VISVESVARAYA TECHNOLOGICAL UNIVERSITY

"JnanaSangama", Belgaum -590014, Karnataka.

LAB RECORD

Bio Inspired Systems (23CS5BSBIS)

Submitted by

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in partial fulfillment for the award of the degree of

BACHELOR OF ENGINEERING
in
COMPUTER SCIENCE AND ENGINEERING

B.M.S. COLLEGE OF ENGINEERING
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(Affiliated To Visvesvaraya Technological University, Belgaum)
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CERTIFICATE

This is to certify that the Lab work entitled " Bio Inspired Systems (23CS5BSBIS)" carried out by **Preetham H D(1BM23CS249),** who is bonafide student of **B.M.S. College of Engineering.** It is in partial fulfillment for the award of **Bachelor of Engineering in Computer Science and Engineering** of the Visvesvaraya Technological University, Belgaum. The Lab report has been approved as it satisfies the academic requirements of the above mentioned subject and the work prescribed for the said degree.

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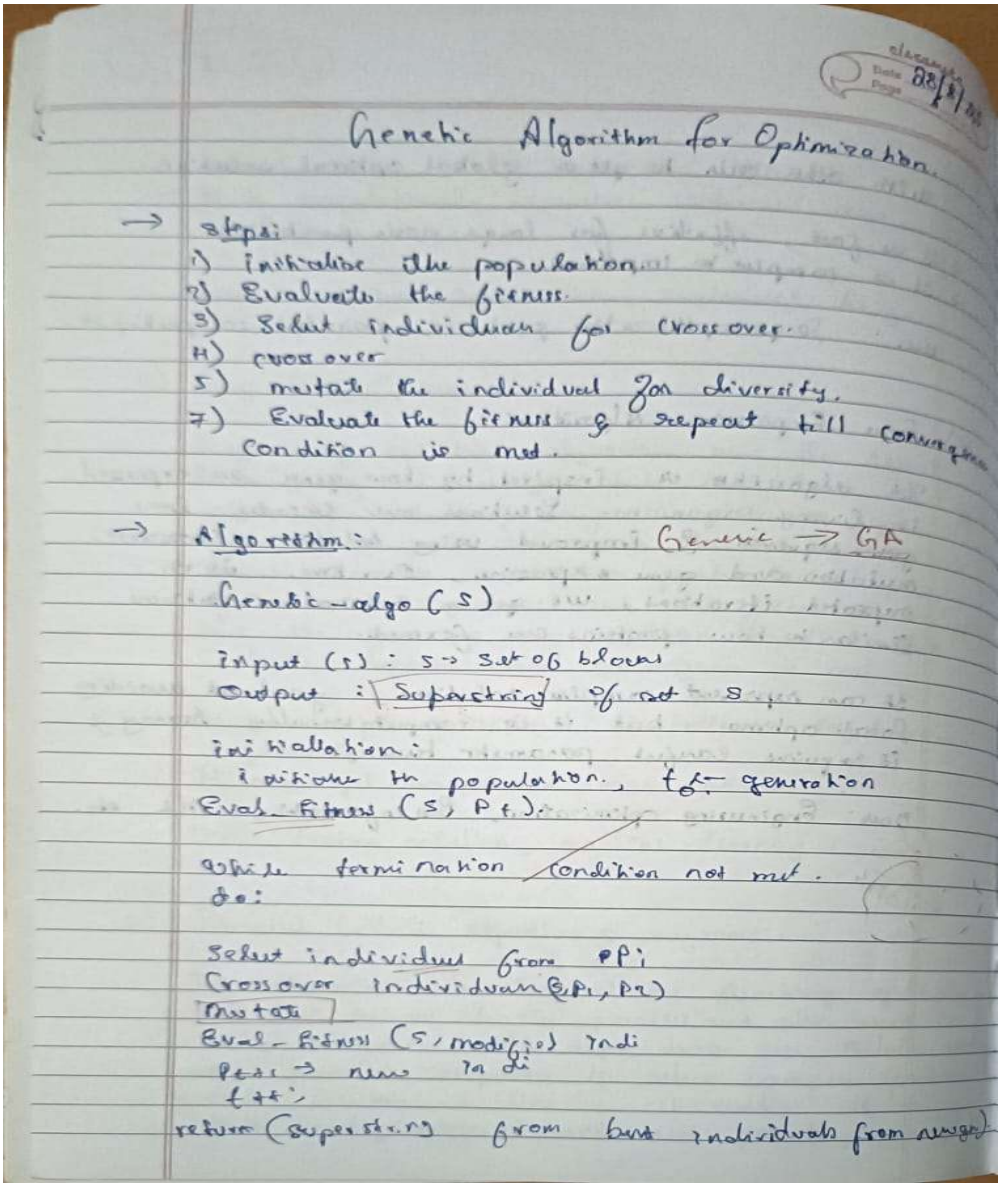
Index

Github Link: https://github.com/Preetham-HD/1BM23CS249-BIS-LAB

Program 1

Genetic Algorithm for Optimization for Neural Networks

Algorithm:



Genetic Algorithm for Optimization.

→ Steps:
1) Initialise the population.
2) Evaluate the fitness.
3) Select individuals for crossover.
4) crossover
5) mutate the individual for diversity.
7) Evaluate the fitness & repeat till convergence condition is met.

→ Algorithm: Generic → GA

Genetic-algo (S)

input (s) : S → set of bloom
Output : Superstring of set S.

initialization:
initialize the population, t_0 ← generation
Eval_fitness (S, P_t).

while termination condition not met.
do:

Select individual from P_i
Crossover individuals(P_1, P_2)
Mutate
Eval_fitness (S, modified) in P_{t+1}
P_{t+1} → new in P_i
t++;
return (superstring) from best individuals from range

mutate (s):
"" s ← target string ""
j : random.random (s);

return j;

⇒ Generic Algorithm.

→ genetic algo (n)
input: n- population size target solution & h.
Output: solution, no of generations ~~(n-typo)~~ iterations.

→ initialise ():
for i in range(N):
population[i] = generate_ini_instance ();

→ fitness ():
for i in population:
eval_fitness ();
while target function not met do:
→ selection ():
Sort the population based on the fitness.
select the individuals from the sorted population.
return p1, p2.

→ crossover ():
~~Selo~~ crossover the p1 & p2 & get a new individual with the new population.
new_popul[i] : crossover (x, y);

mutation ():
mutate the individual in new_popul[i]

→ evaluate the fitness (new-population).

return population[1], gen.;

Execute WRT - Neural N/w s.

Initialize population of N networks with random weights.
For generation = 1 to MAX_GEN:
Evaluate fitness (accuracy) of each network
Select parents based on fitness
perform crossover to create offspring
Apply mutation to offspring
Form new population (elitism + offsprings)
if best fitness >= goal:
Break
Return best neural network.

Output:

Generation 1: Best Accuracy = 0.1600 Avg Accuracy = 0.1028
Generation 2: Best Accuracy = 0.1900 Avg Accuracy: 0.1211
Generation 3: Best Accuracy: 0.1900 Avg Accuracy 0.1154
Generation 4: Best Accuracy: 0.1900 Avg Accuracy: 0.1126
Generation 5: Best Accuracy: 0.1920 Avg Accuracy: 0.118
Generation 6: Best Accuracy: 0.1920 Avg Accuracy: 0.1170
Generation 7: Best Accuracy: 0.1920 Avg Accuracy 0.1170
Generation 8: Best Accuracy: 0.1960 Avg Accuracy 0.1185
Generation 9: Best Accuracy: 0.1970 Avg Accuracy: 0.1185
Generation 10: Best Accuracy: 0.2110 Avg Accuracy: 0.1321
Final training Accuracy: 0.211

Code:

```
import numpy as np
import matplotlib.pyplot as plt
from sklearn.datasets import fetch_openml
from sklearn.model_selection import train_test_split
from sklearn.preprocessing import OneHotEncoder

# ========================
# Neural Network
# ========================
class NeuralNetwork:
    def __init__(self, input_size, hidden_size, output_size):
        self.input_size = input_size
        self.hidden_size = hidden_size
        self.output_size = output_size

    def forward(self, X, weights):
        # Decode genome (weights)
        ih_size = self.input_size * self.hidden_size
        ho_size = self.hidden_size * self.output_size

        w_input_hidden = weights[:ih_size].reshape(self.input_size, self.hidden_size)
        w_hidden_output = weights[ih_size:ih_size+ho_size].reshape(self.hidden_size, self.output_size)

        hidden = np.tanh(np.dot(X, w_input_hidden))
        output = self.softmax(np.dot(hidden, w_hidden_output))
        return output

    def softmax(self, z):
        exp = np.exp(z - np.max(z, axis=1, keepdims=True))
        return exp / exp.sum(axis=1, keepdims=True)

# ========================
# Genetic Algorithm
# ========================
class GeneticAlgorithm:
    def __init__(self, nn, pop_size=50, mutation_rate=0.05):
        self.nn = nn
        self.pop_size = pop_size
        self.mutation_rate = mutation_rate

        self.num_weights = (nn.input_size*nn.hidden_size) + (nn.hidden_size*nn.output_size)
        self.population = np.random.uniform(-1, 1, (pop_size, self.num_weights))
        self.history_best = []  # best accuracy per generation
        self.history_avg = []   # average accuracy per generation
```

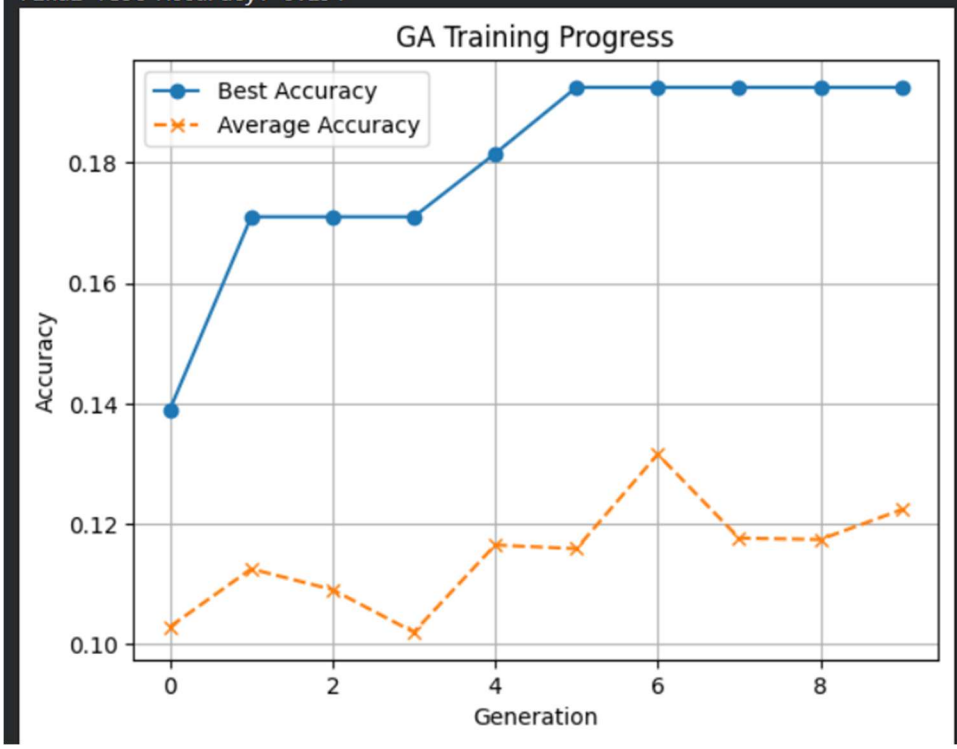
```
    def fitness(self, X, y):
        scores = []
        for individual in self.population:
            preds = self.nn.forward(X, individual)
            acc = np.mean(np.argmax(preds, axis=1) == np.argmax(y, axis=1))
            scores.append(acc)
        return np.array(scores)

    def select(self, fitness_scores):
        probs = fitness_scores / fitness_scores.sum()
        idx = np.random.choice(np.arange(self.pop_size), size=2, p=probs)
        return self.population[idx[0]], self.population[idx[1]]

    def crossover(self, parent1, parent2):
        point = np.random.randint(1, self.num_weights-1)
        child1 = np.concatenate((parent1[:point], parent2[point:]))
        child2 = np.concatenate((parent2[:point], parent1[point:]))
        return child1, child2

    def mutate(self, individual):
        for i in range(len(individual)):
            if np.random.rand() < self.mutation_rate:
                individual[i] += np.random.normal(0, 0.5)
        return individual

    def evolve(self, X, y, generations=20):
        for gen in range(generations):
            fitness_scores = self.fitness(X, y)
            new_population = []

            # Keep elite
            elite_idx = np.argmax(fitness_scores)
            new_population.append(self.population[elite_idx])

            while len(new_population) < self.pop_size:
                p1, p2 = self.select(fitness_scores)
                c1, c2 = self.crossover(p1, p2)
                c1, c2 = self.mutate(c1), self.mutate(c2)
                new_population.extend([c1, c2])

            self.population = np.array(new_population[:self.pop_size])
            best_score = np.max(fitness_scores)
            avg_score = np.mean(fitness_scores)
            self.history_best.append(best_score)
            self.history_avg.append(avg_score)
            print(f"Generation {gen+1}: Best Accuracy = {best_score:.4f}, Avg Accuracy =
{avg_score:.4f}")
```

```
        return self.population[np.argmax(self.fitness(X, y))]

    def plot_progress(self):
        plt.plot(self.history_best, marker='o', label="Best Accuracy")
        plt.plot(self.history_avg, marker='x', linestyle='--', label="Average Accuracy")
        plt.title("GA Training Progress")
        plt.xlabel("Generation")
        plt.ylabel("Accuracy")
        plt.legend()
        plt.grid(True)
        plt.show()

# ========================
# Run GA on MNIST subset
# ========================
if __name__ == "__main__":
    print("Loading MNIST (this may take a minute)...")
    X, y = fetch_openml('mnist_784', version=1, return_X_y=True)
    X = (X / 255.0).astype(np.float32)
    y = y.astype(int)

    # One-hot encode labels
    encoder = OneHotEncoder(sparse_output=False)
    y_onehot = encoder.fit_transform(y.to_numpy().reshape(-1, 1))



    # Train/test split (small subset for demo)
    X_train, X_test, y_train, y_test = train_test_split(X, y_onehot, train_size=2000, test_size=500,
stratify=y, random_state=42)

    nn = NeuralNetwork(input_size=784, hidden_size=64, output_size=10)
    ga = GeneticAlgorithm(nn, pop_size=30, mutation_rate=0.1)
    best_weights = ga.evolve(X_train, y_train, generations=10)

    # Evaluate on training set
    preds_train = nn.forward(X_train, best_weights)
    acc_train = np.mean(np.argmax(preds_train, axis=1) == np.argmax(y_train, axis=1))
    print("Final Training Accuracy:", acc_train)

    # Evaluate on unseen test set
    preds_test = nn.forward(X_test, best_weights)
    acc_test = np.mean(np.argmax(preds_test, axis=1) == np.argmax(y_test, axis=1))
    print("Final Test Accuracy:", acc_test)

    # Plot GA progress (best vs avg accuracy)
```

