IonQ iQuHack2025 Challenge

Before proceeding, register once. Then, comment out the registration function call to avoid re-registering when running the notebook again.

In [1]:
```python
import requests

def register():
    team_name = input("Enter your team name: ")
    in_person = input("Enter participation type - in-person or remote: ")
    data = []

    while email := input("Enter email separated by commas (enter to cancel): "):
        firstname = input("Enter your first name: ")
        lastname = input("Enter your last name: ")
        github = input("Enter your github handle: ")
        data.append((firstname, lastname, email, github))

    for firstname, lastname, email, github in data:
        url = f"https://ionquhack2025.azurewebsites.net/api/registration?TeamName={
        req = requests.post(url)
        print("\n\n\n"+req.text)


# Comment this out after registration:
# register()
```

Enter the `key` you've got on the previous step here:

In [2]:
```python
key = "61f7aaaf50e899e65f777e0e159408b5335faf68fd58ee21d8941de1907d3cfb"
```

Did you comment out the `register()` function call?

Please share your research process on GitHub: https://github.com/iQuHACK/2025-IonQ/discussions

Maximum Cut problem (max-cut) with variational Quantum Imaginary Time Evolution (varQITE) method

In this challenge, we demonstrate how to leverage IonQ Forte's industry-leading capabilities to solve instances of the NP-hard combinatorial optimization problem known as Maximum Cut (MaxCut) using a novel variational Quantum Imaginary Time Evolution (varQITE) algorithm developed by IonQ in conjunction with researchers at Oak Ridge National Labs (ORNL).

What's the problem?

MaxCut 101

The Maximum Cut Problem (MaxCut) is a classic combinatorial optimization problem commonly used as an algorithm benchmark by scientific computing researchers. It has numerous applications in a variety of fields: for example, it is used in circuit desing as part of Very Large Scale Integration (VLSI) to find the optimal layout of circuit components; it is used in the study of social networks to identify communities; it is used in computer vision for image segmentation, etc.

MaxCut is a graph problem: given a graph $G = (V, E)$ with vertex set V and edge set E, it asks for a partition of V into sets S and T maximizing the number of edges crossing between S and T.

Think of it like this: you're trying to cut the graph into two pieces, and you want to make the cut so that it slices through as many edges as possible.

Prepare the code environment

First, we'll set up the coding environment and install necessary dependencies.

```
In [3]:   pip install qiskit qiskit-aer networkx numpy pandas -q
```

Note: you may need to restart the kernel to use updated packages.

To ensure your code runs correctly everywhere, please only use the imported dependencies. Using external libraries may cause your submission to fail due to missing dependencies on our servers.

```
In [4]:   ## IonQ, Inc., Copyright (c) 2025,
          # All rights reserved.
          # Use in source and binary forms of this software, without modification,
          # is permitted solely for the purpose of activities associated with the IonQ
```

```python
# Hackathon at iQuHack2025 hosted by MIT and only during the Feb 1-2, 2025
# duration of such event.

import matplotlib.pyplot as plt
from IPython import display

import networkx as nx
import numpy as np
import pandas as pd
import time

from typing import List
from qiskit import QuantumCircuit, transpile
from qiskit.circuit import ParameterVector
from qiskit.quantum_info import SparsePauliOp
from qiskit_aer import AerSimulator
```

Graph definition

A simple graph, defined using the Python NetworkX library, will serve to illustrate the problem and you can explore further complexities.

```python
In [5]:  # other graphs candidates to check

         import networkx as nx
         import matplotlib.pyplot as plt
         import random

         #-> Cycle Graph C8
         def cycle_graph_c8():
             G = nx.cycle_graph(8)
             plt.figure(figsize=(6, 6))
             pos = nx.circular_layout(G)
             nx.draw(G, pos, with_labels=True, node_color='lightblue', edge_color='gray', no
             plt.title("Cycle Graph C8")
             plt.show()
             return G

         # Path Graph P16
         def path_graph_p16():
             G = nx.path_graph(16)
             plt.figure(figsize=(12, 2))
             pos = nx.spring_layout(G, seed=42)
             nx.draw(G, pos, with_labels=True, node_color='lightgreen', edge_color='gray', n
             plt.title("Path Graph P16")
             plt.show()
             return G

         #-> Complete Bipartite Graph K8,8
         def complete_bipartite_graph_k88():
             G = nx.complete_bipartite_graph(8, 8)
             plt.figure(figsize=(8, 6))
             pos = nx.bipartite_layout(G, nodes=range(8))
```

```python
    nx.draw(G, pos, with_labels=True, node_color=['lightcoral'] * 8 + ['lightblue']
            edge_color='gray', node_size=300)
    plt.title("Complete Bipartite Graph K8,8")
    plt.show()
    return G


#-> Complete Bipartite Graph K8,8
def complete_bipartite_graph_k_nn(n):
    G = nx.complete_bipartite_graph(n, n)
    plt.figure(figsize=(8, 6))
    pos = nx.bipartite_layout(G, nodes=range(n))
    nx.draw(G, pos, with_labels=True, node_color=['lightcoral'] * n + ['lightblue']
            edge_color='gray', node_size=300)
    plt.title("Complete Bipartite Graph K{},{}".format(n,n))
    plt.show()
    return G


# Star Graph S16
def star_graph_s16():
    G = nx.star_graph(16)
    plt.figure(figsize=(8, 8))
    pos = nx.spring_layout(G, seed=42)
    nx.draw(G, pos, with_labels=True, node_color='gold', edge_color='gray', node_si
    plt.title("Star Graph S16")
    plt.show()
    return G


# Grid Graph 8x4
def grid_graph_8x4():
    G = nx.grid_graph(dim=[8, 4])
    plt.figure(figsize=(12, 6))
    pos = {node: node for node in G.nodes()}
    nx.draw(G, pos, with_labels=True, node_color='lightblue', edge_color='gray', no
    plt.title("Grid Graph 8x4")
    plt.show()
    return G


# Grid Graph 8x4
def grid_graph_nxm(n,m):
    G = nx.grid_graph(dim=[n, m])
    plt.figure(figsize=(12, 6))
    pos = {node: node for node in G.nodes()}
    nx.draw(G, pos, with_labels=True, node_color='lightblue', edge_color='gray', no
    plt.title("Grid Graph {}x{}".format(n,m))
    plt.show()
    return G



#-> 4-Regular Graph with 8 Vertices
def regular_graph_4_8():
    G = nx.random_regular_graph(d=4, n=8, seed=42)
    plt.figure(figsize=(6, 6))
    pos = nx.circular_layout(G)
    nx.draw(G, pos, with_labels=True, node_color='lightgreen', edge_color='gray', n
    plt.title("4-Regular Graph with 8 Vertices")
    plt.show()
```

```python
    return G

#-> Cubic (3-Regular) Graph with 16 Vertices
def cubic_graph_3_16():
    G = nx.random_regular_graph(d=3, n=16, seed=42)
    plt.figure(figsize=(8, 6))
    pos = nx.spring_layout(G, seed=42)
    nx.draw(G, pos, with_labels=True, node_color='lightcoral', edge_color='gray', n
    plt.title("Cubic (3-Regular) Graph with 16 Vertices")
    plt.show()
    return G

# Disjoint Union of Four C4 Cycles
def disjoint_union_c4():
    cycles = [nx.cycle_graph(4) for _ in range(4)]
    G = nx.disjoint_union_all(cycles)
    plt.figure(figsize=(12, 6))
    pos = {}
    shift_x = 0
    for component in nx.connected_components(G):
        subgraph = G.subgraph(component)
        pos_sub = nx.circular_layout(subgraph, scale=1, center=(shift_x, 0))
        pos.update(pos_sub)
        shift_x += 3
    nx.draw(G, pos, with_labels=True, node_color='lightblue', edge_color='gray', no
    plt.title("Disjoint Union of Four C4 Cycles")
    plt.show()
    return G

# Complete Bipartite Graph K16,16
def complete_bipartite_graph_k1616():
    G = nx.complete_bipartite_graph(16, 16)
    plt.figure(figsize=(12, 6))
    pos = nx.bipartite_layout(G, nodes=range(16))
    nx.draw(G, pos, with_labels=False, node_color=['lightcoral'] * 16 + ['lightblue
            edge_color='gray', node_size=100)
    plt.title("Complete Bipartite Graph K16,16")
    plt.show()
    return G

# 5-Dimensional Hypercube Graph Q5
def hypercube_graph_q5():
    G = nx.hypercube_graph(5)
    plt.figure(figsize=(10, 8))
    pos = nx.spring_layout(G, seed=42)
    nx.draw(G, pos, with_labels=False, node_color='lightgreen', edge_color='gray',
    plt.title("5-Dimensional Hypercube Graph Q5")
    plt.show()
    return G

# Tree Graph with 8 Vertices
def tree_graph_8():
    G = nx.balanced_tree(r=2, h=2)
    G.add_edge(6, 7)
    plt.figure(figsize=(8, 6))
    pos = nx.spring_layout(G, seed=42)
```

```python
    nx.draw(G, pos, with_labels=True, node_color='lightblue', edge_color='gray', no
    plt.title("Tree Graph with 8 Vertices")
    plt.show()
    return G


# Wheel Graph W16
def wheel_graph_w16():
    G = nx.wheel_graph(16)
    plt.figure(figsize=(8, 8))
    pos = nx.circular_layout(G)
    nx.draw(G, pos, with_labels=True, node_color='lightcoral', edge_color='gray', n
    plt.title("Wheel Graph W16")
    plt.show()
    return G


#-> Random Connected Graph with 16 Vertices
def random_connected_graph_16(p=0.15):
    #n, p = 16, 0.25
    n=16
    while True:
        G = nx.erdos_renyi_graph(n, p, seed=random.randint(1, 10000))
        if nx.is_connected(G):
            break
    plt.figure(figsize=(10, 8))
    pos = nx.spring_layout(G, seed=42)
    nx.draw(G, pos, with_labels=False, node_color='lightgreen', edge_color='gray',
    plt.title("Random Connected Graph with 16 Vertices")
    plt.show()
    return G


# Expander Graph with 32 Vertices
def expander_graph_32():
    G = nx.random_regular_graph(4, 32, seed=42)
    plt.figure(figsize=(10, 8))
    pos = nx.spring_layout(G, seed=42)
    nx.draw(G, pos, with_labels=False, node_color='lightblue', edge_color='gray', n
    plt.title("Expander Graph with 32 Vertices")
    plt.show()
    return G


#-> Expander Graph with n Vertices
def expander_graph_n(n):
    G = nx.random_regular_graph(4, n, seed=42)
    plt.figure(figsize=(10, 8))
    pos = nx.spring_layout(G, seed=42)
    nx.draw(G, pos, with_labels=False, node_color='lightblue', edge_color='gray', n
    plt.title("Expander Graph with {} Vertices".format(n))
    plt.show()
    return G


# Planar Connected Graph with 16 Vertices
def planar_connected_graph_16():
    G = nx.grid_graph(dim=[8, 2])
    G = nx.convert_node_labels_to_integers(G)
    additional_edges = [(0, 9), (1, 10), (2, 11), (3, 12), (4, 13), (5, 14), (6, 15
                        (7, 15), (8, 7)]#, (6, 15), (14, 1), (1, 13), (10, 9), (0,
```

```
        G.add_edges_from([e for e in additional_edges if e[0] < 16 and e[1] < 16])
        assert nx.check_planarity(G)[0], "Graph is not planar."
        pos = {node: (node // 2, node % 2) for node in G.nodes()}
        plt.figure(figsize=(16, 8))
        nx.draw(G, pos, with_labels=False, node_color='lightcoral', edge_color='gray',
        plt.title("Planar Connected Graph with 16 Vertices")
        plt.axis('equal')
        plt.show()
        return G
```

We've suggested a few graph ideas above.

