

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

PACS: 03.67.-a, 03.67.Lx

2000 MSC: 81P68

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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.

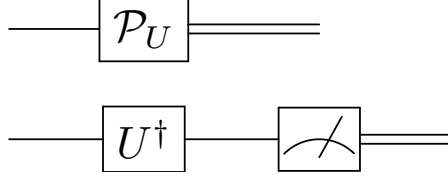


Figure 1: Implementation of a von Neumann measurement using measurement in computational basis. The upper circuit shows a symbolic representation of a von Neumann measurement \mathcal{P}_U . The bottom, equivalent circuit depicts its decomposition into a change of basis followed by measurement in the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

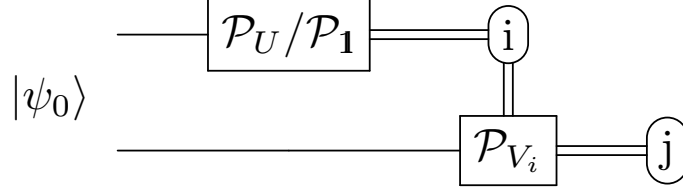


Figure 2: Theoretical scheme of discrimination between von Neumann measurements \mathcal{P}_U and \mathcal{P}_1 .

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.

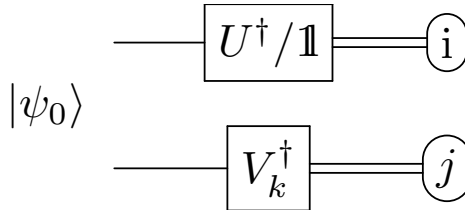


Figure 3: A schematic representation of the setup for distinguishing measurements \mathcal{P}_U and \mathcal{P}_1 using postselection approach. In postselection scheme, one runs such circuits for both $k = 0, 1$ and discards results for cases when there is a mismatch between k and i .

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.

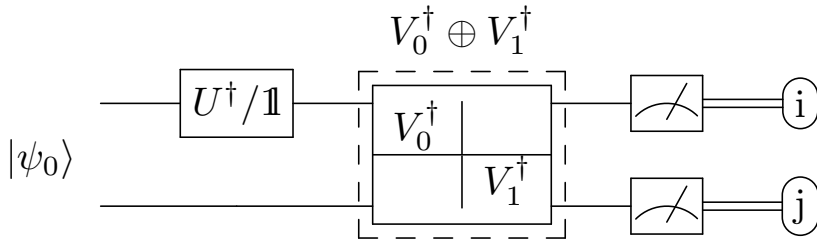


Figure 4: A schematic representation of the setup for distinguishing measurements \mathcal{P}_U and \mathcal{P}_1 using the $V_0^\dagger \oplus V_1^\dagger$ direct sum.

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.

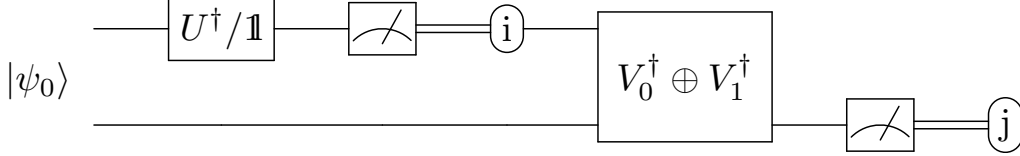


Figure 5: Rewritten representation of the setup for distinguishing measurements \mathcal{P}_U and \mathcal{P}_1 using the $V_0^\dagger \oplus V_1^\dagger$ direct sum.

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.

Compared to these approaches, our approach allows for very simple operational interpretation of the scheme and its results. This is especially useful for newcomers to the field, who may be put off by more complicated approaches. Another benefit is, especially for advanced users, the ability to control resources utilized during the benchmarking. We can consider here resources such as entanglement or coherence. Finally, the figure of merit we wish calculate and to which we compare are results is fairly simple to obtain. The main downside of our approach is the exponential number of circuits we need to consider.

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.

175 4.1. Software Functionalities

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

- 182 1. Assembling circuits for both postselection and direct sum-based dis-
183 crimination schemes.
- 184 2. Executing the whole benchmarking scenario on specified backend (ei-
185 ther real hardware or software simulator).
- 186 3. Interpreting the obtained outputs in terms of discrimination probab-
187 ities.

