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LAB RECORD

Bio Inspired Systems (23CS5BSBIS)

Submitted by

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in partial fulfillment for the award of the degree of

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in
COMPUTER SCIENCE AND ENGINEERING

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CERTIFICATE

This is to certify that the Lab work entitled " Bio Inspired Systems (23CS5BSBIS)" carried out by **PADMASHREE JAIN D(1BM23CS223) ,** who is a 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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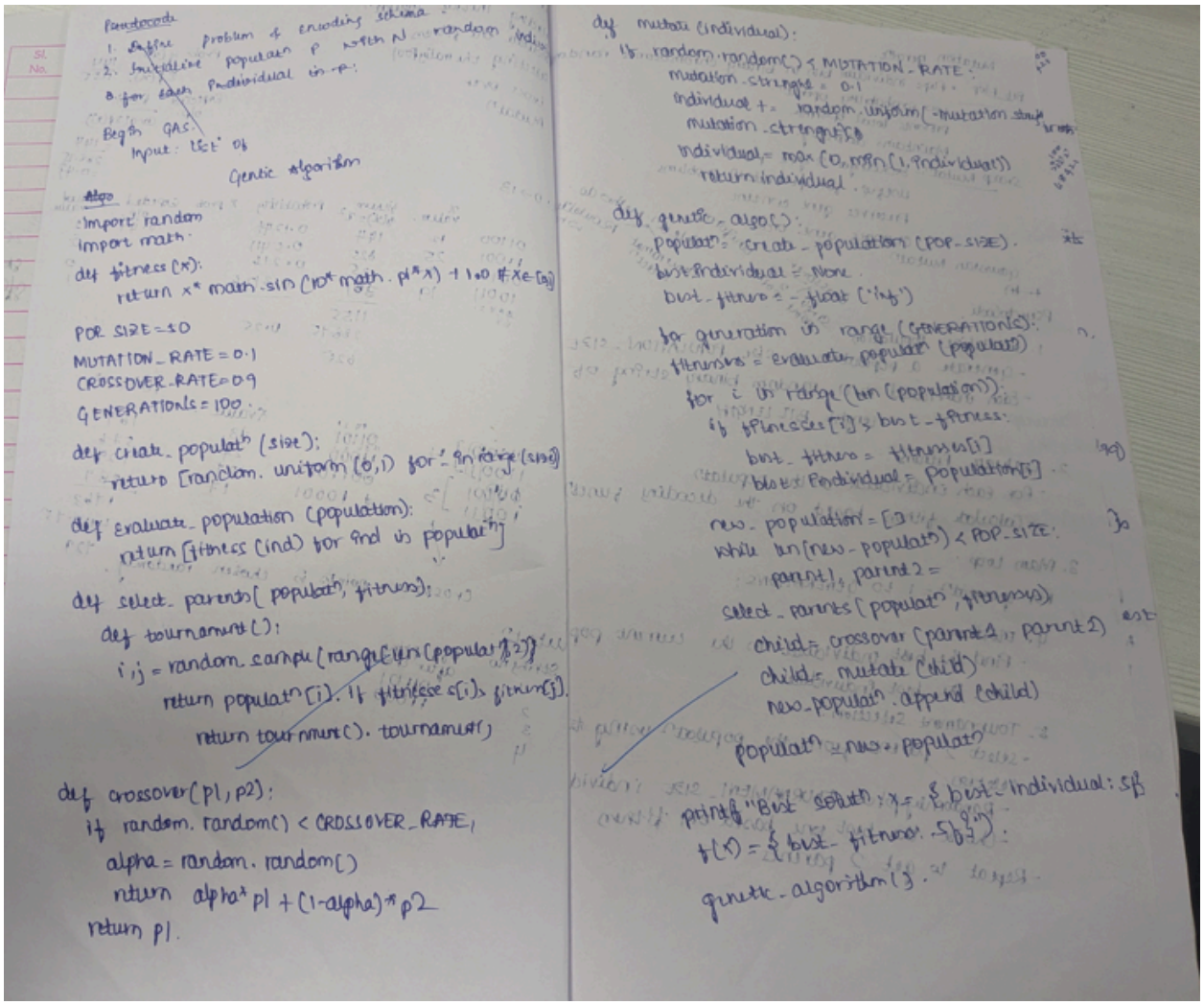
Github Link:
https://github.com/PADMASHREE719/bio-inspired-system

Program 1

Design and implement a **genetic algorithm (Knapsack)**in Python



Pseudocode
1. Define problem & encoding scheme
2. Initialize population P with N random individuals
3. for each individual in P:

Begin GAS:
Input: List of

Genetic Algorithm

Algo
import random
import math
def fitness(x):
return x* math.sin(10* math.pi*x) + 1.0 # x∈[0,2]

POP_SIZE=50
MUTATION_RATE=0.1
CROSSOVER_RATE=0.9
GENERATIONS=100

def create_population(size):
return [random.uniform(0,1) for _ in range(size)]

def evaluate_population(population):
return [fitness(ind) for ind in population]

def select_parents(population, fitness):
def tournament():
i,j = random.sample(range(len(population)),2)
return population[i] if fitness[i]>fitness[j]
return tournament(), tournament()

def crossover(p1,p2):
if random.random() < CROSSOVER_RATE:
alpha = random.random()
return alpha*p1 + (1-alpha)*p2
return p1

def mutate(individual):
if random.random() < MUTATION_RATE:
mutation_strength = 0.1
individual += random.uniform(-mutation_strength,
mutation_strength)
individual = max(0, min(2, individual))
return individual

def genetic_algo():
population = create_population(POP_SIZE)
best_individual = None
best_fitness = -float('inf')

for generation in range(GENERATIONS):
fitness = evaluate_population(population)
for i in range(len(population)):
if fitness[i] > best_fitness:
best_fitness = fitness[i]
best_individual = population[i]
new_population = []
while len(new_population) < POP_SIZE:
parent1, parent2 =
select_parents(population, fitness)
child = crossover(parent1, parent2)
child = mutate(child)
new_population.append(child)
population = new_population

print("Best solution: x = {best_individual:.5f}
f(x) = {best_fitness:.5f}")

genetic_algorithm()

Mutation

Bit Flip - flips individual bits in binary chromosomes randomly
- low probability operator
- Prevents local optima
- Maintains diversity

Swap Mutation - exchanges 2 gene positions
- useful for permutation problems
- Preserves gene content
- Changes gene order

Gaussian Mutation

Crossover
- Single point
- 2 point
- Uniform

Selection Methods
- Tournament selection
- Roulette wheel

Pseudocode

1. Initialize Population
- Generate a population of size POPULATION_SIZE
- Each individual is a random binary string of length BIT_LENGTH

2. Evaluate fitness
- For each individual in the population
- Calculate fitness based on the decoding function

3. Main Loop
For generation = 1 to GENERATIONS:

4. Elitism
- Find the best individual in the current population
- Save the best individual

5. Tournament Selection
- Select 2 parents from the population using tournament selection
- Randomly pick TOURNAMENT_SIZE individuals
- Choose the best one based on fitness
- Repeat to get 2 parents

6. Crossover
- Perform crossover between parents.
- Randomly select a crossover point
- Create 2 children by exchanging parts of the parents chromosomes at the crossover point