The list below highlights those achievable with minimal computational resources, whether on a local laptop or a cloud instance. Some are simply too large.
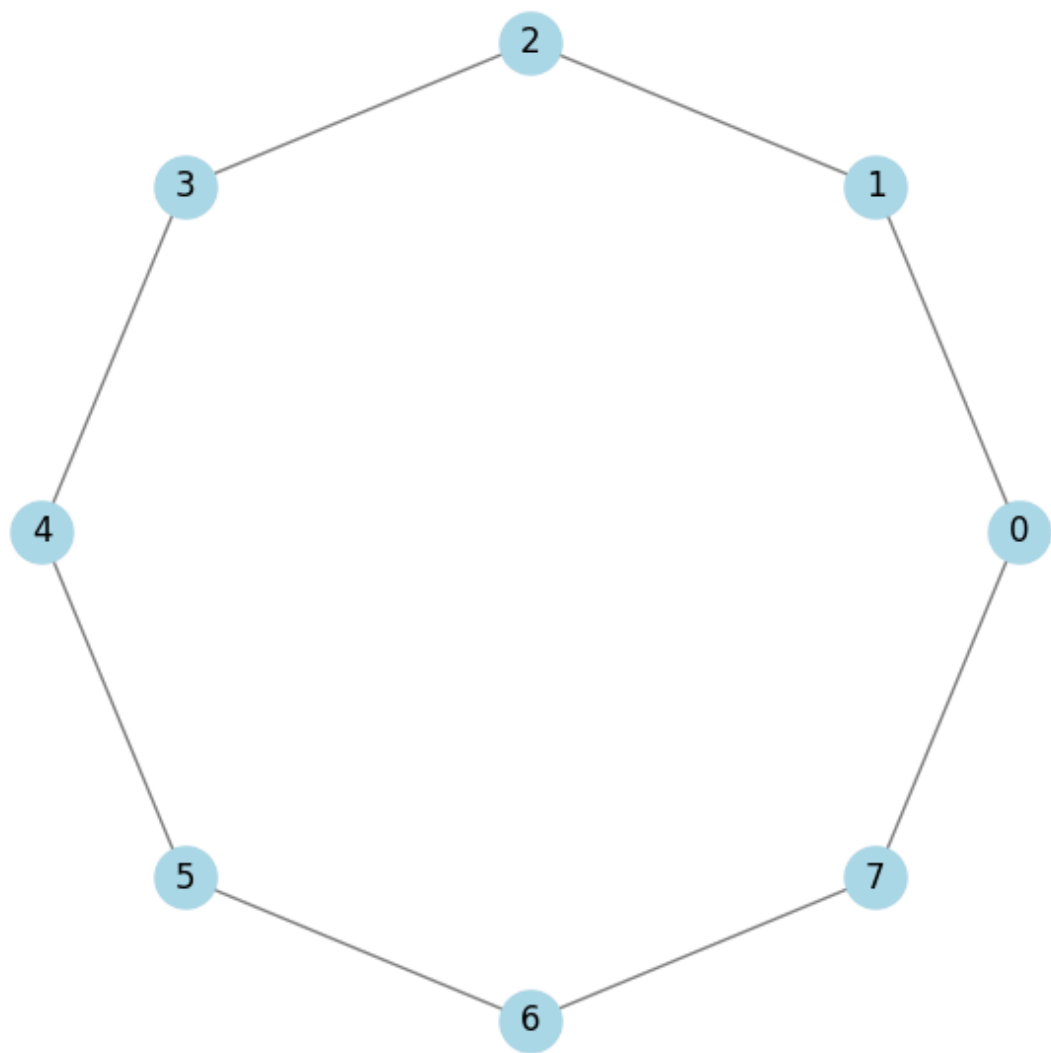
In [6]:
```
# Choose your favorite graph and build your winning ansatz!

graph1 = cycle_graph_c8()
graph2 = complete_bipartite_graph_k88()
graph3 = complete_bipartite_graph_k_nn(5)
graph4 = regular_graph_4_8()
graph5 = cubic_graph_3_16()
graph6 = random_connected_graph_16(p=0.18)
graph7 = expander_graph_n(16)
#graph8 = -> make your own cool graph
```
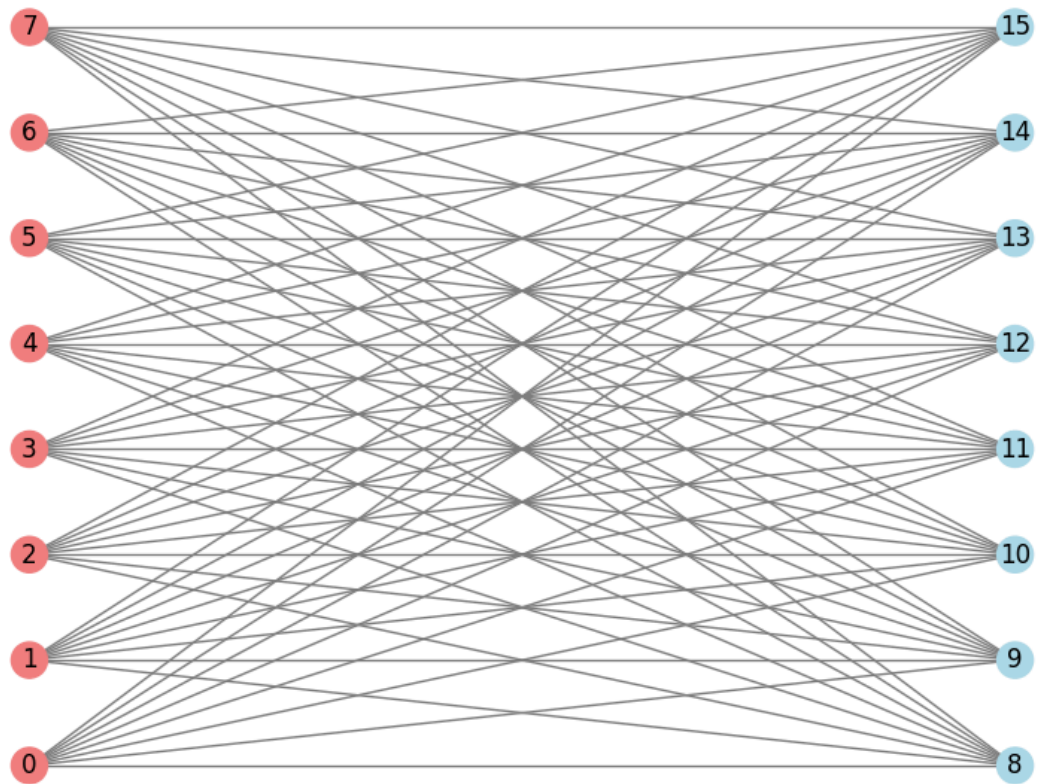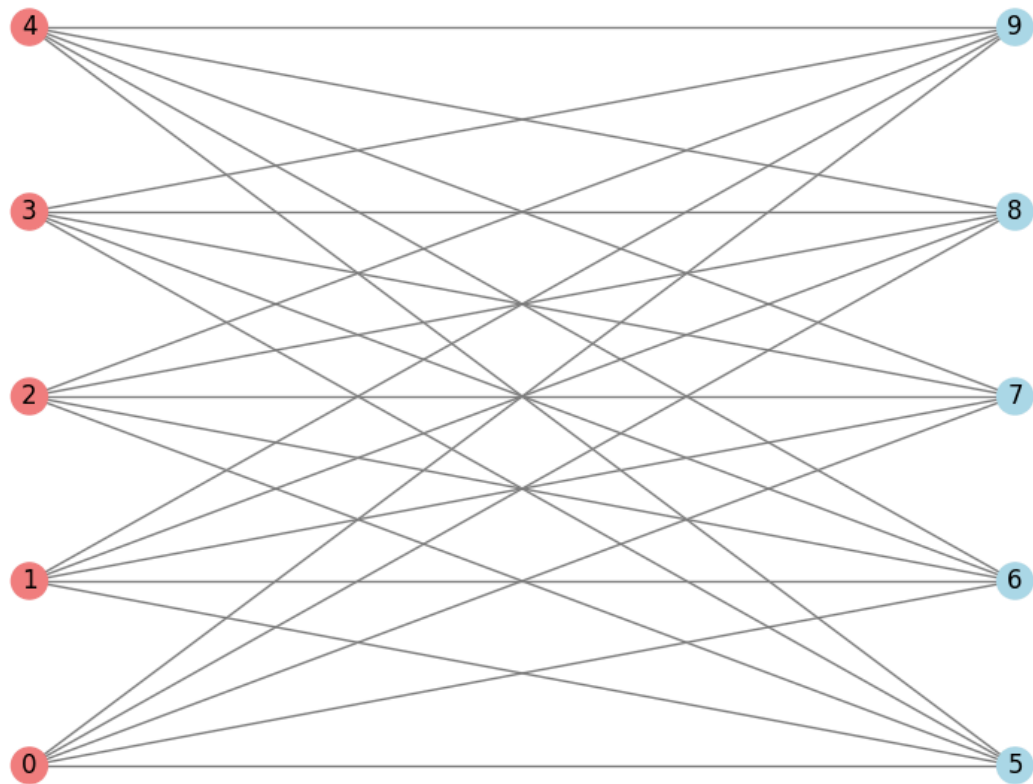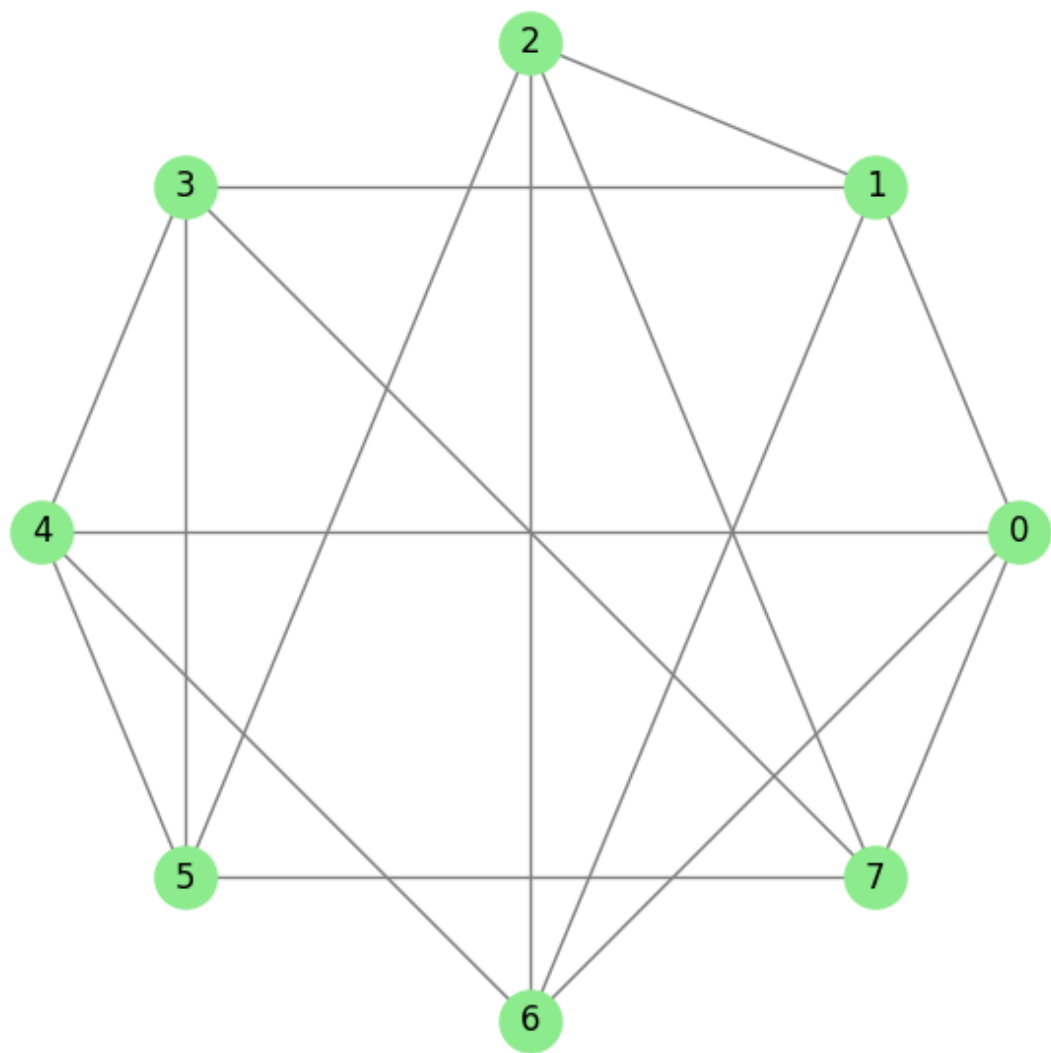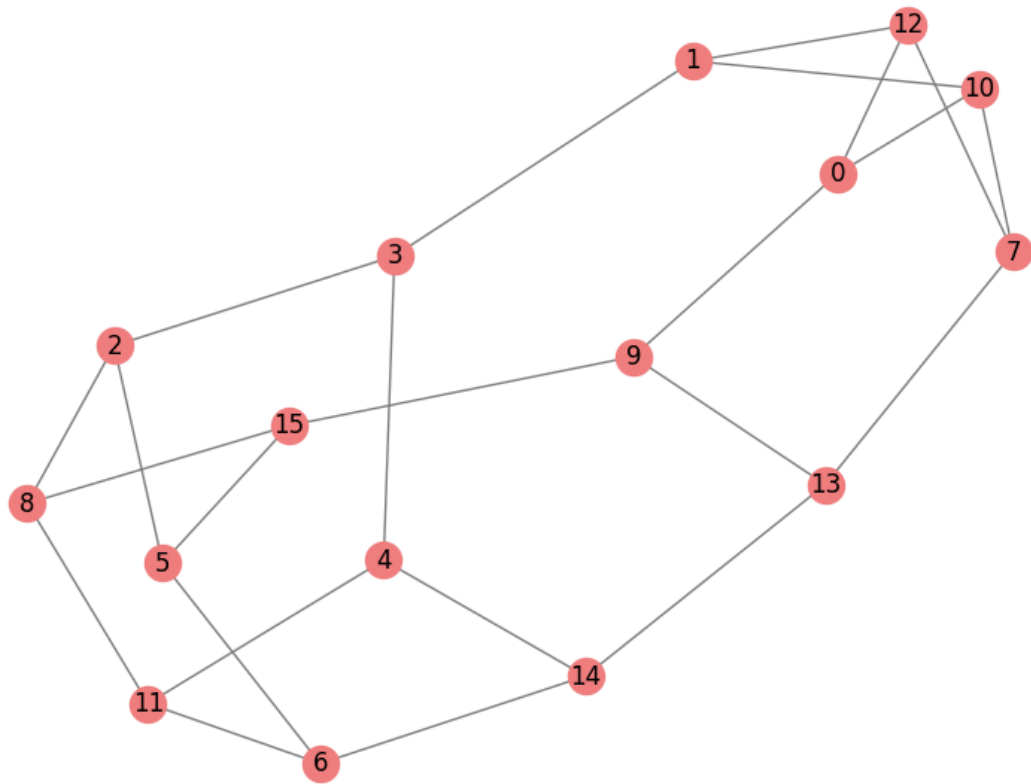
Cycle Graph C8