ga.plot_progress()

Output:

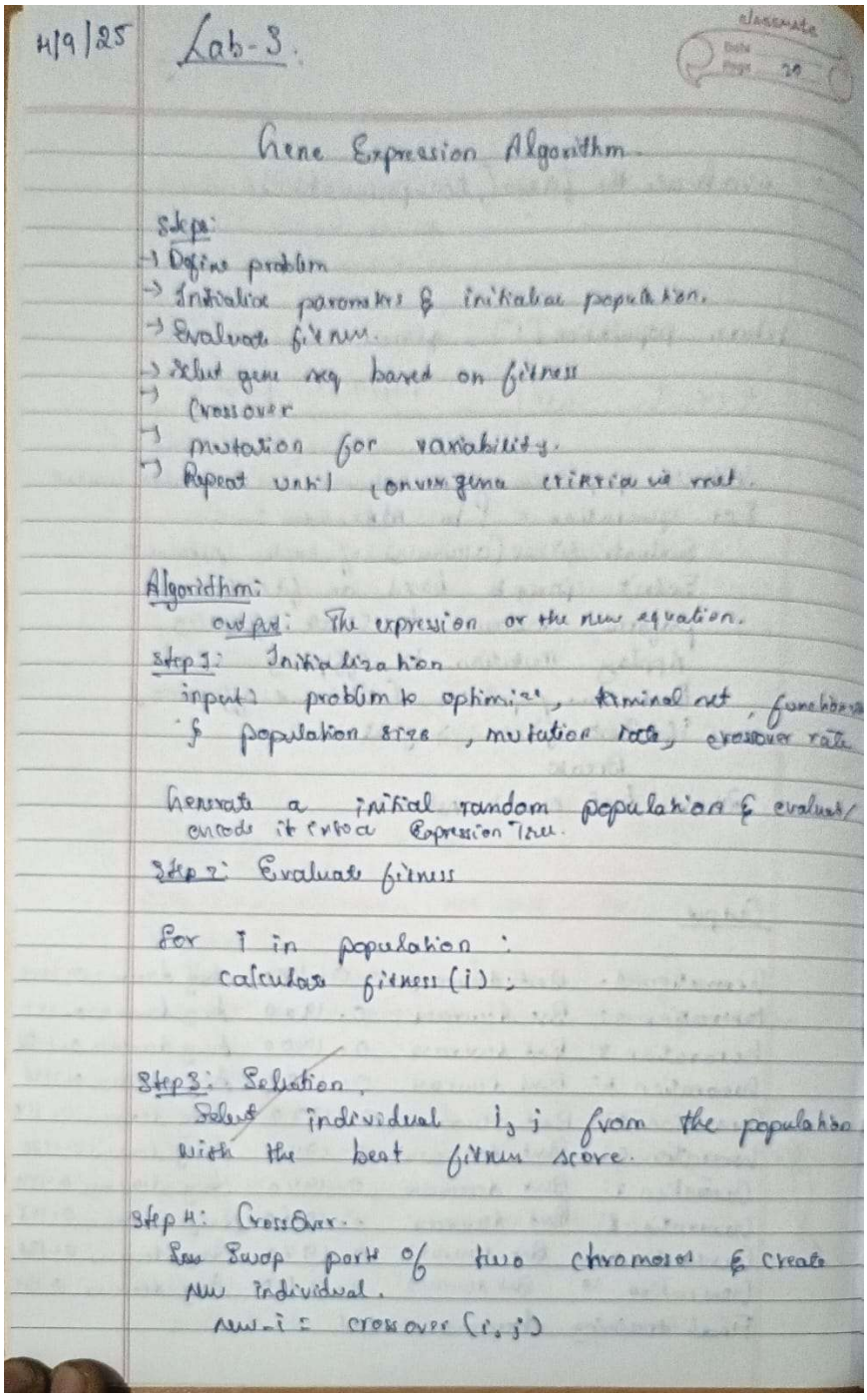
```
Generation 9: Best Accuracy = 0.1925, Avg Accuracy = 0.1174
Generation 10: Best Accuracy = 0.1925, Avg Accuracy = 0.1224
Final Training Accuracy: 0.1925
Final Test Accuracy: 0.194
```



Program 2:

Gene Expression Algorithm for Neural Network

Algorithm:



4/9/25 Lab-3.

Gene Expression Algorithm.

Steps:
→ Define problem
→ Initialize parameters & initial population.
→ Evaluate fitness.
→ Select gen req based on fitness
→ Crossover
→ mutation for variability.
→ Repeat until convergence criteria is met.

Algorithm:
output: The expression or the new equation.
Step 1: Initialization
input: problem to optimize, terminal set, functions & population size, mutation rate, crossover rate.
Generate a initial random population & evaluate/ encode it into a Expression Tree.
Step 2: Evaluate fitness
For I in population :
calculate fitness (i) :
Step 3: Selection.
Select individual i, j from the population with the best fitness score.
Step 4: CrossOver.
Swap parts of two chromosomes & create new individual.
new_i = crossover (i, j)

Step 4: Mutation.

randomly change the value in the new individual.

New_individual[k] = random value;

~~move a substring to another position~~
transpose and inversion of new_individual.

Step5: form new population.

Decode the chromosomes into the population.

New population = new_individual + population[:pop_size]

Step6: Repeat to step 2 to step 5 until the convergence criteria is met.

NN → (GE) → Diff: data

Genetic Algo:

Gen 1, Best Acc = 0.[illegible], Avg Acc = 0.101
Gen 2, Best Acc = 0.201, Avg Acc = 0.101
Gen 3, Best Acc = 0.201, Avg Acc = 0.103
Gen 4, Best Acc = 0.201, Avg Acc = 0.102.
:
Gen 7, Best Acc = 0.203, Avg Acc = 0.101
:
Gen 17, Best Acc = 0.206 Avg Acc = 0.101.
:
Gen 37, Best Acc = 0.209, Avg Acc = 0.105

Code:

```
import numpy as np
import random
import matplotlib.pyplot as plt
from sklearn.datasets import fetch_openml
from sklearn.model_selection import train_test_split
from sklearn.preprocessing import StandardScaler
from sklearn.metrics import accuracy_score

# ============================================================
# 1. Load MNIST subset
# ============================================================
mnist = fetch_openml('mnist_784', version=1)
X = mnist.data.astype(np.float32)[:1000] # use 1000 samples for speed
y = mnist.target.astype(int)[:1000]

scaler = StandardScaler()
X = scaler.fit_transform(X)
X_train, X_test, y_train, y_test = train_test_split(X, y, test_size=0.2, random_state=42)

# ============================================================
# 2. GA + Neural Network
# ============================================================

def softmax(x):
    e = np.exp(x - np.max(x))
    return e / e.sum()

def forward_pass(weights, X, input_size, hidden_size, output_size):
    # unpack weights
    ih_size = input_size * hidden_size
    ho_size = hidden_size * output_size
    w1 = weights[:ih_size].reshape(input_size, hidden_size)
    w2 = weights[ih_size:ih_size+ho_size].reshape(hidden_size, output_size)
    b1 = weights[ih_size+ho_size:ih_size+ho_size+hidden_size]
    b2 = weights[ih_size+ho_size+hidden_size:]
    # forward
    h = np.tanh(X @ w1 + b1)
    o = np.array([softmax(h[i] @ w2 + b2) for i in range(X.shape[0])])
    return o

def accuracy_nn(weights, X, y, input_size, hidden_size, output_size):
    preds = forward_pass(weights, X, input_size, hidden_size, output_size)
    return np.mean(np.argmax(preds, axis=1) == y)
```

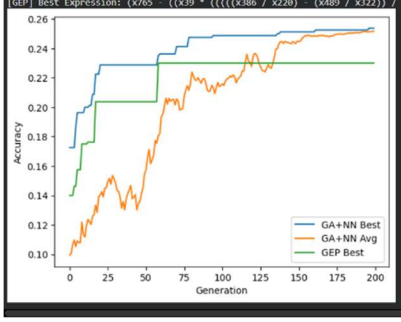
```
def evolve_nn(X_train, y_train, X_test, y_test,
              input_size=784, hidden_size=32, output_size=10,
              pop_size=30, generations=50, mutation_rate=0.1):

    genome_length = input_size*hidden_size + hidden_size*output_size + hidden_size + output_size
    population = [np.random.randn(genome_length) for _ in range(pop_size)]

    best_accs, avg_accs = [], []

    for gen in range(generations):
        scores = [accuracy_nn(ind, X_train, y_train, input_size, hidden_size, output_size) for ind in
population]
        best_idx = np.argmax(scores)
        best_acc, best_ind = scores[best_idx], population[best_idx]
        print(f"[GA+NN] Gen {gen+1}, Best Acc = {best_acc:.3f}, Avg Acc = {np.mean(scores):.3f}")
        best_accs.append(best_acc)
        avg_accs.append(np.mean(scores))

        # next population
        new_pop = [best_ind] # elitism
        while len(new_pop) < pop_size:
            parents = random.sample(population, 2)
            cross_point = random.randint(0, genome_length-1)
            child = np.concatenate([parents[0][:cross_point], parents[1][cross_point:]])
            if random.random() < mutation_rate:
                child[random.randint(0, genome_length-1)] += np.random.randn()
            new_pop.append(child)
        population = new_pop

    final_test_acc = accuracy_nn(best_ind, X_test, y_test, input_size, hidden_size, output_size)
    print("[GA+NN] Final Test Accuracy:", final_test_acc)

    return best_accs, avg_accs

# ============================================================
# 3. Mini GEP (expression trees)
# ============================================================

def add(a, b): return a + b
def sub(a, b): return a - b
def mul(a, b): return a * b
def safe_div(a, b): return a / b if b != 0 else a

FUNCTIONS = [add, sub, mul, safe_div]

def random_expression(num_features, depth=3):
    if depth == 0 or random.random() < 0.3:
```

```
        return ("x", random.randint(0, num_features-1))
    func = random.choice(FUNCTIONS)
    return (func, random_expression(num_features, depth-1), random_expression(num_features,
depth-1))

def eval_expr(expr, sample):
    if expr[0] == "x":
        return sample[expr[1]]
    func, left, right = expr
    return func(eval_expr(left, sample), eval_expr(right, sample))

def fitness(expr, X, y):
    preds = []
    for row in X:
        val = eval_expr(expr, row)
        preds.append(int(val) % 10)
    return accuracy_score(y, preds)

def mutate(expr, num_features):
    if random.random() < 0.2:
        return random_expression(num_features)
    if expr[0] == "x":
        return ("x", random.randint(0, num_features-1))
    func, left, right = expr
    return (func, mutate(left, num_features), mutate(right, num_features))

def crossover(e1, e2):
    return random.choice([e1, e2]) # simple crossover

# ---- Pretty print expression ----
def expr_to_str(expr):
    if expr[0] == "x":
        return f"x{expr[1]}"
    func, left, right = expr
    func_name = {add:"+", sub:"-", mul:"*", safe_div:"/"}[func]
    return f"({expr_to_str(left)} {func_name} {expr_to_str(right)})"

def evolve_gep(X_train, y_train, X_test, y_test, pop_size=20, generations=50):
    population = [random_expression(X_train.shape[1]) for _ in range(pop_size)]
    best_accs = []
    best_expr = None

    for gen in range(generations):
        scored = [(fitness(expr, X_train, y_train), expr) for expr in population]
        scored.sort(key=lambda x: x[0], reverse=True)
        best_fit, best_expr = scored[0]
        best_accs.append(best_fit)
```

```
        print(f"[GEP] Gen {gen+1}, Best Acc = {best_fit:.3f}")

        # next population
        new_pop = [best_expr]
        while len(new_pop) < pop_size:
            parent = random.choice(scored[:5])[1]
            if random.random() < 0.5:
                child = mutate(parent, X_train.shape[1])
            else:
                mate = random.choice(scored[:5])[1]
                child = crossover(parent, mate)
            new_pop.append(child)
        population = new_pop

    final_test_acc = fitness(best_expr, X_test, y_test)
    print("[GEP] Final Test Accuracy:", final_test_acc)
    print("[GEP] Best Expression:", expr_to_str(best_expr))

    return best_accs

# ============================================================
# 4. Run both and compare
# ============================================================

ga_best, ga_avg = evolve_nn(X_train, y_train, X_test, y_test, generations=200)
gep_best = evolve_gep(X_train, y_train, X_test, y_test, generations=200)

# Plot comparison
plt.plot(ga_best, label="GA+NN Best")
plt.plot(ga_avg, label="GA+NN Avg")
plt.plot(gep_best, label="GEP Best")
plt.xlabel("Generation")
plt.ylabel("Accuracy")
plt.legend()
plt.show()
```

