TIPE 2024

Apprendre à une intelligence artificielle à jouer à Snake en utilisant un algorithme génétique

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Introduction

Problématique et pertinence au regard du thème de l'année

- **Le jeu de Snake:** piloter un serpent sur une grille dans le but de manger des pommes, sans rentrer dans les murs ni se replier sur soi-même.
- **Objectif:** mettre en place une intelligence artificielle pouvant jouer efficacement au jeu de Snake, apprenant de manière autonome.
- **Le moyen d'y parvenir:** utiliser un algorithme génétique, qui s'inspire de l'évolution naturelle pour entraîner un réseau de neurone opérant les décisions de mouvement du serpent dont les entrées sont des paramètres de vision.
- **Les réseaux de neurones:** Warren S. McCulloch et Walter Pitts, *A logical calculus of the ideas immanent in nervous activity*, 1943, comparent les neurones à seuil binaire à la logique booléenne puis Frank Rosenblatt, *The perceptron: a probabilistic model for information storage and organization in the brain*, 1958, introduit la notion de poids
- **L'algorithme génétique:** développé par John Holland dans les années 1970, il s'inspire de l'évolution naturelle pour résoudre des problèmes d'optimisation

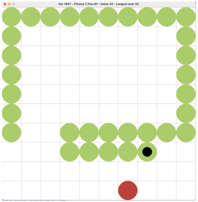
Le jeu de Snake

Brève histoire et règles du jeu

Origine: borne d'arcade *Blockade*, créée par Gremlin en 1976, popularisé par Nokia en 1997 sur mobile

Règles du jeu:

- Le serpent débute avec une longueur initiale donnée sur un échiquier entouré d'un mur et contenant une pomme.
- L'objectif est de le faire grandir en mangeant des pommes.
- Chaque pomme consommée augmente sa longueur d'une unité et fait apparaître une nouvelle pomme à un emplacement aléatoire.
- Le joueur dirige le serpent à l'aide des touches directionnelles du clavier ← ↑ ↓ → .
- Le jeu se termine si le serpent heurte un mur ou son propre corps.
- Le score du joueur est égal au nombre de pommes mangées.



Déplacer le serpent

Grâce à un réseau de neurones

Idée: utiliser un réseau de neurones multicouches à propagation avant pour déterminer le mouvement du serpent.

- Entrées: paramètres de vision.
- Sorties: les directions $\boxed{\leftarrow}$ $\boxed{\uparrow}$ $\boxed{\downarrow}$ $\boxed{\rightarrow}$.

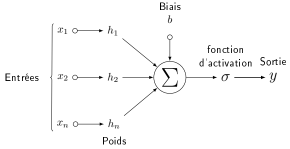
Modélisation d'un neurone: somme pondérée des entrées par un poids synaptique auquel on ajoute un biais. Sortie générée par une fonction d'activation non linéaire.

$$\mathbf{x} = (x_1, \cdots, x_n)^\mathsf{T}, \mathbf{h} = (h_1, \cdots, h_n)^\mathsf{T}$$
$$y = \sigma\left(\mathbf{h}^\mathsf{T}\mathbf{x} + b\right)$$

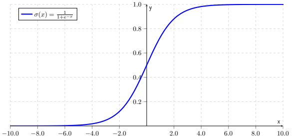
Généralisation à un réseau multicouches: modélisation matricielle avec fonction vectorielle σ

$$\underbrace{\begin{pmatrix} y_1 \\ y_2 \\ \vdots \\ y_k \end{pmatrix}}_{\text{Couche sortie}} = \sigma\left[\underbrace{\begin{pmatrix} h^{(2)}_{1,1} & h^{(2)}_{1,2} & \dots & h^{(2)}_{1,m} \\ h^{(2)}_{2,1} & h^{(2)}_{2,2} & \dots & h^{(2)}_{2,m} \\ \vdots & \vdots & \ddots & \vdots \\ h^{(2)}_{k,1} & h^{(2)}_{k,2} & \dots & h^{(2)}_{k,m} \end{pmatrix}}_{\text{Poids couche 3}} \sigma\left(\underbrace{\begin{pmatrix} h^{(1)}_{1,1} & h^{(1)}_{1,2} & \dots & h^{(1)}_{1,m} \\ h^{(1)}_{2,1} & h^{(1)}_{2,2} & \dots & h^{(1)}_{2,m} \\ \vdots & \vdots & \ddots & \vdots \\ h^{(1)}_{m,1} & h^{(1)}_{m,2} & \dots & h^{(1)}_{m,m} \end{pmatrix}}_{\text{Poids couche 2}} \sigma\left(\underbrace{\begin{pmatrix} h^{(1)}_{1,1} & h^{(1)}_{1,2} & \dots & h^{(1)}_{1,n} \\ h^{(1)}_{2,1} & h^{(1)}_{2,2} & \dots & h^{(1)}_{2,n} \\ \vdots & \vdots & \ddots & \vdots \\ h^{(1)}_{m,1} & h^{(1)}_{m,2} & \dots & h^{(1)}_{m,n} \end{pmatrix}}_{\text{Poids couche 1}} \underbrace{\begin{pmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{pmatrix}}_{\text{Couche entrée}} + \underbrace{\begin{pmatrix} b^{(1)}_1 \\ b^{(1)}_2 \\ \vdots \\ b^{(1)}_n \end{pmatrix}}_{\text{Bais couche 1}}\right) + \underbrace{\begin{pmatrix} b^{(2)}_1 \\ b^{(2)}_2 \\ \vdots \\ b^{(2)}_m \end{pmatrix}}_{\text{Bais couche 2}}\right) + \underbrace{\begin{pmatrix} b^{(3)}_1 \\ b^{(3)}_2 \\ \vdots \\ b^{(3)}_k \end{pmatrix}}_{\text{Bais couche 3}}\right]$$

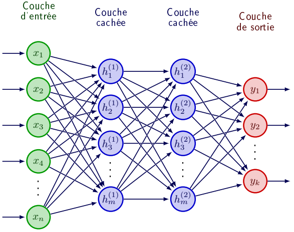
Décision de direction: celle qui a la plus grande valeur de sortie.



Fonctionnement d'un neurone



Fonction d'activation sigmoïde



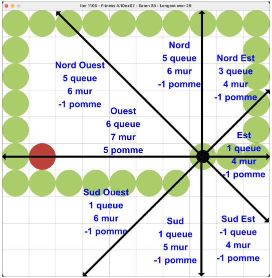
Réseau de neurones multicouches

Stratégies de vision

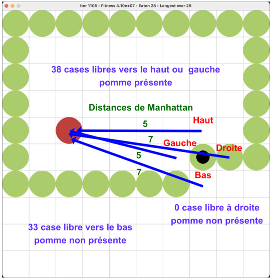
Paramètres en entrée du réseau de neurones

- **Stratégie n°1:** dans les 8 directions de mouvements, 3 informations par direction (distance à la pomme, distance aux murs, distance à la queue)
  $\rightarrow$ réseau $[24, 18, 18, 4]$.
- **Stratégie n°2:** dans les 4 directions de mouvements, 3 informations par direction (espace libre dans la direction du mouvement, distance de Manhattan à la pomme dans la direction du mouvement, la pomme est dans l'espace libre dans cette direction), et la taille du serpent
  $\rightarrow$ réseau $[13, 12, 12, 4]$.

Remarque: la stratégie n°2 est avantagée par la connaissance de la position de la pomme et l'espace libre dans les 4 directions de mouvement.



Stratégie n° 1



Stratégie n° 2

Évaluation de la performance d'un serpent

Objectif: mesurer la performance d'un serpent grâce à une fonction de fitness.

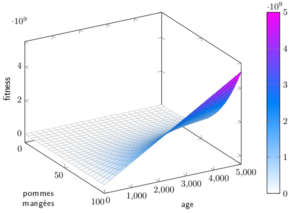
Paramètres: taille du serpent (pommes mangées) et âge (mouvements effectués) à la fin du jeu.

Fonctions de fitness évaluées: maximiser f_1 ou f_2 favorise la croissance et la longévité des serpents.

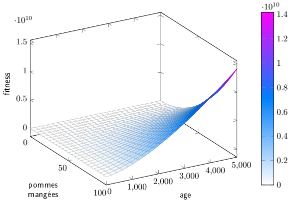
- $f_1(\text{taille}, \text{age}) = \text{taille}^3 \times \text{age}$
- $f_2(\text{taille}, \text{age}) = (2 \times \text{taille})^2 \times \text{age}^{1.5}$

Astuces:

- **Pour éviter les boucles infinies:** un nombre de points de vie est attribué à chaque serpent, décrémenté à chaque mouvement et réinitialisé à chaque pomme mangée. Á 0, le serpent meurt et son âge est pénalisé dans le calcul de la fitness.
- **Pour favoriser une croissance rapide:** f_1 est utilisée au début du jeu. Ensuite on passe à f_2 qui valorise la survie du serpent pour manger plus de pommes.



fitness $f(\textbf{taille}, \textbf{age}) = \textbf{taille}^3 \times \textbf{age}$



fitness
$f(\textbf{taille}, \textbf{age}) = (2 \times \textbf{taille})^2 \times \textbf{age}^{1.5}$

Optimiser les décisions du serpent

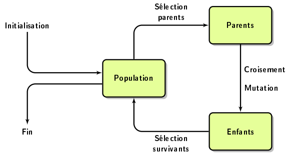
Entrainement du réseau de neurones par algorithme génétique

Principe: approche évolutionniste d'une population de réseaux de neurones par algorithme génétique

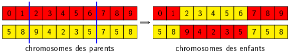
- **Sélection** de parents par la "sélection roulette": chaque serpent a une certaine chance d'être choisi en fonction de sa fitness.
- **Croisement** des serpents sélectionnés par paires aléatoire (parents) en K points (ici K=2) pour recomposer la population totale en générant des enfants.
- **Mutation** par ajustement mineur aléatoire dans le chromosome de chaque serpent pour maintenir la diversité.