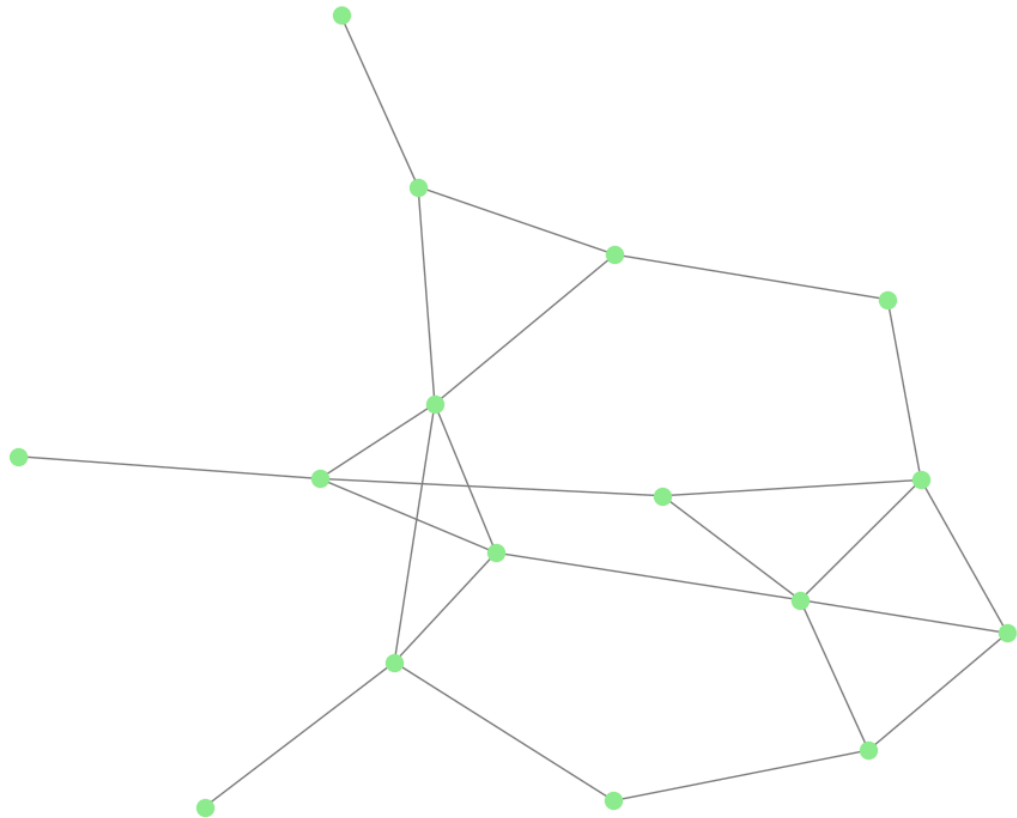Complete Bipartite Graph K8,8

Complete Bipartite Graph K5,5

4-Regular Graph with 8 Vertices

Cubic (3-Regular) Graph with 16 Vertices

Random Connected Graph with 16 Vertices

Expander Graph with 16 Vertices
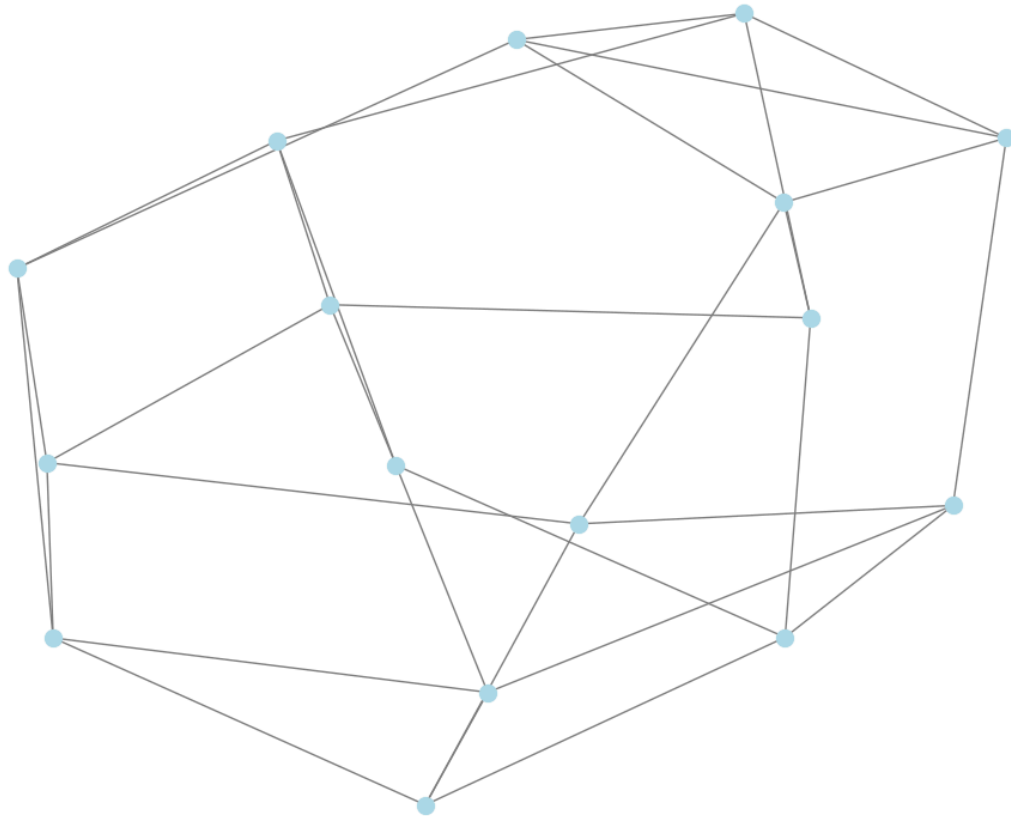

```
In [120...  import cv2
            import matplotlib.pyplot as plt
            import networkx as nx
            import math

            map_width = 610#4425.696
            grid_size = 120
            connection_distance = 180


            white_tolerance = 240


            image_path = 'sat2.png'
            img = cv2.imread(image_path, cv2.IMREAD_GRAYSCALE)
            if img is None:
                raise IOError(f"Failed to load image at {image_path}")

            #create binary image (prob not needed anymore)
            _, working_img = cv2.threshold(img, white_tolerance, 255, cv2.THRESH_BINARY)
            img_height, img_width = working_img.shape


            scale = img_width / map_width  #pixels per meter
            grid_size_pixels = grid_size * scale
```

```python
#number of grid cols and rows based on grid cell size and image size
n_cols = int(img_width // grid_size_pixels)
n_rows = int(img_height // grid_size_pixels)

print(f"Image dimensions: {img_width}x{img_height} pixels")
print(f"Map width: {map_width} m, Grid cell size: {grid_size} m ({grid_size_pixels:
print(f"Grid dimensions: {n_cols} columns x {n_rows} rows")

G = nx.Graph()
for r in range(n_rows):
    for c in range(n_cols):
        #find center of grid in m
        center_m = ((c + 0.5) * grid_size, (r + 0.5) * grid_size)
        #find center of grid in px
        center_px = (center_m[0] * scale, center_m[1] * scale)
        G.add_node((r, c), center_m=center_m, center_px=center_px)


def flood_fill(img, start_x, start_y, target_value=255, fill_value=128):
    h, w = img.shape
    stack = [(start_x, start_y)]
    while stack:
        x, y = stack.pop()
        #prevent oob
        if x < 0 or x >= w or y < 0 or y >= h:
            continue

        if img[y, x] != target_value:
            continue
        img[y, x] = fill_value

        for dx in [-1, 0, 1]:
            for dy in [-1, 0, 1]:
                if dx == 0 and dy == 0:
                    continue
                nx_ = x + dx
                ny_ = y + dy
                if 0 <= nx_ < w and 0 <= ny_ < h and img[ny_, nx_] == target_value:
                    stack.append((nx_, ny_))


for r in range(n_rows):
    for c in range(n_cols):
        #boundaries of grid
        x0 = int(c * grid_size_pixels)
        x1 = int((c + 1) * grid_size_pixels)
        y0 = int(r * grid_size_pixels)
        y1 = int((r + 1) * grid_size_pixels)


        region = working_img[y0:y1, x0:x1]
        #any white px in grid then go, white pixel denotes a path/road
        if np.any(region == 255):
            #tmp image to prevent change to original image
            temp_img = working_img.copy()
            #fidn first white px
```

```python
                white_indices = np.argwhere(region == 255)
                if white_indices.size > 0:
                    first_idx = white_indices[0]
                    #convert from localcc to globalcc
                    start_y = y0 + first_idx[0]
                    start_x = x0 + first_idx[1]
                    #floodfill in mask/temp image
                    flood_fill(temp_img, start_x, start_y, target_value=255, fill_value

            # (Fourth-level iteration)
            #iterate over every grid cell to see if they have a marker in temp_img
            for r2 in range(n_rows):
                for c2 in range(n_cols):
                    # NO self connect
                    if (r, c) == (r2, c2):
                        continue
                    x0_d = int(c2 * grid_size_pixels)
                    x1_d = int((c2 + 1) * grid_size_pixels)
                    y0_d = int(r2 * grid_size_pixels)
                    y1_d = int((r2 + 1) * grid_size_pixels)
                    region_d = temp_img[y0_d:y1_d, x0_d:x1_d]
                    #any markers in grid then it is connected
                    if np.any(region_d == 128):
                        #euclid distance between grid centers
                        source_center = G.nodes[(r, c)]['center_m']
                        dest_center = G.nodes[(r2, c2)]['center_m']
                        dist = math.hypot(source_center[0] - dest_center[0],
                                          source_center[1] - dest_center[1])
                        if dist <= connection_distance: # ensure they are within di
                            G.add_edge((r, c), (r2, c2))


print(f"Graph has {G.number_of_nodes()} nodes and {G.number_of_edges()} edges.")

#floodfill w/ green using mask over original image to prevent changes to orig
img_color = cv2.cvtColor(working_img, cv2.COLOR_GRAY2BGR)
mask_green = (working_img == 128)
img_color[mask_green] = [0, 255, 0]

#BGR to RGB for mpl.
img_rgb = cv2.cvtColor(img_color, cv2.COLOR_BGR2RGB)

plt.figure(figsize=(10, 10))
plt.imshow(img_rgb)
plt.title("Flood-Filled Connectivity (Original Image Unchanged)")

#liness
for col in range(n_cols + 1):
    x = int(col * grid_size_pixels)
    plt.plot([x, x], [0, img_height], color='cyan', linewidth=1, alpha=0.5)
for row in range(n_rows + 1):
    y = int(row * grid_size_pixels)
    plt.plot([0, img_width], [y, y], color='cyan', linewidth=1, alpha=0.5)


node_positions = {node: G.nodes[node]['center_px'] for node in G.nodes()}
```

```python
# draw nodes
isolated_nodes = list(nx.isolates(G))
G.remove_nodes_from(isolated_nodes)

nx.draw_networkx_nodes(G, pos=node_positions, node_color='red', node_size=50, ax=pl
nx.draw_networkx_edges(G, pos=node_positions, edge_color='yellow', width=2, ax=plt.

plt.axis('off')
plt.show()

graph8 = G

# Create a mapping from old node labels to new integer labels (0 to 41)
new_labels = {old_label: new_idx for new_idx, old_label in enumerate(graph8.nodes()

# Relabel the graph
graph8 = nx.relabel_nodes(graph8, new_labels)

# Print to verify
print("New node labels:", graph8.nodes())
```
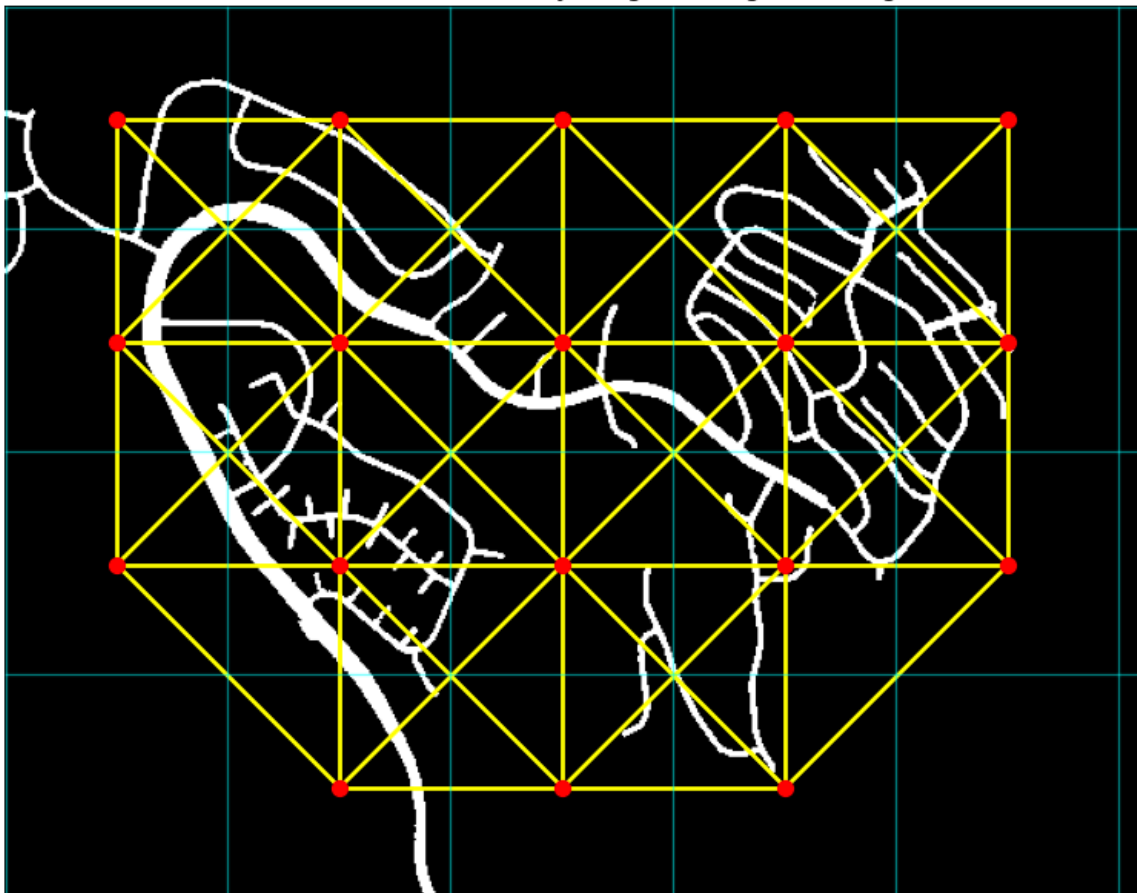
```
Image dimensions: 584x460 pixels
Map width: 610 m, Grid cell size: 120 m (114.9 px)
Grid dimensions: 5 columns x 4 rows
Graph has 20 nodes and 49 edges.
```

Flood-Filled Connectivity (Original Image Unchanged)

```
New node labels: [0, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17]
```

Input graph

```
In [121… graph = graph8
         graph
```

Out[121… `<networkx.classes.graph.Graph at 0x23962a17790>`

Play around with all of them

Quantum Circuit Generator

We start by generating parameterized circuit based on a given graph.

