 115 of empirically obtainable probabilities is only $[\frac{1}{2}, \frac{3}{5}]$. Hence, in the second
 116 case, the discrepancy between theoretical and empirical results will be less
 117 pronounced.

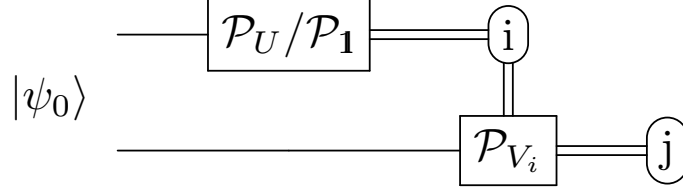


Figure 2: Theoretical scheme of discrimination between von Neumann measurements \mathcal{P}_U and \mathcal{P}_1 .

118 3.2.1. Implementation of discrimination scheme on actual NISQ devices

119 Current NISQ devices are unable to perform conditional measurements,
 120 which is the biggest obstacle to implementing our scheme on real hardware.
 121 However, we circumvent this problem by slightly adjusting our scheme so
 122 that it only uses components available on current devices. For this purpose,
 123 we use two possible options: using a postselection or a direct sum $V_0^\dagger \oplus V_1^\dagger$.

124 **Scheme 1.** (Postselection)

125 The first idea uses a postselection scheme. In the original scheme, we
 126 measure the first qubit and only then determine which measurement should
 127 be performed on the second one. Instead of doing this choice, we can run two
 128 circuits, one with \mathcal{P}_{V_0} and one with \mathcal{P}_{V_1} and measure both qubits. We then
 129 discard the results of the circuit for which label i does not match measurement
 130 label k . Hence, the circuit for postselection looks as depicted in Fig. 3.

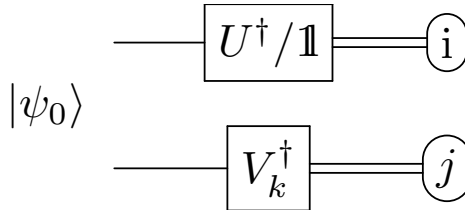


Figure 3: A schematic representation of the setup for distinguishing measurements \mathcal{P}_U and \mathcal{P}_1 using postselection approach. In postselection scheme, one runs such circuits for both $k = 0, 1$ and discards results for cases when there is a mismatch between k and i .

131 To perform the benchmark, one needs to run multiple copies of the post-
 132 selection circuit, with both \mathcal{P}_U and \mathcal{P}_1 . Each circuit has to be run in both

variants, one with final measurement \mathcal{P}_{V_0} and the second with the final measurement \mathcal{P}_{V_1} . The experiments can thus be grouped into classes identified by tuples of the form (\mathcal{Q}, k, i, j) , where $\mathcal{Q} \in \{\mathcal{P}_U, \mathcal{P}_1\}$ denotes the chosen measurement, $k \in \{0, 1\}$ designates the final measurement used, and $i \in \{0, 1\}$ and $j \in \{0, 1\}$ being the labels of outcomes as presented in Fig. 3. We then discard all the experiments for which $i \neq k$. The total number of valid experiments is thus:

$$N_{\text{total}} = \#\{(\mathcal{Q}, k, i, j) : k = i\}. \quad (1)$$

Finally, we count the valid experiments resulting in successful discrimination. If we have chosen \mathcal{P}_U , then we guess correctly iff $j = 0$. Similarly, for \mathcal{P}_1 , we guess correctly iff $j = 1$. If we define

$$N_{\mathcal{P}_U} = \#\{(\mathcal{Q}, k, i, j) : \mathcal{Q} = \mathcal{P}_U, k = i, j = 0\}, \quad (2)$$

$$N_{\mathcal{P}_1} = \#\{(\mathcal{Q}, k, i, j) : \mathcal{Q} = \mathcal{P}_1, k = i, j = 1\}, \quad (3)$$

then the empirical success probability can be computed as

$$p_{\text{succ}}(\mathcal{P}_U, \mathcal{P}_1) = \frac{N_{\mathcal{P}_U} + N_{\mathcal{P}_1}}{N_{\text{total}}}. \quad (4)$$

The p_{succ} is the quantity reported to the user as the result of the benchmark.