Formalisation de la mutation:

- $p_m = 0.1$ probabilité de mutation,
- $c_m = 0.1$ le coefficient de mutation,
- $\forall h_i(t)$ à l'itération t, on tire $U \sim \mathcal{U}(0,1)$ et $C \sim \mathcal{U}(-1,1)$
- Si $U < p_m$, $h_i(t+1) = h_i(t) + C \times c_m$ sinon $h_i(t+1) = h_i(t)$.



Processus itératif



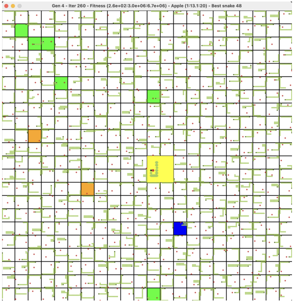
Croisement 2 points (2 points crossover)

Remarque: L'amélioration de la fitness est garantie à chaque génération mais pas la convergence vers un optimum global.

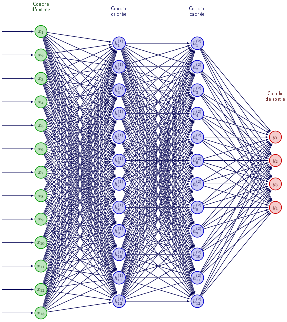
Algorithme d'optimisation

Entrainement du réseau de neurones par algorithme génétique

Population $\mathcal{P} \leftarrow 484 = 22^2$ **serpents**
for all **serpent** $s \in \mathcal{P}$ do
  cerveau c **de** $s \leftarrow$ **réseau neurones** $[13, 12, 12, 4]$, **poids & biais aléatoires**
end for
génération $g \leftarrow 0$
while $g < 2000$ do
  for **serpent** $s \in \mathcal{P}$ do
    age $a_s \leftarrow 0$ **de** s, **longueur** $l_s \leftarrow 3$, **point de vie** $v_s \leftarrow 50$
    vivant $\leftarrow$ **true**, **mortVieillesse**$_s \leftarrow$ **false**
    while **vivant** do
      position$_s \leftarrow$ **avance direction** $= c\,[$**vision**$_s\,($**position**$_s)]$
      if **position**$_s \in \{$**mur**, **queue**$\}$ then
        vivant$_s$ $=$ **false**
      else
        $a_s \leftarrow a_s + 1$
      end if
      if **position**$_s \in \{$**pomme**$\}$ then
        $l_s \leftarrow l_s + 1$, $v_s \leftarrow 50$
        régénère pomme emplacement aléatoire accessible
      else
        $v_s \leftarrow v_s - 1$
      end if
      if $v_s < 0$ then
        mortVieillesse$_s \leftarrow$ **true**, **vivant**$_s \leftarrow$ **false**
      end if
    end while
    fitness$_s \leftarrow f_s(l_s, a_s,$ **mortVieillesse**$_s)$
  end for
  $S \leftarrow$**les** 20% **meilleurs serpents au sens de fitness**$_s$
  Reconstitue $\mathcal{P} \leftarrow S \bigcup$ **mutations** $[$**croisements**$(\mathcal{P})]$
  $g \leftarrow g + 1$
end while

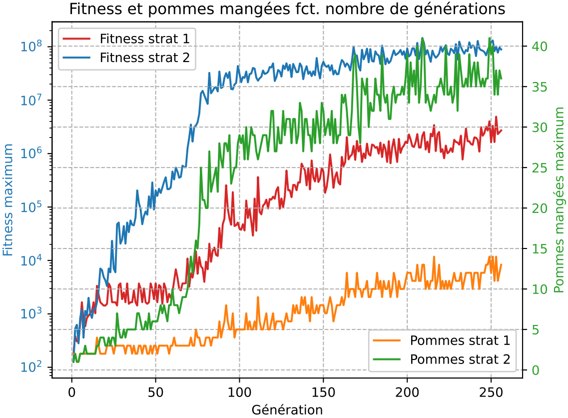


Population de serpents



Cerveau (stratégie n°2)

Résultats de convergence échiquier 10x10



Convergence des stratégies de vision n°1 et n°2

- **Observation:** la stratégie de vision n°2 converge plus rapidement que la stratégie n°1, et atteint un score de fitness plus élevé.
- **Interprétation:** la stratégie de vision n°2 fournit au serpent des informations plus pertinentes pour localiser et atteindre la pomme.
- **Après 2000 générations:** le serpent le plus long atteint en simulation est de taille 58 (plus de la moitié du plateau).

Conclusion

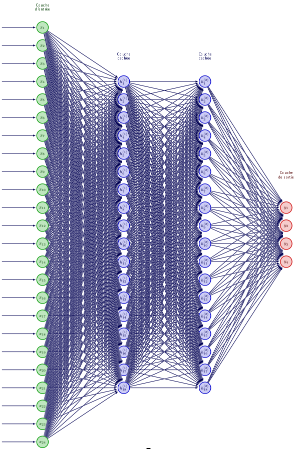
- Deux outils informatiques de modélisation et d'optimisation sont mis en œuvre pour jouer de manière autonome au jeu de Snake:
  - Des réseaux de neurones afin de prendre des décisions de mouvement, dont les entrées sont des informations visuelles.
  - Des algorithmes génétiques pour optimiser les poids et biais des réseaux de neurones.
- Dans les deux cas, ces outils sont inspirés de la nature, grande source d'inspiration pour l'ingénierie.
- Tous les programmes ont été implémentés en python avec une interface graphique pygame sans librairie annexe permettant une visualisation en temps réel de l'optimisation de la population de serpents.
- Différentes stratégies de vision et de fitness ont été proposées et discutées en terme de pertinence et performance.
- Des pistes d'amélioration restent à explorer:
  - Optimisation de la conception du réseau de neurones.
  - Utiliser une fonction de fitness dynamique pour mieux prendre en compte les contraintes de la taille du serpent.

Matrices des poids synaptiques

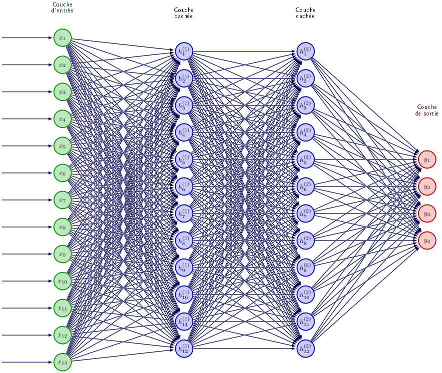
Cerveau du serpent: réseau de neurones $[n, m, m, k]$.

Formulation mathématique: couche d'entrée vision n, deux couches cachées m, couche de sortie direction k.

$$\underbrace{\begin{pmatrix} y_1 \\ y_2 \\ \vdots \\ y_k \end{pmatrix}}_{\text{Couche sortie}} = \sigma\left[\underbrace{\begin{pmatrix} h^{(2)}_{1,1} & h^{(2)}_{1,2} & \dots & h^{(2)}_{1,m} \\ h^{(2)}_{2,1} & h^{(2)}_{2,2} & \dots & h^{(2)}_{2,m} \\ \vdots & \vdots & \ddots & \vdots \\ h^{(2)}_{k,1} & h^{(2)}_{k,2} & \dots & h^{(2)}_{k,m} \end{pmatrix}}_{\text{Poids couche 3}} \sigma\left(\underbrace{\begin{pmatrix} h^{(1)}_{1,1} & h^{(1)}_{1,2} & \dots & h^{(1)}_{1,m} \\ h^{(1)}_{2,1} & h^{(1)}_{2,2} & \dots & h^{(1)}_{2,m} \\ \vdots & \vdots & \ddots & \vdots \\ h^{(1)}_{m,1} & h^{(1)}_{m,2} & \dots & h^{(1)}_{m,m} \end{pmatrix}}_{\text{Poids couche 2}} \sigma\left(\underbrace{\begin{pmatrix} h^{(1)}_{1,1} & h^{(1)}_{1,2} & \dots & h^{(1)}_{1,n} \\ h^{(1)}_{2,1} & h^{(1)}_{2,2} & \dots & h^{(1)}_{2,n} \\ \vdots & \vdots & \ddots & \vdots \\ h^{(1)}_{m,1} & h^{(1)}_{m,2} & \dots & h^{(1)}_{m,n} \end{pmatrix}}_{\text{Poids couche 1}} \underbrace{\begin{pmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{pmatrix}}_{\text{Couche entrée}} + \underbrace{\begin{pmatrix} b^{(1)}_1 \\ b^{(1)}_2 \\ \vdots \\ b^{(1)}_n \end{pmatrix}}_{\text{Bais couche 1}} \right) + \underbrace{\begin{pmatrix} b^{(2)}_1 \\ b^{(2)}_2 \\ \vdots \\ b^{(2)}_m \end{pmatrix}}_{\text{Bais couche 2}} \right) + \underbrace{\begin{pmatrix} b^{(3)}_1 \\ b^{(3)}_2 \\ \vdots \\ b^{(3)}_k \end{pmatrix}}_{\text{Bais couche 3}} \right]$$