🤔 Note: Future experiments will focus on optimizing this circuit generator (this function below). Maximizing your score requires minimizing the number of gates in the generated parameterized circuit.

Set of Rules:

Rules: Do not rename the function, import external libraries (except Qiskit), or use classical solvers. Implement any needed algorithms (e.g., sorting) within the function. Minimize gate count. Run locally for all the graphs before submitting the results.

Let's iterate again.

This challenge requires you to work within the provided function's name and scope. You may only use Qiskit libraries. Do not import additional libraries or call external functions. If your solution requires operations like sorting, implement them directly within the function. Critically, do *not* use a classical algorithm to solve the problem and simply input the result. Optimize your code to minimize the number of quantum gates, while aiming for the correct solutions distribution. Thoroughly get your solution results to report at the end.

Important note: To confirm your results, please save this notebook including all cell outputs and upload it in the form here: https://forms.gle/tAjnUd7b5t3oX3b2A . To avoid exceeding the notebook's 10MB file size limit, please be mindful of the number of print statements you use. Feel free to modify the notebook as needed. However, please ensure your code is readable. Please thoroughly comment your code; we will evaluate your problem-solving approach based on the educational clarity of your explanations.

Good luck, and have fun!

```
In [122… # Visualization will be performed in the cells below;

         def build_ansatz(graph: nx.Graph) -> QuantumCircuit:
```

```python
    ansatz = QuantumCircuit(graph.number_of_nodes())
    ansatz.h(range(graph.number_of_nodes()))

    theta = ParameterVector(r"$\theta$", graph.number_of_edges())
    for t, (u, v) in zip(theta, graph.edges):
        ansatz.cx(u, v)
        ansatz.ry(t, v)
        ansatz.cx(u, v)

    return ansatz
```

In [123…
```python
# alternate method to make the ansatz

# function to generate a maximum spanning tree of the graph
def generate_max_spanning_tree(G):
    # for u, v in G.edges:
    #     G[u][v]['weight'] *= -1
    return nx.minimum_spanning_tree(G, algorithm='kruskal')

# function to return the graph with the spanning tree edges removed
def remove_spanning_tree_edges(G, T):
    H = G.copy()
    for edge in T.edges:
        H.remove_edge(*edge)
    return H
```

In [124…
```python
# get the maximum spanning tree of the graph by negating all the edge weights and c
T = generate_max_spanning_tree(graph)

# remove the edges of the spanning tree from the graph
H = remove_spanning_tree_edges(graph, T)

# visualize the tree and the graph with the tree edges removed
plt.figure(figsize=(12, 6))
plt.subplot(121)
pos = nx.circular_layout(graph)
nx.draw(graph, pos, with_labels=True, node_color='lightblue', edge_color='gray', no
nx.draw_networkx_edges(T, pos, edge_color='red', width=2)
plt.title("Graph with Maximum Spanning Tree")
```

Out[124…
```
Text(0.5, 1.0, 'Graph with Maximum Spanning Tree')
```

Graph with Maximum Spanning Tree
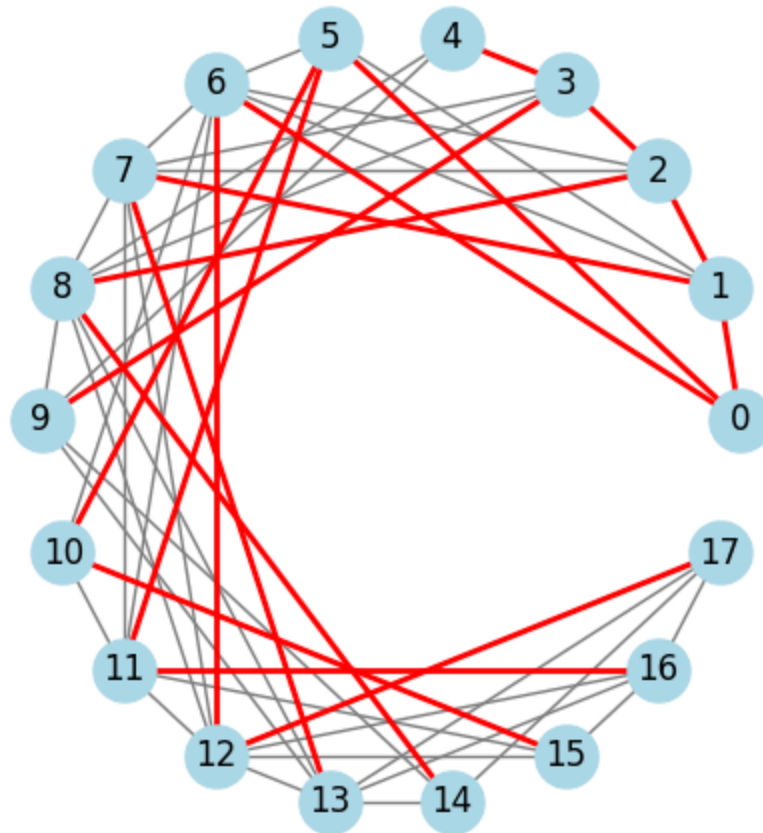

```
In [125…    # build the ansatz circuit for both T and H
            ansatz_T = build_ansatz(T)
            ansatz_H = build_ansatz(H)
```

```
In [126…    # visualize the ansatz circuit for the tree
            ansatz_T.draw("mpl", fold=-1)
```

Out[126…
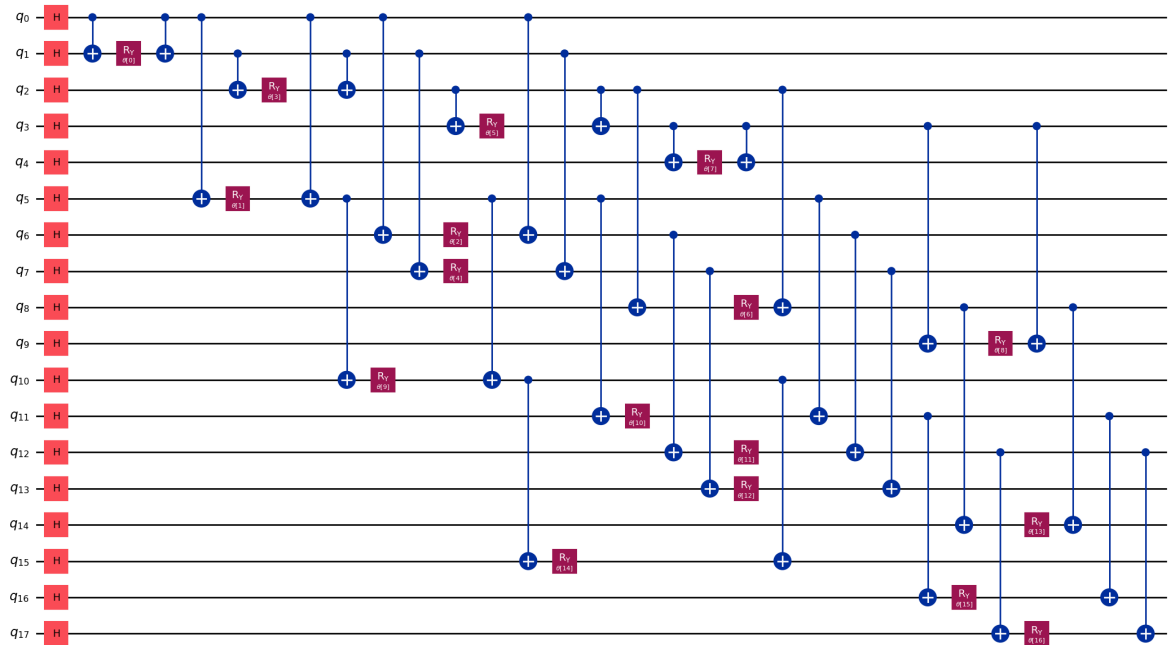
In [127…

```python
# visualize the ansatz circuit for the graph with the tree edges removed
ansatz_H.draw("mpl", fold=-1)
```

Out[127…
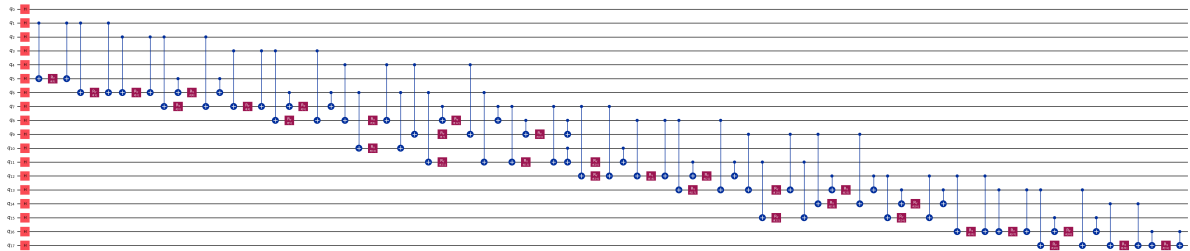
On Parametrized Quantum Circuits

Parametrized quantum circuits (PQC) recently have gained significant attention as a prominent way to reach quantum advantage in many different fields. They are characterized by their use of varying parameters within quantum gates and can be optimized to solve specific problems, such as machine learning, quantum optimization, or quantum chemistry.

PQCs usually consist of three main parts:

1. Initialization: The qubits are set to a known starting state (usually $|0\rangle$) and then set into superposition with Hadamard gates.
2. Parameterized gates, such as rotation gates (Rx, Ry, Rz), and entanglement gates are adjustable. Their parameters can be optimized to reflect the relationships between the encoded problem data.
3. Measurement: After applying the parameterized gates, the qubits are measured to get results.

These circuits are important elements in Variational Quantum Algorithms (VQA), hybrid quantum-classical systems where classical optimization helps to improve quantum operations. Two most notable examples of VQAs are Variational Quantum Eigensolver (VQE), an algorithm that finds a ground state energy of a given Hamiltonian, and Quantum Approximate Optimization Algorithm (QAOA), which is designed for solving combinatorial optimization problems. Near-term quantum computers are noisy and limited in size, and PQCs provide a practical way for us to use them more effectively.
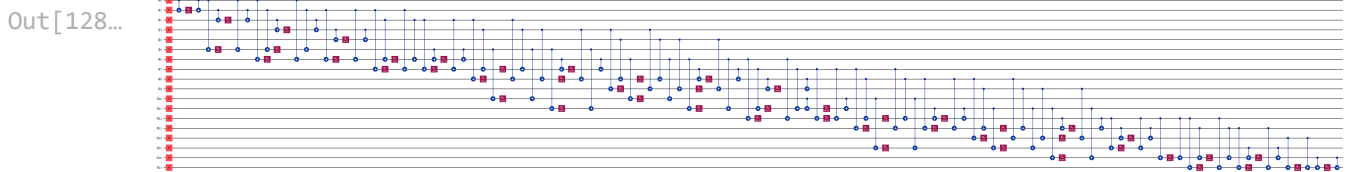
More on that topic: https://arxiv.org/abs/2207.06850

Back to the problem in hand

This function produces parametrized quantum circuits (PQCs), a visualization of which is provided below.

```
In [128... ansatz = build_ansatz(graph)
          ansatz.draw("mpl", fold=-1)
```

Out[128...

Building the MaxCut Hamiltonian

Formally, we write MaxCut as a Quadratic Program (QP) with binary decision variables as follows. For each node $v \in V$, we let x_v denote a binary variable indicating whether v belongs to S or T. The objective is to maximize the number of cut edges:

$$\text{maximize}_x \quad \sum_{(v,w) \in E} (x_v + x_w - 2x_v x_w)$$

Let's break this down. Notice that for each edge $e = (v, w)$ in the graph, the quantity $(x_v + x_w - 2x_v x_w)$ indicates whether e is *cut* by the partition represented by x; that is, the quantity $(x_v + x_w - 2x_v x_w)$ is zero or one, and it equals one only if v and w lie on different sides of the partition specified by x.

