Dynamic Circuit Challenge

Introduction

In the realm of quantum simulation, the quest for efficient generation of complex entangled states has long been hindered by the inherent constraints of unitary dynamics. However, a breakthrough emerges with the concept of non-unitary, dynamic circuits as elucidated in the paper "Efficient long range entanglement using dynamic circuits" by Elisa Bäumer, Vinay Tripathi, and Derek S. Wang. Inspired by their exploration, we delve into a paradigm shift, where measurements and conditional feed-forward operations pave the way for promising advancements in long-range entangling gates and state preparations. By harnessing the power of dynamic circuits, we aim to demonstrate their superiority in creating long-range entanglement on large-scale quantum devices. We worked around writing the Qiskit code for implementing the dynamic circuits for long range entanglement based on a paper called Efficient Long Range Entanglement using Dynamic Circuits.

Quantum Computing and Qiskit

Before delving into Dynamic Circuits, it's crucial to grasp the foundational concepts of Quantum Computing and Qiskit.

Quantum computing revolutionizes computation by leveraging principles of quantum mechanics. Central to this paradigm are qubits, capable of existing in superpositions of 0 and 1, unlike classical bits confined to singular states. This unique attribute enables quantum computers to explore vast computational spaces, solving certain problems exponentially faster than classical counterparts. Quantum computers excel at tasks like simulating molecular interactions, breaking encryption, and optimizing complex systems.

Enter Qiskit, a leading-edge quantum computing software development kit (SDK) developed by IBM. Qiskit provides a robust suite of tools and libraries designed to empower users in constructing, executing, and experimenting with quantum algorithms and applications. Noteworthy is Qiskit's seamless integration of quantum and classical computing, facilitating hybrid workflows. With Qiskit, both novices and experts alike can embark on their quantum journeys, conducting experiments from the comfort of their homes using cloud-based offerings provided by IBM. This accessibility democratizes quantum exploration, ushering in a new era of quantum computing research and development.

Long Range Entanglement and Controlled Hadamard

In order to understand why Dynamic Circuits are better at Long Range Entanglement, let's delve into some foundational concepts.

Quantum entanglement is a fundamental phenomenon in quantum physics where two or more quantum particles become inextricably linked, such that the state of one particle is correlated with the state of the other(s), even when they are separated by large distances. This "spooky action at a distance" as Einstein described it, is a key feature of quantum mechanics that has no classical analogue.

One way to create long-range entanglement is through the use of quantum gates, such as the Hadamard gate and the Controlled-NOT (CNOT) gate. The Hadamard gate puts a qubit (the fundamental unit of quantum information) into a superposition of the 0 and 1 states. The CNOT gate then entangles two qubits by flipping the state of the target qubit if the control qubit is in the 1 state.

By applying a Hadamard gate to one qubit and then a CNOT gate with that qubit as the control and another qubit as the target, a special type of entangled state called a Bell state can be created. In this state, the two qubits are maximally correlated - measuring the state of one qubit instantly reveals the state of the other, no matter how far apart they are.

The Controlled Hadamard gate is a generalization of this idea. It applies a Hadamard gate to the target qubit, but only if the control qubit is in the 1 state. This creates an entangled state where the state of the target qubit depends on the state of the control qubit, even if they are separated by a large distance.

To explain these concepts further, let's consider an analogy. Imagine you have a pair of dice, and you roll them. The outcome of the roll (e.g., 2 and 4) is the state of one die. However, the state of the other die is also affected by the state of the first die. This is similar to how entangled particles are correlated. Now, let's say you have a special die that can be in two states at once (superposition). This is similar to how the Controlled Hadamard gate can create superposition states

Dynamic Circuits

Dynamic circuits introduce a powerful tool for achieving quantum advantage in the near term. By seamlessly integrating real-time classical communication with quantum circuits, they expand the range of circuits feasible on near-term quantum hardware and reduce the number of gates required. Expected to become integral to various quantum applications, dynamic circuits operate within the coherence time of qubits, allowing mid-circuit measurements and feed-forward operations.

Unlike static circuits, which don't depend on runtime data, dynamic circuits leverage classical processing within the qubit coherence time, enabling measurements and feed-forward operations. While both static and dynamic circuits possess equivalent computational power theoretically, dynamic circuits offer practical advantages, particularly in optimizing circuit depth and width, crucial for successful circuit execution amid hardware limitations.