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

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

207 4.2. Software Architecture

208 4.2.1. Overview of the software structure

209 As already described, PyQBench can be used both as a library and a CLI.
210 Both functionalities are implemented as a part of `qbench` Python package.
211 The exposed CLI tool is also named `qbench`. For brevity, we do not discuss

the exact structure of the package here, and instead refer an interested reader to the source code available at GitHub [33] or at the reference manual [34].

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

4.2.2. Integration with hardware providers and software simulators

PyQBench is built around the Qiskit [11] ecosystem. Hence, both the CLI tool and the `qbench` library can use any Qiskit-compatible backend. This includes, IBM Q backends (available by default in Qiskit) and Amazon Braket devices and simulators (available through `qiskit-braket-provider` package [35, 36]).

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

4.2.3. Command Line Interface

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

Listing 1: Invocation of `qbench` script

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

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

- **benchmark**: run benchmarks. This creates either a result YAML file containing the measurements or an intermediate YAML file for asynchronous experiments.
- **status**: query status of experiments submitted for given benchmark. This command is only valid for asynchronous experiments.
- **resolve**: query the results of asynchronously submitted experiments and write the result YAML file. The output of this command is almost identical to the result obtained from synchronous experiments.

- **tabulate**: interpret the results of a benchmark and summarize them in the CSV file.

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

4.2.4. *Asynchronous vs. synchronous execution*

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

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

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

5. Illustrative examples

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

5.1. *Using qbench CLI*

PyQBench offers a simplified way of conducting benchmarks using a Command Line Interface (CLI). The workflow with PyQBench’s CLI can be summarized as the following list of steps:

- 283 1. Preparing configuration files describing the backend and the experiment
284 scenario.
- 285 2. Submitting/running experiments. Depending on the experiment sce-
286 nario, execution can be synchronous, or asynchronous.
- 287 3. (optional) Checking the status of the submitted jobs if the execution
288 is asynchronous.
- 289 4. Resolving asynchronous jobs into the actual measurement outcomes.
- 290 5. Converting obtained measurement outcomes into tabulated form.

291 *5.1.1. Preparing configuration files*

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

Listing 2: Defining the experiment

```

298
299 type: discrimination-fourier
300 qubits:
301   - target: 0
302     ancilla: 1
303   - target: 1
304     ancilla: 2
305 angles:
306   start: 0
307   stop: 2 * pi
308   num_steps: 3
309 gateset: ibmq
310 method: direct_sum
311 num_shots: 100
312

```

313 The second configuration file describes the backend. We decided to de-
314 couple the experiment and the backend files because it facilitates their reuse.
315 For instance, the same experiment file can be used to run benchmarks on
316 multiple backends, and the same backend description file can be used with
317 multiple experiments.

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

Listing 3: IBMQ backend

```

323
324 name: ibmq_quito
325 asynchronous: false
326 provider:
327     hub: ibm-q
328     group: open
329     project: main
330

```

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

334 5.1.2. Running the experiment and collecting measurements data

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

```

337 qbench disc-fourier benchmark experiment_file.yml backend_file.yml
338
339

```

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

```

342 qbench disc-fourier benchmark experiment_file.yml backend_file.yml
343 --output async_results.yml
344

```

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

- 347 • If the backend is asynchronous, the output will contain intermediate
348 data containing, amongst others, `job_ids` correlated with the circuit
349 they correspond to.
- 350 • If the backend is synchronous, the output will contain measurement
351 outcomes (bitstrings) for each of the circuits run.

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

```

355 data:
356 - target: 0
357   ancilla: 1
358   phi: 0.0
359   results_per_circuit:
360   - name: id
361     histogram: {'00': 28, '01': 26, '10': 21, '11': 25}

```

```

363 mitigation_info:
364   target: {prob_meas0_prep1: 0.052200000000000024,
365           prob_meas1_prep0: 0.0172}
366   ancilla: {prob_meas0_prep1: 0.059000000000000005,
367            prob_meas1_prep0: 0.0202}
368   mitigated_histogram: {'00': 0.2637212373658018, '01':
369                        0.25865061319892463, '10': 0.2067279352110304, '11':
370                        0.2709002142242433}
371

```

372 5.1.3. (Optional) Getting status of asynchronous jobs

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

```

375
376 qbench disc-fourier status async_results.yml
377

```

378 and it will display dictionary with histogram of statuses.

