

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

Konrad Jałowiecki*, Paulina Lewandowska, Łukasz Paweł

*Institute of Theoretical and Applied Informatics, Polish Academy of Sciences,
Balttycka 5, 44-100 Gliwice, Poland*

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

*Corresponding author

Email address: `dexter2206@gmail.com` (Konrad Jałowiecki)

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].

Finally, we should mention cross-entropy benchmarking [31], which was utilized in validation of the Sycamore-53 QPU supremacy experiments [32]. In this approach, the quality of an algorithm implemented on the QPU is measured by calculating the cross entropy of bit-strings actually sampled from the QPU, compared to ideal bitstrings.

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.

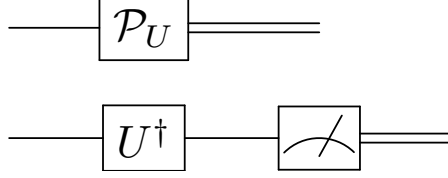


Figure 1: Implementation of a von Neumann measurement using measurement in computational basis. The upper circuit shows a symbolic representation of a von Neumann measurement \mathcal{P}_U . The bottom, equivalent circuit depicts its decomposition into a change of basis followed by measurement in the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

3.2. Discrimination scheme

Benchmarks in PyQBench work by experimentally determining the probability of correct discrimination between two von Neumann measurements by the device under test and comparing the result with the ideal, theoretical predictions.

Without loss of generality¹, we consider discrimination task between single qubit measurements \mathcal{P}_1 , performed in the computational Z -basis, and an alternative measurement \mathcal{P}_U performed in the basis U . The discrimination scheme presented in Fig. 2 requires an auxiliary qubit. First, the joint system is prepared in some state $|\psi_0\rangle$. Then, one of the measurements, either \mathcal{P}_U or \mathcal{P}_1 , is performed on the first part of the system. Based on its outcome i , we choose another binary measurement \mathcal{P}_{V_i} and perform it on the second qubit, obtaining the outcome j . Finally, if $j = 0$, we say that the performed measurement is \mathcal{P}_U , otherwise we say that it was \mathcal{P}_1 .

Note, however, that the discrimination scheme described above can work regardless of dimensionality of the unitary U . The main difference is the dimension of the auxiliary system, which in general can be larger than two. This dimension depends on the Schmidt rank of the optimal input state. However, for most discrimination schemes, the Schmidt rank equals at most two, and hence the auxiliary system is also a qubit, see [33] for details. Note that the final measurement \mathcal{P}_{V_i} is always binary, independently of the dimension of auxiliary system.

Naturally, we need to repeat the same procedure multiple times for both measurements to obtain a reliable estimate of the underlying probability

¹Explaining why we can consider only discrimination scheme between \mathcal{P}_1 and \mathcal{P}_U is beyond the scope of this paper. See [33] for a in depth explanation.

115 distribution. In PyQBench, we assume that the experiment is repeated the
 116 same number of times for both \mathcal{P}_U and \mathcal{P}_1 .

117 In principle, our discrimination scheme could be used with any choice of
 118 $|\psi_0\rangle$ and final measurements \mathcal{P}_{V_i} . However, we argue that it is best to choose
 119 those components so that they maximize the probability of correct discrim-
 120 ination. To see that, suppose that some choice of $|\psi_0\rangle, \mathcal{P}_{V_0}, \mathcal{P}_{V_1}$ allows for
 121 correctly discriminating between two measurements with probability equal
 122 to one, i.e. on a perfect quantum computer you will always make a cor-
 123 rect guess. Then, on real hardware, we might obtain any empirical value in
 124 range $[\frac{1}{2}, 1]$. On the other hand, if we choose the components of our scheme
 125 such that the successful discrimination probability is $\frac{3}{5}$, the possible range
 126 of empirically obtainable probabilities is only $[\frac{1}{2}, \frac{3}{5}]$. Hence, in the second
 127 case, the discrepancy between theoretical and empirical results will be less
 128 pronounced.

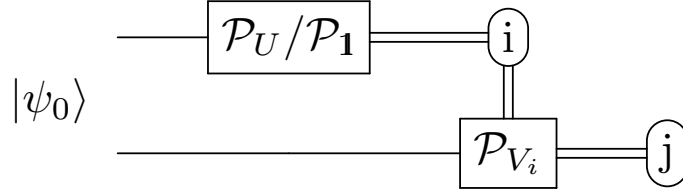


Figure 2: Theoretical scheme of discrimination between von Neumann measurements \mathcal{P}_U and \mathcal{P}_1 .

129 3.2.1. Implementation of discrimination scheme on actual NISQ devices

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

135 **Scheme 1.** (Postselection)

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

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



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 .