Output:

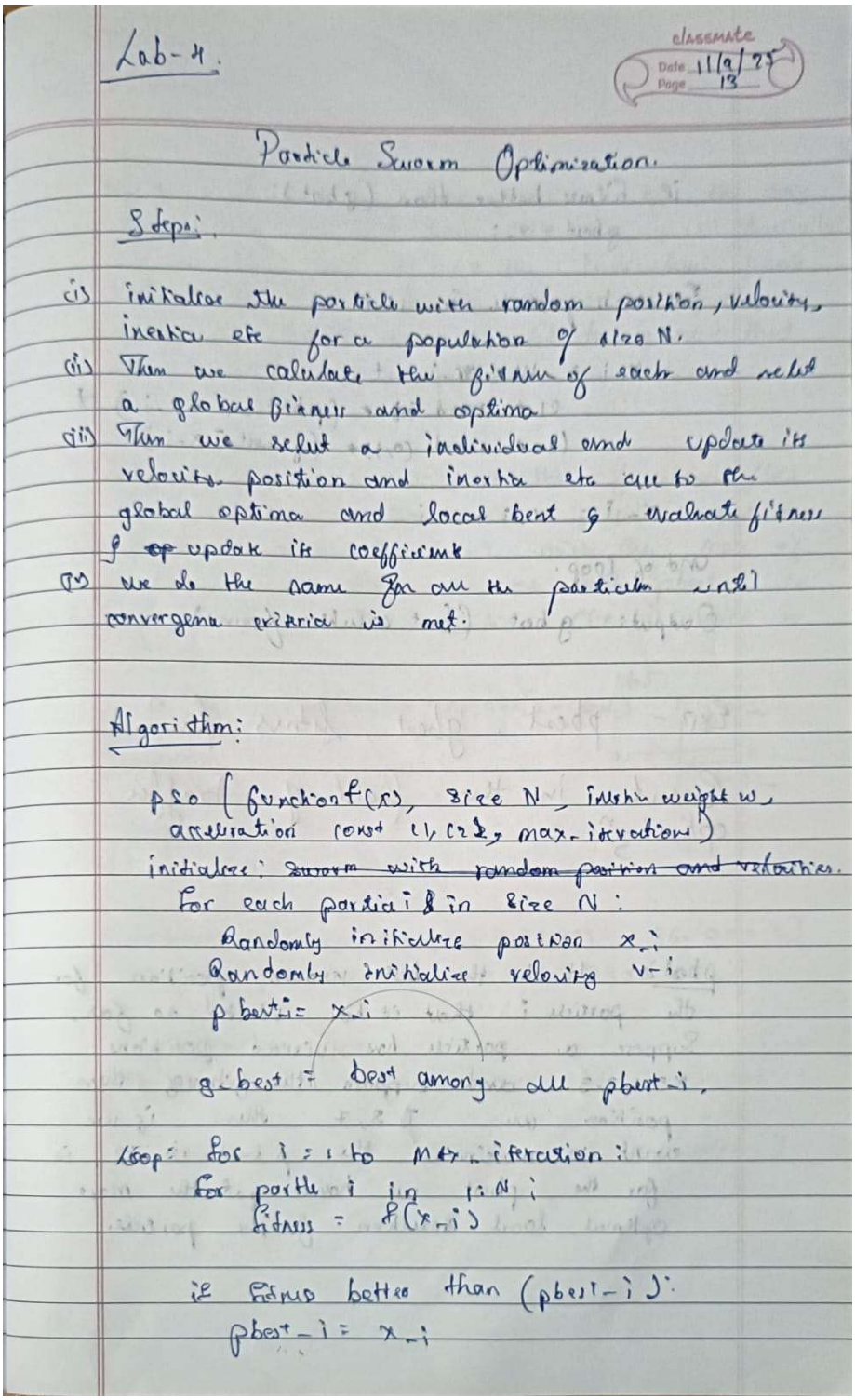
```
[GEP] Gen 180, Best Acc = 0.230
[GEP] Gen 181, Best Acc = 0.230
[GEP] Gen 182, Best Acc = 0.230
[GEP] Gen 183, Best Acc = 0.230
[GEP] Gen 184, Best Acc = 0.230
[GEP] Gen 185, Best Acc = 0.230
[GEP] Gen 186, Best Acc = 0.230
[GEP] Gen 187, Best Acc = 0.230
[GEP] Gen 188, Best Acc = 0.230
[GEP] Gen 189, Best Acc = 0.230
[GEP] Gen 190, Best Acc = 0.230
[GEP] Gen 191, Best Acc = 0.230
[GEP] Gen 192, Best Acc = 0.230
[GEP] Gen 193, Best Acc = 0.230
[GEP] Gen 194, Best Acc = 0.230
[GEP] Gen 195, Best Acc = 0.230
[GEP] Gen 196, Best Acc = 0.230
[GEP] Gen 197, Best Acc = 0.230
[GEP] Gen 198, Best Acc = 0.230
[GEP] Gen 199, Best Acc = 0.230
[GEP] Gen 200, Best Acc = 0.230
[GEP] Final Test Accuracy: 0.195
[GEP] Best Expression: (x765 - ((x39 * (((((x386 / x220) - (x489 / x322)) / ((x277 - x570) - (x278 * x458))) - ((x387 * (x324 - x187)) - ((x373 / x266) / x617))) + (((x175 * x203) * (x211 * x599))
```



Program 3:

Particle Swarm Optimization for Traffic Optimization

Algorithm:



Lab-4.

classmate
Date 11/9/25
Page 13

Particle Swarm Optimization.

Steps:

(i) initialise the particle with random position, velocity, inertia etc for a population of size N.
(ii) Then we calculate the fitness of each and select a global finest and optima
(iii) Then we select a individual and update its velocity position and inertia etc all to the global optima and local best & evaluate fitness & ~~op~~ update its coefficient
(iv) we do the same for all the particles until convergence criteria is met.

Algorithm:

pso (function f(x), size N, inertia weight w, acceleration const c1, c2, max_iteration)
initialise: ~~swarm with random position and velocities.~~
for each particle i in size N:
Randomly initialize position x_i
Randomly initialize velocity v_i
p best_i = x_i

g_best = best among all pbest_i.

Loop: for i = 1 to max_iteration:
for particle i in 1:N:
fitness = f(x_i)

if fitness better than (pbest_i):
pbest_i = x_i

Code:

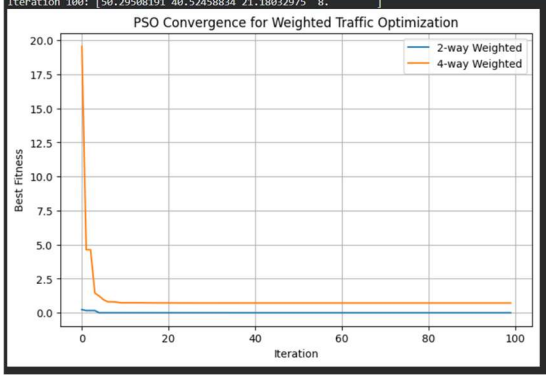
```
import numpy as np
import matplotlib.pyplot as plt

# ----------------------------
# Setup
# ----------------------------
CYCLE_TIME = 120

# Weighted Fitness Functions
def fitness_two_weighted(x, weights=[0.7, 0.3]):
    """2-way: Weighted imbalance penalty (heavier traffic on NS)."""
    t_ns, t_ew = x
    ideal = np.array([CYCLE_TIME * 0.7, CYCLE_TIME * 0.3])
    wait = np.sum(weights * np.abs(x - ideal) ** 1.5)
    return wait

def fitness_four_weighted(x, weights=[0.4, 0.3, 0.2, 0.1]):
    """4-way: Weighted imbalance penalty (heavier traffic on NS straight)."""
    ideal = np.array([50, 40, 20, 10]) # based on demand
    wait = np.sum(weights * np.abs(x - ideal) ** 1.5)
    return wait


# ----------------------------
# Generic PSO Implementation
# ----------------------------
def PSO(fitness_func, dim, num_particles=20, max_iter=100,
        w=0.7, c1=1.5, c2=1.5, min_time=8):

    # Initialize random particles
    particles = np.random.rand(num_particles, dim) * CYCLE_TIME
    particles = np.array([p / sum(p) * CYCLE_TIME for p in particles])
    velocities = np.random.randn(num_particles, dim)

    # Initialize bests
    pbest_positions = particles.copy()
    pbest_scores = np.array([fitness_func(p) for p in particles])
    gbest_index = np.argmin(pbest_scores)
    gbest_position = pbest_positions[gbest_index].copy()
```

```
gbest_score = pbest_scores[gbest_index]

convergence = []
best_positions_history = [] # Store best positions at each iteration

for _ in range(max_iter):
    for i in range(num_particles):
        score = fitness_func(particles[i])

        if score < pbest_scores[i]:
            pbest_scores[i] = score
            pbest_positions[i] = particles[i].copy()

        if score < gbest_score:
            gbest_score = score
            gbest_position = particles[i].copy()

    for i in range(num_particles):
        r1, r2 = np.random.rand(), np.random.rand()
        velocities[i] = (
            w * velocities[i]
            + c1 * r1 * (pbest_positions[i] - particles[i])
            + c2 * r2 * (gbest_position - particles[i])
        )
        particles[i] += velocities[i]

        # Normalize to cycle time
        total = np.sum(particles[i])
        particles[i] = particles[i] / total * CYCLE_TIME

        # Clip min green time
        particles[i] = np.clip(particles[i], min_time, CYCLE_TIME - min_time)
        total = np.sum(particles[i])
        particles[i] = particles[i] / total * CYCLE_TIME

    convergence.append(gbest_score)
    best_positions_history.append(gbest_position.copy())

return gbest_position, gbest_score, convergence, best_positions_history
```

```
# ----------------------------
# Run PSO for 2-way intersection (weighted)
# ----------------------------
best_two, score_two, conv_two, history_two = PSO(fitness_two_weighted, dim=2)
print("=== 2-Way Weighted Traffic Optimization ===")
print("Optimal Signal Timings:", best_two)
print("Best Fitness (waiting cost):", score_two)
print("\nSignal Timings History (2-way):")
for i, pos in enumerate(history_two):
    print(f"Iteration {i+1}: {pos}")


# ----------------------------
# Run PSO for 4-way intersection (weighted)
# ----------------------------
best_four, score_four, conv_four, history_four = PSO(fitness_four_weighted, dim=4)
print("\n=== 4-Way Weighted Traffic Optimization ===")
print("Optimal Signal Timings:", best_four)
print("Best Fitness (waiting cost):", score_four)
print("\nSignal Timings History (4-way):")
for i, pos in enumerate(history_four):
    print(f"Iteration {i+1}: {pos}")


# ----------------------------
# Plot convergence
# ----------------------------
plt.figure(figsize=(8,5))
plt.plot(conv_two, label="2-way Weighted")
plt.plot(conv_four, label="4-way Weighted")
plt.xlabel("Iteration")
plt.ylabel("Best Fitness")
plt.title("PSO Convergence for Weighted Traffic Optimization")
plt.legend()
plt.grid(True)
plt.show()
```

Output:

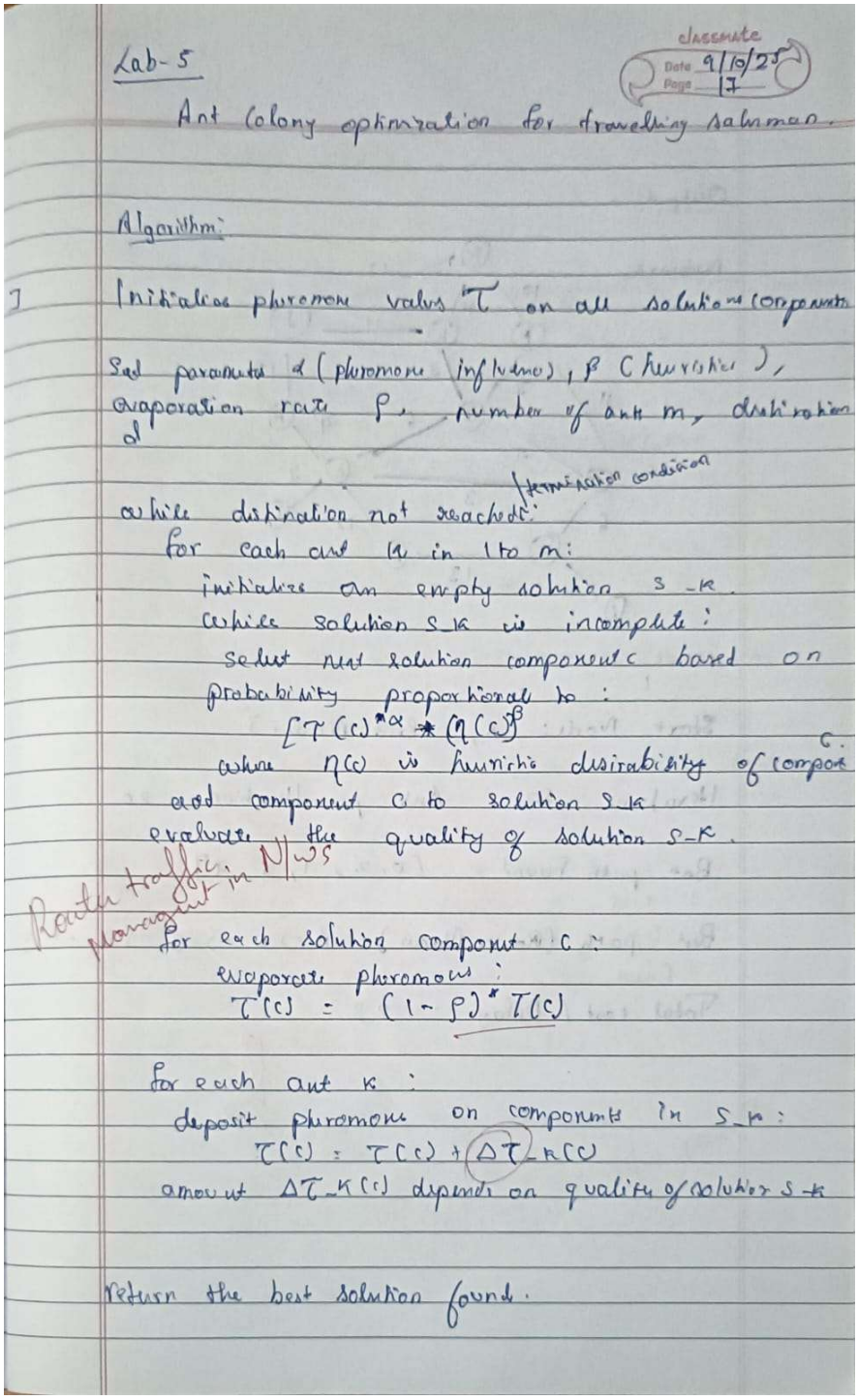
```
Iteration 79: [50.29502899 40.52451952 21.1804515   8.        ]
Iteration 80: [50.29505333 40.52461114 21.18033553  8.        ]
Iteration 81: [50.29505333 40.52461114 21.18033553  8.        ]
Iteration 82: [50.29508088 40.52457612 21.180343    8.        ]
Iteration 83: [50.29508088 40.52457612 21.180343    8.        ]
Iteration 84: [50.29508088 40.52457612 21.180343    8.        ]
Iteration 85: [50.29508088 40.52457612 21.180343    8.        ]
Iteration 86: [50.2950826  40.52457752 21.18033988  8.        ]
Iteration 87: [50.2950826  40.52457752 21.18033988  8.        ]
Iteration 88: [50.29508727 40.52458134 21.18033139  8.        ]
Iteration 89: [50.29508727 40.52458134 21.18033139  8.        ]
Iteration 90: [50.29508608 40.52458037 21.18033355  8.        ]
Iteration 91: [50.29508608 40.52458037 21.18033355  8.        ]
Iteration 92: [50.29508632 40.52458057 21.18033312  8.        ]
Iteration 93: [50.29508632 40.52458057 21.18033312  8.        ]
Iteration 94: [50.2950828  40.52458485 21.18033234  8.        ]
Iteration 95: [50.2950828  40.52458485 21.18033234  8.        ]
Iteration 96: [50.2950828  40.52458485 21.18033234  8.        ]
Iteration 97: [50.29508555 40.52458678 21.18032767  8.        ]
Iteration 98: [50.29508341 40.52458769 21.1803289   8.        ]
Iteration 99: [50.29508191 40.52458834 21.18032975  8.        ]
Iteration 100: [50.29508191 40.52458834 21.18032975  8.        ]
```



Program 4:

Ant colony Optimization for Router traffic management

Algorithm:



Lab-5

Ant Colony optimization for travelling salesman.

Algorithm:

Initialize pheromone value τ on all solution components

Set parameter α (pheromone influence), β (heuristic), evaporation rate ρ, number of ants m, destination d

while destination not reached: (termination condition)

for each ant k in 1 to m:

initialize an empty solution S_k.

while solution S_k is incomplete:

select next solution component c based on probability proportional to:

$[\tau(c)]^{\alpha} * (\eta(c))^{\beta}$

where $\eta(c)$ is heuristic desirability of component c.

add component c to solution S_k

evaluate the quality of solution S_k.

Router traffic management in NWS

for each solution component c:

evaporate pheromone:

$\tau(c) = (1 - \rho) * \tau(c)$

for each ant k:

deposit pheromone on components in S_k:

$\tau(c) = \tau(c) + \Delta\tau_k(c)$

amount $\Delta\tau_k(c)$ depends on quality of solution S_k

return the best solution found.

Code:

```
import numpy as np
import random

class ACO_Router:

    def __init__(self, cost_matrix, n_ants=10, n_iterations=100, alpha=1.0, beta=5.0, rho=0.5, Q=1.0):

        self.cost_matrix = np.array(cost_matrix)
        self.n_nodes = self.cost_matrix.shape[0]


        self.n_ants = n_ants # no of ants
        self.n_iterations = n_iterations #no of cycles
        self.alpha = alpha # Pheromone
        self.beta = beta # Heuristic
        self.rho = rho # Pheromone evaporation rate
        self.Q = Q # Pheromone deposit constant


        self.pheromone = np.ones((self.n_nodes, self.n_nodes)) / self.n_nodes


        self.best_path = None
        self.best_cost = np.inf

    def _get_heuristic(self, i, j):
        return 1.0 / (self.cost_matrix[i, j] + 1e-9)

    def _choose_next_node(self, current_node, visited):
        unvisited = [j for j in range(self.n_nodes) if j not in visited and self.cost_matrix[current_node, j]
> 0]

        if not unvisited:
            return None


        probabilities = []
        for j in unvisited:
            tau = self.pheromone[current_node, j] # Pheromone
```

```
            eta = self._get_heuristic(current_node, j) # Heuristic


            probabilities.append((tau ** self.alpha) * (eta ** self.beta))


        total_prob = sum(probabilities)
        if total_prob == 0:

            return random.choice(unvisited)

        normalized_probs = [p / total_prob for p in probabilities]


        next_node = random.choices(unvisited, weights=normalized_probs, k=1)[0]
        return next_node

    def _run_ant(self, start_node, end_node):

        path = [start_node]
        current_node = start_node
        path_cost = 0

        while current_node != end_node:
            next_node = self._choose_next_node(current_node, path)

            if next_node is None:

                return None, np.inf

            path_cost += self.cost_matrix[current_node, next_node]
            path.append(next_node)
            current_node = next_node


            if len(path) > self.n_nodes:
                return None, np.inf

        return path, path_cost

    def _update_pheromone(self, ant_paths):
```

```
        self.pheromone *= (1 - self.rho)


        for path, cost in ant_paths:
            if path is not None and cost < np.inf:
                deposit = self.Q / cost
                for i in range(len(path) - 1):
                    start, end = path[i], path[i+1]
                    self.pheromone[start, end] += deposit

    def find_shortest_path(self, start_node, end_node):
        for iteration in range(self.n_iterations):
            ant_paths = []

            for _ in range(self.n_ants):
                path, cost = self._run_ant(start_node, end_node)
                ant_paths.append((path, cost))

                if cost < self.best_cost:
                    self.best_cost = cost
                    self.best_path = path

            self._update_pheromone(ant_paths)

        return self.best_path, self.best_cost

COST_MATRIX = [
    [ 0, 7, 3, 0, 6, 11, 0, 0, 0, 0, 0, 0],
   [ 7, 0, 6, 0, 0, 7, 3, 0, 0, 0, 0, 0],
    [ 3, 6, 0, 12, 0, 0, 0, 9, 7, 0, 0, 0],
    [ 0, 0, 12, 0, 13, 0, 0, 0, 0, 0, 0, 0],
    [ 6, 0, 0, 13, 0, 0, 0, 0, 0, 0, 0, 11],
    [11, 7, 0, 0, 0, 0, 0, 0, 0, 0, 12, 0],
    [ 0, 3, 0, 0, 0, 0, 0, 0, 0, 11, 11, 0],
    [ 0, 0, 9, 0, 0, 0, 0, 0, 0, 18, 0, 0],
    [ 0, 0, 7, 0, 0, 0, 0, 0, 0, 0, 0, 0],
    [ 0, 0, 0, 0, 0, 0, 11, 18, 0, 0, 13, 0],
    [ 0, 0, 0, 0, 0, 12, 11, 0, 0, 13, 0, 0],
    [ 0, 0, 0, 0, 0, 11, 0, 0, 0, 0, 0, 0]
]
```

```
START_NODE = 0
END_NODE = 9

aco = ACO_Router(
    cost_matrix=COST_MATRIX,
    n_ants=20,
    n_iterations=50,
    alpha=1.0,
    beta=5.0,
    rho=0.1,
    Q=10.0
)

shortest_path, cost = aco.find_shortest_path(START_NODE, END_NODE)


node_map = {0: 'A', 1: 'B', 2: 'C', 3: 'D', 4: 'E',5: 'F', 6: 'G', 7: 'H', 8: 'I', 9: 'J', 10: 'K'}
path_names = [node_map[n] for n in shortest_path] if shortest_path else "None"

print("--- ACO Router Traffic Management Simulation ---")
print(f"Start Node: {node_map[START_NODE]}, End Node: {node_map[END_NODE]}")
print(f"Iterations: {aco.n_iterations}, Ants per Iteration: {aco.n_ants}\n")

if shortest_path:
    print(f"Best Path Found (Node Indices): {shortest_path}")
    print(f"Best Path (Router Names): {' -> '.join(path_names)}")
    print(f"Total Cost/Delay: {cost}")
else:
    print("No path found.")
```