7. Mutation
- For each child generated:
- With probability MUTATION_RATE, flip random bit in child's chromosome.

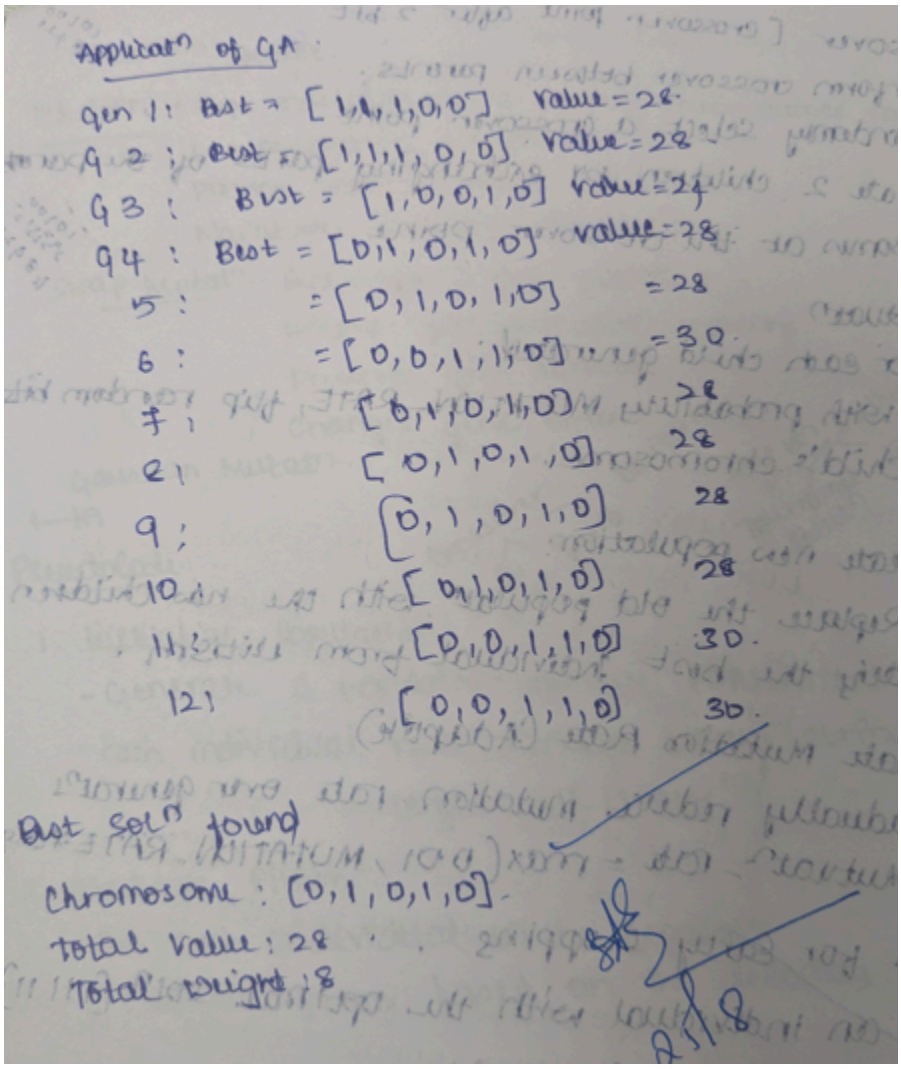
8. Create new population.
- Replace the old population with the new children, including the best individual from elitism.

9. Update Mutation Rate (Adaptive)
- Gradually reduce mutation rate over generations
- Mutation_rate = max(0.01, MUTATION_RATE * 0.99)

10. Check for early stopping.
- If an individual with the optimal solution (1111) is found, stop the algo early.

11. Return Best Solution.
After all generations or early stopping, return the best individual found

Ex



Code:

```
import random

# --------------------------------
# Problem Setup
# --------------------------------
items = [
    (2, 6),   # (weight, value)
    (3, 10),
    (4, 12),
    (5, 18),
    (9, 22)
]
capacity = 10
POP_SIZE = 6      # Number of chromosomes
GENS = 15         # Number of generations
MUT_RATE = 0.1    # Mutation probability

# --------------------------------
```

```
# Helper Functions
# ------------------------------

def fitness(chromosome):
    weight, value = 0, 0
    for gene, (w, v) in zip(chromosome, items):
        if gene == 1:
            weight += w
            value += v
    if weight > capacity:
        return 0  # Invalid solution
    return value

def create_chromosome():
    return [random.randint(0, 1) for _ in range(len(items))]

def selection(pop, fits):
    # Roulette Wheel Selection
    total_fit = sum(fits)
    if total_fit == 0:
        return random.choice(pop)
    pick = random.uniform(0, total_fit)
    current = 0
    for chrom, fit in zip(pop, fits):
        current += fit
        if current >= pick:
            return chrom

def crossover(p1, p2):
    point = random.randint(1, len(items)-1)
    return p1[:point] + p2[point:], p2[:point] + p1[point:]

def mutate(chrom):
    for i in range(len(chrom)):
        if random.random() < MUT_RATE:
            chrom[i] = 1 - chrom[i]  # Flip bit
    return chrom

# ------------------------------
# Genetic Algorithm
# ------------------------------

population = [create_chromosome() for _ in range(POP_SIZE)]

for gen in range(GENS):
    fitnesses = [fitness(c) for c in population]
    best_fit = max(fitnesses)
    best_chrom = population[fitnesses.index(best_fit)]
```

```
    print(f"Generation {gen+1}: Best={best_chrom} Value={best_fit}")

    new_population = []
    while len(new_population) < POP_SIZE:
        parent1 = selection(population, fitnesses)
        parent2 = selection(population, fitnesses)
        child1, child2 = crossover(parent1, parent2)
        new_population.append(mutate(child1))
        if len(new_population) < POP_SIZE:
            new_population.append(mutate(child2))
    population = new_population

# Final Result
fitnesses = [fitness(c) for c in population]
best_fit = max(fitnesses)
best_chrom = population[fitnesses.index(best_fit)]

print("\nBest Solution Found:")
print(f"Chromosome: {best_chrom}")
print(f"Total Value: {best_fit}")
print(f"Total Weight: {sum(w for gene,(w,v) in zip(best_chrom,items) if gene)}")
```


Program 2

gene expression algorithm for finding Travelling salesman problem

Algorithm:

Pseudocode for GEA applied to Routing (TSP):

Algorithm GEA_TSP

1. Define the problem:
   - Input : set of cities with distances.
   - Output: shortest possible route visiting all c

2. Initialize parameters:
   popul^n_size, mutat^n_rate, crossover_rate, gene

3. Initialise popul^n.
   Create random routes (permutat? of cities)

4. Evaluate fitness:
   for each route in population:
      fitness = 1 / (total_distance(route))
5. Repeat until max generations
   a. Selection:
      - select parent routes based on fitness
   b. Crossover:
      - Perform crossover b/n parents to create children
      - Example: Order Crossover (Ox)
   c. Mutation:
      - Randomly swap cities in the route with small probability.
   d. Gene Expression:
      - Ensure valid route (all cities appear exactly once)
   e. Evaluate new population's fitness.
   f. Replace old population with new population
6. Output best solution (shortest route found)

Ip: Best distance: 20 15
Best Route: [0,1,3,2,0] [0,1,2,3,0].