The code cell below obtains a symbolic representation of the maximization objective corresponding to the graph above.

```
In [129... def build_maxcut_hamiltonian(graph: nx.Graph) -> SparsePauliOp:
             """
             Build the MaxCut Hamiltonian for the given graph H = (|E|/2)*I - (1/2)*Σ_{(i,j)
             """
             num_qubits = len(graph.nodes)
```

```python
        edges = list(graph.edges())
        num_edges = len(edges)

        pauli_terms = ["I"*num_qubits] # start with identity
        coeffs = [-num_edges / 2]

        for (u, v) in edges: # for each edge, add -(1/2)*Z_i Z_j
            z_term = ["I"] * num_qubits
            z_term[u] = "Z"
            z_term[v] = "Z"
            pauli_terms.append("".join(z_term))
            coeffs.append(0.5)

        return SparsePauliOp.from_list(list(zip(pauli_terms, coeffs)))
```

In [130...
```python
# get the maxcut hamiltonian for the tree
H_maxcut_T = build_maxcut_hamiltonian(T)

# get the maxcut hamiltonian for the graph with the tree edges removed
H_maxcut_H = build_maxcut_hamiltonian(H)
```

In [131...
```python
print(H_maxcut_T)
print(H_maxcut_H)
```

```
SparsePauliOp(['IIIIIIIIIIIIIIIIII', 'ZZIIIIIIIIIIIIIIII', 'ZIIIIZIIIIIIIIIIII', 'ZI
IIIIZIIIIIIIIIII', 'IZZIIIIIIIIIIIIIII', 'IZIIIIIZIIIIIIIIII', 'IIZZIIIIIIIIIIIIII',
'IIZIIIIIZIIIIIIIII', 'IIIZZIIIIIIIIIIIII', 'IIIZIIIIIZIIIIIIII', 'IIIIIZIIIIZIIIIII
I', 'IIIIIZIIIIIZIIIIII', 'IIIIIIZIIIIIZIIIII', 'IIIIIIIZIIIIIZIIII', 'IIIIIIIIZIIII
IZIII', 'IIIIIIIIIIZIIIIZII', 'IIIIIIIIIIIZIIIIZI', 'IIIIIIIIIIIIZIIIIZ'],
              coeffs=[-8.5+0.j,  0.5+0.j,  0.5+0.j,  0.5+0.j,  0.5+0.j,  0.5+0.j,
0.5+0.j,
  0.5+0.j,  0.5+0.j,  0.5+0.j,  0.5+0.j,  0.5+0.j,  0.5+0.j,  0.5+0.j,
  0.5+0.j,  0.5+0.j,  0.5+0.j,  0.5+0.j])
SparsePauliOp(['IIIIIIIIIIIIIIIIII', 'IZIIIZIIIIIIIIIIII', 'IZIIIIZIIIIIIIIIII', 'II
ZIIZIIIIIIIIIIII', 'IIZIIIIZIIIIIIIIII', 'IIIZIIIZIIIIIIIIII', 'IIIZIIIIZIIIIIIIII',
'IIIIZIIIZIIIIIIIII', 'IIIIZIIIIZIIIIIIII', 'IIIIIZZIIIIIIIIIII', 'IIIIIIZZIIIIIIIIII
I', 'IIIIIIZIIIZIIIIIII', 'IIIIIIIZIIIZIIIIII', 'IIIIIIIIZZIIIIIIII', 'IIIIIIIZIIIIZI
IIIII', 'IIIIIIIZIIIZIIIIII', 'IIIIIIIIZZIIIIIIII', 'IIIIIIIIZIIIZIIIII', 'IIIIIIIIZ
IIIIZIIII', 'IIIIIIIIIZIIIZIIII', 'IIIIIIIIIZIIIIZIII', 'IIIIIIIIIIZZIIIIII', 'IIIII
IIIIIIZZIIIII', 'IIIIIIIIIIIIZIIIZII', 'IIIIIIIIIIIIZZIIII', 'IIIIIIIIIIIIZIIZII', 'I
IIIIIIIIIIIZIIIZI', 'IIIIIIIIIIIIIZZIII', 'IIIIIIIIIIIIIZIIZI', 'IIIIIIIIIIIIIZIII
Z', 'IIIIIIIIIIIIIZIIZ', 'IIIIIIIIIIIIIIIZZI', 'IIIIIIIIIIIIIIIIZZ'],
              coeffs=[-16. +0.j,   0.5+0.j,   0.5+0.j,   0.5+0.j,   0.5+0.j,   0.5+
0.j,
  0.5+0.j,   0.5+0.j,   0.5+0.j,   0.5+0.j,   0.5+0.j,   0.5+0.j,
  0.5+0.j,   0.5+0.j,   0.5+0.j,   0.5+0.j,   0.5+0.j,   0.5+0.j,
  0.5+0.j,   0.5+0.j,   0.5+0.j,   0.5+0.j,   0.5+0.j,   0.5+0.j,
  0.5+0.j,   0.5+0.j,   0.5+0.j,   0.5+0.j,   0.5+0.j,   0.5+0.j,
  0.5+0.j,   0.5+0.j,   0.5+0.j])
```

Let's keep this function contained within its own cell, as you might need to adapt it for various max-cut problem types later.

In [132...
```python
ham = build_maxcut_hamiltonian(graph)
ham
```

```
Out[132… SparsePauliOp(['IIIIIIIIIIIIIIIIII', 'ZZIIIIIIIIIIIIIIIII', 'ZIIIIZIIIIIIIIIIIII',
          'ZIIIIIZIIIIIIIIIIII', 'IZZIIIIIIIIIIIIIIII', 'IZIIIZIIIIIIIIIIIII', 'IZIIIIZIIIIIIII
          III', 'IZIIIIIZIIIIIIIIIII', 'IIZZIIIIIIIIIIIIIII', 'IIZIIIZIIIIIIIIIIII', 'IIZIIIIZI
          IIIIIIIII', 'IIZIIIIIZIIIIIIIII', 'IIIZZIIIIIIIIIIIIII', 'IIIZIIIZIIIIIIIIIII', 'III
          ZIIIIZIIIIIIIIII', 'IIIZIIIIIZIIIIIIIII', 'IIIIZIIIZIIIIIIIII', 'IIIIZIIIIZIIIIIIIII
          I', 'IIIIIZZIIIIIIIIIII', 'IIIIIZIIIZIIIIIIII', 'IIIIIZIIIIZIIIIIII', 'IIIIIIZZIII
          IIIIIII', 'IIIIIIZIIIZIIIIIII', 'IIIIIIZIIIIZIIIIII', 'IIIIIIZIIIIIZIIIII', 'IIIII
          IIZZIIIIIIIIII', 'IIIIIIIZIIIZIIIIII', 'IIIIIIIZIIIIZIIIII', 'IIIIIIIZIIIIIZIIII',
          'IIIIIIIIZZIIIIIIII', 'IIIIIIIIZIIIZIIIII', 'IIIIIIIIZIIIIZIIII', 'IIIIIIIIZIIIIIZ
          III', 'IIIIIIIIIZIIIZIIII', 'IIIIIIIIIZIIIIZIII', 'IIIIIIIIIIZZIIIIII', 'IIIIIIIII
          IZIIIIZII', 'IIIIIIIIIIIZZIIIII', 'IIIIIIIIIIIIZIIIZII', 'IIIIIIIIIIIZIIIIZI', 'III
          IIIIIIIIIZZIIII', 'IIIIIIIIIIIIZIIZII', 'IIIIIIIIIIIIZIIIZI', 'IIIIIIIIIIIIIZIIII
          Z', 'IIIIIIIIIIIIIZZIII', 'IIIIIIIIIIIIIZIIZI', 'IIIIIIIIIIIIIIZIIIZ', 'IIIIIIIIIII
          IIIZIIZ', 'IIIIIIIIIIIIIIIZZI', 'IIIIIIIIIIIIIIIIZZ'],
                    coeffs=[-24.5+0.j,   0.5+0.j,   0.5+0.j,   0.5+0.j,   0.5+0.j,   0.5
          +0.j,
             0.5+0.j,   0.5+0.j,   0.5+0.j,   0.5+0.j,   0.5+0.j,   0.5+0.j,
             0.5+0.j,   0.5+0.j,   0.5+0.j,   0.5+0.j,   0.5+0.j,   0.5+0.j,
             0.5+0.j,   0.5+0.j,   0.5+0.j,   0.5+0.j,   0.5+0.j,   0.5+0.j,
             0.5+0.j,   0.5+0.j,   0.5+0.j,   0.5+0.j,   0.5+0.j,   0.5+0.j,
             0.5+0.j,   0.5+0.j,   0.5+0.j,   0.5+0.j,   0.5+0.j,   0.5+0.j,
             0.5+0.j,   0.5+0.j,   0.5+0.j,   0.5+0.j,   0.5+0.j,   0.5+0.j,
             0.5+0.j,   0.5+0.j,   0.5+0.j,   0.5+0.j,   0.5+0.j,   0.5+0.j,
             0.5+0.j,   0.5+0.j])
```

As a Hamiltonian energy minimization problem

Quantum MaxCut

Quantum computers are good at finding the ground state of particle systems evolving under the action of a given Hamiltonian. In this section, we'll construct a Hamiltonian whose energies are exactly the values of the MaxCut objective function. This correspondence will effectively translate our classical combinatorial optimization problem into a quantum problem, which we'll approach using our novel heuristic.

Given an objective function $C(x)$, with domain $x \in \{0,1\}^n$, we'll produce a Hamiltonian H_C on n qubits such that

$$H_C \ket x = C(x) \ket x.$$

In the last equation, $\ket x$ denotes the n-qubit computational basis state indexed by the bit-string $x \in \{0,1\}$. Thus the last equation says each of the 2^n computational basis states is an eigenvector of H_C, and the eigenvalue corresponding to $\ket x$ is $C(x)$; that is, H_C is diagonal with respect to the computational basis, and its energies are the values of the objective function C.

We'll obtain the Hamiltonian H_C by replacing each x_j in the expression of $C(x)$ by the operator

$$\hat{X}_j \coloneqq \frac{1}{2}(I - Z_j),$$

where I denotes the identity operator on n qubits and Z_j denotes the Pauli-Z operator acting on the jth qubit. Notice that $\hat{X}_j$ is diagonal with respect to the computational basis, and its eigenvalues are zero and one; in particular,

$$\hat{X}_j \ket{x} = x_j \ket{x}.$$

MaxCut Hamiltonian

When we apply the Ising map construction to the MaxCut objective

$$M(x) = \sum_{(v,w) \in E} (x_v + x_w - 2x_v x_w)$$

we obtain the Hamiltonian

$$H_M = \sum_{(v,w) \in E} (X_v + X_w - 2X_v X_w) = \frac{1}{2} \sum_{(v,w) \in E} \left(2I - Z_v - Z_w - (I - Z_v)(I - Z_w)\right) = \frac{1}{2}|$$

In the last equation, $|E|$ denotes the number of edges in the graph.

Energy minimization via QITE

Enter varQITE

With the MaxCut Hamiltonian in hand, we can turn to minimizing its energy using our novel quantum-classical varQITE heuristic. Much like any Variataional Quantum Algorithm (VQA), our novel varQITE method provides a recipe for iteratively updating the parameters in a variational quantum circuit to minimize the expectation value of the MaxCut Hamiltonian, measured with respect to the parametrized state.

A key novelty is that our varQITE algorithm does *not* rely on a classical optimizer to update the circuit parameters; instead, it specifies an explicit update rule based on the solution of a system linear Ordinary Differential Equations (ODEs). The ODEs relate the gradient of the variational circuit parameters to the expected value of certain operators related to the MaxCut Hamiltonian, and they are derived from an Ehrenfest Theorem that applies to imaginary time evolution. For details, see Equation (5) in our varQITE paper.

In any case, setting up the ODE system at each step of the algorithm requires executing a batch of quantum circuits and running some post-processing to evaluate the results.

The code cell below illustrates how to set up the variational ansatz $\ket{\Psi}(\theta)$ introduced by our varQITE paper in Equation (2). We'll set up the required circuits and the ODEs further down.

Below is simplified version of Quantum Imaginary Time Evolution (QITE). It uses a finite differences approach to estimate gradients, then performs gradient descent updates.

```
In [133...  class QITEvolver:
               """
               A class to evolve a parametrized quantum state under the action of an Ising
               Hamiltonian according to the variational Quantum Imaginary Time Evolution
               (QITE) principle described in IonQ's latest joint paper with ORNL.
               """
               def __init__(self, hamiltonian: SparsePauliOp, ansatz: QuantumCircuit):
                   self.hamiltonian = hamiltonian
                   self.ansatz = ansatz

                   # Define some constants
                   self.backend = AerSimulator()
                   self.num_shots = 10000
                   self.energies, self.param_vals, self.runtime = list(), list(), list()

               def evolve(self, num_steps: int, lr: float = 0.4, verbose: bool = True):
                   """
                   Evolve the variational quantum state encoded by ``self.ansatz`` under
                   the action of ``self.hamiltonian`` according to varQITE.
                   """
                   curr_params = np.zeros(self.ansatz.num_parameters)
                   for k in range(num_steps):
                       # Get circuits and measure on backend
                       iter_qc = self.get_iteration_circuits(curr_params)
                       job = self.backend.run(iter_qc, shots=self.num_shots)
                       q0 = time.time()
                       measurements = job.result().get_counts()
                       quantum_exec_time = time.time() - q0

                       # Update parameters-- set up defining ODE and step forward
                       Gmat, dvec, curr_energy = self.get_defining_ode(measurements)
                       dcurr_params = np.linalg.lstsq(Gmat, dvec, rcond=1e-2)[0]
                       curr_params += lr * dcurr_params

                       # Progress checkpoint!
                       if verbose:
                           self.print_status(measurements)
                       self.energies.append(curr_energy)
                       self.param_vals.append(curr_params.copy())
                       self.runtime.append(quantum_exec_time)

               def get_defining_ode(self, measurements: List[dict[str, int]]):
                   """
                   Construct the dynamics matrix and load vector defining the varQITE
                   iteration.
                   """
                   # Load sampled bitstrings and corresponding frequencies into NumPy arrays
                   dtype = np.dtype([("states", int, (self.ansatz.num_qubits,)), ("counts", "f
                   measurements = [np.fromiter(map(lambda kv: (list(kv[0]), kv[1]), res.items(

                   # Set up the dynamics matrix by computing the gradient of each Pauli word
                   # with respect to each parameter in the ansatz using the parameter-shift ru
```

```python
        pauli_terms = [SparsePauliOp(op) for op, _ in self.hamiltonian.label_iter()
        Gmat = np.zeros((len(pauli_terms), self.ansatz.num_parameters))
        for i, pauli_word in enumerate(pauli_terms):
            for j, jth_pair in enumerate(zip(measurements[1::2], measurements[2::2]
                for pm, pm_shift in enumerate(jth_pair):
                    Gmat[i, j] += (-1)**pm * expected_energy(pauli_word, pm_shift)

        # Set up the load vector
        curr_energy = expected_energy(self.hamiltonian, measurements[0])
        dvec = np.zeros(len(pauli_terms))
        for i, pauli_word in enumerate(pauli_terms):
            rhs_op_energies = get_ising_energies(pauli_word, measurements[0]["state
            rhs_op_energies *= get_ising_energies(self.hamiltonian, measurements[0]
            dvec[i] = -np.dot(rhs_op_energies, measurements[0]["counts"]) / self.nu
        return Gmat, dvec, curr_energy

    def get_iteration_circuits(self, curr_params: np.array):
        """
        Get the bound circuits that need to be evaluated to step forward
        according to QITE.
        """
        # Use this circuit to estimate your Hamiltonian's expected value
        circuits = [self.ansatz.assign_parameters(curr_params)]

        # Use these circuits to compute gradients
        for k in np.arange(curr_params.shape[0]):
            for j in range(2):
                pm_shift = curr_params.copy()
                pm_shift[k] += (-1)**j * np.pi/2
                circuits += [self.ansatz.assign_parameters(pm_shift)]

        # Add measurement gates and return
        [qc.measure_all() for qc in circuits]
        return circuits

    def plot_convergence(self):
        """
        Plot the convergence of the expected value of ``self.hamiltonian`` with
        respect to the (imaginary) time steps.
        """
        plt.plot(self.energies)
        plt.xlabel("(Imaginary) Time step")
        plt.ylabel("Hamiltonian energy")
        plt.title("Convergence of the expected energy")

    def print_status(self, measurements):
        """
        Print summary statistics describing a QITE run.
        """
        stats = pd.DataFrame({
            "curr_energy": self.energies,
            "num_circuits": [len(measurements)] * len(self.energies),
            "quantum_exec_time": self.runtime
        })
        stats.index.name = "step"
```

```python
            display.clear_output(wait=True)
            display.display(stats)
```