Dynamic Circuits are more efficient at Long Range Entanglement

Dynamic circuits, unlike their unitary counterparts, capitalize on measurements alongside conditional feed-forward operations, presenting a promising strategy for realizing long-range entangling gates and facilitating more efficient state preparations. The crux lies in their ability to teleport CNOT gates over extensive distances using mid-circuit measurements and classical feed-forward operations. Unlike unitary circuits, where the depth scales linearly with the number of qubits involved, dynamic circuits maintain a constant depth, irrespective of the qubit count. This inherent feature enables dynamic circuits to create long-range entanglement with unprecedented efficiency.

Experimental validation conducted on a superconducting quantum processor underscores the superiority of dynamic circuits in teleporting CNOT gates across more than ten qubits. The study attributes this success to reduced idle time, fewer two-qubit gates, and enhanced parallelization of operations offered by dynamic circuits compared to their unitary counterparts. Moreover, dynamic circuits exhibit promising potential in efficiently preparing long-range entangled states such as the Greenberger-Horne-Zeilinger (GHZ) state.

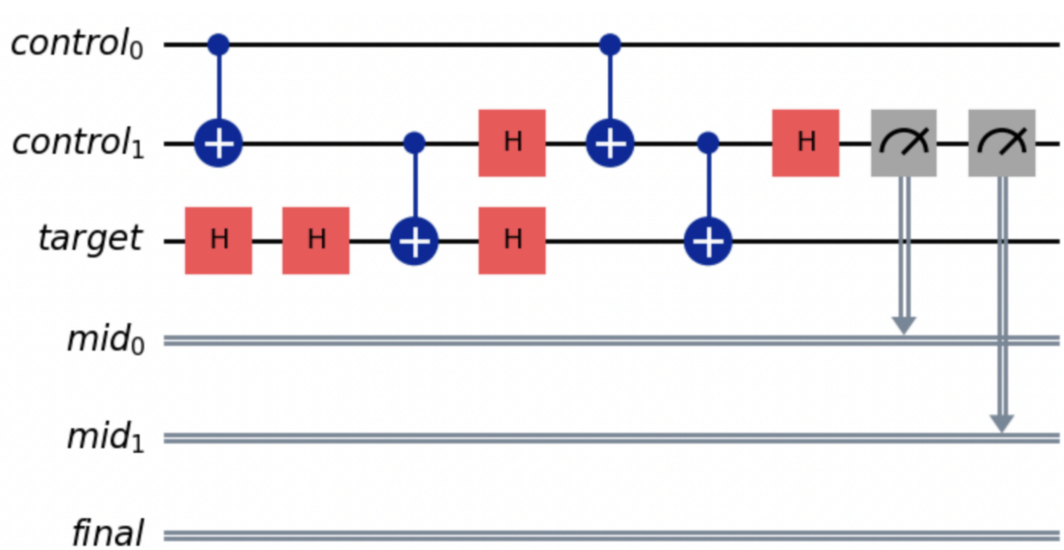
Qiskit Code Implementation

Here is the code one would require for implementing a dynamic circuit for CNOT long range entanglement.

```
[1]: # dynamic circuits
     # Qiskit imports
     from qiskit import QuantumCircuit, QuantumRegister, ClassicalRegister
     from qiskit import transpile

     # Qiskit IBM Provider
     from qiskit_ibm_provider import IBMProvider, least_busy

     provider = IBMProvider()
     backend = least_busy(provider.backends(simulator=False, operational=True))
     backend

[1]: <IBMBackend('ibm_osaka')>
```

```
controls = QuantumRegister(2, name="control")
target = QuantumRegister(1, name="target")

mid_measure = ClassicalRegister(2, name="mid")
final_measure = ClassicalRegister(1, name="final")

circuit = QuantumCircuit(controls, target, mid_measure, final_measure)
```

```
def trial(circuit, target, controls, measures):
    """Probabilistically perform an Rx gate for an
    angle that is an irrational multiple of pi."""
    circuit.h(target)

    circuit.cx(controls[0], controls[1])
    circuit.cx(controls[1],target)
    circuit.h(controls[1])
    circuit.measure(controls[1],measures)

trial(circuit, target, controls, mid_measure)
circuit.draw(output="mpl", style='iqp', cregbundle=False)
```



Discussion

We were initially supposed to implement a controlled Hadamard entanglement using dynamic circuits and compare the error rates. However, due to some difficult circumstances, the work had to be stopped midway.
We would like to point out that using the papers provided in the references allowed us to experiment with dynamic circuits. We implore future researchers to do further research on dynamic circuits in such a way that their work can be replicable by curious teams. There should also be tutorials in various other Quantum Computing software to achieve the same or similar level of implementation

references

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