Benchmarks Summary

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1 Introduction

We present **qbench**, a categorized and as of now the most comprehensive set of quantum algorithms (benchmarks) from various sources and platforms and in different quantum programming languages. Most of the currently existing and used quantum algorithms, synthetically generated and application-based circuits are included in this collection and classified based on different criteria. This benchmark collection has benchmarks from various sources cataloged in folders based on how they are implemented (e.g., based on real algorithm, random, application-based), the language they are written in, and their size. The set also contains various scripts for translating circuits from one language to another and circuit interaction graphs. We hope that this collection will be useful for testing new quantum processors, updated regularly by the research community to keep up with the new technologies, compilers, programming languages and most importantly applications, and eliminate the over-the-top amount of benchmark sources. We are also hoping that this circuits set will be used for benchmarking quantum computing systems as well as parts of it, such as compilation techniques, and to encourage the development of new better benchmarks and their success metrics.

Quantum algorithms (hardware-agnostic circuits) used as benchmarks for analyzing the performance of the mappers are not representative as they are in most cases reversible circuits that will not provide any computational advantage compared to their classical counterparts. In addition, they are usually only profiled in terms of a number of gates, circuit depth, percentage of two-qubit gates and number of interactions between qubits pairs (this latter is used for deriving an optimal placement of qubits). By having a more in-depth profiling of the quantum algorithms in which characteristics of the interaction graphs (i.e. how many times each pair of qubits interact and how those interactions are distributed among qubits and in time) and of the quantum instruction dependency graph (i.e. identifying clusters of operations) can be beneficial for obtaining optimal mapping solutions. These variables derived from the algorithm profiling will also be essential for developing application-specific quantum systems.

2 Real Benchmarks

According to Nielsen and Chuang there are 3 groups of currently used real benchmarks that can make some advantage for quantum in comparison to classical devices:

- Algorithms based on Fourier Transform: Schor's, QFT, Deutsch-Jozsa, ripple adders ...
- Search algorithms: Grover's...
- Algorithms simulating real-life applications: Quantum chemistry, quantum mechanics and

quantum machine learning algorithms...

Table 1: Real Algorithms with Speed-up

Name	Speed-up	References	Code Ref.	Language	Scalable
Grover's Search Algorithm	quadratic	[41, 40, 1, 2, 32]	[20]	Qiskit Jupiter	Yes
			[57]	C++	Yes
			[47]	Openql Python	Yes
			[45]	CQASM	No
			[15]	Cirq Python	Yes
			[49]	OpenQl Python	No
			[53, 10]	Riggeti Python	Yes
			[35]	Q# / Jupyter	Yes
Square Root	exponential	[24, 40, 62, 26, 63]	[43]	OpenQl Python	No
			[14]	.scaffold	Yes
QFT	exponential	[39, 1, 38, 41, 2, 24, 62, 59, 5]	[57]	C++	Yes
			[46]	CQASM	No
			[15]	Cirq Python	No
			[18]	OpenQASM	No
			[14]	.scaffold	Yes
			[53, 10]	Riggeti Python	Yes
			[35]	Q# / Jupyter	Yes
Shor's Factoring Algorithm	exponential	[24, 2, 26]	[20]	Qiskit Jupiter	Yes
			[15]	Cirq Python	Yes
			[14]	.scaffold	Yes
			[43]	OpenQl Python	No
Deutsch-Jozsa	exponential		[20]	Qiskit Jupiter	Yes

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Name	Speed-up	References	Code Ref.	Language	Scalable
			[15]	Cirq Python	No
			[49]	OpenQl Python	No
			[53, 10]	Riggeti Python / Jupyter	yes
			[35]	Q# / Jupyter	Yes
Jordan Gradient	exponential	[25]	[53, 10]	Riggeti Python / Jupyter	Yes
QAOA	Still negotiable	[16, 13]	[15]	Python	Yes
			[20]	Python	Yes
			[53, 10]	Riggeti Python	Yes
			[50]	cQASM	No
Hidden Shift Algorithm (uses QFT)	exponential	[9, 41, 39, 8]	[15]	Cirq Python	Yes
Application-based circuits		[51, 6, 12]	[51, 49]	OpenQl Python	No
			[7]	OpenQASM	No
			[19]	Qiskit Python	No
			[34]	Q#	No

Table 2: Real Algorithms with NO Speed-up

Name	Parametrizable	References	Code Ref.	Language
Bernstein-Vazirani	YES	[39, 41, 40]	[20]	Qiskit Jupiter
			[15]	Python
			[49]	OpenQl Python
			[18]	OpenQASM
			[53, 10]	Riggeti Python
Supremacy Circuits	YES	[41]	[15]	Python
Peres Gate	PROBABLY NO	[41, 39]	[48]	.pla
Adder	YES	[41, 39, 58, 26]	[18]	OpenQASM
Ising model	YES	[40, 39, 63]	[14]	.scaffold
			[53, 10]	Riggeti Jupyter

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Table 2 – continued from previous page

Name	Parametrizable	References	Code Ref.	Language
Fredkin (controlled-swap)	NO	[41, 33]	[48]	.pla
Toffoli (Gate)	YES	[33, 41, 39, 32]	[48]	.pla
VQE	YES	[4, 24]	[20] [14] [53, 10] [18]	Qiskit Jupiter .scaffold Riggeti Python openQASM

RevLib benchmarks are within the domain of reversible and quantum circuit design. References: [26, 63, 64, 61, 23, 29, 30, 60, 62, 59]. RevLib benchmarks: [48].