A few utility functions:

In [134...
```python
def compute_cut_size(graph, bitstring):
    """
    Get the cut size of the partition of ``graph`` described by the given
    ``bitstring``.
    """
    cut_sz = 0
    for (u, v) in graph.edges:
        if bitstring[u] != bitstring[v]:
            cut_sz += 1
    return cut_sz
```

In [135...
```python
def get_ising_energies(
        operator: SparsePauliOp,
        states: np.array
):
    """
    Get the energies of the given Ising ``operator`` that correspond to the
    given ``states``.
    """
    # Unroll Hamiltonian data into NumPy arrays
    paulis = np.array([list(ops) for ops, _ in operator.label_iter()]) != "I"
    coeffs = operator.coeffs.real

    # Vectorized energies computation
    energies = (-1) ** (states @ paulis.T) @ coeffs
    return energies
```

In [136...
```python
def expected_energy(
        hamiltonian: SparsePauliOp,
        measurements: np.array
):
    """
    Compute the expected energy of the given ``hamiltonian`` with respect to
    the observed ``measurement``.

    The latter is assumed to by a NumPy records array with fields ``states``
    --describing the observed bit-strings as an integer array-- and ``counts``,
    describing the corresponding observed frequency of each state.
    """
    energies = get_ising_energies(hamiltonian, measurements["states"])
    return np.dot(energies, measurements["counts"]) / measurements["counts"].sum()
```

In [137...
```python
def interpret_solution(graph, bitstring):
    """
    Visualize the given ``bitstring`` as a partition of the given ``graph``.
    """
    pos = nx.spring_layout(graph, seed=42)
    set_0 = [i for i, b in enumerate(bitstring) if b == '0']
    set_1 = [i for i, b in enumerate(bitstring) if b == '1']
```

```python
    plt.figure(figsize=(4, 4))
    nx.draw_networkx_nodes(graph, pos=pos, nodelist=set_0, node_color='blue', node_
    nx.draw_networkx_nodes(graph, pos=pos, nodelist=set_1, node_color='red', node_s

    cut_edges = []
    non_cut_edges = []
    for (u, v) in graph.edges:
        if bitstring[u] != bitstring[v]:
            cut_edges.append((u, v))
        else:
            non_cut_edges.append((u, v))

    nx.draw_networkx_edges(graph, pos=pos, edgelist=non_cut_edges, edge_color='gray
    nx.draw_networkx_edges(graph, pos=pos, edgelist=cut_edges, edge_color='green',

    nx.draw_networkx_labels(graph, pos=pos, font_color='white', font_weight='bold')
    plt.axis('off')
    plt.show()
```

In [138…
```python
%%time

# Set up your QITEvolver and evolve!
qit_evolver = QITEvolver(ham, ansatz)
qit_evolver.evolve(num_steps=40, lr=0.1, verbose=True) # lr was 0.5

# Visualize your results!
qit_evolver.plot_convergence()
```
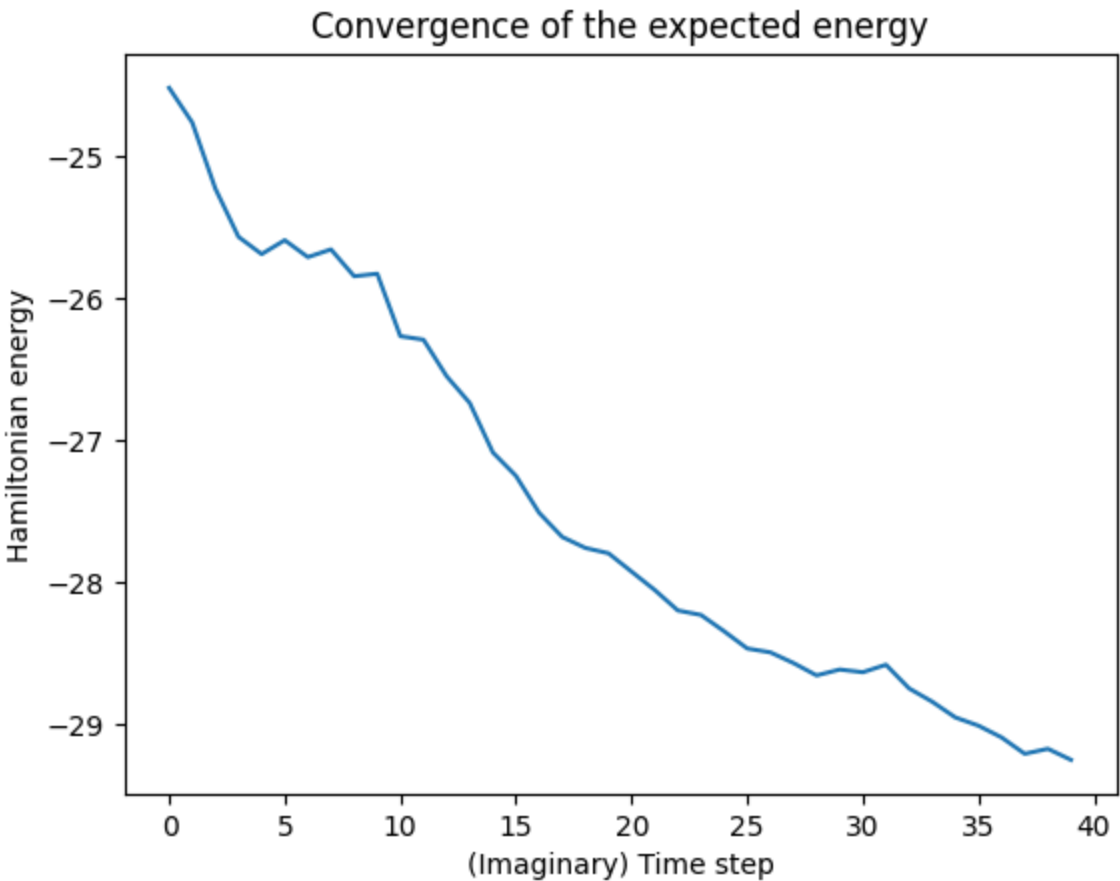
	curr_energy	num_circuits	quantum_exec_time
step			
0	-24.5161	99	13.046225
1	-24.7607	99	11.995473
2	-25.2262	99	12.022765
3	-25.5653	99	12.005826
4	-25.6868	99	12.191788
5	-25.5889	99	12.025228
6	-25.7081	99	11.466827
7	-25.6538	99	11.347621
8	-25.8425	99	11.609754
9	-25.8251	99	11.454012
10	-26.2649	99	12.495337
11	-26.2893	99	12.215010
12	-26.5465	99	11.975374
13	-26.7350	99	11.452847
14	-27.0833	99	11.380674
15	-27.2488	99	11.382104
16	-27.5081	99	11.431701
17	-27.6783	99	11.154673
18	-27.7557	99	10.843593
19	-27.7932	99	11.191629
20	-27.9227	99	10.800186
21	-28.0518	99	10.599889
22	-28.1961	99	10.337057
23	-28.2276	99	10.583629
24	-28.3423	99	10.720108
25	-28.4637	99	10.383408
26	-28.4909	99	10.575004
27	-28.5662	99	10.369325
28	-28.6534	99	12.265579

step	curr_energy	num_circuits	quantum_exec_time
29	-28.6118	99	11.057265
30	-28.6308	99	10.420431
31	-28.5782	99	10.626589
32	-28.7447	99	10.676877
33	-28.8385	99	10.824251
34	-28.9490	99	10.669858
35	-29.0072	99	10.635778
36	-29.0899	99	10.446118
37	-29.2051	99	10.400066
38	-29.1699	99	10.441642

```
CPU times: total: 1h 25min 23s
Wall time: 11min 39s
```


Convergence of the expected energy

```
In [139…   %%time

           # Set up QITEvolver for the tree
           qit_evolver_T = QITEvolver(H_maxcut_T, ansatz_T)
```
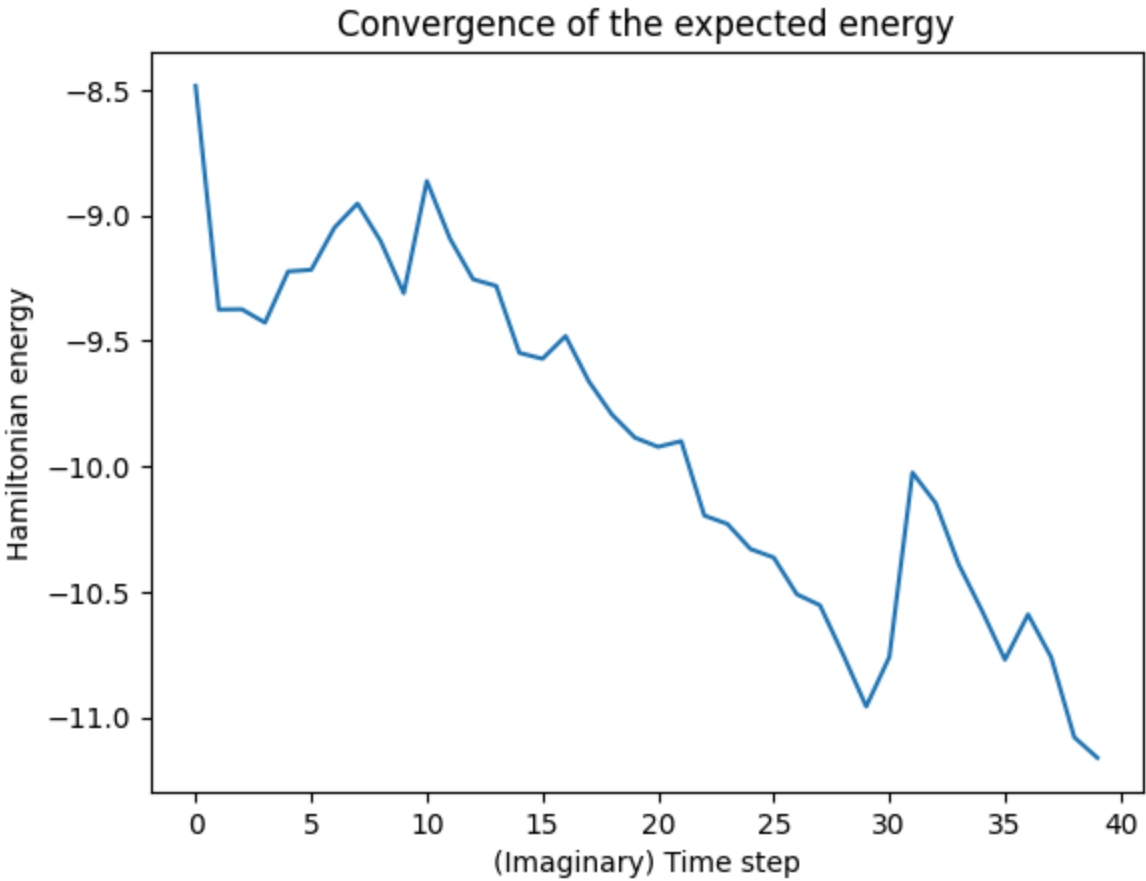
```python
qit_evolver_T.evolve(num_steps=40, lr=0.1, verbose=True)

# Visualize your results!
qit_evolver_T.plot_convergence()
```

step	curr_energy	num_circuits	quantum_exec_time
0	-8.4848	35	4.377498
1	-9.3763	35	3.239739
2	-9.3752	35	3.308048
3	-9.4285	35	3.358895
4	-9.2244	35	3.316975
5	-9.2177	35	3.294371
6	-9.0502	35	3.608275
7	-8.9538	35	3.594734
8	-9.1032	35	3.566774
9	-9.3111	35	2.862212
10	-8.8640	35	3.430489
11	-9.0938	35	2.981951
12	-9.2556	35	3.002177
13	-9.2822	35	3.217374
14	-9.5489	35	3.137902
15	-9.5723	35	3.419396
16	-9.4819	35	3.237982
17	-9.6618	35	3.325864
18	-9.7940	35	3.106374
19	-9.8867	35	3.481524
20	-9.9233	35	3.229274
21	-9.9005	35	3.254333
22	-10.1972	35	3.221189
23	-10.2306	35	3.403425
24	-10.3307	35	3.308919
25	-10.3642	35	3.488432
26	-10.5108	35	3.106372
27	-10.5545	35	3.279656
28	-10.7507	35	3.138768

step	curr_energy	num_circuits	quantum_exec_time
29	-10.9581	35	3.004971
30	-10.7606	35	3.140584
31	-10.0257	35	3.262426
32	-10.1472	35	3.200090
33	-10.3915	35	3.080774
34	-10.5748	35	3.480251
35	-10.7713	35	3.135106
36	-10.5910	35	3.174833
37	-10.7618	35	3.118654
38	-11.0808	35	3.285385

```
CPU times: total: 24min 50s
Wall time: 2min 57s
```