Stratégie vision n°1: $[24, 18, 18, 4]$

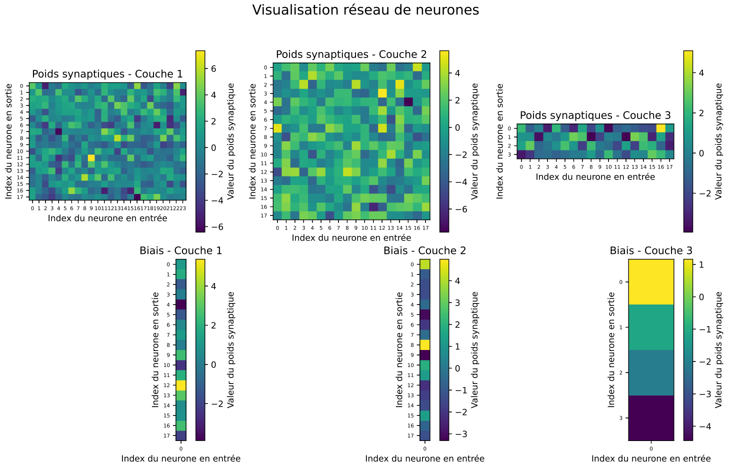


Stratégie vision n°2: $[13, 12, 12, 4]$

Convergence des matrices de poids synaptiques

Stratégie vision n°1: $[24, 18, 18, 4]$

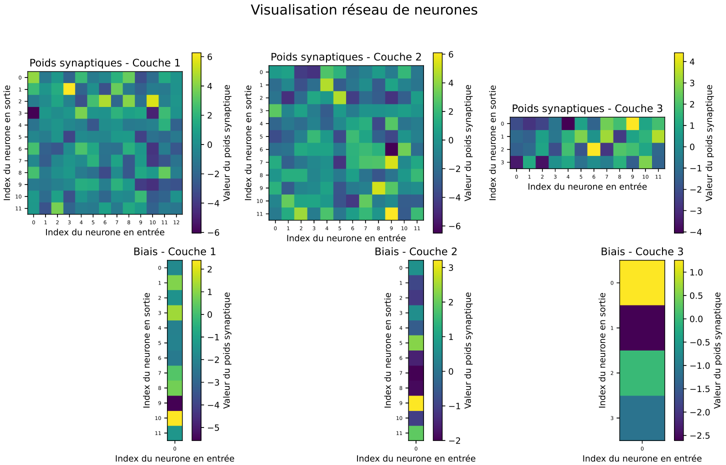
Couche d'entrée vision $n = 24$, deux couches cachées $m = 18$, couche de sortie direction $k = 4$.



Convergence des matrices de poids synaptiques

Stratégie vision n°2: $[13, 12, 12, 4]$

Couche d'entrée vision $n = 13$, deux couches cachées $m = 12$, couche de sortie direction $k = 4$.



Configuration I

config.py

```
DEBUG = False
ORIGINAL_SIZE_THREE = True
DISPLAY_ALL_POPULATION = True

DISPLAY_LARGEST_SNAKE = False

DISPLAY_GRAPHICS = False

# number of cells for the snake to move in each game
WIDTH = 10
HEIGHT = 10

BOARD_SIDE = 880 # indication of largest board side (for max of WIDTH and
↪   HEIGHT)
POPULATION = 22**2 # 484 population of snakes or number of games in the
↪   collection
ZOOM_FACTOR = 2 # zoom factor for the longest snake

# game strategy, 1:24,18,18,4; 2:9,10,10,4
GAME_STRATEGY = 5
FITNESS_STRATEGY = 3

MAX_ITERATION = 2000 # number of iterations before stopping the program
SAVE = True # save the game brains to a file
RESTORE = True # restore the game brains from a file
```

Configuration II
config.py

```
BRAINS_FILE = 'saved_brains' + '-' + str(POPULATION) + '-' +
↪  str(GAME_STRATEGY) + str(FITNESS_STRATEGY) + '.pickle' # name of the
↪  file to save the brains
CURVES_FILES = 'saved_curves' + '-' + str(POPULATION) + '-' +
↪  str(GAME_STRATEGY) + str(FITNESS_STRATEGY) + '.pickle' # name of the
↪  file to save the curves

NUMBER_CROSSOVER_POINTS = 2 # number of crossover points for the genetic
↪  algorithm
MUTATION_CHANCE = 0.1 # chance of mutation for the genetic algorithm
MUTATION_COEFF = 0.1 # coefficient for the mutation
PORTION_BESTS = 20 # percentage of bests brains to keep for the genetic
↪  algorithm

# antoine libs/game/lib.rs and game_wasm/src/lib.rs
# k=1 KPointsCrossover
#NUMBER_GAMES: u32 = 2_000; WIDTH: u32 = 30; HEIGHT: u32 = 30;
#MUTATION_CHANCE: f64 = 0.5; MUTATION_COEFF: f32 = 0.5; SAVE_BESTS: usize
↪  = 100; MAX_AGE: u32 = 500; APPLE_LIFETIME_GAIN: i32 = 50;

LIFE_TIME = True # apply life time constraint to the snake to avoid
↪  infinite loops
MAX_LIFE_POINTS = 50 # maximum number of life points for the snake
APPLE_LIFETIME_GAIN = 20 # number of life points gained when eating an
↪  apple
```

Configuration III

config.py

```
RESET_LIFETIME = True # reset life points when eating an apple
NORMALIZE_BOARD = False

SINGLE_SNAKE_BRAIN = 1 # number of snakes in the single snake game

PLAY_SNAKE_ITERATIONS = 1  # number of iterations for the play snake game

up = (0, 1);
down = (0, -1)
left = (-1, 0)
right = (1, 0)
up_right = (1, 1)
up_left = (-1, 1)
down_left = (-1, -1)
down_right = (1, -1)
eight_directions = [right, up_right, up, up_left, left, down_left, down,
↪  down_right]
four_directions = [right, up, left, down]
```

Un jeu I

game.py

```python
# un jeu = un seul serpent

from random import randrange
from neural_network import NeuralNetwork
from numpy import argmax
import collections
import config as c
from typing import Tuple, List
import math

class Game:

    vision = []

    def __init__(self, width: int = 10, height: int = 10, max_life_points:
    ↪   int = 50, apple_lifetime_gain: int = 500, strategy: int = 2,
    ↪   num_fitness: int = 1) -> None:
        self.width = width
        self.height = height
        self.max_life_points = max_life_points
        self.apple_lifetime_gain = apple_lifetime_gain
        self.strategy = strategy
        self.last_space = 0
        self.last_visited = set()
```

Un jeu II

game.py

```
"""
Various rules to create a neural network:
* The number of hidden neurons should be between the size of the
↪  input layer and the size of the output layer.
* The number of hidden neurons should be 2/3 the size of the input
↪  layer, plus the size of the output layer.
* The number of hidden neurons should be less than twice the size
↪  of the input layer.
* The number of hidden neurons should be between the size of the
↪  input layer and the output layer.
* The most appropriate number of hidden neurons is sqrt(input
↪  layer nodes * output layer nodes)
"""

if strategy == 1:
    # Neural network composed of 4 layers, input layer has 24
    ↪  neurons, 2 hidden layers each with 18 neurons, output
    ↪  layer has 4 neurons (4 directions)
    # in total it has 24 + 18 + 18 + 4 = 64 neurons.
    self.brain = NeuralNetwork([24, 18, 18, 4])
    self.vision_strategy = self.process_vision
elif strategy == 2:
    self.brain = NeuralNetwork([9, 10, 10, 4])
    self.vision_strategy = self.process_vision2
elif strategy == 3:
```

Un jeu III

game.py

```
        self.brain = NeuralNetwork([13, 12, 12, 4])
        self.vision_strategy = self.process_vision3
    elif strategy == 4:
        self.brain = NeuralNetwork([25, 18, 18, 4])
        self.vision_strategy = self.process_vision4
    elif strategy == 5:
        self.brain = NeuralNetwork([13, 12, 12, 4])
        self.vision_strategy = self.process_vision5

    self.age = 0
    self.lost = False
    self.apples_eaten = 0
    #self.direction = (-1, 0) # default direction is left for first
    ↪  move
    self.direction = (randrange(-1, 2), randrange(-1, 2)) # make first
    ↪  move random
    self.snake_body = [ # snake starts at the center and has 3 bits
        (int(width / 2), int(height / 2))
        ]
    if c.ORIGINAL_SIZE_THREE:
        self.snake_body.append((int(width / 2) + 1, int(height / 2)))
        self.snake_body.append((int(width / 2) + 2, int(height / 2))
        )
    self.original_size = len(self.snake_body)
    self.seed_new_apple()
```