Scheme 2. (Direct sum)

The second idea uses the direct sum $V_0^\dagger \oplus V_1^\dagger$ implementation. Here, instead of performing a conditional measurement \mathcal{P}_{V_k} , where $k \in \{0, 1\}$, we run circuits presented in Fig. 4.

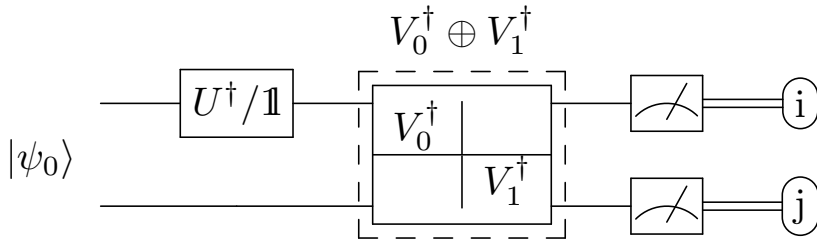


Figure 4: A schematic representation of the setup for distinguishing measurements \mathcal{P}_U and \mathcal{P}_1 using the $V_0^\dagger \oplus V_1^\dagger$ direct sum.

One can see why such a circuit is equivalent to the original discrimination scheme. If we rewrite the block-diagonal matrix $V_0^\dagger \oplus V_1^\dagger$ as follows:

$$V_0^\dagger \oplus V_1^\dagger = |0\rangle\langle 0| \otimes V_0^\dagger + |1\rangle\langle 1| \otimes V_1^\dagger, \quad (5)$$

we can see that the direct sum in Eq. (5) commutes with the measurement on the first qubit. Thanks to this, we can switch the order of operations to obtain the circuit from Fig. 5. Now, depending on the outcome i , one of the summands in Eq. (5) vanishes, and we end up performing exactly the same operations as in the original scheme.

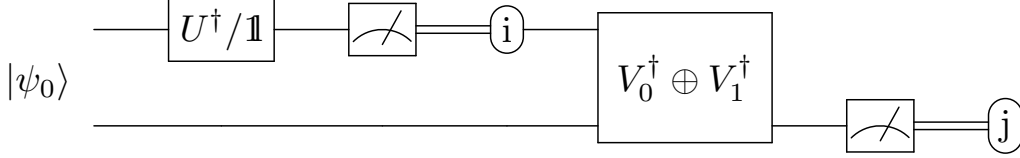


Figure 5: Rewritten representation of the setup for distinguishing measurements \mathcal{P}_U and \mathcal{P}_1 using the $V_0^\dagger \oplus V_1^\dagger$ direct sum.

In this scheme, the experiment can be characterized by a pair (\mathcal{Q}, i, j) , where $\mathcal{Q} = \{\mathcal{P}_U, \mathcal{P}_1\}$ and $i, j \in \{0, 1\}$ are the output labels. The number of successful trials for U and $\mathbb{1}$, respectively, can be written as

$$N_{\mathcal{P}_U} = \#\{(\mathcal{Q}, i, j) : \mathcal{Q} = \mathcal{P}_U, j = 0\}, \quad (6)$$

$$N_{\mathcal{P}_1} = \#\{(\mathcal{Q}, i, j) : \mathcal{Q} = \mathcal{P}_1, j = 1\}. \quad (7)$$

Then, the probability of correct discrimination between \mathcal{P}_U and \mathcal{P}_1 is given by

$$p_{\text{succ}} = \frac{N_{\mathcal{P}_U} + N_{\mathcal{P}_1}}{N_{\text{total}}}, \quad (8)$$

where N_{total} is the number of trials.

4. Software description

This section is divided into two parts. In Section 4.1 we describe functionalities of PyQBench package. Next, in Section 4.2, we give a general overview of the software architecture.

4.1. Software Functionalities

The PyQBench can be used in two modes: as a Python library and as a CLI script. When used as a library, PyQBench allows the customization of discrimination scheme. The user provides a unitary matrix U defining the measurement to be discriminated, the discriminator $|\psi_0\rangle$, and unitaries V_0 and V_1 describing the final measurement. The PyQBench library provides then the following functionalities.

1. Assembling circuits for both postselection and direct sum-based discrimination schemes.

- 175 2. Executing the whole benchmarking scenario on specified backend (ei-
176 ther real hardware or software simulator).
- 177 3. Interpreting the obtained outputs in terms of discrimination probab-
178 ities.

