Assignment - 3 (CS F316) Name: **Abhay Kamble(2019A7PS0128G)**

1. From the given suite of benchmarking techniques I'm choosing the following benchmarking techniques -
    a. Hamiltonian Simulation
    b. Vanilla QAOA

    A set of feature vectors are used to quantify the coverage of the selected benchmark applications. These features are necessary as they indicate how each of the benchmarks would stress the processor and that to what degree[1]. And, the three feature vectors that I'm choosing are -
    a. Critical Depth
    b. Entanglement Ratio
    c. Parallelism

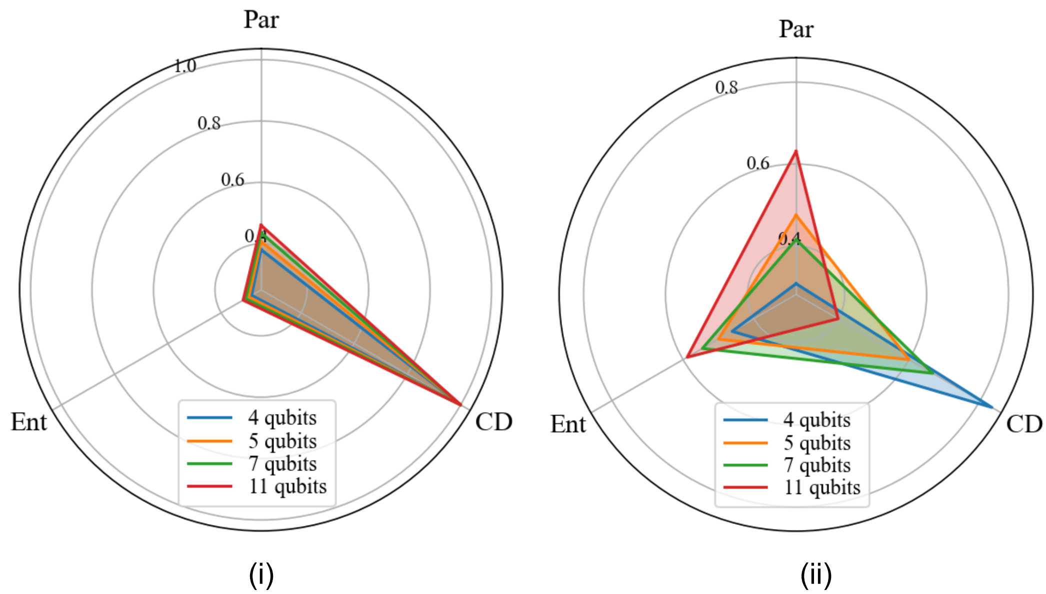
    I have chosen the above three feature vectors because of the following reasons:
    i. Since the lifetime of the information stored in the QPU are limited, and along with the accumulated gate error, it results in a lower fidelity circuit. Thus the quantum circuits should be of the shortest duration possible. Thus, here we use the critical path/depth i.e. the longest span of dependent operations from circuit input to output. The critical path is a valuable benchmarking metric because quantum hardware performance must reach specific thresholds to accommodate continuously compounding gate errors.

    ii. Entanglement gives quantum computing its strength and it is a useful benchmark for quantum machines since entanglement can be used in various computing tasks. Since, entanglement cannot be simulated on a classical computer, it is an important factor in determining the quantum processing power.

    iii. Many quantum algorithms allow varying levels of parallelization, and this can lead to increased correlated noise events(e.g. Cross-talk). This is the common source of error in the NISQ era of quantum computers. Thus, this feature vector aims at finding the susceptibility of a benchmark degradation via cross-talk. Highly parallel applications fit a large number of operations into a relatively small circuit depth and will therefore have a parallelism feature close to 1.

    After running the two benchmarking experiments, and plotting the plots on the various input parameters(which is the number of qubits) we get the following graphs.

    <u>Observation:</u>
    We observe that for Hamiltonian Simulation technique, the Critical Depth is always 1 irrespective of the number of qubits in the quantum machine. It can be observed from the radar plot that the parallelism and entanglement ratio decreases with the increase in the number of qubits used in the process of Hamiltonian Simulation benchmarking. Also, the value of parallelism is maximum at around 0.4 and the value of entanglement ratio is below 0.4 and near 0.2-0.3 for each of the qubit cases.