Convergence of the expected energy

```
In [140…  %%time

          # Set up your QITEvolver for the graph with the tree edges removed
          qit_evolver_H = QITEvolver(H_maxcut_H, ansatz_H)
```

```python
qit_evolver_H.evolve(num_steps=40, lr=0.1, verbose=True)

# Visualize your results!
qit_evolver_H.plot_convergence()
```

step	curr_energy	num_circuits	quantum_exec_time
0	-16.0020	65	7.682864
1	-15.8663	65	7.595247
2	-15.9510	65	7.291927
3	-16.6448	65	7.753627
4	-16.7890	65	7.578979
5	-16.7576	65	7.421815
6	-16.6328	65	7.361537
7	-16.8719	65	7.407220
8	-17.0890	65	7.406227
9	-17.0407	65	7.140904
10	-16.2982	65	7.183761
11	-16.9482	65	7.017447
12	-16.7733	65	7.005842
13	-17.1443	65	7.009007
14	-17.3441	65	6.742421
15	-17.0406	65	7.785486
16	-16.8930	65	6.965373
17	-16.9763	65	6.992816
18	-17.1430	65	6.979550
19	-17.2357	65	7.204777
20	-17.4052	65	6.948048
21	-17.6139	65	7.798715
22	-17.7056	65	6.421741
23	-17.8639	65	7.222641
24	-18.0730	65	7.271662
25	-17.9298	65	6.694088
26	-17.9874	65	6.986475
27	-17.8082	65	7.051002
28	-17.7729	65	6.929981

step	curr_energy	num_circuits	quantum_exec_time
29	-17.7836	65	6.684179
30	-17.8178	65	6.542243
31	-17.9242	65	6.703811
32	-17.9319	65	6.838773
33	-17.9267	65	6.771591
34	-18.0254	65	6.729550
35	-17.7333	65	6.830483
36	-17.7501	65	6.816209
37	-17.5711	65	6.454080
38	-17.7796	65	6.868003

```
CPU times: total: 51min 38s
Wall time: 7min 21s
```


Convergence of the expected energy
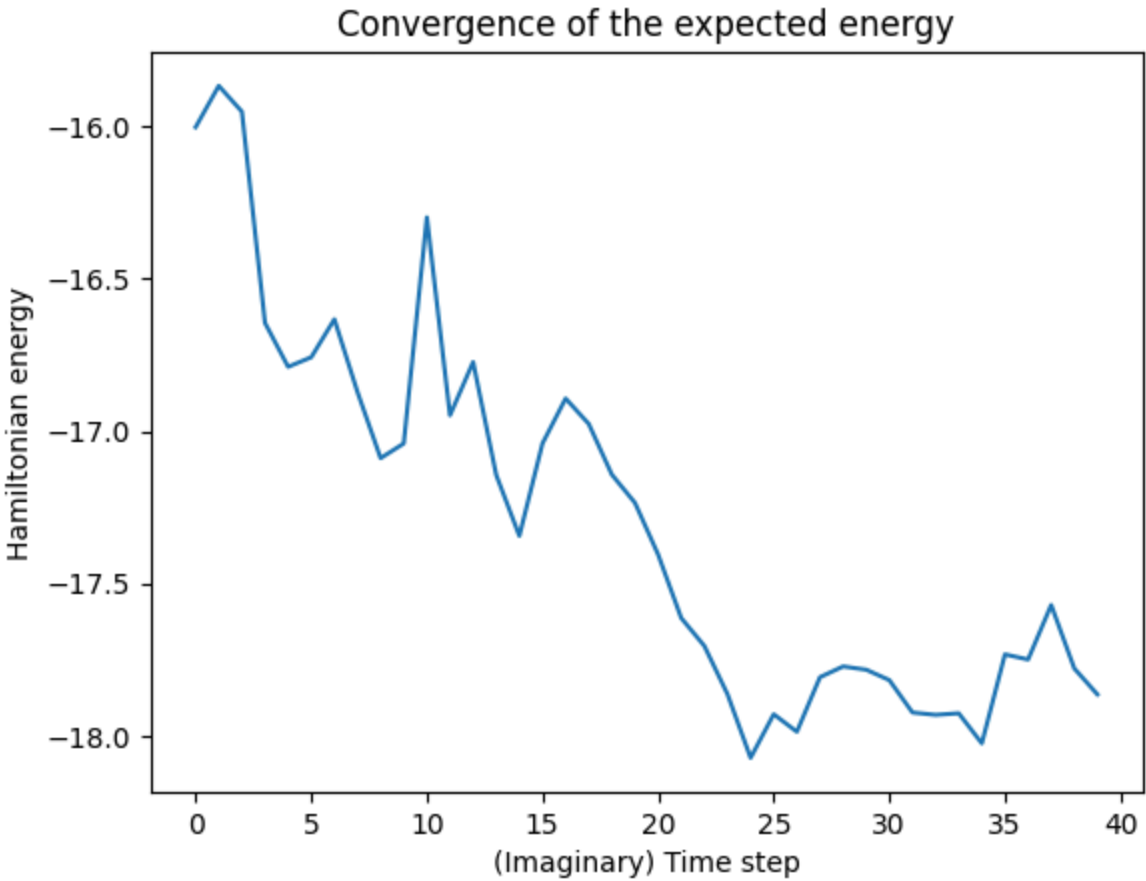
Check out your best / most frequent cut!

Following the variational quantum imaginary time evolution (vQITE) loop, we sample the quantum circuit to obtain classical bitstrings. The most frequent bitstring represents our solution, the final score though will take into account all of the right solutions...

In [141...
```python
from qiskit_aer import AerSimulator

shots = 100_000
backend = AerSimulator()
```

In [142...
```python
# Sample your optimized quantum state using Aer for the tree

optimized_state_T = ansatz_T.assign_parameters(qit_evolver_T.param_vals[-1])
optimized_state_T.measure_all()
counts_T = backend.run(optimized_state_T, shots=shots).result().get_counts()

# Find the sampled bitstring with the largest cut value
cut_vals_T = sorted(((bs, compute_cut_size(T, bs)) for bs in counts_T), key=lambda
best_bs_T = cut_vals_T[-1][0]

# Now find the most likely MaxCut solution as sampled from your optimized state
# We'll leave this part up to you!!!
most_likely_soln = ""

print(counts_T)
```

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```
In [143…   interpret_solution(T, best_bs_T)
           print("Cut value: "+str(compute_cut_size(T, best_bs_T)))
           print(T, best_bs_T)
```
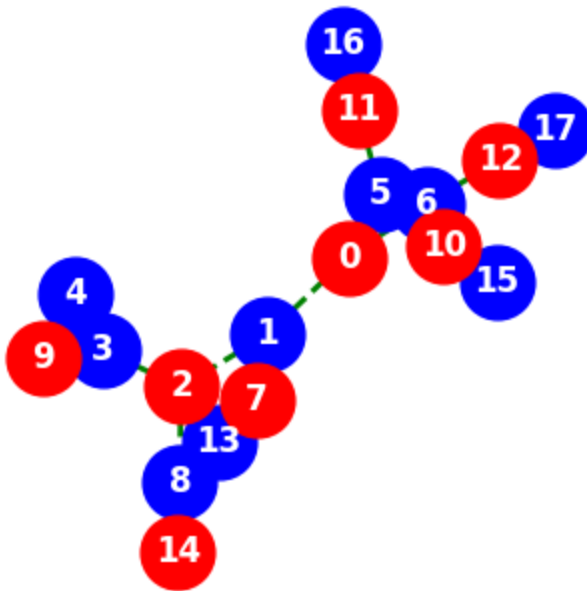


```
Cut value: 16
Graph with 18 nodes and 17 edges 101000010111101000
```

```
In [144…   # interpret the same solution, but with the whole graph instead of the tree
           interpret_solution(graph, best_bs_T)
           print("Cut value: "+str(compute_cut_size(graph, best_bs_T)))
           print(graph, best_bs_T)
```
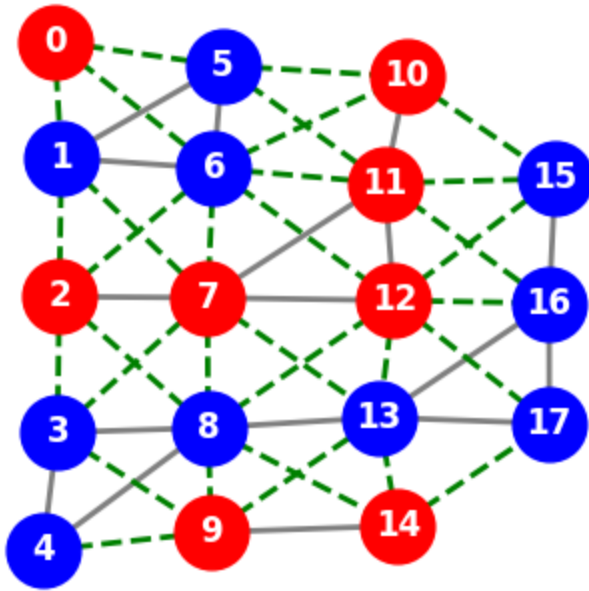
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Cut value: 32
Graph with 18 nodes and 49 edges 101000010111101000
```

In [145…

```python
# Sample your optimized quantum state using Aer for the tree

optimized_state_H = ansatz_H.assign_parameters(qit_evolver_H.param_vals[-1])
optimized_state_H.measure_all()
counts_H = backend.run(optimized_state_H, shots=shots).result().get_counts()

# Find the sampled bitstring with the largest cut value
cut_vals_H = sorted(((bs, compute_cut_size(H, bs)) for bs in counts_H), key=lambda
best_bs_H = cut_vals_H[-1][0]

# Now find the most likely MaxCut solution as sampled from your optimized state
# We'll leave this part up to you!!!

most_likely_soln = ""

print(counts_H)
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In [146…
```python
interpret_solution(H, best_bs_H)
print("Cut value: "+str(compute_cut_size(H, best_bs_H)))
print(H, best_bs_H)
```
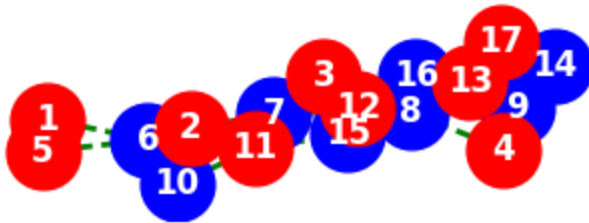


```
Cut value: 22
Graph with 18 nodes and 32 edges 011111000001110001
```

In [147…
```python
interpret_solution(graph, best_bs_H)
print("Cut value: "+str(compute_cut_size(graph, best_bs_H)))
print(graph, best_bs_H)
```
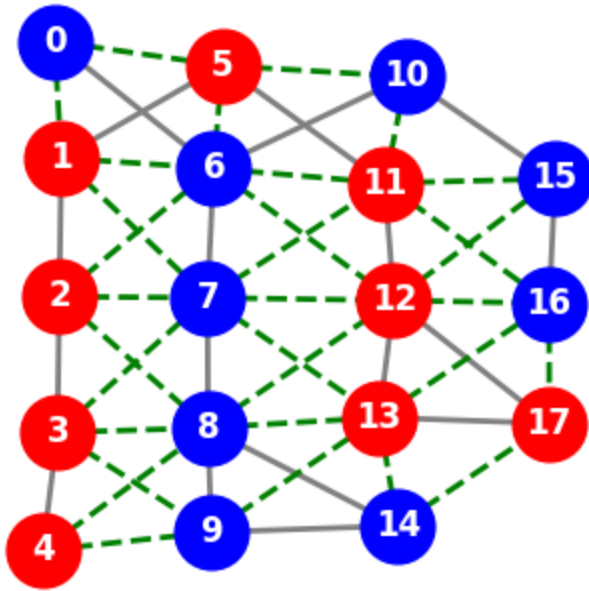
```
Cut value: 31
Graph with 18 nodes and 49 edges 011111000001110001
```

In [148…
```python
# choose the better result from best_bs_T and best_bs_H
best_bs_final = best_bs_H if compute_cut_size(graph, best_bs_H) > compute_cut_size(
final_cut_value = compute_cut_size(graph, best_bs_final)

# choose the better result ansatz from ansatz_T and ansatz_H
ansatz_final = ansatz_H if compute_cut_size(graph, best_bs_H) > compute_cut_size(gr

interpret_solution(graph, best_bs_final)
print("Cut value: "+str(final_cut_value))
print(graph, best_bs_final)
```
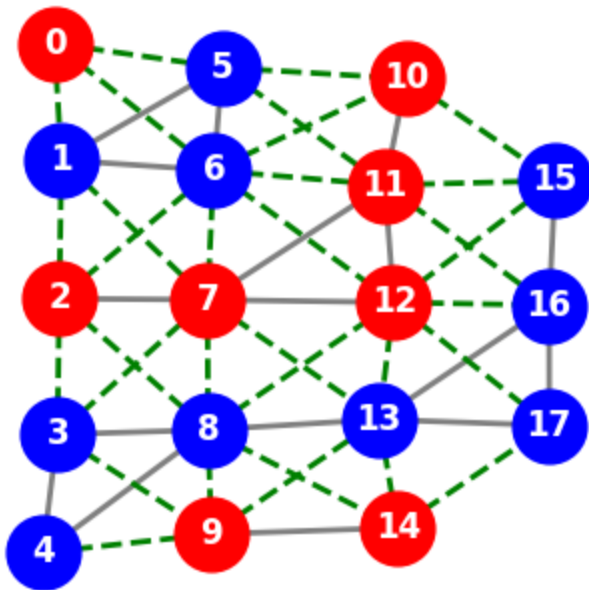


```
Cut value: 32
Graph with 18 nodes and 49 edges 101000010111101000
```

In [149...