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

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

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

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

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

154 then the empirical success probability can be computed as

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

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

156 **Scheme 2.** (Direct sum)

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

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

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

162 we can see that the direct sum in Eq. (5) commutes with the measurement
 163 on the first qubit. Thanks to this, we can switch the order of operations to



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.

164 obtain the circuit from Fig. 5. Now, depending on the outcome i , one of the
 165 summands in Eq. (5) vanishes, and we end up performing exactly the same
 166 operations as in the original scheme.

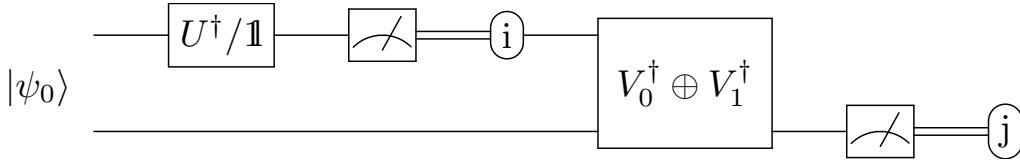


Figure 5: Rewritten representation of the setup for distinguishing measurements \mathcal{P}_U and \mathcal{P}_1 using the $V_0^\dagger \oplus V_1^\dagger$ direct sum.

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

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

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

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

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

172 where N_{total} is the number of trials.

173 4. Software description

174 This section is divided into two parts. In Section 4.1 we describe func-
 175 tionalities of PyQBench package. Next, in Section 4.2, we give a general
 176 overview of the software architecture.

177 4.1. Software Functionalities

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

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

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

198 The PyQBench library also contains a readily available implementation
199 of all necessary components needed to run discrimination experiments for
200 parametrized Fourier family of measurements (see Section 3 in supplemental
201 material). However, if one only wishes to use this particular family of mea-
202 surements in their benchmarks, then using PyQBench as a command line
203 tool might be more straightforward. PyQBench’s command line interface
204 allows running the benchmarking process without writing Python code. The
205 configuration of CLI is done by YAML [34] files describing the benchmark
206 to be performed and the description of the backend on which the benchmark
207 should be run. The same benchmark can be used with different backends
208 and vice versa.

209 4.2. Software Architecture

210 4.2.1. Overview of the software structure

211 As already described, PyQBench can be used both as a library and a CLI.
212 Both functionalities are implemented as a part of **qbench** Python package.
213 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 [35] or at the reference manual [36].

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 [37, 38]).

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 [36], 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:

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

293 5.1.1. *Preparing configuration files*

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

Listing 2: Defining the experiment

```

300 type: discrimination-fourier
301 qubits:
302   - target: 0
303     ancilla: 1
304   - target: 1
305     ancilla: 2
306 angles:
307   start: 0
308   stop: 2 * pi
309   num_steps: 3
310 gateset: ibmq
311 method: direct_sum
312 num_shots: 100
313
314

```

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

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

Listing 3: IBMQ backend

```

325
326 name: ibmq_quito
327 asynchronous: false
328 provider:
329   hub: ibm-q
330   group: open
331   project: main
332

```

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

336 5.1.2. Running the experiment and collecting measurements data

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

```

339 qbench disc-fourier benchmark experiment_file.yml backend_file.yml
340
341

```

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

```

344 qbench disc-fourier benchmark experiment_file.yml backend_file.yml
345 --output async_results.yml
346
347

```

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

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

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

```

357 data:
358 - target: 0
359   ancilla: 1
360   phi: 0.0
361   results_per_circuit:
362   - name: id
363     histogram: {'00': 28, '01': 26, '10': 21, '11': 25}
364

```

```

365 mitigation_info:
366   target: {prob_meas0_prep1: 0.052200000000000024,
367           prob_meas1_prep0: 0.0172}
368   ancilla: {prob_meas0_prep1: 0.059000000000000005,
369            prob_meas1_prep0: 0.0202}
370   mitigated_histogram: {'00': 0.2637212373658018, '01':
371                        0.25865061319892463, '10': 0.2067279352110304, '11':
372                        0.2709002142242433}
373

```

374 5.1.3. (Optional) Getting status of asynchronous jobs

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

```

377
378 qbench disc-fourier status async_results.yml
379

```

380 and it will display dictionary with histogram of statuses.

381 5.1.4. Resolving asynchronous jobs

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

```

385
386 qbench disc-fourier resolve async_results.yml resolved.yml
387

```

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

393 5.1.5. Computing probabilities

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

```

396
397 qbench disc-fourier tabulate results.yml results.csv
398

```

399 A sample CSV file is provided in Table 2.

400 6. Impact

401 With the surge of availability of quantum computing architectures in
402 recent years it becomes increasingly difficult to keep track of their relative
403 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 [39, 40], if it was applied.