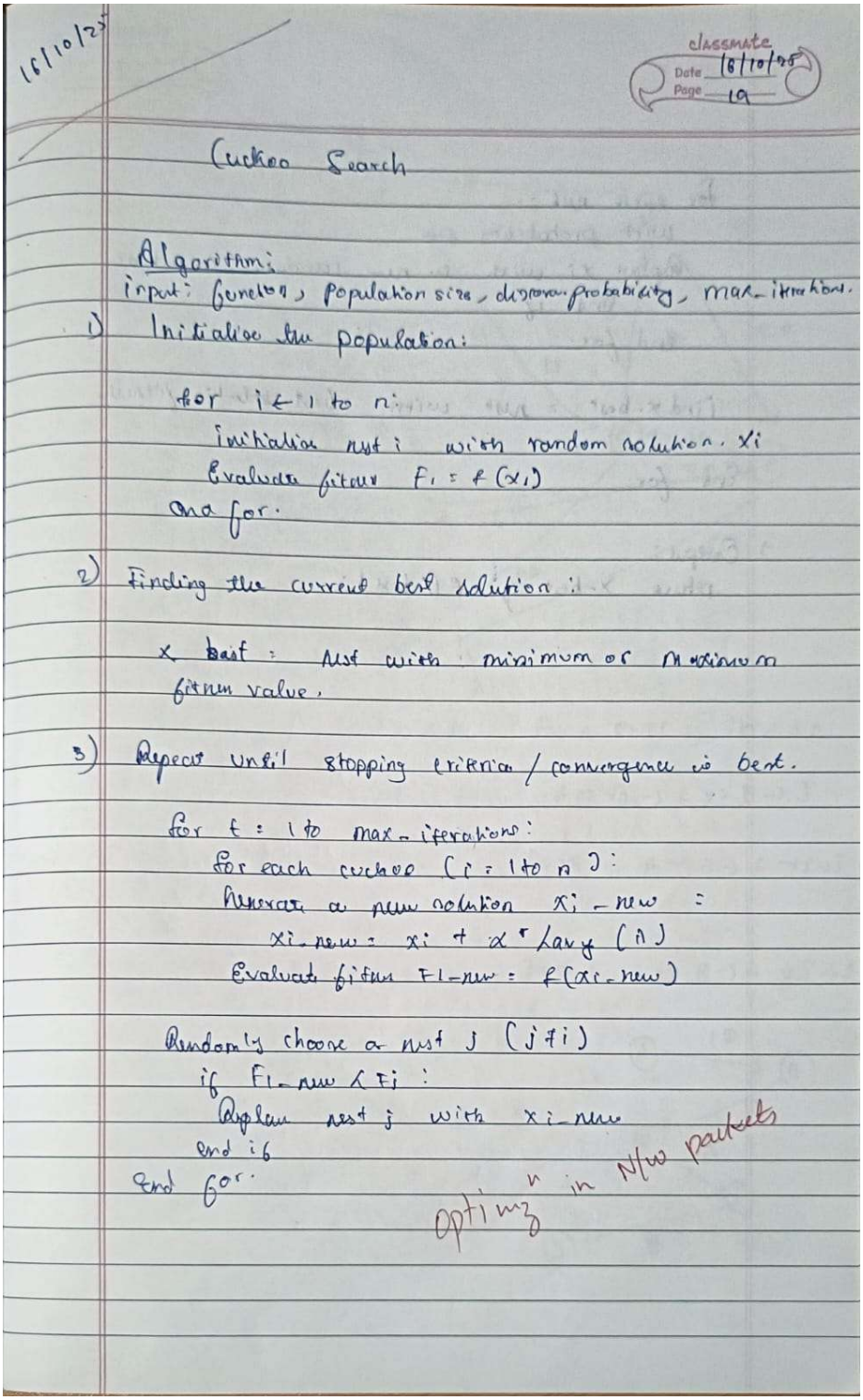
Output:

```
--- ACO Router Traffic Management Simulation ---
Start Node: A, End Node: J
Iterations: 50, Ants per Iteration: 20

Best Path Found (Node Indices): [0, 2, 1, 6, 9]
Best Path (Router Names): A -> C -> B -> G -> J
Total Cost/Delay: 23
```

Program 5:

Cuckoo Search for Optimization in Network Packets

Algorithm:



Cuckoo Search

Algorithm:
input: function, population size, discovery probability, max_iterations.

1) Initialise the population:

for i ← 1 to n:
Initialise nest i with random solution xi
Evaluate fitness Fi = f(xi)
end for.

2) Finding the current best solution:

x best : Nest with minimum or maximum fitness value.

3) Repeat until stopping criteria / convergence is best.

for t = 1 to max_iterations:
for each cuckoo (i = 1 to n):
Generate a new solution xi_new =
xi_new = xi + α * Levy(λ)
Evaluate fitness Fi_new = f(xi_new)

Randomly choose a nest j (j ≠ i)
if Fi_new < Fj:
Replace nest j with xi_new
end if
end for.

optimization in N/w packets

for each nest i:
with probability pa:
Replace xi with a new random solution.
end if
End for.

Find x-best = nest with best ~~solution~~ fitness.

End for.

→ Output:
return x-best $f(x\text{-best})$;

Code:

```
import networkx as nx
import matplotlib.pyplot as plt
import numpy as np
import random
import math

# --- 1. Graph Setup ---
def create_complex_graph():
    """
    Creates a complex, directed graph representing a network.
    Edges have 'cost' attributes for optimization.
    """
    G = nx.DiGraph()

    # Nodes (e.g., routers)
    nodes = ['A', 'B', 'C', 'D', 'E', 'F', 'G', 'H', 'I', 'J']
    G.add_nodes_from(nodes)

    # Edges with costs (e.g., latency in ms)
    # (source, target, cost)
    edges = [
        ('A', 'B', 10), ('A', 'C', 15), ('A', 'D', 25),
        ('B', 'E', 20), ('B', 'F', 5),
        ('C', 'E', 10), ('C', 'G', 40),
        ('D', 'F', 30), ('D', 'H', 15),
        ('E', 'I', 10), ('E', 'G', 5),
        ('F', 'I', 15), ('F', 'H', 20),
        ('G', 'J', 10),
        ('H', 'J', 12),
        ('I', 'J', 8),
        # Backwards/Alternative paths for complexity
        ('B', 'A', 12), ('C', 'B', 5), ('E', 'C', 15),
        ('H', 'E', 25), ('I', 'G', 15)
    ]

    for u, v, cost in edges:
        G.add_edge(u, v, cost=cost)
```

```
    return G

# --- 2. Path Encoding and Fitness ---

def calculate_path_cost(G, path):
    """
    Calculates the total cost (fitness) of a path.
    A path is a list of nodes, e.g., ['A', 'B', 'E', 'I', 'J'].
    Returns a very high cost for invalid paths.
    """
    if not path or len(path) < 2:
        return float('inf')

    total_cost = 0
    for i in range(len(path) - 1):
        u, v = path[i], path[i+1]
        if G.has_edge(u, v):
            total_cost += G[u][v]['cost']
        else:
            # High cost for an invalid hop (broken link)
            return float('inf')

    return total_cost

def generate_random_valid_path(G, source, destination, max_length=10):
    """
    Generates a random, valid path between source and destination.
    Uses a simple random walk until the destination is reached or max_length is exceeded.
    """
    path = [source]
    current_node = source

    while current_node != destination and len(path) < max_length:
        neighbors = list(G.successors(current_node))
        if not neighbors:
            return [] # Dead end

        # Choose a random neighbor that is not the previous node (to avoid immediate cycles)
        next_node = random.choice(neighbors)
        if len(path) > 1 and next_node == path[-2]:
            # Try another one, or just take the step if only one option
```

```
            pass

        path.append(next_node)
        current_node = next_node

    return path if current_node == destination else []


def levy_flight(path, G, destination):
    """
    Simulates a 'Lévy Flight' for path optimization.
    This creates a new "egg" (path) from an existing one, promoting global search.

    The discrete adaptation works by:
    1. Randomly selecting a segment of the current path (local search/mutation).
    2. Generating a new random path segment (Lévy jump) from the selected node
       to a point near the destination, then continuing to the destination.
    """
    if len(path) < 2: return generate_random_valid_path(G, path[0], destination)

    # 1. Select a random crossover point (excluding source and destination)
    if len(path) > 2:
        crossover_idx = random.randint(1, len(path) - 2)
    else:
        crossover_idx = 1 # Only one hop

    start_node = path[crossover_idx]

    # 2. Randomly decide to jump to a random neighbor or make a long jump
    if random.random() < 0.7: # Small step (Local search)
        new_segment = generate_random_valid_path(G, start_node, destination, max_length=5)
    else: # Large step (Global search, via a randomly chosen intermediate node)
        intermediate_nodes = [n for n in G.nodes() if n not in [start_node, destination]]
        if intermediate_nodes:
            intermediate_node = random.choice(intermediate_nodes)

            # Segment 1: Start node to intermediate node
            try:
                seg1 = nx.shortest_path(G, start_node, intermediate_node, weight='cost')
            except nx.NetworkXNoPath:
                seg1 = [start_node] # Fallback if no path
```

```
            # Segment 2: Intermediate node to destination
            try:
                seg2 = nx.shortest_path(G, intermediate_node, destination, weight='cost')
            except nx.NetworkXNoPath:
                seg2 = [destination]

            # Combine, removing duplicates
            new_segment = seg1 + seg2[1:]
        else:
            new_segment = generate_random_valid_path(G, start_node, destination, max_length=5)

    if not new_segment or new_segment[0] != start_node or new_segment[-1] != destination:
        # If new segment failed, try a totally new path from the start node of the segment
        new_segment = generate_random_valid_path(G, start_node, destination)

    # 3. Create the new solution: old path up to crossover, plus the new segment
    new_path = path[:crossover_idx] + new_segment

    # 4. Cleanup: Remove immediate cycles (e.g., A -> B -> A -> C)
    cleaned_path = []
    for node in new_path:
        if cleaned_path and node == cleaned_path[-1]: continue # Skip duplicates
        if len(cleaned_path) >= 2 and node == cleaned_path[-2]:
            cleaned_path.pop() # Remove the previous node to clear the cycle

        cleaned_path.append(node)

    return cleaned_path if cleaned_path[-1] == destination else []

# --- 3. Cuckoo Search Algorithm ---

def cuckoo_search_path_optimization(G, source, destination, N_nests=10, Pa=0.25, max_iter=100):

    print(f"\n--- Starting Cuckoo Search: {source} to {destination} ---\n")
    print(f"Parameters: Nests={N_nests}, Pa={Pa}, Max Iter={max_iter}\n")

    # Initialization: Generate an initial population of host nests (paths)
    nests = []
    for _ in range(N_nests):
        path = generate_random_valid_path(G, source, destination)
```

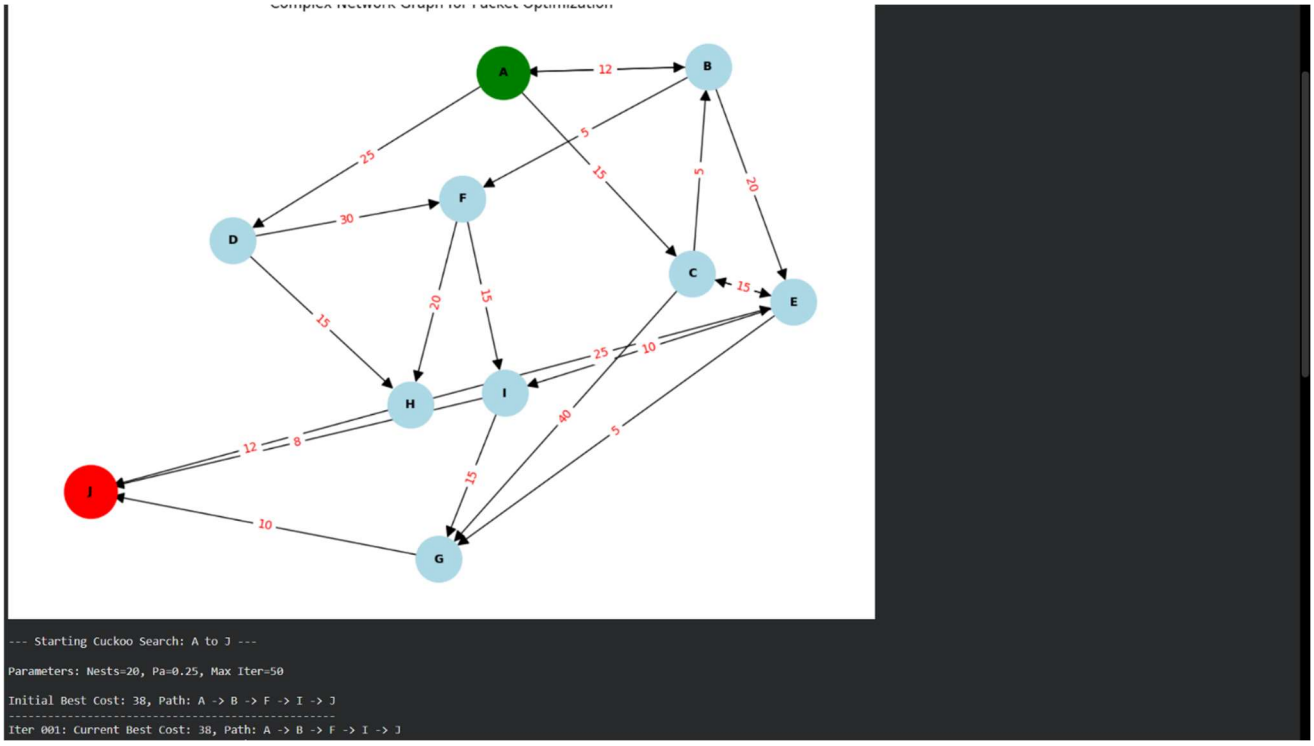
```
    if path:
        cost = calculate_path_cost(G, path)
        nests.append({'path': path, 'cost': cost})
    else:
        nests.append({'path': [], 'cost': float('inf')})

# Sort nests by cost (best is lowest cost)
nests.sort(key=lambda x: x['cost'])

best_path = nests[0]['path']
best_cost = nests[0]['cost']

if best_cost == float('inf'):
    print("Error: Could not find any initial valid path. Adjust graph or path generation.")
    return best_path, best_cost

print(f"Initial Best Cost: {best_cost}, Path: {' -> '.join(best_path)}")
print("-" * 50)

# Main optimization loop
for t in range(max_iter):
    # 1. Generate a new cuckoo egg (solution) via Lévy flight
    idx_cuckoo = random.randint(0, N_nests - 1)
    current_nest_path = nests[idx_cuckoo]['path']

    # Ensure we have a path to start the flight
    if not current_nest_path or current_nest_path[-1] != destination:
        current_nest_path = generate_random_valid_path(G, source, destination)
        if not current_nest_path: continue # Skip if path can't be generated

    new_cuckoo_path = levy_flight(current_nest_path, G, destination)
    new_cuckoo_cost = calculate_path_cost(G, new_cuckoo_path)

    # 2. Choose a random nest (j) to compare with
    idx_host = random.randint(0, N_nests - 1)
    host_cost = nests[idx_host]['cost']

    # 3. Replace nest (j) if the new cuckoo egg is better
    if new_cuckoo_cost < host_cost:
        nests[idx_host] = {'path': new_cuckoo_path, 'cost': new_cuckoo_cost}
```

```
        # 4. Abandon a fraction (Pa) of worse nests and build new ones
        num_abandon = int(N_nests * Pa)
        # The nests are already sorted, so we abandon the last 'num_abandon' ones (worst solutions)

        for i in range(1, num_abandon + 1):
            idx_worst = N_nests - i
            new_path = generate_random_valid_path(G, source, destination)
            if new_path:
                new_cost = calculate_path_cost(G, new_path)
                nests[idx_worst] = {'path': new_path, 'cost': new_cost}
            else:
                # In case new path generation fails, keep the original worst solution
                pass

        # 5. Re-sort the nests and update the global best
        nests.sort(key=lambda x: x['cost'])

        current_best_cost = nests[0]['cost']
        current_best_path = nests[0]['path']

        if current_best_cost < best_cost:
            best_cost = current_best_cost
            best_path = current_best_path

        # Print iteration results
        print(f"Iter {t+1:03d}: Current Best Cost: {current_best_cost}, Path: {' ->
'.join(current_best_path)}")


    print("-" * 50)
    return best_path, best_cost


# --- 4. Main Execution and Visualization ---

# 1. Create the complex graph
NETWORK_GRAPH = create_complex_graph()
SOURCE_NODE = 'A'
DESTINATION_NODE = 'J'

print("--- Network Graph Definition ---")
```

```
# 2. Print the graph details
print("Nodes:", list(NETWORK_GRAPH.nodes()))
print("Edges and Costs (Sample):")
for u, v, data in list(NETWORK_GRAPH.edges(data=True))[:5]:
   print(f"  {u} -> {v}: Cost {data['cost']}")
print(f"Total Edges: {NETWORK_GRAPH.number_of_edges()}")

# 3. Visualize the graph
plt.figure(figsize=(10, 7))
pos = nx.spring_layout(NETWORK_GRAPH, seed=42) # Layout for visualization
nx.draw(NETWORK_GRAPH, pos, with_labels=True, node_size=1500, node_color='lightblue',
        font_size=10, font_weight='bold', arrowsize=20)

# Draw edge labels (costs)
edge_labels = nx.get_edge_attributes(NETWORK_GRAPH, 'cost')
nx.draw_networkx_edge_labels(NETWORK_GRAPH, pos, edge_labels=edge_labels,
font_color='red')

# Highlight source and destination
nx.draw_networkx_nodes(NETWORK_GRAPH, pos, nodelist=[SOURCE_NODE],
node_color='green', node_size=2000, label='Source')
nx.draw_networkx_nodes(NETWORK_GRAPH, pos, nodelist=[DESTINATION_NODE],
node_color='red', node_size=2000, label='Destination')

plt.title("Complex Network Graph for Packet Optimization")
#
plt.show()

# 4. Run the Cuckoo Search optimization
FINAL_BEST_PATH, FINAL_BEST_COST = cuckoo_search_path_optimization(
   G=NETWORK_GRAPH,
   source=SOURCE_NODE,
   destination=DESTINATION_NODE,
   N_nests=20, # Number of solutions to maintain
   Pa=0.25,    # Probability of abandoning the worst nest
   max_iter=50  # Number of generations
)

# 5. Print the final best result
print("\n" * 2)
```

```
print("=" * 60)
print(f"FINAL BEST PATH FOUND BY CUCKOO SEARCH")
print(f"   BEST PATH: {' -> '.join(FINAL_BEST_PATH)}")
print(f"   BEST COST: {FINAL_BEST_COST}")
print("=" * 60)
```