Simple example:

Distance Matrix:

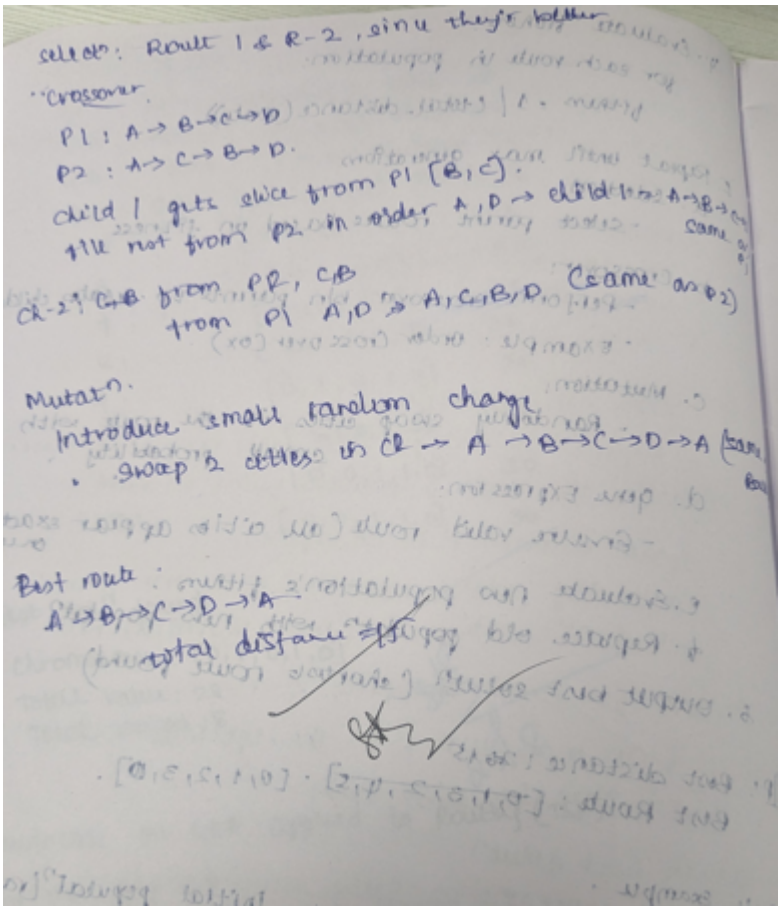
	A	B	C	D
A	0	4	1	3
B	1	0	2	5
C	1	2	0	6
D	3	5	6	0

S-1: Initial population (random Routes):
A → B → C → D.
A → C → B → D
A → D → B → C
A → C → D → B

Evaluate fitness (calculate the round-trip distance).

A → B → C → D → A = 15
4 2 6 3
A → C → B → D → A = 17

Shortest = 15



Code:

```
import random

# ---- Step 1: Problem Setup ----
cities = list(range(6))  # 6 cities labeled 0 to 5
distance_matrix = [
    [0, 2, 9, 10, 7, 3],
    [2, 0, 6, 4, 3, 8],
    [9, 6, 0, 8, 5, 6],
    [10, 4, 8, 0, 6, 7],
    [7, 3, 5, 6, 0, 4],
    [3, 8, 6, 7, 4, 0]
]

# Parameters
POP_SIZE = 20
MUTATION_RATE = 0.1
GENERATIONS = 200

# ---- Step 2: Fitness Function ----
def total_distance(route):
    distance = 0
    for i in range(len(route)):
        distance += distance_matrix[route[i]][route[(i+1) % len(route)]]
```

```
    return distance

def fitness(route):
    return 1 / total_distance(route)

# ---- Step 3: Initialize Population ----
def create_route():
    route = cities[:]
    random.shuffle(route)
    return route

def initial_population():
    return [create_route() for _ in range(POP_SIZE)]

# ---- Step 4: Selection ----
def selection(population):
    population.sort(key=total_distance)
    return population[:POP_SIZE//2]  # take best half

# ---- Step 5: Crossover ---- (Order Crossover)
def crossover(parent1, parent2):
    start, end = sorted(random.sample(range(len(parent1)), 2))
    child = [None]*len(parent1)
    child[start:end] = parent1[start:end]

    fill_values = [gene for gene in parent2 if gene not in child]
    pos = 0
    for i in range(len(child)):
        if child[i] is None:
            child[i] = fill_values[pos]
            pos += 1
    return child

# ---- Step 6: Mutation ----
def mutate(route):
    if random.random() < MUTATION_RATE:
        i, j = random.sample(range(len(route)), 2)
        route[i], route[j] = route[j], route[i]
    return route

# ---- Step 7: Main Loop ----
def gene_expression_algorithm():
    population = initial_population()
    best_route = None
    best_distance = float('inf')

    for gen in range(GENERATIONS):
        selected = selection(population)
```

```
        children = []
        while len(children) < POP_SIZE:
            p1, p2 = random.sample(selected, 2)
            child = crossover(p1, p2)
            child = mutate(child)
            children.append(child)
        population = children

        # Track best
        current_best = min(population, key=total_distance)
        current_dist = total_distance(current_best)
        if current_dist < best_distance:
            best_route = current_best
            best_distance = current_dist

        if gen % 20 == 0:  # log progress
            print(f"Gen {gen}: Best Distance = {best_distance}")

    return best_route, best_distance

# ---- Run ----
best_route, best_distance = gene_expression_algorithm()
print("\nBest Route:", best_route)
print("Best Distance:", best_distance)
```

Program 3

Find the maximum of the function f(x)=−x^2+y^2 using **Particle Swarm Optimization** by iteratively updating particle positions and velocities.

Algorithm:

Particle swarm optimization.

X → position
V → velocity
w → inertia
c_2 → social
c_1 → cognitive const
r_1, r_2 → random value

Eg:
Obj func $f(x,y) = x^2+y^2$.
$x \in [-10, 10]$.
Number of particles: N
Max number of iterations: max_iter
Parameters: inertia weight w, cognitive co-efficient c_1.
social coefficient c_2

op: Maximum value $f(x^*, y^*)$.

Steps:

1. Initialize the swarm

for each particle $i = 1, 2 \dots N$
Randomly initialize position $P_i = (x_i, y_i)$ within bounds
Initialize velocity $v_i = (0, 0)$
Set personal best position $pbest_i = P_i$
Evaluate fitness $f(P_i)$ & set as personal best value f_{pbest}.

2. Determine the global best particle

find particle with the ~~best~~ max value.
set global best position $g_{best} = pbest_{best}$.
set global best fitness $f_{gbest} = \max(f_{pbest_i})$.

3. for each iteration $t = 1$ to max_iter:

for each particle i:

(a) Update velocity.

$$v_i^{t+1} = w \cdot v_i^t + c_1 r_1 (pbest_i - p_i^t) + c_2 r_2 (g_{best} - p_i^t)$$