379 5.1.4. Resolving asynchronous jobs

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

```

383
384 qbench disc-fourier resolve async-results.yml resolved.yml
385

```

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

391 5.1.5. Computing probabilities

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

```

394
395 qbench disc-fourier tabulate results.yml results.csv
396

```

397 A sample CSV file is provided in Table 2.

398 6. Impact

399 With the surge of availability of quantum computing architectures in
400 recent years it becomes increasingly difficult to keep track of their relative
401 performance. To make this case even more difficult, various providers give

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.

access to different figures of merit for their architectures. Our package allows the user to test various architectures, available through `qiskit` and Amazon BraKet using problems with simple operational interpretation. We provide one example built-in in the package. Furthermore, we provide a powerful tool for the users to extend the range of available problems in a way that suits their needs.

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

425 more advanced scenarios, PyQBench offers a way of employing user-defined
426 measurements instead of predefined ones.

427 **8. Conflict of Interest**

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

431 **Acknowledgements**

432 This work is supported by the project “Near-term quantum computers
433 Challenges, optimal implementations and applications” under Grant Num-
434 ber POIR.04.04.00-00-17C1/18-00, which is carried out within the Team-Net
435 programme of the Foundation for Polish Science co-financed by the Euro-
436 pean Union under the European Regional Development Fund. PL is also a
437 holder of European Union scholarship through the European Social Fund,
438 grant InterPOWER (POWR.03.05.00-00-Z305).

439 **References**

- 440 [1] John Preskill. Quantum computing in the nisc era and beyond. *Quan-*
441 *tum*, 2:79, 2018.
- 442 [2] Rigetti computing. <https://www.rigetti.com/>. Accessed on 2023-02-
443 18.
- 444 [3] IBM Quantum. <https://www.ibm.com/quantum>. Accessed on 2023-02-
445 18.
- 446 [4] Oxford quantum. <http://oxfordquantum.org/>. Accessed on 2023-02-
447 18.
- 448 [5] IonQ. <https://ionq.com/>. Accessed on 2023-02-18.
- 449 [6] Xanadu. <https://www.xanadu.ai/>. Accessed on 2023-02-18.
- 450 [7] D-Wave Systems. <https://www.dwavesys.com/>. Accessed on 2023-02-
451 18.
- 452 [8] QuEra. <https://www.quera.com/>. Accessed on 2023-02-18.
- 453 [9] QCS Documentation. <https://docs.rigetti.com/qcs/>. Accessed on
454 2023-02-18.

- [10] PyQuil Documentation. <https://pyquil-docs.rigetti.com/en/stable/>. Accessed on 2023-02-18.
- [11] Qiskit. <https://qiskit.org/>. Accessed on 2023-02-18.
- [12] IBM Quantum Experience. <https://quantum-computing.ibm.com/>. Accessed on 2023-02-18.
- [13] Amazon Braket. <https://aws.amazon.com/braket/>. Accessed on 2023-02-18.
- [14] Zapata Orquestra Platform. <https://www.zapatacomputing.com/orquestra-platform/>. Accessed on 2023-02-18.
- [15] J. Preskill. Quantum computing 40 years later. *arXiv preprint arXiv:2106.10522*, 2021.
- [16] Y. Liu, M. Otten, R. Bassirianjahromi, L. Jiang, and B. Fefferman. Benchmarking near-term quantum computers via random circuit sampling. *arXiv preprint arXiv:2105.05232*, 2021.
- [17] E. Knill, D. Leibfried, R. Reichle, J. Britton, R. B. Blakestad, J. D. Jost, C. Langer, R. Ozeri, S. Seidelin, and D. J. Wineland. Randomized benchmarking of quantum gates. *Physical Review A*, 77(1):012307, 2008.
- [18] J. J. Wallman and S. T. Flammia. Randomized benchmarking with confidence. *New Journal of Physics*, 16(10):103032, 2014.
- [19] J. Helsen, I. Roth, E. Onorati, A. H. Werner, and J. Eisert. General framework for randomized benchmarking. *PRX Quantum*, 3(2):020357, 2022.
- [20] A. Cornelissen, J. Bausch, and A. Gilyén. Scalable benchmarks for gate-based quantum computers. *arXiv preprint arXiv:2104.10698*, 2021.
- [21] A. W. Cross, L. S. Bishop, S. Sheldon, P. D. Nation, and J. M. Gambetta. Validating quantum computers using randomized model circuits. *Physical Review A*, 100(3):032328, 2019.
- [22] N. Moll, P. Barkoutsos, L. S. Bishop, J. M. Chow, A. Cross, D. J. Egger, S. Filipp, A. Fuhrer, J. M. Gambetta, M. Ganzhorn, A. Kandala, A. Mezzacapo, P. Müller, W. Riess, G. Salis, J. Smolin, I. Tavernelli, and K. Temme. Quantum optimization using variational algorithms on near-term quantum devices. *Quantum Science and Technology*, 3(3):030503, 2018.