Un jeu IV

game.py

```
        self.life_points = self.max_life_points
        self.died_bc_no_apple = 0
        self.death_reason = "None"
        if c.NORMALIZE_BOARD:
            self.norm_constant_diag = math.sqrt(width ** 2 + height ** 2)
            self.norm_constant_board = width * height / 10.0
        else:
            self.norm_constant_diag = 1
            self.norm_constant_board = 20.0

        if num_fitness == 1:
            self.fitness = self.fitness1
        elif num_fitness == 2:
            self.fitness = self.fitness2
        elif num_fitness == 3:
            self.fitness = self.fitness3
        elif num_fitness == 4:
            self.fitness = self.fitness4
        elif num_fitness == 5:
            self.fitness = self.fitness5

    def seed_new_apple(self):
        self.apple = (randrange(0, self.width), randrange(0, self.height))
        while self.apple in self.snake_body:
            self.apple = (randrange(0, self.width), randrange(0,
            ↪   self.height))
```

Un jeu V

game.py

```python
def step(self, life_time: bool) -> bool:
    # process the vision output through the neural network and output
    ↪  activation
    activation = self.brain.feedforward(self.vision_strategy())
    # take the highest activation index for the direction to take
    index = argmax(activation)

    match index:
        case 0:
            self.direction = c.right
        case 1:
            self.direction = c.up
        case 2:
            self.direction = c.left
        case 3:
            self.direction = c.down

    return self.move_snake(self.direction, life_time)

def move_snake(self, incrementer: Tuple[int, int], life_time: bool) ->
↪  bool:
    moved_head = (self.snake_body[0][0] + incrementer[0],
    ↪  self.snake_body[0][1] + incrementer[1])
```

Un jeu VI

game.py

```python
# vérification de la présence de la tête dans la grille
if not (0 <= moved_head[0] < self.width and 0 <= moved_head[1] <
↪   self.height):
    self.death_reason = "Wall"
    self.lost = True
    return False

# sauvegarde de la fin de la queue
end_tail = self.snake_body[-1]

# déplacement du serpent
for i in reversed(range(1, len(self.snake_body))):
    self.snake_body[i] = self.snake_body[i - 1]

self.snake_body[0] = moved_head

#collisions avec le corps
for bit in self.snake_body[1:]:
    if bit == self.snake_body[0]:
        self.lost = True
        self.death_reason = "Body"
        return False

self.age += 1
self.life_points -= 1
```

Un jeu VII

game.py

```
#collisions avec la pomme
if self.snake_body[0] == self.apple:
    self.snake_body.append(end_tail) # agrandir le serpent avec la
    ↪ queue précédente
    self.seed_new_apple()
    self.apples_eaten += 1
    if c.RESET_LIFETIME:
        self.life_points = self.max_life_points # on réinitialise
        ↪ la durée de vie au max
    else:
        self.life_points += self.apple_lifetime_gain # on
        ↪ réinitialise la durée de vie conformément au
        ↪ commentaire en dessous:
    # optimize not to recalculate last_visited and last_space for
    ↪ strategy 2
    # if moved_head is in last_visited it needs to be removed
    ↪ since the snake has its head there now
    if self.strategy == 2  or self.strategy == 5: # update
    ↪ last_visited and last_space
        if moved_head in self.last_visited: # adapt last_visited
        ↪ and last_space
            self.last_visited.remove(moved_head) # only head is to
            ↪ be removed since tail not moved with apple eaten
            self.last_space -= 1
```

Un jeu VIII

game.py

```
        else: # reset last_visited and last_space
            self.last_space = 0
            self.last_visited = set()
else:
    # optimize not to recalculate last_visited and last_space for
    ↪ strategy 2
    if self.strategy == 2 or self.strategy == 5: # update
    ↪ last_visited and last_space
        if moved_head in self.last_visited: # adapt last_visited
        ↪ and last_space
            self.last_visited.remove(moved_head) # only head is to
            ↪ be removed since tail not moved with apple eaten
            self.last_space -= 1
            # check if end_tail is connected to last_visited
            ↪ elements (can be visited) since it has moved and
            ↪ leaves an empty space
            if any(abs(end_tail[0] - x) == 1 ^ abs(end_tail[1] -
            ↪ y) == 1 for (x, y) in self.last_visited):
                self.last_visited.add((end_tail[0], end_tail[1]))
                self.last_space += 1
        else: # reset last_visited and last_space
            self.last_space = 0
            self.last_visited = set()

# vérification de la durée de vie
```

Un jeu IX

game.py

```
    if life_time and self.life_points <= 0:
        self.death_reason = "Life"
        self.lost = True
        self.died_bc_no_apple = 1
        return False

    return True

# vision strategy: 8 directions, 3 informations per direction
# (1D distance to apple in direction of move, 1 / wall_distance in
↪  direction of move, tail_distance in direction of move) +
↪  apples_eaten + original_size
def process_vision(self) -> List[float]:
    vision = [0 for _ in range(3*8)]

    for (i, incrementer) in enumerate(c.eight_directions):
        apple_distance = -1
        wall_distance = -1
        tail_distance = -1

        (x, y) = self.snake_body[0]
        distance = 0

        while True:
            x += incrementer[0]
```

Un jeu X

game.py

```
                y += incrementer[1]
                distance += 1

                # sortie de grille
                if not self.is_on_board(x, y):
                    wall_distance = distance
                    break

                # sur la pomme
                if (x, y) == self.apple and apple_distance == -1:
                    apple_distance = distance

                # sur la queue
                if (x, y) in self.snake_body and tail_distance == -1:
                    tail_distance = distance

            vision[3*i] = 0 if apple_distance == -1 else 1
            vision[3*i + 1] = 1 / wall_distance
            vision[3*i + 2] = tail_distance if tail_distance != -1 else 0

        self.vision = vision
        return vision

    # vision strategy: 4 directions, 3 informations per direction
    # (manhattan distance to apple, 1 / wall_distance in direction of
    ↪  move, tail_distance in direction of move) + apples_eaten +
    ↪  original_size
```

Un jeu XI

game.py

```
def process_vision3(self) -> List[float]:
    vision = []

    for (i, incrementer) in enumerate(c.four_directions):
        apple_distance = -1
        wall_distance = -1
        tail_distance = -1

        (x, y) = self.snake_body[0]
        distance = 0

        # try to get inputs between [0,1] for the neural network

        distance_apple = self.manhattan_distance_to_apple((x +
        ↪  incrementer[0], y + incrementer[1]))

        vision.append(1.0 / distance_apple if distance_apple != 0 else
        ↪  1)

        while True:
            x += incrementer[0]
            y += incrementer[1]
            distance += 1

            # sortie de grille
```

Un jeu XII

game.py

```
            if not self.is_on_board(x, y):
                wall_distance = distance
                break

            # sur la queue
            if (x, y) in self.snake_body and tail_distance == -1:
                tail_distance = distance

        vision.append(1.0 / wall_distance)
        vision.append(1.0 / tail_distance if tail_distance != -1 else
        ↪   1)

    vision.append(1 / (self.apples_eaten + self.original_size))

    self.vision = vision
    return vision

# vision strategy: 4 directions, 3 informations per direction
# (1 if direction is the closest to the apple, 1 / wall_distance in
↪   direction of move, tail_distance in direction of move) +
↪   apples_eaten + original_size
def process_vision4(self) -> List[float]:
    vision = []

    min_distance_index = min(range(len(c.eight_directions)),
    ↪   key=lambda i:
    ↪   self.manhattan_distance_to_apple((self.snake_body[0][0] +
    ↪   c.eight_directions[i][0], self.snake_body[0][1] +
```

Un jeu XIII

game.py

```python
for (i, incrementer) in enumerate(c.eight_directions):
    apple_distance = -1
    wall_distance = -1
    tail_distance = -1

    (x, y) = self.snake_body[0]
    distance = 0

    while True:
        x += incrementer[0]
        y += incrementer[1]
        distance += 1

        # sortie de grille
        if not self.is_on_board(x, y):
            wall_distance = distance
            break

        # sur la queue
        if (x, y) in self.snake_body and tail_distance == -1:
            tail_distance = distance

    vision.append(1 if i == min_distance_index else 0)
    vision.append(1.0 / wall_distance)
```

Un jeu XIV

game.py

```
        vision.append(tail_distance if tail_distance != -1 else 0)

    vision.append(self.apples_eaten + self.original_size)
    self.vision = vision
    return vision

#? weights 8 bits vs. float? normalization?

# vision strategy: 4 directions, 3 informations per direction
# (free spaces in direction of move, manhattan distance to apple in
↪   direction of move, apple is in the free space in this direction) +
↪   apples_eaten + original_size
def process_vision5(self) -> List[float]:
    # neural network input contains free space in all directions,
    ↪   distance to apple in all directions, and number of apples
    ↪   eaten (size of snake)
    # 9 inputs in total
    neural_network_input = []
    (hx, hy) = self.snake_body[0] # head of the snake body
    for direction in c.four_directions:
        (dx, dy) = direction
        (cnx, cny) = (hx + dx, hy + dy)
        #metric = self.count_free_moving_spaces(cnx, cny)
        #neural_network_input.append(1.0 / metric if metric != 0 else
        ↪   1)
```