where $r_1, r_2 \sim$ Uniform $(0,1)$

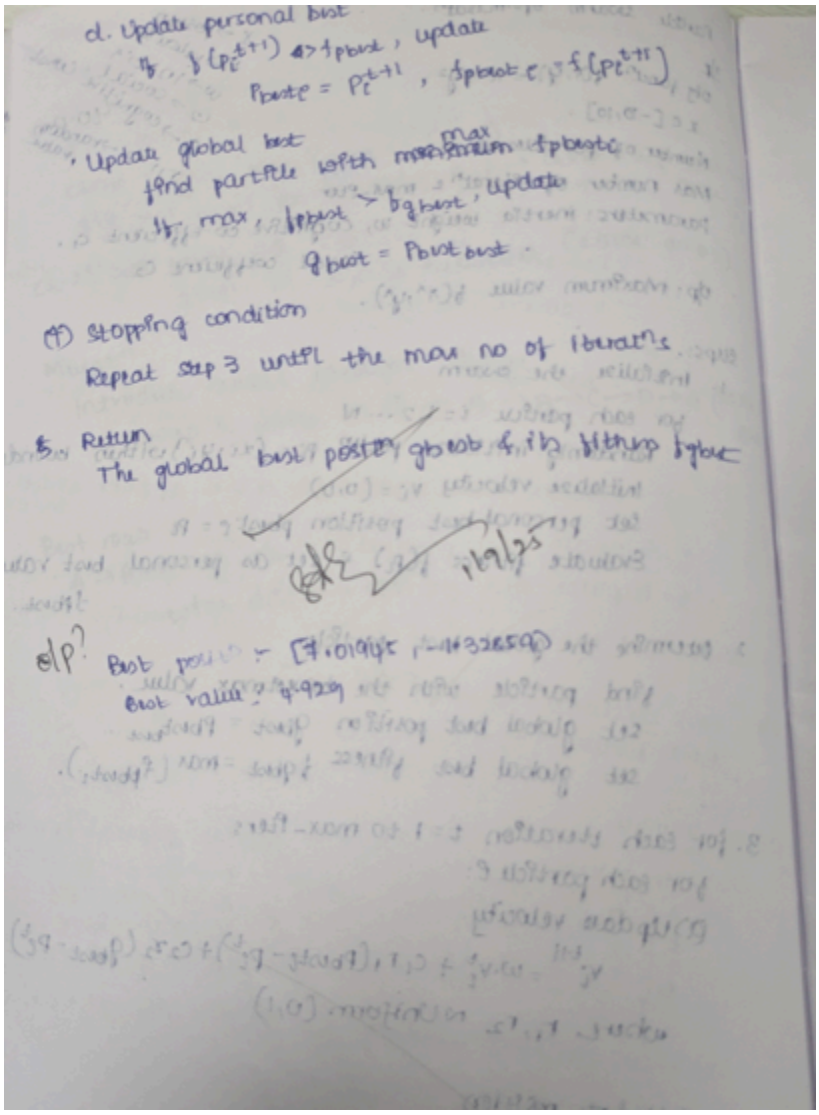
(b) Update position

$$P_i^{t+1} = P_i^t + v_i^{t+1}$$

Clip P_i^{t+1} to stay within bounds.

(c) Evaluate fitness

$$f(P_i^{t+1}) = (x_i^{t+1})^2 + (y_i^{t+1})^2$$



Code:

```
import numpy as np

# Objective function
def f(position):
    x, y = position
    return x**2 + y**2

class Particle:
    def __init__(self, bounds):
        self.position = np.array([np.random.uniform(bounds[0][0], bounds[0][1]),
                                  np.random.uniform(bounds[1][0], bounds[1][1])])
        self.velocity = np.zeros_like(self.position)
        self.pbest_position = self.position.copy()
        self.pbest_value = float('inf')

    def update_velocity(self, gbest_position, w, c1, c2):
        r1, r2 = np.random.rand(2)
```

```
        cognitive = c1 * r1 * (self.pbest_position - self.position)
        social = c2 * r2 * (gbest_position - self.position)
        self.velocity = w * self.velocity + cognitive + social

    def update_position(self, bounds):
        self.position += self.velocity
        # Keep particle inside bounds
        for i in range(len(bounds)):
            self.position[i] = np.clip(self.position[i], bounds[i][0], bounds[i][1])

def pso(objective_function, bounds, num_particles, max_iter, w=0.5, c1=1.5,
c2=1.5):
    swarm = [Particle(bounds) for _ in range(num_particles)]
    gbest_value = float('inf')
    gbest_position = None

    for iteration in range(max_iter):
        for particle in swarm:
            fitness = objective_function(particle.position)

            # Update personal best
            if fitness < particle.pbest_value:
                particle.pbest_value = fitness
                particle.pbest_position = particle.position.copy()

            # Update global best
            if fitness < gbest_value:
                gbest_value = fitness
                gbest_position = particle.position.copy()

        # Update velocity and position for each particle
        for particle in swarm:
            particle.update_velocity(gbest_position, w, c1, c2)
            particle.update_position(bounds)

        print(f"Iteration {iteration+1}/{max_iter}, Best Fitness: {gbest_value}")

    return gbest_position, gbest_value

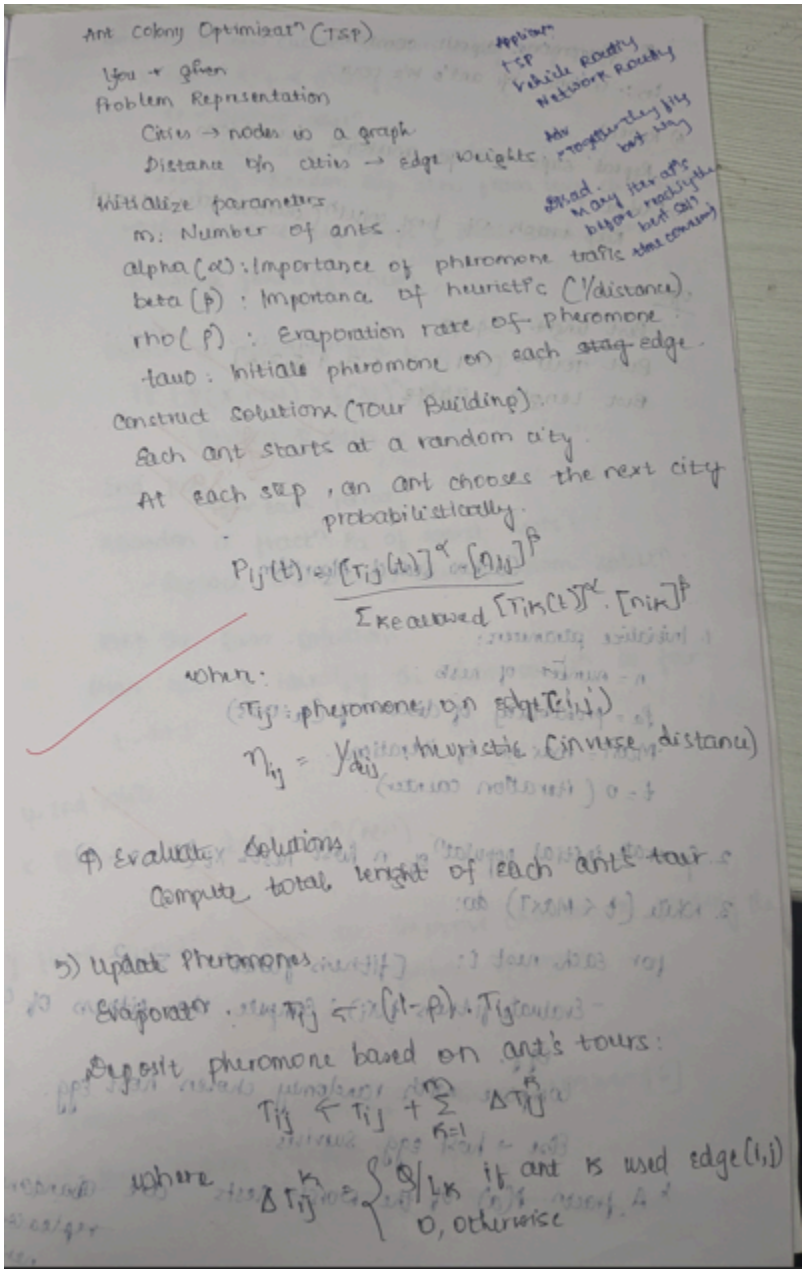
# Parameters
bounds = [(-10, 10), (-10, 10)]  # Search space for x and y
num_particles = 30
max_iter = 50

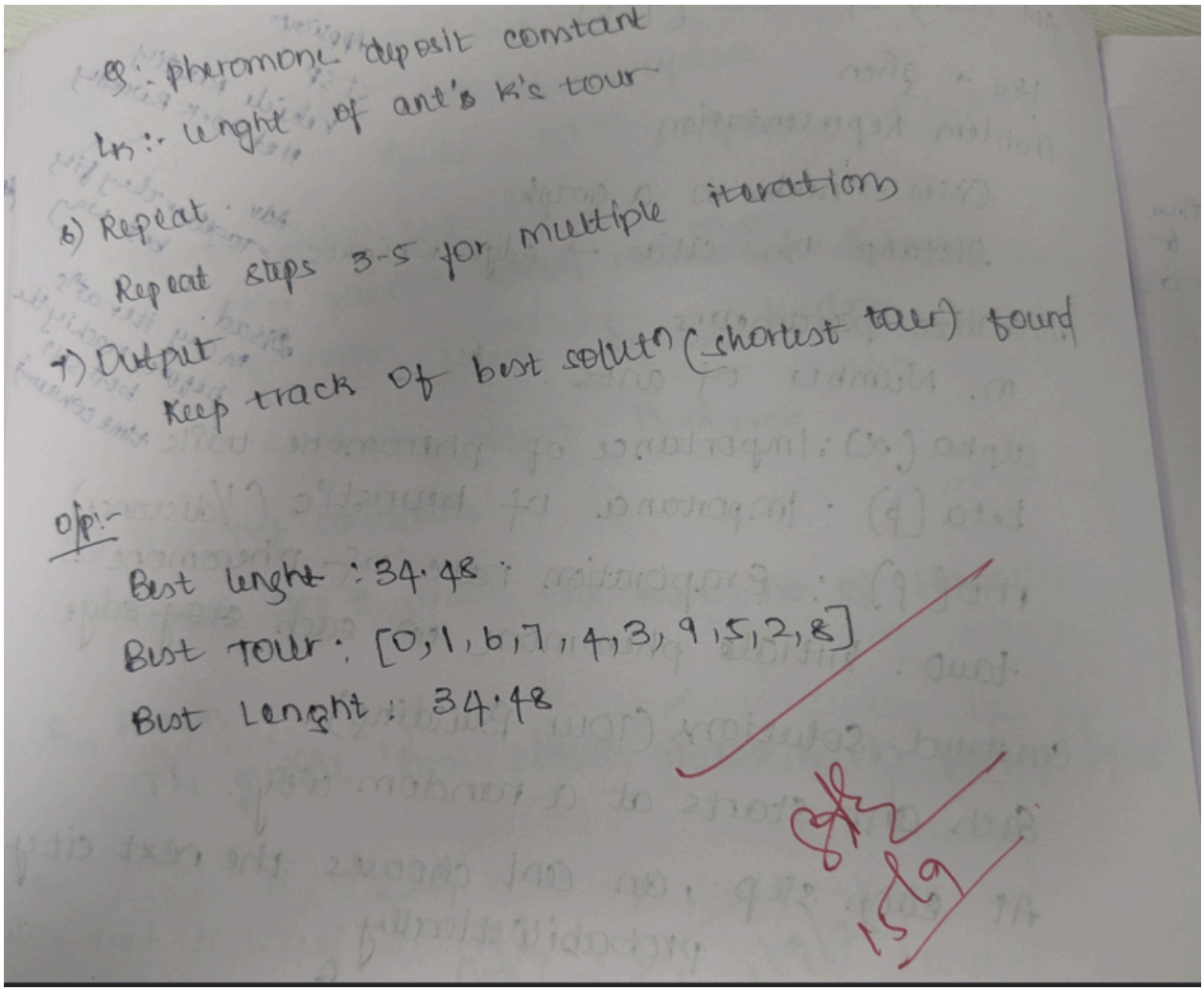
best_pos, best_val = pso(f, bounds, num_particles, max_iter)
print(f"Best position: {best_pos}, Best value: {best_val}")
```