- [23] E. Pelofske, A. Bäertschi, and S. Eidenbenz. Quantum volume in practice: What users can expect from nisq devices. *IEEE Transactions on Quantum Engineering*, 3:1–19, 2022.
- [24] N. Quetschlich, L. Burgholzer, and R. Wille. Mqt bench: Benchmarking software and design automation tools for quantum computing. *arXiv preprint arXiv:2204.13719*, 2022.
- [25] MQTBench. <https://github.com/cda-tum/MQTBench>. Accessed on 2023-02-18.
- [26] T. Tomesh, P. Gokhale, V. Omole, G. S. Ravi, K. N. Smith, J. Visslai, X. Wu, N. Hardavellas, M. R. Martonosi, and F. T. Chong. SupermarQ: A scalable quantum benchmark suite. In *2022 IEEE International Symposium on High-Performance Computer Architecture (HPCA)*, pages 587–603. IEEE, 2022.
- [27] SupermarQ. <https://github.com/SupertechLabs/SupermarQ>. Accessed on 2023-02-18.
- [28] Qiskit benchmarks. <https://github.com/qiskit-community/qiskit-benchmarks>. Accessed on 2023-02-18.
- [29] Forest Benchmarking: QCVV using PyQuil. <https://github.com/rigetti/forest-benchmarking>. Accessed on 2023-02-18.
- [30] Quantum volume in practice. <https://github.com/lanl/Quantum-Volume-in-Practice>. Accessed on 2023-02-18.
- [31] Z. Puchała, Ł. Paweł, A. Krawiec, and R. Kukulski. Strategies for optimal single-shot discrimination of quantum measurements. *Physical Review A*, 98(4):042103, 2018.
- [32] YAML Ain’t Markup Language (YAML) Version 1.2. <https://yaml.org/spec/1.2.2/>. Accessed on 2023-02-18.
- [33] PyQBench GitHub Repository. <https://github.com/iitis/PyQBench>. Accessed on 2023-02-18.
- [34] PyQBench Documentation. <https://pyqbench.readthedocs.io/en/latest/>. Accessed on 2023-02-18.
- [35] Introducing the Qiskit Provider for Amazon Braket. <https://aws.amazon.com/blogs/quantum-computing/introducing-the-qiskit-provider-for-amazon-braket/>. Accessed on 2023-02-18.

- 522 [36] Qiskit Braket Provider GitHub Repository. [https://github.com/](https://github.com/qiskit-community/qiskit-braket-provider)
523 [qiskit-community/qiskit-braket-provider](https://github.com/qiskit-community/qiskit-braket-provider). Accessed on 2023-02-
524 18.
- 525 [37] mthree Documentation. [https://qiskit.org/documentation/](https://qiskit.org/documentation/partners/mthree/stubs/mthree.M3Mitigation.html)
526 [partners/mthree/stubs/mthree.M3Mitigation.html](https://qiskit.org/documentation/partners/mthree/stubs/mthree.M3Mitigation.html). Accessed on
527 2023-02-10.
- 528 [38] P. D. Nation, H. Kang, N. Sundaresan, and J. M. Gambetta. Scalable
529 mitigation of measurement errors on quantum computers. *PRX Quan-*
530 *tum*, 2(4):040326, 2021.