Un jeu XV

game.py

```
            #metric = self.manhattan_distance_to_apple((cnx, cny))
            #neural_network_input.append(1.0 / metric if metric != 0 else
            ↪  1)
            neural_network_input.append(self.count_free_moving_spaces(cnx,
            ↪  cny) / self.norm_constant_board)

            ↪  neural_network_input.append(self.manhattan_distance_to_apple((cnx,
            ↪  cny)) / self.norm_constant_diag)
            neural_network_input.append(1 if self.apple in
            ↪  self.last_visited else 0) # apple can be reached going in
            ↪  this direction
        #neural_network_input.append(1.0 / (self.apples_eaten +
        ↪  self.original_size))
        neural_network_input.append(self.apples_eaten +
        ↪  self.original_size)
        self.vision = neural_network_input
        return neural_network_input

    # vision strategy: 4 directions, 2 informations per direction
    # (free spaces in direction of move, manhattan distance to apple in
    ↪  direction of move) + apples_eaten + original_size
    def process_vision2(self) -> List[float]:
        # neural network input contains free space in all directions,
        ↪  distance to apple in all directions, and number of apples
        ↪  eaten (size of snake)
```

Un jeu XVI

game.py

```
        # 9 inputs in total
        neural_network_input = []
        (hx, hy) = self.snake_body[0] # head of the snake body
        for direction in c.four_directions:
            (dx, dy) = direction
            (cnx, cny) = (hx + dx, hy + dy)
            #metric = self.count_free_moving_spaces(cnx, cny)
            #neural_network_input.append(1.0 / metric if metric != 0 else
            ↪   1)
            #metric = self.manhattan_distance_to_apple((cnx, cny))
            #neural_network_input.append(1.0 / metric if metric != 0 else
            ↪   1)
            neural_network_input.append(self.count_free_moving_spaces(cnx,
            ↪   cny) / self.norm_constant_board)

            ↪   neural_network_input.append(self.manhattan_distance_to_apple((cnx,
            ↪   cny)) / self.norm_constant_diag)
        #neural_network_input.append(1.0 / (self.apples_eaten +
        ↪   self.original_size))
        neural_network_input.append(self.apples_eaten +
        ↪   self.original_size)
        self.vision = neural_network_input
        return neural_network_input

    def is_on_board(self, x, y) -> bool:
```

Un jeu XVII

game.py

```
        return 0 <= x < self.width and 0 <= y < self.height

    def is_possible_move(self, x, y) -> bool:
        # check if the move is on the board and not on the snake body
        ↪  except for the tail (since it has moved)
        return self.is_on_board(x, y) and (x, y) not in
        ↪  self.snake_body[:-1]

    def get_possible_moves(self, cur):
        (x, y) = cur
        moves = []
        for direction in c.eight_directions:
            (i, j) = direction
            if self.is_possible_move(x + i, y + j):
                moves.append(direction)
        return moves

    def count_free_moving_spaces(self, x, y) -> int:
        # Breadth-First Search, BFS, snake heads moves to (x, y) and
        ↪  tail's end is no more
        if not self.is_possible_move(x, y): # does not check snake's tail
            return 0
        if (x, y) in self.last_visited:
            return self.last_space
        space = 0
```

Un jeu XVIII

game.py

```
        visited = set([(x, y)])
        queue = collections.deque([(x, y)]) # efficient for pop(0) and
        ↪   append
        while (len(queue) > 0):
            cur = queue.popleft()
            space += 1
            for direction in self.get_possible_moves(cur):
                (i, j) = direction
                (cx, cy) = cur
                cn = (cx + i, cy + j)
                (cnx, cny) = cn
                if cn not in visited and self.is_possible_move(cnx, cny):
                ↪   # does not check snake's tail
                    queue.append(cn)
                    visited.add(cn)
        self.last_visited = visited
        self.last_space = space
        return space

    def manhattan_distance_to_apple(self, head):
        return abs(self.apple[0] - head[0]) + abs(self.apple[1] - head[1])

    def fitness1(self):
        return pow(3, self.apples_eaten) * (self.age - c.MAX_LIFE_POINTS *
        ↪   self.died_bc_no_apple)
```

Un jeu XIX

game.py

```
def fitness2(self):
    return (self.apples_eaten ** 3) * (self.age - c.MAX_LIFE_POINTS *
    ↪   self.died_bc_no_apple)

def fitness3(self):
    return ((self.apples_eaten * 2) ** 2) * ((self.age -
    ↪   c.MAX_LIFE_POINTS * self.died_bc_no_apple) ** 1.5)

def fitness4(self):
    return (self.age * self.age) * pow(2, self.apples_eaten) * (100 *
    ↪   self.apples_eaten + 1)

def fitness5(self):
    return (self.age * self.age * self.age * self.age) * pow(2,
    ↪   self.apples_eaten) * (500 * self.apples_eaten + 1)

# age^2*2^apple*(coeff*apple+1)
# age^2*2^10*(apple-9)*(coeff*10)

# score = self.apples_eaten, frame_score = self.age
# ((score^3)*(frame_score)
# ((score*2)^2)*(frame_score^1.5)
```

Un jeu XX

game.py

```
# remarks
# * 3^apple*(age): pow(3, self.apples_eaten) * (self.age - 50 *
↪   self.died_bc_no_apple) trains faster
```

La population: collection de jeux I

game_collection.py

```
# serpents en parallèle

from game import Game
from genetic_algorithm import GeneticAlgorithm
import pickle
import config as c
import math
from typing import List, Tuple

class GameCollection:
    games = []
    ga = GeneticAlgorithm(math.ceil(c.PORTION_BESTS * c.POPULATION / 100),
    ↪  c.NUMBER_CROSSOVER_POINTS, c.MUTATION_CHANCE, c.MUTATION_COEFF)
    iteration = 0
    generation = 1

    def __init__(self, number_games:int, width:int, height:int) -> None:
        self.games = [Game(width, height, c.MAX_LIFE_POINTS,
        ↪  c.APPLE_LIFETIME_GAIN, c.GAME_STRATEGY, c.FITNESS_STRATEGY)
        ↪  for _ in range(number_games)]

    def snake_to_display(self) -> Tuple[Game, int]:
        for i in range(len(self.games)):
            if not self.games[i].lost:
                return self.games[i], i
```

La population: collection de jeux II

game_collection.py

```
        return self.games[0], 0

    def longest_snake(self) -> Tuple[Game, int]:
        longest = 0
        index = 0
        for i in range(len(self.games)):
            if len(self.games[i].snake_body) > longest:
                longest = len(self.games[i].snake_body)
                index = i
        return self.games[index], index

    def step(self, life_time: bool) -> bool:

        self.iteration += 1

        one_game_not_lost = False

        for game in self.games:
            if not game.lost:
                one_game_not_lost = True
                game.step(life_time)

        # if all games are lost, evolve
        if not one_game_not_lost:
            self.evolve()
```

La population: collection de jeux III

game_collection.py

```
        return one_game_not_lost

    def evolve(self):

        new_population = self.ga.evolve([
            (game.brain, game.fitness())
            for game in self.games
        ])

        width, height = self.games[0].width, self.games[0].height

        for i in range(len(new_population)):
            g = Game(width, height, c.MAX_LIFE_POINTS,
            ↪   c.APPLE_LIFETIME_GAIN, c.GAME_STRATEGY,
            ↪   c.FITNESS_STRATEGY) # create new game
            g.brain = new_population[i] # inject brain in game
            self.games[i] = g # replace current game with new one

        self.iteration = 0
        self.generation += 1

    def save_brains(self, filename):
        # save the game collection and all the games in the game
        ↪   collection to a file
        #for game in self.games:
```

La population: collection de jeux IV

game_collection.py

```
        #    print(game.brain.layers_sizes)
        new_games = sorted(self.games, key=lambda game: game.fitness())
        game_brains = [game.brain for game in new_games]
        if c.DEBUG:
            for brain in game_brains:
                print(brain.weights, end=' ')
            print()
        print("save_brains: len(game_brains): ", len(game_brains))
        with open(filename, 'wb') as f:
            pickle.dump(game_brains, f)

    def restore_brains(self, filename):
        with open(filename, 'rb') as f:
            game_brains = pickle.load(f)
            print("restore_brains: len(game_brains): ", len(game_brains))
            for i in range(len(self.games)):
                self.games[i].brain = game_brains[i]
            if c.DEBUG:
                for brain in game_brains:
                    print(brain.weights, end=' ')
                print()

    def save_to_file(self, filename):
        with open(filename, 'wb') as f:
            pickle.dump(self, f)
```

La population: collection de jeux V

game_collection.py

```python
@classmethod
def load_from_file(cls, filename):
    with open(filename, 'rb') as f:
        return pickle.load(f)

def best_fitness(self):
    return max(game.fitness() for game in self.games)

def worst_fitness(self):
    return min(game.fitness() for game in self.games)

def average_fitness(self):
    return sum(game.fitness() for game in self.games) /
    ↪  len(self.games)

def max_apple_eaten(self):
    return max(game.apples_eaten for game in self.games)

def min_apple_eaten(self):
    return min(game.apples_eaten for game in self.games)

def average_apple_eaten(self):
    return sum(game.apples_eaten for game in self.games) /
    ↪  len(self.games)
```