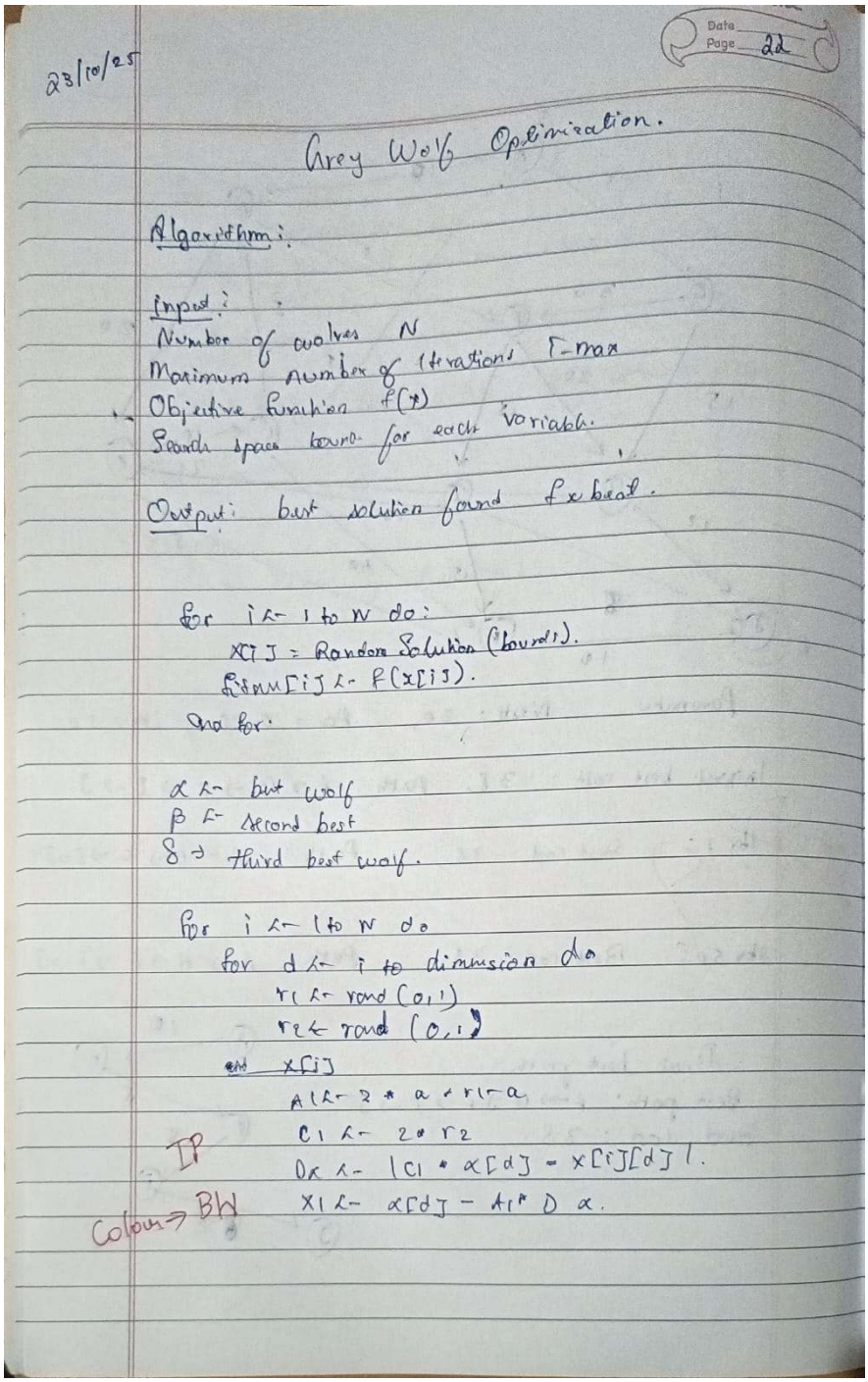
Output:



Program 6:

Grey Wolf Optimization for Image Preocessing Color to black and white

Algorithm:



r1 ← rand (0,1)
r2 ← rand (0,1)
A2 ← 2 * a * r1 - a
C2 ← 2 * r2
Dβ ← |C2 * β[d] - x[i][d]|
x2 ← β[d] - A2 * Dβ

r1 ← rand (0,1)
r2 ← rand (0,1)
A3 ← 2 * a * r1 - a
C3 ← r1 r2
Dδ ← |C3 * δ[d] - x[i][d]|
x3 ← δ[d] - A3 * Dδ

x_new[d] ← (x1 + x2 + x3)/3
end for.

x[i] ← Apply Bounds (x_new, bounds)
fitness[i] ← f(x[i])
end for.

Update α, β, δ based on new fitness values
end for

return α, f(α).

Code:

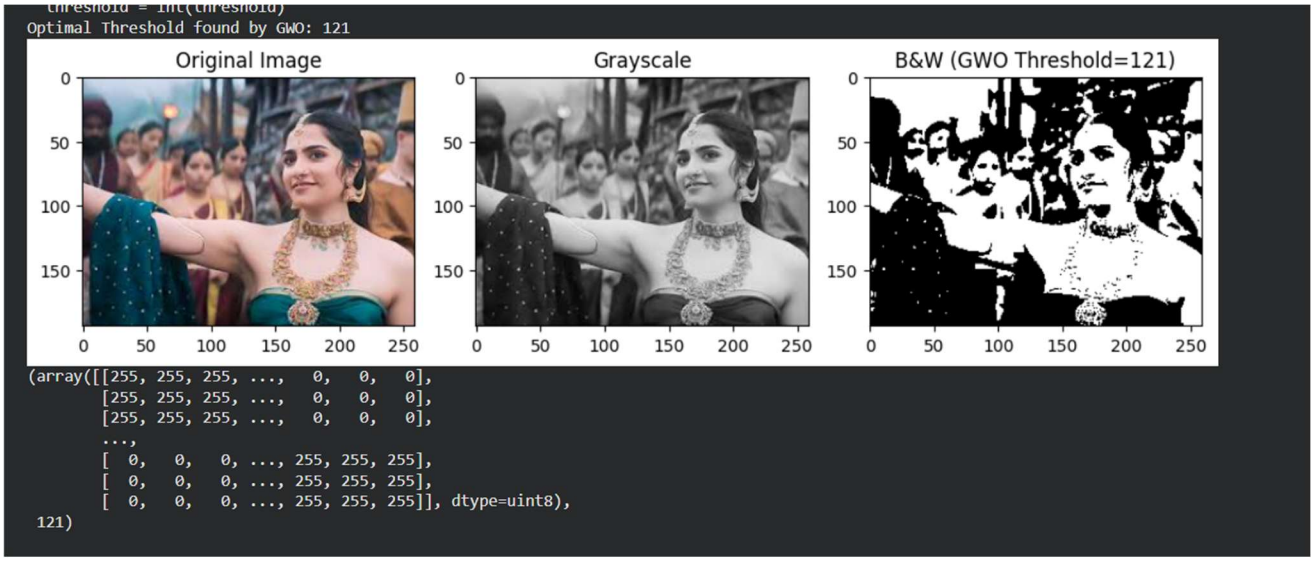
```
import cv2
import numpy as np
import matplotlib.pyplot as plt

# ----------------------------
# Grey Wolf Optimization (GWO)
# ----------------------------
def gwo_optimize(obj_func, lb, ub, dim, num_agents=10, max_iter=50):
    # Initialize the positions of search agents
    positions = np.random.uniform(lb, ub, (num_agents, dim))

    # Initialize alpha, beta, and delta wolves
    alpha_pos = np.zeros(dim)
    beta_pos = np.zeros(dim)
    delta_pos = np.zeros(dim)
    alpha_score = float('inf')
    beta_score = float('inf')
    delta_score = float('inf')

    # Main loop
    for t in range(max_iter):
        for i in range(num_agents):
            # Keep search agents within bounds
            positions[i] = np.clip(positions[i], lb, ub)

            # Calculate fitness
            fitness = obj_func(positions[i])

            # Update alpha, beta, delta
            if fitness < alpha_score:
                delta_score = beta_score
                delta_pos = beta_pos.copy()
                beta_score = alpha_score
                beta_pos = alpha_pos.copy()
                alpha_score = fitness
                alpha_pos = positions[i].copy()
            elif fitness < beta_score:
                delta_score = beta_score
                delta_pos = beta_pos.copy()
```

```
            beta_score = fitness
            beta_pos = positions[i].copy()
        elif fitness < delta_score:
            delta_score = fitness
            delta_pos = positions[i].copy()

    # Coefficients a, A, and C
    a = 2 - t * (2 / max_iter)

    # Update positions
    for i in range(num_agents):
        for j in range(dim):
            r1, r2 = np.random.rand(), np.random.rand()
            A1 = 2 * a * r1 - a
            C1 = 2 * r2
            D_alpha = abs(C1 * alpha_pos[j] - positions[i][j])
            X1 = alpha_pos[j] - A1 * D_alpha

            r1, r2 = np.random.rand(), np.random.rand()
            A2 = 2 * a * r1 - a
            C2 = 2 * r2
            D_beta = abs(C2 * beta_pos[j] - positions[i][j])
            X2 = beta_pos[j] - A2 * D_beta

            r1, r2 = np.random.rand(), np.random.rand()
            A3 = 2 * a * r1 - a
            C3 = 2 * r2
            D_delta = abs(C3 * delta_pos[j] - positions[i][j])
            X3 = delta_pos[j] - A3 * D_delta

            positions[i][j] = (X1 + X2 + X3) / 3.0

    return alpha_pos, alpha_score


# ----------------------------
# Objective Function (Otsu's variance)
# ----------------------------
def otsu_threshold_objective(threshold, gray_img):
    threshold = int(threshold)
    if threshold <= 0 or threshold >= 255:
```

```
        return float('inf')

    hist, _ = np.histogram(gray_img, bins=256, range=(0, 256))
    hist = hist.astype(np.float32)
    total = gray_img.size

    w0 = np.sum(hist[:threshold]) / total
    w1 = np.sum(hist[threshold:]) / total
    if w0 == 0 or w1 == 0:
        return float('inf')

    m0 = np.sum(np.arange(threshold) * hist[:threshold]) / (np.sum(hist[:threshold]) + 1e-6)
    m1 = np.sum(np.arange(threshold, 256) * hist[threshold:]) / (np.sum(hist[threshold:]) + 1e-6)

    # Between-class variance (maximize, so we return negative for minimization)
    var_between = w0 * w1 * (m0 - m1) ** 2
    return -var_between


# ----------------------------
# Main function
# ----------------------------
def gwo_image_threshold(image_path):
    # Read and convert to grayscale
    img = cv2.imread(image_path)
    gray = cv2.cvtColor(img, cv2.COLOR_BGR2GRAY)

    # Define objective wrapper
    def obj_func(threshold):
        return otsu_threshold_objective(threshold, gray)

    # Run GWO
    best_threshold, best_score = gwo_optimize(obj_func, lb=0, ub=255, dim=1, num_agents=15,
max_iter=50)
    best_threshold = int(best_threshold[0])
    print(f"Optimal Threshold found by GWO: {best_threshold}")

    # Apply threshold
    _, bw_img = cv2.threshold(gray, best_threshold, 255, cv2.THRESH_BINARY)

    # Display results
```

```
    plt.figure(figsize=(10, 4))
    plt.subplot(1, 3, 1)
    plt.title("Original Image")
    plt.imshow(cv2.cvtColor(img, cv2.COLOR_BGR2RGB))

    plt.subplot(1, 3, 2)
    plt.title("Grayscale")
    plt.imshow(gray, cmap='gray')

    plt.subplot(1, 3, 3)
    plt.title(f"B&W (GWO Threshold={best_threshold})")
    plt.imshow(bw_img, cmap='gray')
    plt.tight_layout()
    plt.show()

    return bw_img, best_threshold

gwo_image_threshold("download.jpeg")
```