179 Note that the execution of circuits by PyQBench is optional. Instead, the
180 user might want to opt in for fine-grained control over the execution of the
181 circuits. For instance, suppose the user wants to simulate the discrimination
182 experiment on a noisy simulator. In such a case, they can define the necessary
183 components and assemble the circuits using PyQBench. The circuits can
184 then be altered, e.g. to add noise to particular gates, and then run using any
185 Qiskit backend by the user. Finally, PyQBench can be used to interpret the
186 measurements to obtain discrimination probability.

187 The PyQBench library also contains a readily available implementation
188 of all necessary components needed to run discrimination experiments for
189 parametrized Fourier family of measurements (see Section 3 in supplemental
190 material). However, if one only wishes to use this particular family of mea-
191 surements in their benchmarks, then using PyQBench as a command line
192 tool might be more straightforward. PyQBench’s command line interface
193 allows running the benchmarking process without writing Python code. The
194 configuration of CLI is done by YAML [32] files describing the benchmark
195 to be performed and the description of the backend on which the benchmark
196 should be run. The same benchmark can be used with different backends
197 and vice versa.

198 4.2. Software Architecture

199 4.2.1. Overview of the software structure

200 As already described, PyQBench can be used both as a library and a CLI.
201 Both functionalities are implemented as a part of **qbench** Python package.
202 The exposed CLI tool is also named **qbench**. For brevity, we do not discuss
203 the exact structure of the package here, and instead refer an interested reader
204 to the source code available at GitHub [33] or at the reference manual [34].

205 PyQBench can be installed from official Python Package Index (PyPI)
206 by running `pip install pyqbench`. In a properly configured Python en-
207 vironment the installation process should also make the **qbench** command
208 available to the user without a need for further configuration.

209 4.2.2. Integration with hardware providers and software simulators

210 PyQBench is built around the Qiskit [11] ecosystem. Hence, both the
211 CLI tool and the **qbench** library can use any Qiskit-compatible backend.
212 This includes, IBM Q backends (available by default in Qiskit) and Amazon

213 Braket devices and simulators (available through `qiskit-braket-provider`
214 package [35, 36]).

215 When using PyQBench as library, instances of Qiskit backends can be
216 passed to functions that expect them as parameters. However, in CLI mode,
217 the user has to provide a YAML file describing the backend. An example
218 of such file can be found in Section 5, and the detailed description of the
219 expected format can be found at PyQBench’s documentation.

220 4.2.3. Command Line Interface

221 The Command Line Interface (CLI) of PyQBench has nested structure.
222 The general form of the CLI invocation is shown in listing 1.

Listing 1: Invocation of `qbench` script

```
223 qbench <benchmark-type> <command> <parameters>
```

226 Currently, PyQBench’s CLI supports only one type of benchmark (discrimi-
227 nation of parametrized Fourier family of measurements), but we decided on
228 hierarchically structuring the CL to allow for future extensions. Thus, the
229 only accepted value of `<benchmark-type>` is `disc-fourier`. The `qbench`
230 `disc-fourier` command has four subcommands:

- 231 • **benchmark**: run benchmarks. This creates either a result YAML file
232 containing the measurements or an intermediate YAML file for asyn-
233 chronous experiments.
- 234 • **status**: query status of experiments submitted for given benchmark.
235 This command is only valid for asynchronous experiments.
- 236 • **resolve**: query the results of asynchronously submitted experiments
237 and write the result YAML file. The output of this command is almost
238 identical to the result obtained from synchronous experiments.
- 239 • **tabulate**: interpret the results of a benchmark and summarize them
240 in the CSV file.

241 We present usage of each of the above commands later in section 5.

242 4.2.4. Asynchronous vs. synchronous execution

243 PyQBench’s CLI can be used in synchronous and asynchronous modes.
244 The mode of execution is defined in the YAML file describing the backend
245 (see Section 5 for an example of this configuration). We decided to couple
246 the mode of execution to the backend description because some backends
247 cannot work in asynchronous mode.

248 When running `qbench disc-fourier benchmark` in asynchronous mode,
 249 the PyQBench submits all the circuits needed to perform a benchmark and
 250 then writes an intermediate YAML file containing metadata of submitted
 251 experiments. In particular, this metadata contains information on correlating
 252 submitted job identifiers with particular circuits. The intermediate file can
 253 be used to query the status of the submitted jobs or to resolve them, i.e. to
 254 wait for their completion and get the measurement outcomes.