Program 4

Find the shortest route visiting all cities once and returning to the start using **Ant Colony Optimization.**

Algorithm:





Code:

```
import numpy as np
import random
import math

# Step 1: Define the problem (set of cities with coordinates)
cities=[
 (0, 0),
 (1, 5),
 (5, 2),
 (6, 6),
 (8, 3),
 (7, 9),
 (2, 7),

 (3, 3)
]
N = len(cities)
```

```
# Calculate Euclidean distance matrix
def euclidean_distance(a, b):
 return math.sqrt((a[0] - b[0]) ** 2 + (a[1] - b[1]) ** 2)

distance_matrix = [[euclidean_distance(cities[i], cities[j]) for j in range(N)] for i in range(N)]

# Step 2: Initialize Parameters
num_ants = N
max_iterations = 100
alpha = 1.0
beta = 5.0
rho = 0.5
Q = 100.0
tau_0 = 1.0

pheromone = [[tau_0 for _ in range(N)] for _ in range(N)]
heuristic = [[1 / distance_matrix[i][j] if i != j else 0 for j in range(N)] for i in range(N)]

best_tour = None
best_length = float('inf')

# Step 3, 4, 5: Iterate
for iteration in range(max_iterations):
 all_tours = []
 all_lengths = []

 for ant in range(num_ants):
 unvisited = list(range(N))
 current_city = random.choice(unvisited)
 tour = [current_city]
 unvisited.remove(current_city)

 while unvisited:
 probabilities = []
 for j in unvisited:
 tau = pheromone[current_city][j] ** alpha
 eta = heuristic[current_city][j] ** beta
 probabilities.append(tau * eta)
 total = sum(probabilities)
 probabilities = [p / total for p in probabilities]
 next_city = random.choices(unvisited, weights=probabilities, k=1)[0]
tour.append(next_city)
 unvisited.remove(next_city)
 current_city = next_city
```



```
 # Return to starting city
 tour.append(tour[0])
```

```
 tour_length = sum(distance_matrix[tour[i]][tour[i+1]] for i in range(N))
all_tours.append(tour)
 all_lengths.append(tour_length)

 if tour_length < best_length:
 best_length = tour_length
 best_tour = tour

 # Step 4: Update Pheromones
 # Evaporation
 for i in range(N):
 for j in range(N):
 pheromone[i][j] *= (1 - rho)

 # Deposit
 for tour, length in zip(all_tours, all_lengths):
 for i in range(N):
 a = tour[i]
 b = tour[i+1]
 pheromone[a][b] += Q / length
 pheromone[b][a] += Q / length # because TSP is symmetric

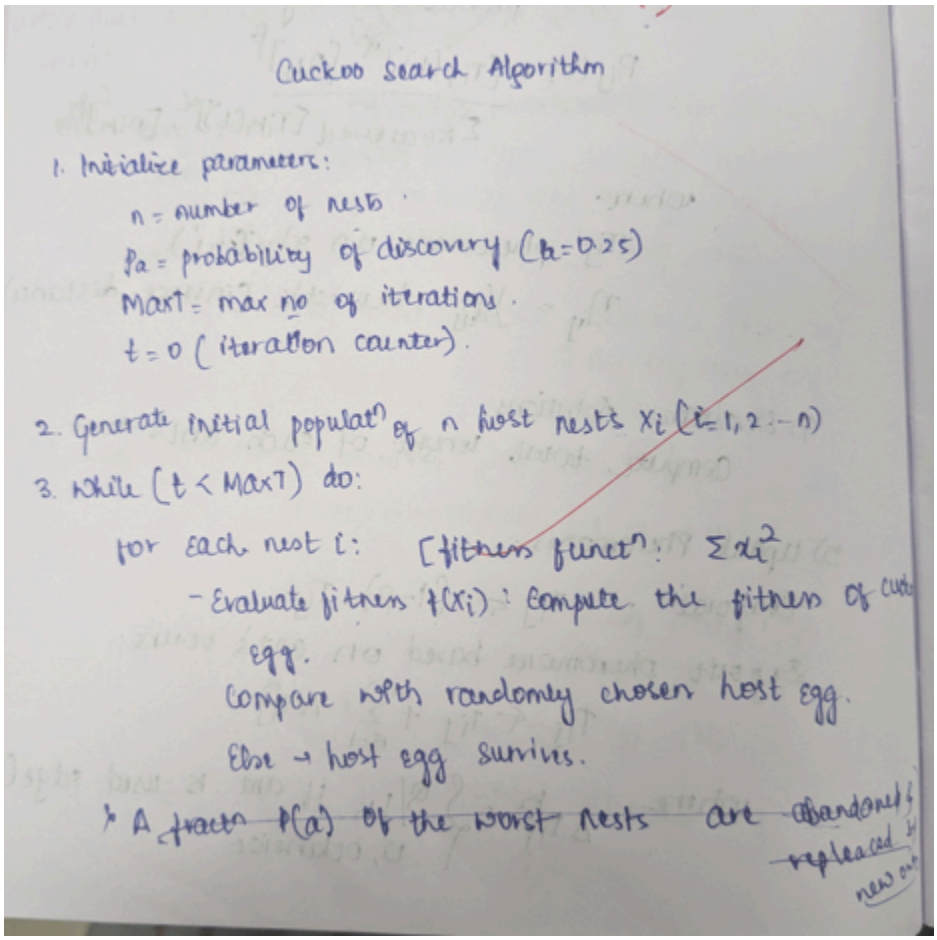
# Step 6: Output the Best Solution
print("Best tour:", best_tour)
print("Best tour length:", round(best_length, 2))
```