Algorithme génétique I

genetic_algorithm.py

```
import numpy as np

from neural_network import NeuralNetwork
from typing import List, Tuple
import copy

class GeneticAlgorithm:

    def __init__(self, save_bests: int = 10, k: int = 5, mut_chance: float
    ↪ = 0.5, coeff: float = 0.5) -> None:
        self.save_bests = save_bests
        self.k = k
        self.mut_chance = mut_chance
        self.coeff = coeff

    def select_parent(self, population: List[Tuple[NeuralNetwork, int]])
    ↪ -> Tuple[NeuralNetwork, NeuralNetwork]:
        # Roulette-wheel selection: numpy.random.choice
        maxi = sum([x[1] for x in population])
        selection_probability = [x[1] / maxi for x in population]
        parent1, parent2 = np.random.choice(len(population),
        ↪ p=selection_probability), np.random.choice(len(population),
        ↪ p=selection_probability)
        return population[parent1][0], population[parent2][0]
```

Algorithme génétique II

genetic_algorithm.py

```
def crossover(self, parent_a: List[float], parent_b: List[float]) ->
↪   List[float]:
    """
    K-point crossover cf Wikipedia:
    - select k random points in range(len(parent_a))
    - create a new array which alternate between coefficients of
    ↪   parent_a and parent_b
    """
    n = len(parent_a)
    # list of crossover points
    l = sorted([np.random.randint(0, n) for _ in range(self.k)]) # to
    ↪   avoid having two times the same index
    l.append(-1) # to avoid index out of range but never ued
    child = []
    current_parent = 0
    current_index = 0
    for i in range(n):
        if i == l[current_index]:
            current_parent = 1 - current_parent
            current_index += 1
        if current_parent == 0:
            child.append(parent_a[i])
        else:
            child.append(parent_b[i])
    return child
```

Algorithme génétique III

genetic_algorithm.py

```
def mutate(self, genome: List[float]) -> None:
    """
    Gaussian mutation:
    - for each coefficient:
        - if random() <=  mutation chance (paramètre réglé):
            - generate a sign at random
            - generate an amplitude (between 0 and 1)
            - add sign * amplitude * coeff to the coefficient (coeff
            ↪  is a parameter)
    """
    for i in range(len(genome)):
        if np.random.random() <= self.mut_chance:
            sign = 1 if np.random.random() <= 0.5 else -1
            amplitude = np.random.random()
            genome[i] += sign * amplitude * self.coeff

def evolve(self, population: Tuple[NeuralNetwork, int]) -> list:
    assert(len(population) != 0)
    new_population = []
    # sélection des meilleurs
    population.sort(key=lambda x : x[1], reverse=True)
    for i in range(len(population)):
        if i < self.save_bests:
            new_population.append(copy.deepcopy(population[i][0])) #
            ↪  to avoid reference
```

Algorithme génétique IV

genetic_algorithm.py

```
        else:
            parent_a, parent_b = self.select_parent(population)
            child = self.crossover(parent_a.to_genome(),
            ↪  parent_b.to_genome())
            self.mutate(child)
            new_population.append(NeuralNetwork.from_genome(child,
            ↪  population[i][0].layers_sizes))
    return new_population
```

Réseau de neurones I

neural_network.py

```python
import numpy as np
from typing import List

def sigmoid(x):
    return 1.0/(1.0 + np.exp(-x))

class NeuralNetwork:

    layers_sizes = []
    weights = []
    biases = []
    activation_function = None

    def __init__(self, layers_sizes:List[int]) -> None:
        self.biases = [np.random.randn(i, 1) for i in layers_sizes[1:]]
        self.weights = [np.random.randn(i, j) for (i, j) in
        ↪  zip(layers_sizes[1:], layers_sizes[:-1])]
        self.activation_function = sigmoid
        self.layers_sizes = layers_sizes

    def feedforward(self, activation):
        for w, b in zip(self.weights, self.biases):
            activation = self.activation_function(np.dot(w, activation) +
            ↪  b)
        return activation
```

Réseau de neurones II

neural_network.py

```python
"""
def to_genome(self) -> List[float]:
    genome = []
    for w in self.weights:
        for line in w:
            for c in line:
                genome.append(c)
    for b in self.biases:
        for c in b:
            genome.append(c)
    return genome
"""

def to_genome(self) -> List[float]:
    genome = np.concatenate([w.flatten() for w in self.weights] +
    ↪  [b.flatten() for b in self.biases])
    return genome.tolist()

@classmethod
def from_genome(cls, genome: List[float], layers: List[int]):
    assert len(layers) > 0
    nn = cls(layers)
    # this code is more efficient than the commented code below
    ↪  because it avoids the list inversions
```

Réseau de neurones III

neural_network.py

```
offset = 0
for i, (j, k) in enumerate(zip(layers[:-1], layers[1:])):
    nn.weights[i] = np.reshape(genome[offset:offset + j * k], (k,
    ↪  j))
    offset += j * k
for i, k in enumerate(layers[1:]):
    nn.biases[i] = np.reshape(genome[offset:offset + k], (k, 1))
    offset += k
"""
genome = list(reversed(genome))
nn.weights = [np.array([[genome.pop() for _ in range(j)] for _ in
↪  range(i)]) for (i, j) in zip(nn.layers_sizes[1:],
↪  nn.layers_sizes[:-1])]
nn.biases = [np.array([genome.pop() for _ in range(i)]) for i in
↪  nn.layers_sizes[1:]]
"""
return nn
```

Programme principal I

main.py

```
import pygame
import os
import signal
import sys
from game_collection import GameCollection
import math
import matplotlib.pyplot as plt
import numpy as np
import config as c
from scipy.interpolate import make_interp_spline
import pickle
import sys

game_collection = GameCollection(c.POPULATION, c.WIDTH, c.HEIGHT)

if c.RESTORE and os.path.exists(c.BRAINS_FILE):
    game_collection.restore_brains(c.BRAINS_FILE)
# board with all populations has games_per_side games per side
# each game has WIDTH x HEIGHT cells

if c.DISPLAY_ALL_POPULATION:
    games_per_side = math.ceil(math.sqrt(c.POPULATION))
else:
    games_per_side = 1
```

Programme principal II

main.py

```
CELL_SIDE = (c.BOARD_SIDE // games_per_side) // max(c.WIDTH, c.HEIGHT)
GAME_WIDTH = CELL_SIDE * c.WIDTH
GAME_HEIGHT = CELL_SIDE * c.HEIGHT
BOARD_WIDTH = games_per_side * GAME_WIDTH
BOARD_HEIGHT = games_per_side * GAME_HEIGHT

print(f"CELL_SIDE: {CELL_SIDE}, GAME_WIDTH: {GAME_WIDTH}, GAME_HEIGHT:
↪   {GAME_HEIGHT}, BOARD_WIDTH: {BOARD_WIDTH}, BOARD_HEIGHT:
↪   {BOARD_HEIGHT}")

if c.DISPLAY_GRAPHICS:
    # pygame setup
    pygame.init()
    screen = pygame.display.set_mode((BOARD_WIDTH, BOARD_HEIGHT))
    clock = pygame.time.Clock()

running = True
dt = 0

iteration = 0

max_fitness = []
min_fitness = []
avg_fitness = []
max_apple_eaten = []
```

Programme principal III

main.py

```
min_apple_eaten = []
avg_apple_eaten = []
max_snake_length = 0

def save_curves(filename):
    with open(filename, 'wb') as f:
        pickle.dump((max_fitness, min_fitness, avg_fitness,
        ↪  max_apple_eaten, min_apple_eaten, avg_apple_eaten,
        ↪  max_snake_length), f)

def restore_curves(filename):
    with open(filename, 'rb') as f:
        data = pickle.load(f)
    return data

def save_and_exit(signal, frame):
    if c.SAVE:
        game_collection.save_brains(c.BRAINS_FILE)
        save_curves(c.CURVES_FILES)
    sys.exit(0)

# save program state in case of interruption
signal.signal(signal.SIGINT, save_and_exit)

while running:
```

Programme principal IV

main.py

```
cur_max_fitness = game_collection.best_fitness()
cur_min_fitness = game_collection.worst_fitness()
cur_avg_fitness = game_collection.average_fitness()
cur_max_apple_eaten = game_collection.max_apple_eaten()
cur_min_apple_eaten = game_collection.min_apple_eaten()
cur_avg_apple_eaten = game_collection.average_apple_eaten()

if cur_max_apple_eaten >= max_snake_length:
    max_snake_length = cur_max_apple_eaten + 1

# retrieve the new game
if c.DISPLAY_LARGEST_SNAKE:
    game, current_snake = game_collection.longest_snake() # to see the
    ↪  longest snake
else:
    game, current_snake = game_collection.snake_to_display()

# display game iteration and fitness of the game (generation) as
↪  window title
#info = f"Gen {game_collection.generation} - Iter
↪  {game_collection.iteration} - Fitness {game.fitness():.2e} - Max
↪  fitness {cur_max_fitness:.2e} - Avg fitness
↪  {round(cur_avg_fitness, 2):.2e} - Max eaten {cur_max_apple_eaten}
↪  - Longest ever {max_snake_length}"
```