255 In synchronous mode, PyQBench first submits all jobs required to run the
 256 benchmark and then immediately waits for their completion. The advantage
 257 of this approach is that no separate invocation of `qbench` command is needed
 258 to actually download the measurement outcomes. The downside, however,
 259 is that if the script is interrupted while the command is running, the inter-
 260 mediate results will be lost. Therefore, we recommend using asynchronous
 261 mode whenever possible.

262 5. Illustrative examples

263 In this section, we demonstrate the usage of PyQBench. For brevity, we
 264 decided to present only the usage of the CLI tool, as it is likely to be the
 265 most popular use case. We refer readers interested in implementing their
 266 discrimination schemes using custom measurements to PyQBench’s docu-
 267 mentation [34], where we describe the whole process, and to the Section 2
 268 in the supplemental material, where we discuss the relevant mathematical
 269 details.

270 5.1. Using *qbench* CLI

271 PyQBench offers a simplified way of conducting benchmarks using a Com-
 272 mand Line Interface (CLI). The workflow with PyQBench’s CLI can be sum-
 273 marized as the following list of steps:

- 274 1. Preparing configuration files describing the backend and the experiment
 275 scenario.
- 276 2. Submitting/running experiments. Depending on the experiment sce-
 277 nario, execution can be synchronous, or asynchronous.
- 278 3. (optional) Checking the status of the submitted jobs if the execution
 279 is asynchronous.
- 280 4. Resolving asynchronous jobs into the actual measurement outcomes.
- 281 5. Converting obtained measurement outcomes into tabulated form.

282 *5.1.1. Preparing configuration files*

283 The configuration of PyQBench CLI is driven by YAML files. The first
284 configuration file describes the experiment scenario to be executed. The
285 second file describes the backend. Typically, this backend will correspond to
286 the physical device to be benchmarked, but for testing purposes, one might
287 as well use any other Qiskit-compatible backend including simulators. Let us
288 first describe the experiment configuration file, which might look as follow.

Listing 2: Defining the experiment

```
289  
290 type: discrimination-fourier  
291 qubits:  
292   - target: 0  
293     ancilla: 1  
294   - target: 1  
295     ancilla: 2  
296 angles:  
297   start: 0  
298   stop: 2 * pi  
299   num_steps: 3  
300 gateset: ibmq  
301 method: direct_sum  
302 num_shots: 100  
303
```

304 The second configuration file describes the backend. We decided to de-
305 couple the experiment and the backend files because it facilitates their reuse.
306 For instance, the same experiment file can be used to run benchmarks on
307 multiple backends, and the same backend description file can be used with
308 multiple experiments.

309 Different Qiskit backends typically require different data for their initial-
310 ization. Hence, there are multiple possible formats of the backend config-
311 uration files understood by PyQBench. We refer the interested reader to
312 the PyQBench's documentation. Below we describe an example YAML file
313 describing IBM Q backend named Quito.

Listing 3: IBMQ backend

```
314  
315 name: ibmq_quito  
316 asynchronous: false  
317 provider:  
318   hub: ibm-q  
319   group: open  
320   project: main  
321
```

322 IBMQ backends typically require an access token to IBM Quantum Experi-
 323 ence. Since it would be unsafe to store it in plain text, the token has to be
 324 configured separately in `IBMQ_TOKEN` environmental variable.

325 5.1.2. Running the experiment and collecting measurements data

326 After preparing YAML files defining experiment and backend, running the
 327 benchmark can be launched by using the following command line invocation:

```
328 qbench disc-fourier benchmark experiment_file.yml backend_file.yml
```

331 The output file will be printed to stdout. Optionally, the `- --output OUTPUT`
 332 parameter might be provided to write the output to the `OUTPUT` file instead.

```
333 qbench disc-fourier benchmark experiment_file.yml backend_file.yml
334 --output async_results.yml
```

337 The result of running the above command can be twofold:

- 338 • If the backend is asynchronous, the output will contain intermediate
 339 data containing, amongst others, `job_ids` correlated with the circuit
 340 they correspond to.
- 341 • If the backend is synchronous, the output will contain measurement
 342 outcomes (bitstrings) for each of the circuits run.