```python
# from qiskit_aer import AerSimulator

# shots = 100_000

# # Sample your optimized quantum state using Aer
# backend = AerSimulator()
optimized_state = ansatz.assign_parameters(qit_evolver.param_vals[-1])
optimized_state.measure_all()
counts = backend.run(optimized_state, shots=shots).result().get_counts()

# Find the sampled bitstring with the largest cut value
cut_vals = sorted(((bs, compute_cut_size(graph, bs)) for bs in counts), key=lambda
best_bs = cut_vals[-1][0]

# Now find the most likely MaxCut solution as sampled from your optimized state
# We'll leave this part up to you!!!
most_likely_soln = ""

print(counts)
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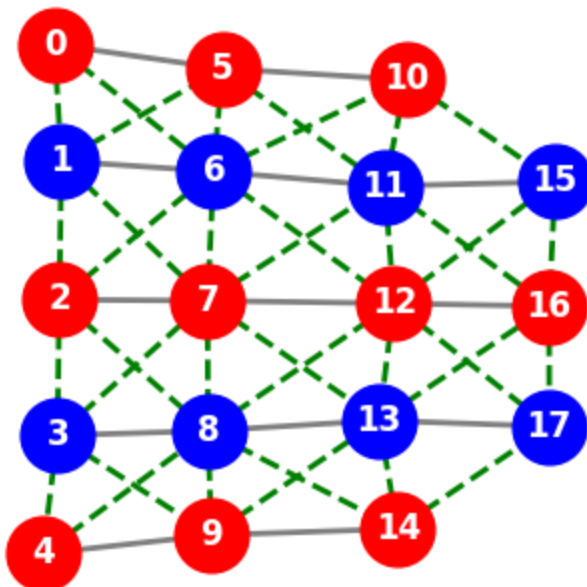1': 1, '111111000001100100': 1}

```
interpret_solution(graph, best_bs)
print("Cut value: "+str(compute_cut_size(graph, best_bs)))
print(graph, best_bs)
```

```
Cut value: 36
Graph with 18 nodes and 49 edges 101011010110101010
```

Drumroll please... the scores!

In [151...
```python
%%time
# Brute-force approach with conditional checks

verbose = False

G = graph
n = len(G.nodes())
w = np.zeros([n, n])
for i in range(n):
    for j in range(n):
        temp = G.get_edge_data(i, j, default=0)
        if temp != 0:
            w[i, j] = 1.0
if verbose:
    print(w)

best_cost_brute = 0
best_cost_balanced = 0
best_cost_connected = 0

for b in range(2**n):
    x = [int(t) for t in reversed(list(bin(b)[2:].zfill(n)))]

    # Create subgraphs based on the partition
    subgraph0 = G.subgraph([i for i, val in enumerate(x) if val == 0])
    subgraph1 = G.subgraph([i for i, val in enumerate(x) if val == 1])

    bs = "".join(str(i) for i in x)

    # Check if subgraphs are not empty
    if len(subgraph0.nodes) > 0 and len(subgraph1.nodes) > 0:
        cost = 0
        for i in range(n):
            for j in range(n):
                cost = cost + w[i, j] * x[i] * (1 - x[j])
        if best_cost_brute < cost:
            best_cost_brute = cost
            xbest_brute = x
            XS_brut = []
        if best_cost_brute == cost:
            XS_brut.append(bs)

        outstr = "case = " + str(x) + " cost = " + str(cost)

        if (len(subgraph1.nodes)-len(subgraph0.nodes))**2 <= 1:
            outstr += " balanced"
            if best_cost_balanced < cost:
                best_cost_balanced = cost
                xbest_balanced = x
```

```
                XS_balanced = []
            if best_cost_balanced == cost:
                XS_balanced.append(bs)

        if nx.is_connected(subgraph0) and nx.is_connected(subgraph1):
            outstr += " connected"
            if best_cost_connected < cost:
                best_cost_connected = cost
                xbest_connected = x
                XS_connected = []
            if best_cost_connected == cost:
                XS_connected.append(bs)
        if verbose:
            print(outstr)
```

```
CPU times: total: 45 s
Wall time: 1min 42s
```

In [152…
```
# This is classical brute force solver results:
interpret_solution(graph, xbest_brute)
print(graph, xbest_brute)
print("\nBest solution = " + str(xbest_brute) + " cost = " + str(best_cost_brute))
print(XS_brut)

interpret_solution(graph, xbest_balanced)
print(graph, xbest_balanced)
print("\nBest balanced = " + str(xbest_balanced) + " cost = " + str(best_cost_balan
print(XS_balanced)

interpret_solution(graph, xbest_connected)
print(graph, xbest_connected)
print("\nBest connected = " + str(xbest_connected) + " cost = " + str(best_cost_con
print(XS_connected)
plt.show()
```
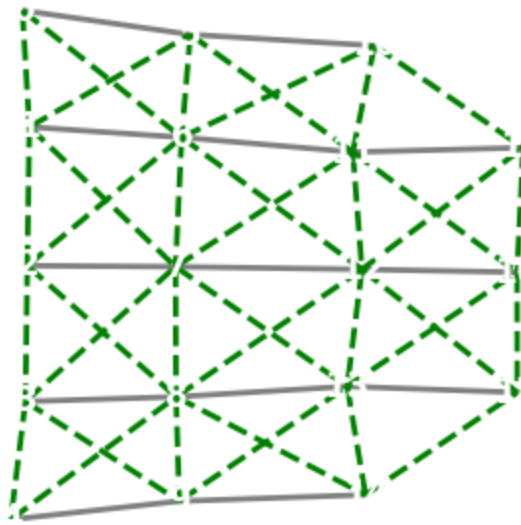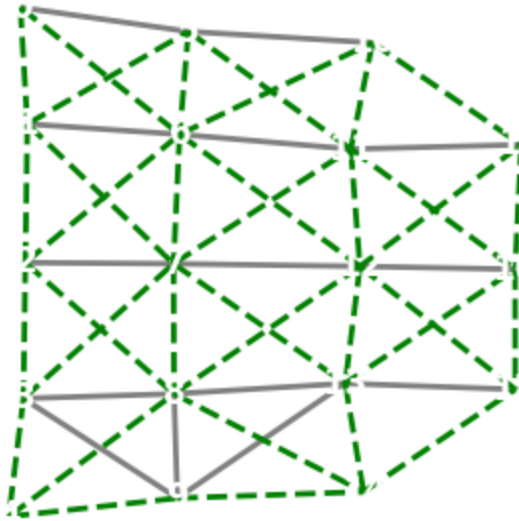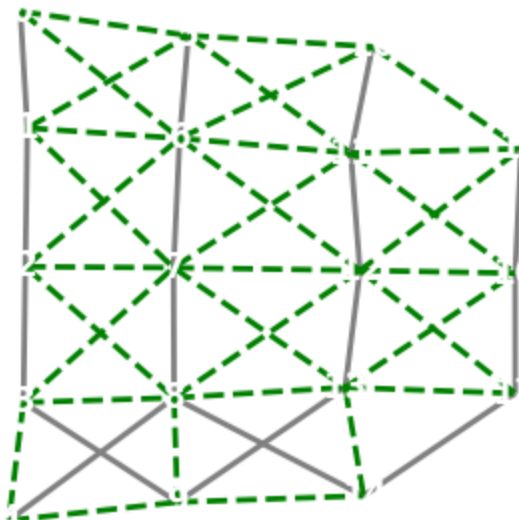
Graph with 18 nodes and 49 edges [1, 0, 1, 0, 1, 1, 0, 1, 0, 1, 1, 0, 1, 0, 1, 0, 1, 0]

Best solution = [1, 0, 1, 0, 1, 1, 0, 1, 0, 1, 1, 0, 1, 0, 1, 0, 1, 0] cost = 36.0
['101011010110101010', '010100101001010101']

Graph with 18 nodes and 49 edges [1, 0, 1, 0, 1, 1, 0, 1, 0, 0, 1, 0, 1, 0, 1, 0, 1, 0]

Best balanced = [1, 0, 1, 0, 1, 1, 0, 1, 0, 0, 1, 0, 1, 0, 1, 0, 1, 0] cost = 35.0
['101011010010101010', '101010010110101010', '101001010110101010', '001011010110101010', '110100101001010101', '010110101001010101', '010101101001010101', '010100101101010101']

Graph with 18 nodes and 49 edges [1, 1, 1, 1, 0, 0, 0, 0, 0, 1, 1, 1, 1, 1, 0, 0, 0, 0]

Best connected = [1, 1, 1, 1, 0, 0, 0, 0, 0, 1, 1, 1, 1, 1, 0, 0, 0, 0] cost = 33.0
['111100000111110000', '011111000001111000', '001111100000111100', '0101001010010100
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100001', '101010101001010101', '101011010101010101', '101011010110101101', '11000001
1111000011', '100000111110000111', '000011111000001111']

```python
# And this is how we calculate the shots counted toward scores for each class of th

sum_counts = 0
for bs in counts:
    if bs in XS_brut:
        sum_counts += counts[bs]

print(f"Pure max-cut: {sum_counts} out of {shots}")

sum_balanced_counts = 0
for bs in counts:
    if bs in XS_balanced:
        sum_balanced_counts += counts[bs]

print(f"Balanced max-cut: {sum_balanced_counts} out of {shots}")

sum_connected_counts = 0
for bs in counts:
    if bs in XS_connected:
        sum_connected_counts += counts[bs]

print(f"Connected max-cut: {sum_connected_counts} out of {shots}")
```

```
Pure max-cut: 13 out of 100000
Balanced max-cut: 48 out of 100000
Connected max-cut: 11 out of 100000
```

```python
def final_score(graph, XS_brut,counts,shots,ansatz,challenge):

    if(challenge=='base'):
        sum_counts = 0
        for bs in counts:
            if bs in XS_brut:
                sum_counts += counts[bs]
    elif(challenge=='balanced'):
        sum_balanced_counts = 0
        for bs in counts:
            if bs in XS_balanced:
                sum_balanced_counts += counts[bs]
        sum_counts = sum_balanced_counts
    elif(challenge=='connected'):
        sum_connected_counts = 0
        for bs in counts:
            if bs in XS_connected:
                sum_connected_counts += counts[bs]
        sum_counts = sum_connected_counts
```

```
    transpiled_ansatz = transpile(ansatz, basis_gates = ['cx','rz','sx','x'])
    cx_count = transpiled_ansatz.count_ops()['cx']
    score = (4*2*graph.number_of_edges())/(4*2*graph.number_of_edges() + cx_count)

    return np.round(score,5)
```

In [155…
```
print("Base score: " + str(final_score(graph,XS_brut,counts,shots,ansatz,'base')))
print("Balanced score: " + str(final_score(graph,XS_brut,counts,shots,ansatz,'balan
print("Connected score: " + str(final_score(graph,XS_brut,counts,shots,ansatz,'conn
```

Base score: 0.0001
Balanced score: 0.00038
Connected score: 9e-05

In [156…
```
# calculate our version of the score for the final solution
print("Base score: " + str(final_score(graph,XS_brut,counts,shots,ansatz_H,'base'))
print("Balanced score: " + str(final_score(graph,XS_brut,counts,shots,ansatz_H,'bal
print("Connected score: " + str(final_score(graph,XS_brut,counts,shots,ansatz_H,'co
```

Base score: 0.00011
Balanced score: 0.00041
Connected score: 9e-05

In [157…
```
# calculate our version of the score for the final solution
print("Base score: " + str(final_score(graph,XS_brut,counts,shots,ansatz_T,'base'))
print("Balanced score: " + str(final_score(graph,XS_brut,counts,shots,ansatz_T,'bal
print("Connected score: " + str(final_score(graph,XS_brut,counts,shots,ansatz_T,'co
```

Base score: 0.00012
Balanced score: 0.00044
Connected score: 0.0001

This is the main challenge: design optimal ansatz generators and Hamiltonians for the max-cut problem, subject to three specific conditions. Solutions for each condition can be submitted independently; however, a unified approach applicable to all three conditions will receive additional credit.

Submit your results

I guess this is the most important part. You probably want to report your results.

Please, follow the link: https://forms.gle/gkpSCe7HGr7QHZXQ6

Let's revisit the problem statement. **This is important!!!** We have three scoring methods to report:

1. Counts shots achieving the optimal max-cut value. Sorry, no approximation value this time.
2. Adds a balance constraint—subgraphs must have equal cardinality.
3. Requires connected subgraphs—all vertices within a subgraph must be mutually reachable.

For **in-person participants**: Prepare a presentation that explains your research and demonstrates the value of your proposed solution. You can modify any parts of the code, if you can defend your modifications during the presentation.

For **remote participants** (per Daiwei's comment in Discord channel): @everyone, just summarize a few clarifications we just made.

1. you are only suppose to change ansatz builder and hamiltonian builder function, without making any changes to the function signature. So we can do auto-grading.
2. You should submit three notebook. One for each challenge. This way you don't need a argument to specify the challenge type in the ansatz and hamiltonian builder.
3. We will push an update to the git page with all the anoucements and clarifications we did(will do) at 3pm today. ✅

Can you solve this? Good luck!

Feedback

If you have any suggestions or recommendations abou the hackathon challange, please, don't hesitatate to leave your comment here: https://iter.ly/u42um

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