Programme principal V

main.py

```python
info = f"Gen {game_collection.generation} - Iter {game_collection.iteration} - Fitness ({cur_min_fitness:.1e}:{cur_avg_fitness:.1e}:{cur_max_fitness:.1e}) - Apple ({cur_min_apple_eaten}:{round(cur_avg_apple_eaten, 1)}:{cur_max_apple_eaten}) - Best snake {max_snake_length}"

if c.DISPLAY_GRAPHICS:
    # poll for events
    # pygame.QUIT event means the user clicked X to close your window
    for event in pygame.event.get():
        if event.type == pygame.QUIT:
            running = False
    # fill the screen with a color to wipe away anything from last frame
    screen.fill("white")

    pygame.display.set_caption(info)

    if not c.DISPLAY_ALL_POPULATION:
        for (x, y) in game.snake_body:
            pygame.draw.circle(screen, "darkolivegreen3", (x * CELL_SIDE + CELL_SIDE / 2, y * CELL_SIDE + CELL_SIDE / 2), CELL_SIDE / 2)
        (x, y) = game.snake_body[0] # head of the snake
        pygame.draw.circle(screen, "black", (x * CELL_SIDE + CELL_SIDE / 2, y * CELL_SIDE + CELL_SIDE / 2), CELL_SIDE / 4)
```

Programme principal VI

main.py

```
        (x, y) = game.apple
        pygame.draw.circle(screen, "brown3", (x * CELL_SIDE +
        ↪  CELL_SIDE / 2, y * CELL_SIDE + CELL_SIDE / 2), CELL_SIDE /
        ↪  2)
        # surround the current game with a black rectangle
        pygame.draw.rect(screen, "black", (BOARD_WIDTH, BOARD_HEIGHT,
        ↪  BOARD_WIDTH, BOARD_HEIGHT), 1)
    else:
        # draw all games of the game collection in one big table and
        ↪  each game has coordinate and use a square matrix of
        ↪  sqrt(POPULATION) x sqrt(POPULATION)
        # Iterate over each game in the collection
        for i, game in enumerate(game_collection.games):
            # Calculate the row and column of the current game in the
            ↪  table
            row = i // games_per_side
            col = i % games_per_side

            # if game is lost change the color of the rectangle to red
            if game.lost:
                pygame.draw.rect(screen, "red", (col * GAME_WIDTH, row
                ↪  * GAME_HEIGHT, GAME_WIDTH, GAME_HEIGHT))

            # do a case switch to change the color of the rectangle
            ↪  depending on the death reason
```

Programme principal VII

main.py

```python
if game.death_reason == "Wall":
    pygame.draw.rect(screen, "orange", (col * GAME_WIDTH,
    ↪  row * GAME_HEIGHT, GAME_WIDTH, GAME_HEIGHT))
elif game.death_reason == "Body":
    pygame.draw.rect(screen, "blue", (col * GAME_WIDTH,
    ↪  row * GAME_HEIGHT, GAME_WIDTH, GAME_HEIGHT))
elif game.death_reason == "Life":
    pygame.draw.rect(screen, "green", (col * GAME_WIDTH,
    ↪  row * GAME_HEIGHT, GAME_WIDTH, GAME_HEIGHT))

# surround the current game with a black rectangle
pygame.draw.rect(screen, "black", (col * GAME_WIDTH, row *
↪  GAME_HEIGHT, GAME_WIDTH, GAME_HEIGHT), 1)

# Calculate the position of the game cell on the screen
cell_x = col * GAME_WIDTH
cell_y = row * GAME_HEIGHT

# Draw the game on the screen at the calculated position
for (x, y) in game.snake_body:
    pygame.draw.circle(screen, "darkolivegreen3", (cell_x
    ↪  + x * CELL_SIDE + CELL_SIDE / 2, cell_y + y *
    ↪  CELL_SIDE + CELL_SIDE / 2), CELL_SIDE / 2)
(x, y) = game.snake_body[0]
pygame.draw.circle(screen, "black", (cell_x + x *
↪  CELL_SIDE + CELL_SIDE / 2, cell_y + y * CELL_SIDE +
↪  CELL_SIDE / 2), CELL_SIDE / 4)
```

Programme principal VIII

main.py

```
    (x, y) = game.apple
    pygame.draw.circle(screen, "brown3", (cell_x + x *
    ↪   CELL_SIDE + CELL_SIDE / 2, cell_y + y * CELL_SIDE +
    ↪   CELL_SIDE / 2), CELL_SIDE / 2)

# zoom on longest snake
game, current_snake = game_collection.longest_snake() # to see
↪   the longest snake
row = current_snake // games_per_side
col = current_snake % games_per_side
cell_x = col * GAME_WIDTH
cell_y = row * GAME_HEIGHT
# draw a white rectangle centred on (cell_x, cell_y) with a
↪   width of c.ZOOM_FACTOR * WIDTH + CELL_SIDE and a height of
↪   c.ZOOM_FACTOR * HEIGHT + CELL_SIDE
pygame.draw.rect(screen, "yellow", (cell_x, cell_y,
↪   c.ZOOM_FACTOR * GAME_WIDTH, c.ZOOM_FACTOR * GAME_HEIGHT))
for (x, y) in game.snake_body:
    pygame.draw.circle(screen, "darkolivegreen3", (cell_x +
    ↪   c.ZOOM_FACTOR * (x + CELL_SIDE + CELL_SIDE / 2),
    ↪   cell_y + c.ZOOM_FACTOR * (y * CELL_SIDE + CELL_SIDE /
    ↪   2)), c.ZOOM_FACTOR * CELL_SIDE / 2)
(x, y) = game.snake_body[0]
pygame.draw.circle(screen, "black", (cell_x + c.ZOOM_FACTOR *
↪   (x + CELL_SIDE + CELL_SIDE / 2), cell_y + c.ZOOM_FACTOR *
↪   (y * CELL_SIDE + CELL_SIDE / 2)), c.ZOOM_FACTOR *
↪   CELL_SIDE / 4)
```

Programme principal IX

main.py

```
            (x, y) = game.apple
            pygame.draw.circle(screen, "brown3", (cell_x + c.ZOOM_FACTOR *
            ↪  (x + CELL_SIDE + CELL_SIDE / 2), cell_y + c.ZOOM_FACTOR *
            ↪  (y * CELL_SIDE + CELL_SIDE / 2)), c.ZOOM_FACTOR *
            ↪  CELL_SIDE / 2)
    else:
        print(info)


    # update your game state here
    if not game_collection.step(c.LIFE_TIME): # all sakes in collection
    ↪  dead go next iteration
        max_fitness.append(cur_max_fitness)
        min_fitness.append(cur_min_fitness)
        avg_fitness.append(cur_avg_fitness)
        max_apple_eaten.append(cur_max_apple_eaten)
        min_apple_eaten.append(cur_min_apple_eaten)
        avg_apple_eaten.append(cur_avg_apple_eaten)
        # plot max_fitness as function of 0:iteration
        iteration += 1
        if iteration >= c.MAX_ITERATION:
            break

    if c.DISPLAY_GRAPHICS:
        # flip() the display to put your work on screen
```

Programme principal X

main.py

```
        pygame.display.flip()

        clock.tick(500)

if c.SAVE:
    game_collection.save_brains(c.BRAINS_FILE)
    save_curves(c.CURVES_FILES)

print(max_fitness)

fig, ax1 = plt.subplots()

color1 = 'tab:blue'
color2 = 'tab:red'
color3 = 'tab:green'
color4 = 'tab:orange'

ax1.set_xlabel('Génération')
ax1.set_ylabel('Fitness maximum', color=color1)
ax1.set_yscale('log')

# Key change: Use iterations as the x-axis data
ax1.plot(range(len(max_fitness)), max_fitness, color=color2,
↪  label='Fitness max')
ax1.plot(range(len(avg_fitness)), avg_fitness, color=color1,
↪  label='Fitness avg')
```

Programme principal XI

main.py

```
ax1.tick_params(axis='y', labelcolor=color1)

ax1.legend(loc='upper left')  # Add a legend for clarity

color3 = 'tab:green'
ax2 = ax1.twinx()
ax2.set_ylabel('Pommes mangées maximum', color=color3)
# Key change: Use iterations as the x-axis data
ax2.plot(range(len(max_apple_eaten)), max_apple_eaten, color=color4,
↪  label='Pommes')
ax2.tick_params(axis='y', labelcolor=color3)

ax2.legend(loc='lower right')

# Add Vertical Gridlines (The Key Change)
ax1.grid(axis='x', linestyle='--')  # Gridlines on the x-axis (iterations)
ax2.grid(axis='y', linestyle='--')  # You need to add it for the second
↪  axis too

# Additional styling improvement
plt.title('Fitness et pommes mangées fct. nombre de générations')
fig.tight_layout()

plt.show()
```

Programme principal XII

main.py

```python
if c.DISPLAY_GRAPHICS:
    pygame.quit()
```

Rejouer le meilleur serpent sauvé I

play_snake.py

```
import pygame
import os
import pickle
from game import Game
import config as c
from PIL import Image

def restore_snake(brain_number: int) -> Game:
    # restore brain from file and inject it into the snake
    assert(os.path.exists(c.BRAINS_FILE))
    game = Game(c.WIDTH, c.HEIGHT, c.MAX_LIFE_POINTS,
    ↪  c.APPLE_LIFETIME_GAIN, c.GAME_STRATEGY, c.FITNESS_STRATEGY)
    with open(c.BRAINS_FILE, 'rb') as f:
        game_brains = pickle.load(f)
        game.brain = game_brains[brain_number]
        if c.DEBUG:
            print(game.brain, end=' ')
            print()
    return game

game = restore_snake(c.SINGLE_SNAKE_BRAIN)

frames = []

# pygame setup
```