343 For the synchronous experiment, the part of the output looks similar
 344 to the one below. The whole YAML file can be seen in Section 5 in the
 345 supplemental material.

```
346 data:
347 - target: 0
348   ancilla: 1
349   phi: 0.0
350   results_per_circuit:
351   - name: id
352     histogram: {'00': 28, '01': 26, '10': 21, '11': 25}
353     mitigation_info:
354       target: {prob_meas0_prep1: 0.052200000000000024,
355               prob_meas1_prep0: 0.0172}
356       ancilla: {prob_meas0_prep1: 0.059000000000000005,
357                prob_meas1_prep0: 0.0202}
358     mitigated_histogram: {'00': 0.2637212373658018, '01':
359                          0.25865061319892463, '10': 0.2067279352110304, '11':
360                          0.2709002142242433}
```

363 *5.1.3. (Optional) Getting status of asynchronous jobs*

364 PyQBench provides also a helper command that will fetch the statuses
365 of asynchronous jobs. The command is:

366 `qbench disc-fourier status async_results.yml`
367
368

369 and it will display dictionary with histogram of statuses.

370 *5.1.4. Resolving asynchronous jobs*

371 For asynchronous experiments, the stored intermediate data has to be
372 resolved in actual measurements' outcomes. The following command will
373 wait until all jobs are completed and then write a result file.

374 `qbench disc-fourier resolve async_results.yml resolved.yml`
375
376

377 The resolved results, stored in `resolved.yml`, would look just like if the
378 experiment was run synchronously. Therefore, the final results will look the
379 same no matter in which mode the benchmark was run, and hence in both
380 cases the final output file is suitable for being an input for the command
381 computing the discrimination probabilities.

382 *5.1.5. Computing probabilities*

383 As a last step in the processing workflow, the results file has to be passed
384 to `tabulate` command:

385 `qbench disc-fourier tabulate results.yml results.csv`
386
387

388 A sample CSV file is provided in Table 2.

389 **6. Impact**

390 With the surge of availability of quantum computing architectures in
391 recent years it becomes increasingly difficult to keep track of their relative
392 performance. To make this case even more difficult, various providers give
393 access to different figures of merit for their architectures. Our package allows
394 the user to test various architectures, available through `qiskit` and Amazon
395 BraKet using problems with simple operational interpretation. We provide
396 one example built-in in the package. Furthermore, we provide a powerful
397 tool for the users to extend the range of available problems in a way that
398 suits their needs.

399 Due to this possibility of extension, the users are able to test specific
400 aspects of their architecture of interest. For example, if their problem is
401 related to the amount of coherence (the sum of absolute value of off-diagonal

target	ancilla	phi	ideal_prob	disc_prob	mit_disc_prob
0	1	0	0.5	0.46	0.45
0	1	3.14	1	0.95	0.98
0	1	6.28	0.5	0.57	0.58
1	2	0	0.5	0.57	0.57
1	2	3.14	1	0.88	0.94
1	2	6.28	0.5	0.55	0.56

Table 2: The resulting CSV file contains table with columns `target`, `ancilla`, `phi`, `ideal_prob`, `disc_prob` and, optionally, `mit_disc_prob`. Each row in the table describes results for a tuple of (`target`, `ancilla`, `phi`). The reference optimal value of discrimination probability is present in `ideal_prob` column, whereas the obtained, empirical discrimination probability can be found in the `disc_prob` column. The `mit_disc_prob` column contains empirical discrimination probability after applying the `Mthree` error mitigation [37, 38], if it was applied.

elements) of the states present during computation, they are able to quickly prepare a custom experiment, launch it on desired architectures, gather the result, based on which they can decide which specific architecture they should use.

Finally, we provide the source code of PyQBench on GitHub [33] under an open source license which will allow users to utilize and extend our package in their specific applications.

7. Conclusions

In this paper, we presented a Python library PyQBench, an innovative open-source framework for benchmarking gate-based quantum computers. PyQBench can benchmark NISQ devices by verifying their capability of discriminating between two von Neumann measurements. PyQBench offers a simplified, ready-to-use, command line interface (CLI) for running benchmarks using a predefined parameterized Fourier family of measurements. For more advanced scenarios, PyQBench offers a way of employing user-defined measurements instead of predefined ones.

8. Conflict of Interest

We wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

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