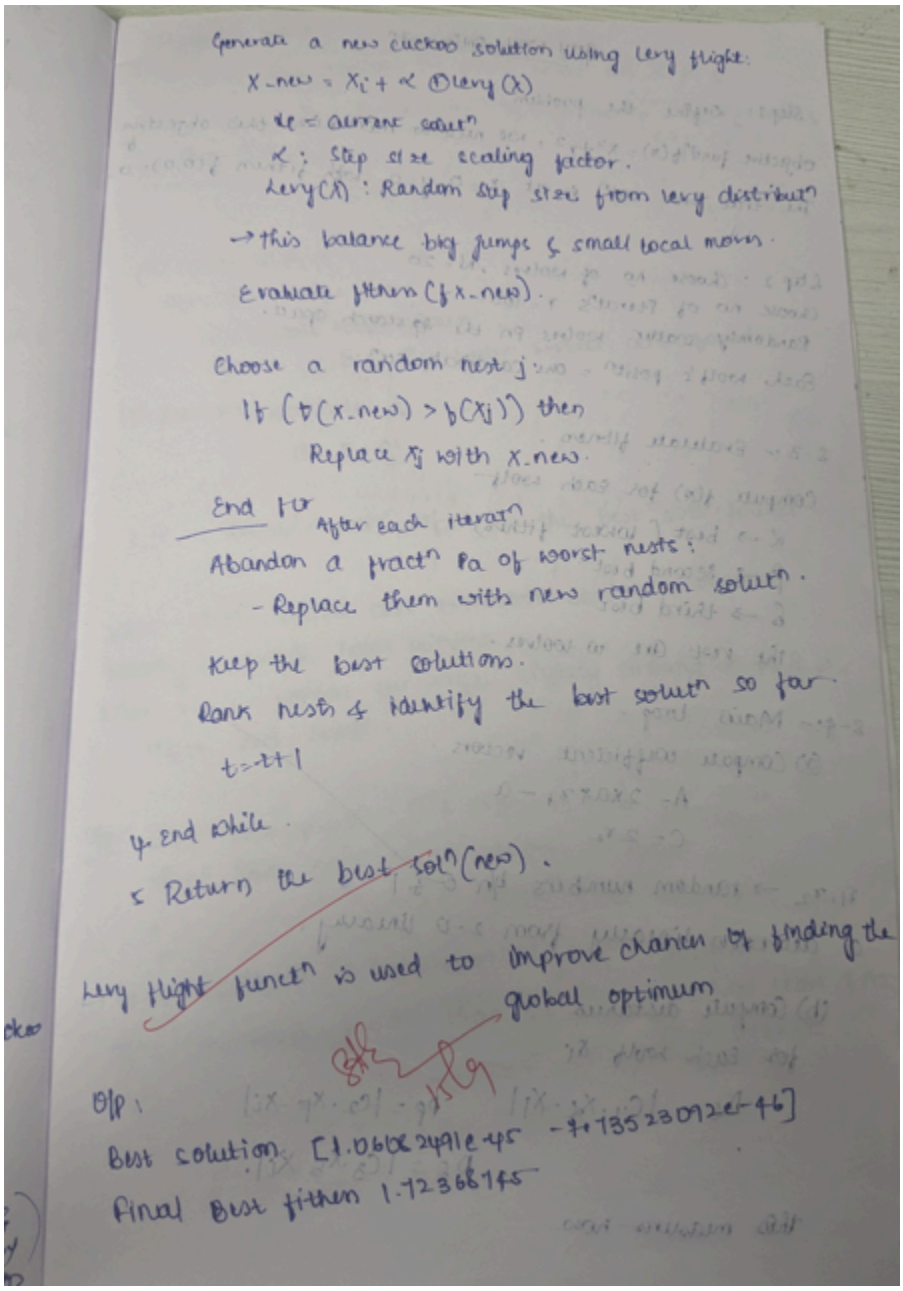

Program 5

Solve the 0/1 Knapsack Problem by using **Cuckoo Search** to maximize total item value

without exceeding the weight limit.

Algorithm:





Code:

```
import random
import numpy as np

# Step 1: Define the Knapsack Problem
# Sample data: values and weights of items
values = [60, 100, 120, 80, 30]
weights = [10, 20, 30, 15, 5]
max_weight = 50
num_items = len(values)

# Fitness function: maximize value while staying under weight limit
def fitness(nest):
 total_value = 0
```

```
 total_weight = 0
 for i in range(num_items):
 if nest[i] == 1:
 total_value += values[i]
```



```
 total_weight += weights[i]
 if total_weight > max_weight:
 return 0 # Penalty for exceeding capacity
 return total_value

# Step 2: Initialize Parameters
num_nests = 25
max_iterations = 100
discovery_rate = 0.25 # Probability of discovering a nest
alpha = 1.0 # Step size for Lévy flights

# Step 3: Initialize Population
def initialize_population():
 return [[random.randint(0, 1) for _ in range(num_items)] for _ in range(num_nests)]

population = initialize_population()

# Step 4: Evaluate Fitness
fitness_values = [fitness(nest) for nest in population]

# Step 5: Generate New Solutions using Lévy flights (simple binary flipping)
def levy_flight(nest):
 new_nest = nest.copy()
 for i in range(num_items):
 if random.random() < 0.3: # 30% chance to flip each bit
 new_nest[i] = 1 - new_nest[i]
 return new_nest

# Step 6: Replace worst nests
def abandon_worst_nests(population, fitness_values):
 num_abandon = int(discovery_rate * num_nests)
 worst_indices = np.argsort(fitness_values)[:num_abandon]

 for idx in worst_indices:
 population[idx] = [random.randint(0, 1) for _ in range(num_items)]
 return population

# Step 7: Main Loop
best_nest = None
best_fitness = -1

for iteration in range(max_iterations):
 for i in range(num_nests):
```

```
# Generate a new solution by Lévy flight
new_nest = levy_flight(population[i])
new_fitness = fitness(new_nest)

# Greedy selection
```



```
if new_fitness > fitness_values[i]:
population[i] = new_nest
fitness_values[i] = new_fitness

# Track the global best
if new_fitness > best_fitness:
best_fitness = new_fitness
best_nest = new_nest.copy()

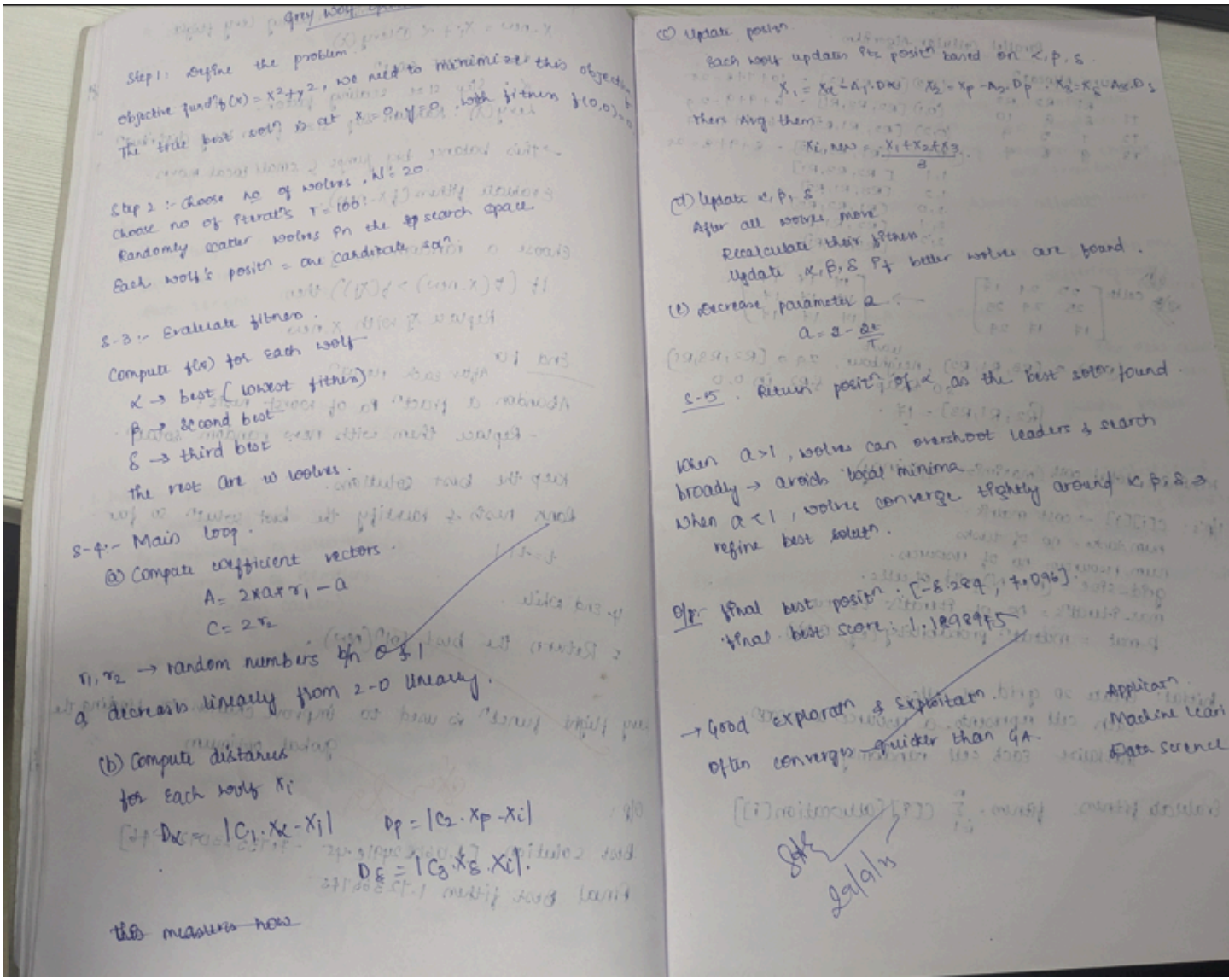
# Abandon a fraction of the worst nests
population = abandon_worst_nests(population, fitness_values)
fitness_values = [fitness(nest) for nest in population]

# Step 8: Output the Best Solution
print("Best Solution (Item Inclusion):", best_nest)
print("Best Total Value:", best_fitness)
print("Total Weight:",
 sum(weights[i] for i in range(num_items) if best_nest[i] == 1))
```

Program 6

Optimize the assignment of cars to parking slots to minimize total walking distance using **Grey Wolf Optimization**, simulating the social hierarchy and hunting behavior of grey wolves to iteratively improve solutions.

Algorithm:



Code:

```
import numpy as np

# Example Data:
num_cars = 5
num_slots = 5
slot_distances = np.array([10, 20, 15, 30, 25]) # Distances of parking slots to entrance
num_wolves = 10
max_iter = 50

# Initialize wolves: each wolf is a permutation of slot indices representing car assignments
def initialize_population(num_wolves, num_slots):
```



```
 population = []
 for _ in range(num_wolves):
 wolf = np.random.permutation(num_slots)
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```
 population.append(wolf)
 return population

# Fitness function: total walking distance for assigned slots
def fitness(wolf):
 total_distance = 0
 for car_index, slot_index in enumerate(wolf):
 total_distance += slot_distances[slot_index] # Distance of car's assigned slot
return total_distance

# Update position of wolf based on alpha, beta, delta (GWO update mechanism)
def update_position(wolf, alpha, beta, delta, a):
 # Generate a new wolf position by exploring around alpha, beta, delta wolves
new_wolf = wolf.copy()

 for i in range(len(wolf)):
 r1 = np.random.rand()
 r2 = np.random.rand()

 # Move the wolf toward the alpha, beta, or delta
 if r1 < 0.33:
 new_wolf[i] = alpha[i] # Move toward alpha wolf
 elif r1 < 0.66:
 new_wolf[i] = beta[i] # Move toward beta wolf
 else:
 new_wolf[i] = delta[i] # Move toward delta wolf

 # Ensure new_wolf is a valid permutation (no duplicates)
 new_wolf = np.unique(new_wolf)
 if len(new_wolf) < len(wolf):
 # if duplicates occur, randomly swap elements to maintain uniqueness
 missing_values = list(set(range(len(wolf))) - set(new_wolf))
 np.random.shuffle(missing_values)
 new_wolf = np.append(new_wolf, missing_values)

 # Now we randomly swap some elements to increase diversity and exploration
swap_indices = np.random.choice(len(wolf), 2, replace=False)
 new_wolf[swap_indices[0]], new_wolf[swap_indices[1]] = new_wolf[swap_indices[1]],
new_wolf[swap_indices[0]]

 return new_wolf

# Main GWO loop for parking slot allocation
def gwo_parking_allocation():
 # Initialize wolves (population)
```



```
 population = initialize_population(num_wolves, num_slots)
```

```
# Variables to keep track of the best solutions
alpha = None
beta = None
delta = None

alpha_score = float('inf')
beta_score = float('inf')
delta_score = float('inf')

# GWO main loop (iterations)
for iteration in range(max_iter):
# Evaluate the fitness of each wolf in the population
fitness_scores = []
for wolf in population:
score = fitness(wolf)
fitness_scores.append(score)

# Update alpha, beta, delta based on fitness
if score < alpha_score:
delta_score, delta = beta_score, beta
beta_score, beta = alpha_score, alpha
alpha_score, alpha = score, wolf
elif score < beta_score:
delta_score, delta = beta_score, beta
beta_score, beta = score, wolf
elif score < delta_score:
delta_score, delta = score, wolf

# Update positions of wolves based on best wolves (alpha, beta, delta)
new_population = []
for wolf in population:
# Adjust the exploration factor "a" to control the step size over iterations  a = 2
- iteration * (2 / max_iter)
new_wolf = update_position(wolf, alpha, beta, delta, a)
new_population.append(new_wolf)
population = new_population

# Print progress
print(f"Iteration {iteration+1}: Best total walking distance = {alpha_score}")
# Final best result
print("\nBest Assignment of Cars to Slots (car i -> slot number):")
print(alpha)
print("Slot distances:", slot_distances[alpha])
print("Total walking distance:", alpha_score)
```