Multi-Dimensional Radar plots for (i) Hamiltonian Simulation and (ii) Vanilla QAOA Quantum Benchmarking techniques

We observe that for Vanilla QAOA technique, the Critical Depth decreases gradually with respect to the number of qubits in the quantum machine, i.e. as the number of qubits increases the critical depth decreases. It can be observed from the radar plot that the parallelism and entanglement ratio decreases with the increase in the number of qubits used in the process of Vanilla QAOA benchmarking. Also, the value of parallelism is maximum at around 0.6 and then decreases drastically, upto below 0.2, when the number of qubits increases. The value of entanglement ratio decreases with increasing number of qubits, but the change/decrease is not that drastic, as in the case of parallelism.

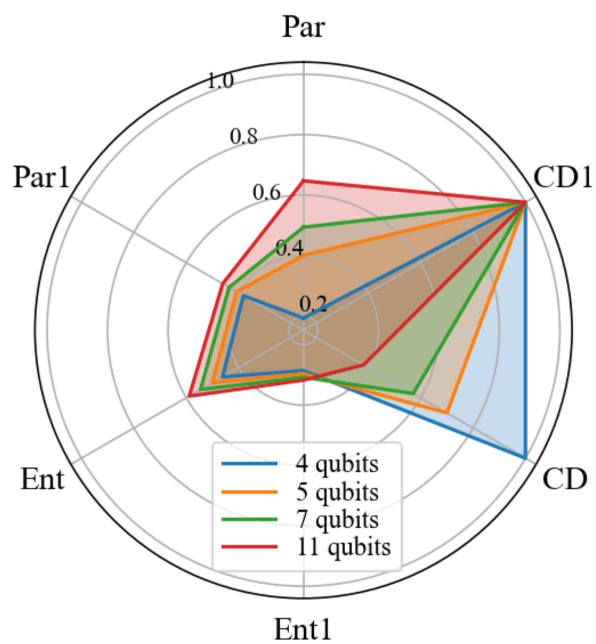
<u>Inferences:</u>
Ques 1. Why do feature vectors have the particular values given a benchmark circuit?
Answer :

a. Critical Depth - The critical depth(D) is defined as the ratio between the number of two-qubit interactions on the longest path that sets the circuit depth(n_{ed}) and the total number of two-qubit interactions in the circuit(n_e). Thus, it means that the circuits which are heavily serialized would be having a circuit depth close to 1. Since, the Hamiltonian Simulation is a series of implementations of a specific number of gates in a particular order and that too in repetition, it clearly indicates to us that the critical depth will be around 1 always, which is true from the plot. In the case of Vanilla QAOA, the two-qubit interaction on the longest path will decrease as the CNOT are evenly spaced out, and are arranged in a circular manner. So the number of two-qubit gates can increase with no major increase in the longest length of the circuit, thus giving us a reducing critical depth.
b. Entanglement ratio - The entanglement ratio(E) is defined(here) as the ratio of two-qubit gates(n_e) and the total number of gates(n_g). In the case of Hamiltonian

Simulation and Vanilla QAOA, the overall number of gates increases with each iteration, but the number of CNOT gates applied in the implementation does not increase as quickly. Thus, the total number of 2-qubit gates grows slower than the total number of gates, explaining the reason for decreasing entanglement ratio.

c. Parallelism - We define parallelism as the following formula -
$P = (n_g/d - 1)(1/(n-1))$, where n_g - number of gates, n - number of qubits, d- depth
Thus, we can say that high parallel applications fit a large number of operations into a relatively small circuit depth and will therefore have a parallelism feature close to 1. In the case of Hamiltonian Simulation and Vanilla QAOA, the amount of achievable parallelism increases but the size of the circuit increases by a greater amount. Thus, the circuit depth increases easily with each increase in the number of qubits, and hence the parallelism decreases in both cases.

Ques 2. Discuss how a feature vector for one benchmark compares against another?
Answer :



Here, the labels Par, CD, Ent are for Vanilla QAOA and the labels Par1, CD1,Ent1 are for the Hamiltonian Simulation

Critical Depth - As it is visible by the comparison of the CD and CD1 labels, that the CD Decreases faster in the case of Vanilla QAOA rather than in the case of Hamiltonian Simulation. Both start at CD = 1 but CD decreases eventually upto 0.4 while the CD1 remains at around 1.

Entanglement Ratio - The entanglement ratio also is less in the Hamiltonian Simulation as all of them are below 0.2 and in the case of QAOA the Ent decreases from 0.4 to slightly above 0.2 as the number of qubits increases.

Parallelism - As it is visible from the graph that inthe case of QAOA the Par value Decreases drastically from 0.6 to near almost 0, and in the case of Hamiltonian Simulation the value of Par1 decreases from slightly above 0.4 to slightly below 0.2(near 0.1 in fact).