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

410 Due to this possibility of extension, the users are able to test specific
411 aspects of their architecture of interest. For example, if their problem is
412 related to the amount of coherence (the sum of absolute value of off-diagonal
413 elements) of the states present during computation, they are able to quickly
414 prepare a custom experiment, launch it on desired architectures, gather the
415 result, based on which they can decide which specific architecture they should
416 use.

417 Finally, we provide the source code of PyQBench on GitHub [35] under an
418 open source license which will allow users to utilize and extend our package
419 in their specific applications.

420 7. Conclusions

421 In this paper, we presented a Python library PyQBench, an innovative
422 open-source framework for benchmarking gate-based quantum computers.
423 PyQBench can benchmark NISQ devices by verifying their capability of dis-
424 criminating between two von Neumann measurements. PyQBench offers a
425 simplified, ready-to-use, command line interface (CLI) for running bench-
426 marks using a predefined parameterized Fourier family of measurements. For

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

429 8. Conflict of Interest

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

433 Acknowledgements

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

441 References

- 442 [1] John Preskill. Quantum computing in the nisc era and beyond. *Quan-*
443 *tum*, 2:79, 2018.
- 444 [2] Rigetti computing. <https://www.rigetti.com/>. Accessed on 2023-02-
445 18.
- 446 [3] IBM Quantum. <https://www.ibm.com/quantum>. Accessed on 2023-02-
447 18.
- 448 [4] Oxford quantum. <http://oxfordquantum.org/>. Accessed on 2023-02-
449 18.
- 450 [5] IonQ. <https://ionq.com/>. Accessed on 2023-02-18.
- 451 [6] Xanadu. <https://www.xanadu.ai/>. Accessed on 2023-02-18.
- 452 [7] D-Wave Systems. <https://www.dwavesys.com/>. Accessed on 2023-02-
453 18.
- 454 [8] QuEra. <https://www.quera.com/>. Accessed on 2023-02-18.
- 455 [9] QCS Documentation. <https://docs.rigetti.com/qcs/>. Accessed on
456 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. Viszlai, 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] Sergio Boixo, Sergei V Isakov, Vadim N Smelyanskiy, Ryan Babbush, Nan Ding, Zhang Jiang, Michael J Bremner, John M Martinis, and Hartmut Neven. Characterizing quantum supremacy in near-term devices. *Nature Physics*, 14(6):595–600, 2018.
- [32] Frank Arute, Kunal Arya, Ryan Babbush, Dave Bacon, Joseph C Bardin, Rami Barends, Rupak Biswas, Sergio Boixo, Fernando GSL Brandao, David A Buell, et al. Quantum supremacy using a programmable superconducting processor. *Nature*, 574(7779):505–510, 2019.
- [33] 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.

- 523 [34] YAML Ain't Markup Language (YAML) Version 1.2. [https://yaml.](https://yaml.org/spec/1.2.2/)
524 [org/spec/1.2.2/](https://yaml.org/spec/1.2.2/). Accessed on 2023-02-18.
- 525 [35] PyQBench GitHub Repository. [https://github.com/iitis/](https://github.com/iitis/PyQBench)
526 [PyQBench](https://github.com/iitis/PyQBench). Accessed on 2023-02-18.
- 527 [36] PyQBench Documentation. [https://pyqbench.readthedocs.io/en/](https://pyqbench.readthedocs.io/en/latest/)
528 [latest/](https://pyqbench.readthedocs.io/en/latest/). Accessed on 2023-02-18.
- 529 [37] Introducing the Qiskit Provider for Amazon Braket.
530 [https://aws.amazon.com/blogs/quantum-computing/](https://aws.amazon.com/blogs/quantum-computing/introducing-the-qiskit-provider-for-amazon-braket/)
531 [introducing-the-qiskit-provider-for-amazon-braket/](https://aws.amazon.com/blogs/quantum-computing/introducing-the-qiskit-provider-for-amazon-braket/). Ac-
532 cessed on 2023-02-18.
- 533 [38] Qiskit Braket Provider GitHub Repository. [https://github.com/](https://github.com/qiskit-community/qiskit-braket-provider)
534 [qiskit-community/qiskit-braket-provider](https://github.com/qiskit-community/qiskit-braket-provider). Accessed on 2023-02-
535 18.
- 536 [39] mthree Documentation. [https://qiskit.org/documentation/](https://qiskit.org/documentation/partners/mthree/stubs/mthree.M3Mitigation.html)
537 [partners/mthree/stubs/mthree.M3Mitigation.html](https://qiskit.org/documentation/partners/mthree/stubs/mthree.M3Mitigation.html). Accessed on
538 2023-02-10.
- 539 [40] P. D. Nation, H. Kang, N. Sundaresan, and J. M. Gambetta. Scalable
540 mitigation of measurement errors on quantum computers. *PRX Quan-*
541 *tum*, 2(4):040326, 2021.