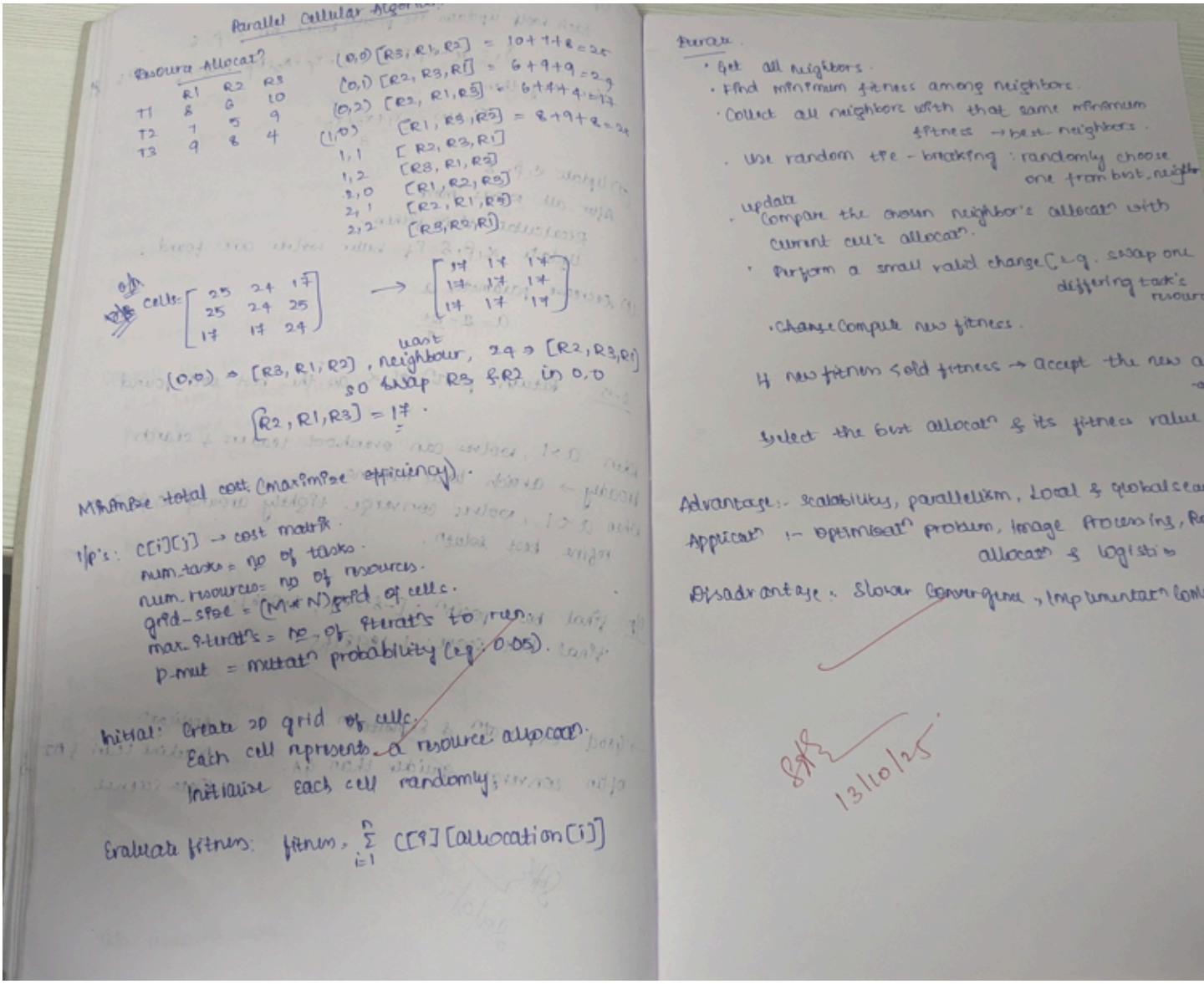


```
# Run the optimizer
gwo_parking_allocation()
```

Program 7

using **Parallel Cellular Algorithm** for resource allocation

Algorithm:



Code:

```
import random

# ---------------------------
# Cost matrix (task-resource)
# ---------------------------
```

```
C = [
    [8, 6, 10],  # Task 1 costs
    [7, 5, 9],   # Task 2 costs
    [9, 8, 4]    # Task 3 costs
]

num_tasks = len(C)
num_resources = len(C[0])

# ----------------------------
# PCA Parameters
# ----------------------------
M, N = 3, 3          # Grid size
max_iter = 5         # Number of iterations
p_mut = 0.1          # Mutation probability

# ----------------------------
# Helper Functions
# ----------------------------
def compute_cost(allocation):
    """Compute total cost for a given allocation."""
    return sum(C[i][allocation[i]] for i in range(num_tasks))

def random_allocation():
    """Generate a random valid allocation (permutation)."""
    alloc = list(range(num_resources))
    random.shuffle(alloc)
    return alloc

def random_swap(alloc):
    """Randomly swap two tasks' resource assignments."""
    a = alloc[:]
    i, j = random.sample(range(num_tasks), 2)
    a[i], a[j] = a[j], a[i]
    return a

def swap_first_difference(a, b):
    """Move a slightly toward b by swapping the first differing task."""
    a = a[:]
    for i in range(num_tasks):
        if a[i] != b[i]:
            # Find index where b[i] currently exists in a
            j = a.index(b[i])
            a[i], a[j] = a[j], a[i]
            break
    return a

def get_neighbors(grid, x, y):
```

```
    """Return Moore neighborhood of (x,y)."""
    neighbors = []
    for dx in [-1, 0, 1]:
        for dy in [-1, 0, 1]:
            if dx == 0 and dy == 0:
                continue
            nx, ny = x + dx, y + dy
            if 0 <= nx < M and 0 <= ny < N:
                neighbors.append(grid[nx][ny])
    return neighbors

# ----------------------------
# Initialize grid
# ----------------------------
grid = []
for i in range(M):
    row = []
    for j in range(N):
        alloc = random_allocation()
        cost = compute_cost(alloc)
        row.append({"alloc": alloc, "cost": cost})
    grid.append(row)

# Track global best
best_cell = min((grid[i][j] for i in range(M) for j in range(N)), key=lambda c: c["cost"])
best_alloc = best_cell["alloc"][:]
best_cost = best_cell["cost"]

# ----------------------------
# Main PCA Loop
# ----------------------------
for iteration in range(1, max_iter + 1):
    new_grid = [[cell.copy() for cell in row] for row in grid]

    for i in range(M):
        for j in range(N):
            cell = grid[i][j]
            neighbors = get_neighbors(grid, i, j)

            # Find best neighbor (tie-break randomly)
            min_cost = min(n["cost"] for n in neighbors)
            best_neighbors = [n for n in neighbors if n["cost"] == min_cost]
            chosen = random.choice(best_neighbors)

            # Move slightly toward best neighbor
            candidate = swap_first_difference(cell["alloc"], chosen["alloc"])
            candidate_cost = compute_cost(candidate)
```

```
            # Mutation
            if random.random() < p_mut:
                candidate = random_swap(candidate)
                candidate_cost = compute_cost(candidate)

            # Accept if better
            if candidate_cost < cell["cost"]:
                new_grid[i][j] = {"alloc": candidate, "cost": candidate_cost}

    # Update grid
    grid = new_grid

    # Update global best
    current_best = min((grid[i][j] for i in range(M) for j in range(N)), key=lambda c: c["cost"])
    if current_best["cost"] < best_cost:
        best_cost = current_best["cost"]
        best_alloc = current_best["alloc"][:]

    # Print iteration summary
    print(f"\nIteration {iteration}:")
    for r in range(M):
        for c in range(N):
            print(grid[r][c]["alloc"], "->", grid[r][c]["cost"], end="   ")
        print()
    print("Best so far:", best_alloc, "Cost:", best_cost)

# ---------------------------
# Final Result
# ---------------------------
print("\nFinal Best Allocation:", best_alloc)
print("Minimum Total Cost:", best_cost)
```