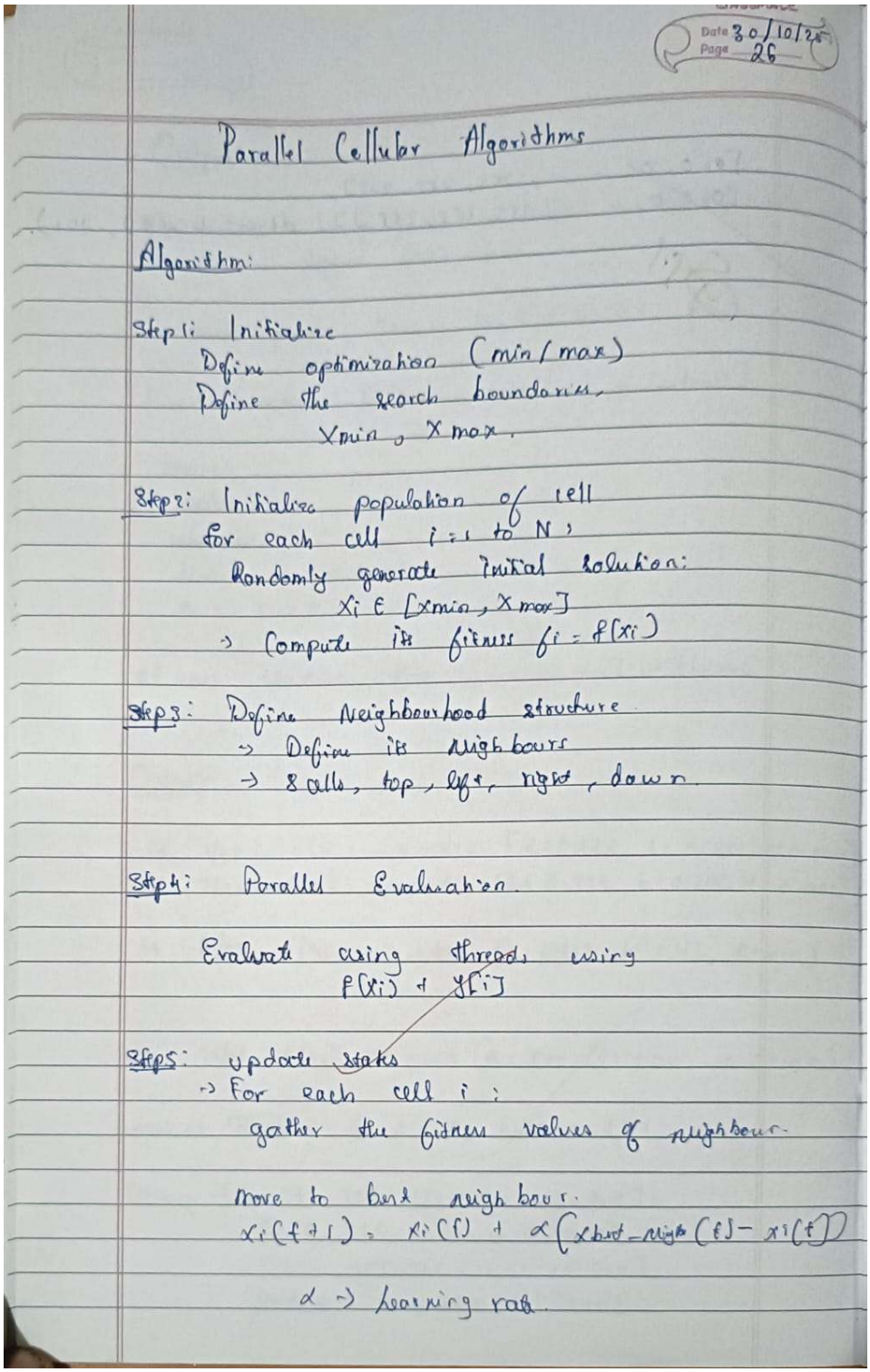
Output:



Program 7:

Parallel Cellular Algorithm for Routing

Algorithm:



Parallel Cellular Algorithms

Algorithm:

Step 1: Initialize
Define optimization (min / max)
Define the search boundaries.
Xmin, Xmax.

Step 2: Initialize population of cell
for each cell i = 1 to N,
Randomly generate initial solution:
$x_i \in [x_{min}, x_{max}]$
→ Compute its fitness $f_i = f(x_i)$

Step 3: Define Neighbourhood structure
→ Define its neighbours
→ 8 cells, top, left, right, down.

Step 4: Parallel Evaluation.

Evaluate using threads, using
f(xi) & yfij

Step 5: update states
→ For each cell i:
gather the fitness values of neighbour.

move to best neighbour.
$x_i(t+1) = x_i(t) + \alpha(x_{best\_neigh}(t) - x_i(t))$

α → learning rate.

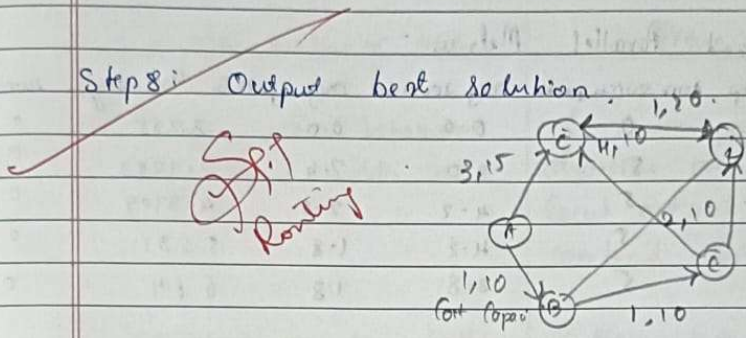
Step6: New fitness

$f_i(t+1) = f(x_i(t+1))$

$f_i(t+1) < f_{best}$ update x_{best}.

Step7: Repeat until convergence.

Step8: Output best solution.



Output:

Average Successful Router per step (Parallel): 4.16
Average Successful Router per step (Sequential): 3.98
Average Traffic load at End (parallel): 12.51
Average Traffic load at End (Sequential): 12.57

Starting optimized parallel cellular Simulation with Routing...
Optimized Parallel Time Step 10/100 completed.
Optimized Parallel Time Step 20/100 completed.
.
.
Optimized Parallel Time Step 100/100 completed.