Qlib Benchmarks: [43, 31]

Most common reversible circuits code in OpenQl Python can be found in [43].

OpenQASM version of all benchmarks classified in 3 groups: large-, medium- and small-scale can be found in [27, 28].

All the codes written in C++ can be directly run through Quantum Inspire, Rigetti Forest, IBM Q Experience or OpenQl by using LibKet tool[37].

Finally, some real-algorithm benchmarks were generated by software for generating benchmarks called MQTBench [44].

3 Synthetic Benchmarks

Synthetic benchmarks represent the group of randomly generated circuits, which provide is bigger variety in terms of their parameters (e.g. number of qubits, gates, two-qubit gate ratio). Some examples include volumetric benchmarks already described in previous section of this document. The random circuits however, can be generated in various ways. Summary of different random circuits used so far in previous works can be found in the table below:

Table 3: Synthetic circuits

Name	Method for generating circuits	References	Code Ref	Language
Quantum volume model circuit	Random square circuits with the same width and depth. Trying to use up all qubits per layer. Using any two-qubit gate from SU(4).	[11]	[22] [21] [15]	OpenQASM Python Python / Jupyter

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Table 3 – Continued from previous page

Name	Method for generating circuits	References	Code Ref	Language
Volumetric benchmarks	Family of random circuits that includes not just QV circuit but also circuits with different width and depth, as well as periodic circuits, shallow complex circuits and application-based circuits.	[6, 36]	—-	—-
'Realistic' random circuits	Generated random circuits in a way that they see more realistic, with assigning different probabilities on edges for interactions between qubits.	[2]	[15]	Python
Random circuits 1 from reinforcement learning paper	One layer random circuit which is engaging all the qubits into two-qubit gates. (max. circ. density)E.g. if there are 16 qubits there will be one layer of 8 two-qubit gates performed on different pairs of qubits.	[17, 42]	—	—
Random circuits 2 from reinforcement learning paper	More realistic version of random circuit where they choose qubits at random as well (they do not force engaging all qubits per layer into two-qubit gates), what therefore leads to higher circuit depth. They played with circuit density parameter and compared results instead of using the max. one like in previous case.	[17, 42]	—	—
Uniformly generated random circuits	Random circuits are generated uniformly random (considering used qubits and and single- and two-qubit gates). Two-qubit gates are chosen from already predefined set.	[52]	[56] [7]	OpenQl Python OpenQASM MCHECK
QUEKO	Depth-optimal generated circuits based on generic input quantum circuit and device graph.	[54]	[55]	OpenQASM

All the circuits that are not derived from the mentioned sources are originally written or translated by authors and their collaborators.

4 Metrics for interaction graph characterisation

In this paragraph we listed all the graph metrics relevant for characterizing interaction graphs relevant to mapping problem.

1)Standard metrics:

- # of qubits
- # of gates
- percentage of two-qubit gates

2)Hopcount related metrics:

- Avg. hopcount (shortest path) in graph - global, the smaller the better
- Closeness (avg. distance from each node to other nodes in hopcounts) - local, the smaller the better
- Diameter (longest shortest path in graph, sparsity) - global, the bigger the better

3)Degree related metrics:

- Degree (num. of nodes to which some node is connected) - local
- Avg. degree - global, the smaller the better
- Min. and max. degree - global, the smaller the better, we should compare max. min degree values to see uniformity of graph
- Degree distribution

4)Clustering related metrics:

- Clique/n-clique (subset of nodes such that they are all connected / connected in n hops) - global
- Clustering coefficient (Measuring cliquishness of neighbourhood. (betw. 0 and 1, 1 means fully-connected graph - local or global, the lower the better)

5)Adjacency matrix related metrics:

- Weight distribution
- Min. and max. weight
- Std. deviation
- Variance

After we characterize interaction graphs based on this metric the plan is to characterize coupling graphs (connectivity of physical qubits in device), compare and use these both information for improvements of the mapper. One of the mapping methods we are considering is involving graph partitioning for which we in addition to previously mentioned metrics also use these ones:

- Persistence (smallest of links whose removal increases diameter or disconnects the graph) - for graph partitioning

- Central point of dominance (Max betweenness of any point in the graph, 0 for complete and 1 for star graphs (with one central node). Betweennes is how many shortest paths go through some node or link) - for improving mapping method -> choosing the best initial placement
- Distortion (after presenting graph as a spanning tree check how many extra hops we need between nodes that were connected in original graph) ?
- Clique,clustering coefficient - for graph partitioning
- Vertex/edge connectivity and other reliability-related metrics(respective smallest number of nodes and links whose removal disconnects graph) - for graph partitioning
- Giant component (maximal subgraph of directed graph such that for every pair of nodes there is directed path PA->B and PB->A for hopcount k) - for directed coupling graph analysis.

For all other information and results please refer to: [3].

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