Code:

```
import networkx as nx
import random
import time
import pandas as pd
import heapq
from concurrent.futures import ProcessPoolExecutor, as_completed
import multiprocessing

# 1. Define the network structure
G = nx.DiGraph()
edges = [
    ('A', 'B', {'cost': 1, 'capacity': 10}),
    ('A', 'C', {'cost': 3, 'capacity': 15}),
    ('B', 'C', {'cost': 1, 'capacity': 10}),
    ('B', 'D', {'cost': 2, 'capacity': 10}),
    ('C', 'D', {'cost': 1, 'capacity': 15}),
    ('C', 'E', {'cost': 4, 'capacity': 10}),
    ('D', 'E', {'cost': 1, 'capacity': 20})
]
G.add_edges_from(edges)

# Define source-destination pairs for routing attempts
source_destination_pairs = [
    ('A', 'D'),
    ('A', 'E'),
    ('B', 'E'),
    ('C', 'D')
]

# Initialize CA grid state and simulation parameters
initial_pheromone = 0.1
ca_grid_state_initial = {}
for u, v in G.edges():
    ca_grid_state_initial[(u, v)] = {
        'is_active_route': 0,
        'pheromone_level': initial_pheromone,
        'traffic_load': 0
```

```
    }

simulation_parameters = {
    'num_time_steps': 100,
    'pheromone_evaporation_rate': 0.05,
    'pheromone_deposit_amount': 0.1,
    'random_exploration_factor': 0.01,
    'traffic_increase_factor': 0.01,
    'traffic_decrease_factor': 0.02,
    'route_deactivation_threshold': 0.8,
    'pheromone_deposit_threshold': 0.2,
    'activation_factor': 0.05,
    'routing_attempts_per_step': 5,
    'pheromone_deposit_on_success': 0.5,
    'dijkstra_traffic_factor': 0.5,
    'dijkstra_pheromone_factor': 0.05
}

# Helper function to get neighborhood (from previous step)
def get_neighborhood(u, v, graph):
    neighborhood = []
    for in_edge_u, in_edge_v in graph.in_edges(u):
        neighborhood.append((in_edge_u, in_edge_v))
    for out_edge_u, out_edge_v in graph.out_edges(v):
        neighborhood.append((out_edge_u, out_edge_v))
    return neighborhood

# Helper function to update cell state (from previous step)
def update_cell_state(u, v, current_state, neighbor_states, graph, simulation_parameters):
    new_state = current_state.copy()
    pheromone_evaporation_rate = simulation_parameters['pheromone_evaporation_rate']
    pheromone_deposit_amount = simulation_parameters['pheromone_deposit_amount']
    random_exploration_factor = simulation_parameters['random_exploration_factor']
    traffic_increase_factor = simulation_parameters['traffic_increase_factor']
    traffic_decrease_factor = simulation_parameters['traffic_decrease_factor']
    route_deactivation_threshold = simulation_parameters['route_deactivation_threshold']

    new_state['pheromone_level'] *= (1 - pheromone_evaporation_rate)

    for (nu, nv), state in neighbor_states.items():
        if state['pheromone_level'] > simulation_parameters['pheromone_deposit_threshold']:
```

```
            new_state['pheromone_level'] += pheromone_deposit_amount * state['pheromone_level']

    max_pheromone = simulation_parameters.get('max_pheromone', float('inf'))
    new_state['pheromone_level'] = min(new_state['pheromone_level'], max_pheromone)

    active_neighbors = sum(state['is_active_route'] for state in neighbor_states.values())
    new_state['traffic_load'] += active_neighbors * traffic_increase_factor
    new_state['traffic_load'] *= (1 - traffic_decrease_factor)

    edge_capacity = graph[u][v].get('capacity', float('inf'))
    new_state['traffic_load'] = min(new_state['traffic_load'], edge_capacity)
    graph[u][v]['traffic_load'] = new_state['traffic_load']

    cost = graph[u][v].get('cost', 1)
    available_capacity = edge_capacity - new_state['traffic_load']
    attractiveness = (new_state['pheromone_level'] + 1e-6) / (cost + 1e-6) * (available_capacity + 1e-
6)

    activation_probability = attractiveness * simulation_parameters['activation_factor']

    if random.random() < random_exploration_factor:
        activation_probability = random.random()

    if new_state['is_active_route'] == 0:
        if random.random() < activation_probability:
            new_state['is_active_route'] = 1
    else:
        if new_state['traffic_load'] > edge_capacity * route_deactivation_threshold:
            new_state['is_active_route'] = 0
        elif random.random() > activation_probability and random.random() > (1 -
random_exploration_factor):
            new_state['is_active_route'] = 0

    return new_state

# Pathfinding function using Dijkstra's algorithm (optimized version)
def find_route_with_dijkstra_ca(source, destination, graph, ca_grid_state):
    def get_dynamic_weight(u, v):
        edge_state = ca_grid_state.get((u, v), {'is_active_route': 0, 'pheromone_level': 0, 'traffic_load':
float('inf')})
        original_cost = graph[u][v].get('cost', 1)
```

```
        traffic_load = edge_state.get('traffic_load', 0)
        pheromone_level = edge_state.get('pheromone_level', 0)

        alpha = simulation_parameters.get('dijkstra_traffic_factor', 0.1)
        beta = simulation_parameters.get('dijkstra_pheromone_factor', 0.01)

        dynamic_weight = original_cost + alpha * traffic_load - beta * pheromone_level
        return max(0, dynamic_weight)

    distances = {node: float('inf') for node in graph.nodes()}
    distances[source] = 0
    previous_nodes = {}
    priority_queue = [(0, source)]

    while priority_queue:
        current_distance, current_node = heapq.heappop(priority_queue)

        if current_node == destination:
            path = []
            while current_node is not None:
                path.append(current_node)
                current_node = previous_nodes.get(current_node)
            return path[::-1]

        if current_distance > distances[current_node]:
            continue

        for neighbor in graph.neighbors(current_node):
            edge = (current_node, neighbor)
            if edge in graph.edges():
                weight = get_dynamic_weight(current_node, neighbor)
                distance = current_distance + weight

                if distance < distances[neighbor]:
                    distances[neighbor] = distance
                    previous_nodes[neighbor] = current_node
                    heapq.heappush(priority_queue, (distance, neighbor))

    return None

# Parallel update function (from previous step)
```

```
def update_cell_state_parallel(edge_chunk, ca_grid_state, graph, simulation_parameters):
    updated_chunk_state = {}
    for u, v in edge_chunk:
        current_state = ca_grid_state[(u, v)]
        neighborhood = get_neighborhood(u, v, graph)
        neighbor_states = {
            (nu, nv): ca_grid_state.get((nu, nv), {'is_active_route': 0, 'pheromone_level': 0, 'traffic_load':
0})
            for (nu, nv) in neighborhood
        }
        new_state = update_cell_state(u, v, current_state, neighbor_states, graph,
simulation_parameters)
        updated_chunk_state[(u, v)] = new_state
    return updated_chunk_state

# Metrics calculation function (from previous step)
def calculate_metrics(ca_grid_history, graph, simulation_parameters, successful_routes_history):
    num_time_steps = simulation_parameters['num_time_steps']
    metrics = {
        'time_step': list(range(num_time_steps + 1)),
        'num_successful_routes': [0],
        'avg_route_cost': [0],
        'avg_path_length': [0],
        'avg_traffic_load': [],
        'num_overloaded_edges': []
    }

    for t in range(num_time_steps + 1):
        current_ca_state = ca_grid_history[t]

        total_traffic_load = 0
        overloaded_edges_count = 0
        num_edges = 0
        for (u, v), state in current_ca_state.items():
            num_edges += 1
            traffic_load = state.get('traffic_load', 0)
            capacity = graph[u][v].get('capacity', float('inf'))

            total_traffic_load += traffic_load
            if capacity != float('inf') and traffic_load > capacity:
                overloaded_edges_count += 1
```

```
        metrics['avg_traffic_load'].append(total_traffic_load / num_edges if num_edges > 0 else 0)
        metrics['num_overloaded_edges'].append(overloaded_edges_count)

        if t > 0:
            successful_routes_this_step = successful_routes_history[t-1]
            metrics['num_successful_routes'].append(len(successful_routes_this_step))

            if successful_routes_this_step:
                total_cost_this_step = 0
                total_length_this_step = 0
                for source, destination, route in successful_routes_this_step:
                    route_cost = sum(graph[route[i]][route[i+1]].get('cost', 1) for i in range(len(route) - 1))
                    total_cost_this_step += route_cost
                    total_length_this_step += len(route) - 1

                metrics['avg_route_cost'].append(total_cost_this_step / len(successful_routes_this_step))
                metrics['avg_path_length'].append(total_length_this_step /
len(successful_routes_this_step))
            else:
                metrics['avg_route_cost'].append(0)
                metrics['avg_path_length'].append(0)

    return metrics

# Main simulation runner (adapted from previous step)
def run_simulation_optimized_routing(graph, initial_ca_grid_state, simulation_parameters,
source_destination_pairs, parallel=True):
    if parallel:
        print("\nStarting Optimized Parallel Cellular Automaton Simulation with Routing...")
    else:
        print("\nStarting Optimized Sequential Cellular Automaton Simulation with Routing...")

    ca_grid_state_run = initial_ca_grid_state.copy()
    ca_grid_history_run = [ca_grid_state_run.copy()]
    successful_routes_history_run = []

    start_time = time.time()

    for t in range(simulation_parameters['num_time_steps']):
        for edge in graph.edges():
```

```
            ca_grid_state_run[edge]['is_active_route'] = 0

        successful_routes_this_step = []
        for _ in range(simulation_parameters['routing_attempts_per_step']):
            source, destination = random.choice(source_destination_pairs)
            found_route = find_route_with_dijkstra_ca(source, destination, graph, ca_grid_state_run)

            if found_route:
                successful_routes_this_step.append((source, destination, found_route))
                for i in range(len(found_route) - 1):
                    u, v = found_route[i], found_route[i+1]
                    edge = (u, v)
                    if edge in ca_grid_state_run:
                        ca_grid_state_run[edge]['pheromone_level'] +=
simulation_parameters['pheromone_deposit_on_success']
                        ca_grid_state_run[edge]['is_active_route'] = 1
                        ca_grid_state_run[edge]['traffic_load'] += 1
                        edge_capacity = graph[u][v].get('capacity', float('inf'))
                        ca_grid_state_run[edge]['traffic_load'] = min(ca_grid_state_run[edge]['traffic_load'],
edge_capacity)
                        graph[u][v]['traffic_load'] = ca_grid_state_run[edge]['traffic_load']

        successful_routes_history_run.append(successful_routes_this_step)

        next_ca_grid_state_run = {}
        edges_list = list(graph.edges())

        if parallel:
            num_processes = multiprocessing.cpu_count()
            chunk_size = max(1, len(edges_list) // num_processes)
            edge_chunks = [edges_list[i:i + chunk_size] for i in range(0, len(edges_list), chunk_size)]

            with ProcessPoolExecutor(max_workers=num_processes) as executor:
                future_to_chunk = {
                    executor.submit(update_cell_state_parallel, chunk, ca_grid_state_run.copy(), graph,
simulation_parameters): chunk
                    for chunk in edge_chunks
                }

                for future in as_completed(future_to_chunk):
                    try:
```

```
                    updated_chunk_state = future.result()
                    next_ca_grid_state_run.update(updated_chunk_state)
                except Exception as exc:
                    print(f'Edge chunk generated an exception: {exc}')
        else:
            for u, v in graph.edges():
                current_state = ca_grid_state_run[(u, v)]
                neighborhood = get_neighborhood(u, v, graph)
                neighbor_states = {
                    (nu, nv): ca_grid_state_run.get((nu, nv), {'is_active_route': 0, 'pheromone_level': 0,
'traffic_load': 0})
                    for (nu, nv) in neighborhood
                }
                new_state = update_cell_state(u, v, current_state, neighbor_states, graph,
simulation_parameters)
                next_ca_grid_state_run[(u, v)] = new_state

        ca_grid_state_run = next_ca_grid_state_run
        ca_grid_history_run.append(ca_grid_state_run.copy())

        if (t + 1) % 10 == 0:
            if parallel:
                print(f"Optimized Parallel Time Step {t + 1}/{simulation_parameters['num_time_steps']}
completed.")
            else:
                print(f"Optimized Sequential Time Step {t +
1}/{simulation_parameters['num_time_steps']} completed.")

    end_time = time.time()
    execution_time = end_time - start_time
    if parallel:
        print(f"Optimized Parallel Simulation Finished in {execution_time:.4f} seconds.")
    else:
        print(f"Optimized Sequential Simulation Finished in {execution_time:.4f} seconds.")

    return ca_grid_history_run, successful_routes_history_run, execution_time

# --- Run optimized simulations and compare ---
# Reset graph traffic load before running simulations
for u,v in G.edges():
    G[u][v]['traffic_load'] = 0
```

```
# Run optimized parallel simulation
ca_grid_history_opt_parallel, successful_routes_history_opt_parallel, execution_time_opt_parallel =
run_simulation_optimized_routing(
    G.copy(),
    ca_grid_state_initial.copy(),
    simulation_parameters,
    source_destination_pairs,
    parallel=True
)

# Reset graph traffic load for sequential run
for u,v in G.edges():
    G[u][v]['traffic_load'] = 0

# Run optimized sequential simulation
ca_grid_history_opt_sequential, successful_routes_history_opt_sequential,
execution_time_opt_sequential = run_simulation_optimized_routing(
    G.copy(),
    ca_grid_state_initial.copy(),
    simulation_parameters,
    source_destination_pairs,
    parallel=False
)

# Calculate metrics for optimized simulations
print("\nCalculating Metrics for Optimized Simulations...")
parallel_metrics_opt = calculate_metrics(ca_grid_history_opt_parallel, G, simulation_parameters,
successful_routes_history_opt_parallel)
sequential_metrics_opt = calculate_metrics(ca_grid_history_opt_sequential, G,
simulation_parameters, successful_routes_history_opt_sequential)

parallel_metrics_opt_df = pd.DataFrame(parallel_metrics_opt)
sequential_metrics_opt_df = pd.DataFrame(sequential_metrics_opt)

print("\nOptimized Parallel Metrics:")
display(parallel_metrics_opt_df.head())

print("\nOptimized Sequential Metrics:")
display(sequential_metrics_opt_df.head())
```

```
print(f"\nOptimized Parallel Execution Time: {execution_time_opt_parallel:.4f} seconds")
print(f'Optimized Sequential Execution Time: {execution_time_opt_sequential:.4f} seconds")

# Compare average successful routes
avg_successful_routes_opt_parallel = parallel_metrics_opt_df['num_successful_routes'].mean()
avg_successful_routes_opt_sequential = sequential_metrics_opt_df['num_successful_routes'].mean()

print(f"\nAverage Successful Routes per Step (Optimized Parallel):
{avg_successful_routes_opt_parallel:.2f}")
print(f'Average Successful Routes per Step (Optimized Sequential):
{avg_successful_routes_opt_sequential:.2f}")

# Compare average traffic load at the end
avg_traffic_end_opt_parallel = parallel_metrics_opt_df['avg_traffic_load'].iloc[-1]
avg_traffic_end_opt_sequential = sequential_metrics_opt_df['avg_traffic_load'].iloc[-1]

print(f"\nAverage Traffic Load at End (Optimized Parallel): {avg_traffic_end_opt_parallel:.2f}")
print(f'Average Traffic Load at End (Optimized Sequential): {avg_traffic_end_opt_sequential:.2f}")
```

Output:

```
Sequential Time Step 70/100 completed.
Sequential Time Step 80/100 completed.
Sequential Time Step 90/100 completed.
Sequential Time Step 100/100 completed.
Sequential Simulation Finished in 0.0219 seconds.

Calculating Metrics...

Parallel Metrics:
```

	time_step	num_successful_routes	avg_route_cost	avg_path_length	avg_traffic_load	num_overloaded_edges
0	0	0	0.00	0.0	1.857143	0
1	1	5	4.00	2.6	2.985257	0
2	2	4	2.75	2.0	4.366723	0
3	3	4	2.75	2.5	6.010475	0
4	4	5	2.60	2.4	7.335637	0

```
Sequential Metrics:
```

	time_step	num_successful_routes	avg_route_cost	avg_path_length	avg_traffic_load	num_overloaded_edges
0	0	0	0.000000	0.0	1.428571	0
1	1	5	4.200000	2.0	3.136686	0
2	2	4	4.250000	3.0	4.950695	0
3	3	5	4.800000	2.6	5.727024	0
4	4	3	4.333333	2.0	7.052255	0

```
Parallel Execution Time: 3.6789 seconds
Sequential Execution Time: 0.0219 seconds

Average Successful Routes per Step (Parallel): 4.16
Average Successful Routes per Step (Sequential): 3.98

Average Traffic Load at End (Parallel): 12.51
Average Traffic Load at End (Sequential): 12.57

Number of Overloaded Edges at End (Parallel): 0
Number of Overloaded Edges at End (Sequential): 0
```