Rejouer le meilleur serpent sauvé II

play_snake.py

```python
pygame.init()

# board contains one game/snake

#CELL_SIDE = c.BOARD_SIDE // max(c.WIDTH, c.HEIGHT)
CELL_SIDE = 10
GAME_WIDTH = CELL_SIDE * c.WIDTH
GAME_HEIGHT = CELL_SIDE * c.HEIGHT

screen = pygame.display.set_mode((GAME_WIDTH, GAME_HEIGHT))

clock = pygame.time.Clock()
running = True
dt = 0

iteration = 0

max_snake_length = 0

for n in range(c.PLAY_SNAKE_ITERATIONS):
    while running:

        iteration += 1

        cur_fitness = game.fitness()
```

Rejouer le meilleur serpent sauvé III

play_snake.py

```python
cur_apple_eaten = game.apples_eaten
if cur_apple_eaten >= max_snake_length:
    max_snake_length = cur_apple_eaten + 1

# display game iteration and fitness of the game (generation) as
↪  window title
info = f"Iter {iteration} - Fitness {cur_fitness:.2e} - Eaten
↪  {cur_apple_eaten} - Longest ever {max_snake_length}"

# poll for events
# pygame.QUIT event means the user clicked X to close your window
for event in pygame.event.get():
    if event.type == pygame.QUIT:
        running = False
# fill the screen with a color to wipe away anything from last
↪  frame
screen.fill("white")
# draw grid
for x in range(0, GAME_WIDTH, CELL_SIDE):
    pygame.draw.line(screen, "gray", (x, 0), (x, GAME_HEIGHT))
for y in range(0, GAME_HEIGHT, CELL_SIDE):
    pygame.draw.line(screen, "gray", (0, y), (GAME_WIDTH, y))

pygame.display.set_caption(info)
```

Rejouer le meilleur serpent sauvé IV

play_snake.py

```
        for (x, y) in game.snake_body:
            pygame.draw.circle(screen, "darkolivegreen3", (x * CELL_SIDE +
            ↪  CELL_SIDE / 2, y * CELL_SIDE + CELL_SIDE / 2), CELL_SIDE /
            ↪  2)
        (x, y) = game.snake_body[0] # head of the snake
        pygame.draw.circle(screen, "black", (x * CELL_SIDE + CELL_SIDE /
        ↪  2, y * CELL_SIDE + CELL_SIDE / 2), CELL_SIDE / 4)
        (x, y) = game.apple
        pygame.draw.circle(screen, "brown3", (x * CELL_SIDE + CELL_SIDE /
        ↪  2, y * CELL_SIDE + CELL_SIDE / 2), CELL_SIDE / 2)
        # suround the current game with a black rectangle
        pygame.draw.rect(screen, "black", (GAME_WIDTH, GAME_HEIGHT,
        ↪  GAME_WIDTH, GAME_HEIGHT), 1)

        # update your game state here (do not constrain snake life time)
        if not game.step(False): # snake is dead
            break;
        # flip() the display to put your work on screen
        pygame.display.flip()
        frame_str = pygame.image.tostring(screen, "RGB")
        frame_image = Image.frombytes("RGB", (GAME_WIDTH, GAME_HEIGHT),
        ↪  frame_str)
        frames.append(frame_image)
        clock.tick(25)
    iteration = 0;
```

Rejouer le meilleur serpent sauvé V

play_snake.py

```
    game = restore_snake(c.SINGLE_SNAKE_BRAIN)

frames[0].save("game_animation.gif", save_all=True,
↪  append_images=frames[1:], duration=100, loop=0)
pygame.quit()
```

Courbes de convergence I

plot_compare_convergences.py

```python
import pickle
import matplotlib.pyplot as plt

def restore_curves(filename):
    with open(filename, 'rb') as f:
        data = pickle.load(f)
    return data

max_iterations = 256

(max_fitness5, min_fitness5, avg_fitness5, max_apple_eaten5,
↪   min_apple_eaten5, avg_apple_eaten5, max_snake_length5) =
↪   restore_curves("curve_53.pickle")
(max_fitness1, min_fitness1, avg_fitness1, max_apple_eaten1,
↪   min_apple_eaten1, avg_apple_eaten1, max_snake_length1) =
↪   restore_curves("curve_13.pickle")

fig, ax1 = plt.subplots()

color1 = 'tab:blue'
color2 = 'tab:red'
color3 = 'tab:green'
color4 = 'tab:orange'

ax1.set_xlabel('Génération')
```

Courbes de convergence II

plot_compare_convergences.py

```
ax1.set_ylabel('Fitness maximum', color=color1)
ax1.set_yscale('log')
# Key change: Use iterations as the x-axis data
ax1.plot(range(1, max_iterations + 1), max_fitness1[1:max_iterations + 1],
↪  color=color2, label='Fitness strat 1')
ax1.plot(range(1, max_iterations + 1), max_fitness5[1:max_iterations + 1],
↪  color=color1, label='Fitness strat 2')
ax1.tick_params(axis='y', labelcolor=color1)

ax1.legend(loc='upper left')  # Add a legend for clarity

color3 = 'tab:green'
ax2 = ax1.twinx()
ax2.set_ylabel('Pommes mangées maximum', color=color3)
# Key change: Use iterations as the x-axis data
ax2.plot(range(1, max_iterations + 1), max_apple_eaten1[1:max_iterations +
↪  1], color=color4, label='Pommes strat 1')
ax2.plot(range(1, max_iterations + 1), max_apple_eaten5[1:max_iterations +
↪  1], color=color3, label='Pommes strat 2')
ax2.tick_params(axis='y', labelcolor=color3)

ax2.legend(loc='lower right')

# Add Vertical Gridlines (The Key Change)
ax1.grid(axis='x', linestyle='--')  # Gridlines on the x-axis (iterations)
```

Courbes de convergence III

plot_compare_convergences.py

```
ax2.grid(axis='y', linestyle='--')  # You need to add it for the second
↪  axis too

# Additional styling improvement
plt.title('Fitness et pommes mangées fct. nombre de générations')
fig.tight_layout()
plt.savefig("curve_compare_cv.svg")
plt.savefig("curve_compare_cv.eps")
plt.savefig("curve_compare_cv.pdf")
plt.savefig("curve_compare_cv.png")
plt.show()
```

Matrice des poids synaptiques I

plot_brain.py

```
import os
import pickle
from game import Game
import config as c
import matplotlib.pyplot as plt
import numpy as np
import matplotlib.gridspec as gridspec
import matplotlib.animation as animation

def restore_brain(brain_number: int) -> Game:
    # restore brain from file and inject it into the snake
    with open("brains_53.pickle", 'rb') as f:
        game_brains = pickle.load(f)
        brain = game_brains[brain_number]
        if c.DEBUG:
            print(game.brain, end=' ')
            print()
    return brain

def visualize_neural_network(brain):
    fig, axes = plt.subplots(nrows=2, ncols=3, figsize=(12, 8))
    fig.suptitle("Visualisation réseau de neurones", fontsize=16)
    for i in range(3):
        visualize_matrix(brain.weights[i], f"Poids synaptiques - Couche
        ↪  {i+1}", axes[0, i])
```

Matrice des poids synaptiques II

plot_brain.py

```
        visualize_matrix(brain.biases[i], f"Biais - Couche {i+1}", axes[1,
        ↪   i])
    plt.tight_layout(rect=[0, 0.03, 1, 0.95])
    plt.savefig("brain_matrix.svg")
    plt.savefig("brain_matrix.eps")
    plt.savefig("brain_matrix.pdf")
    plt.savefig("brain_matrix.png")
    plt.show()

def visualize_matrix(matrix, title, ax=None):
    if ax is None:
        ax = plt.gca() # Get the current axes if not provided
    im = ax.imshow(matrix, cmap='viridis', interpolation='nearest')
    plt.colorbar(im, ax=ax, label='Valeur du poids synaptique')
    ax.set_xlabel('Index du neurone en entrée')
    ax.set_ylabel('Index du neurone en sortie')
    ax.set_title(title)
    # Setting tick parameters
    ax.tick_params(axis='both', which='major', labelsize=6)
    ax.set_xticks(range(matrix.shape[1]))
    ax.set_yticks(range(matrix.shape[0]))

def visualize_neural_network2(brain, fig, axes):
    fig.suptitle("Visualisation réseau de neurones", fontsize=16)
    for i in range(3):
```

Matrice des poids synaptiques III

plot_brain.py

```
        visualize_matrix(brain.weights[i], f"Poids synaptiques - Couche
        ↪  {i+1}", axes[0, i])
        visualize_matrix(brain.biases[i], f"Biais - Couche {i+1}", axes[1,
        ↪  i])

def update_visualization(i):
    brain = restore_brain(i)
    visualize_neural_network2(brain, fig, axes)

brain = restore_brain(c.SINGLE_SNAKE_BRAIN)
# brain has layers_sizes = [] weights = [] biases = []

for i, (w, b) in enumerate(zip(brain.weights, brain.biases)):
    print(f"Layer {i+1}:")
    print(f"  Weights: {w.shape}")
    print(f"  Biases: {b.shape}")

visualize_neural_network(brain)

# do an animation of the brain matrices

fig, axes = plt.subplots(nrows=2, ncols=3, figsize=(12, 8))
fig.suptitle("Visualisation réseau de neurones", fontsize=16)

ims = []  # List to store the animation frames (heatmaps)
```

Matrice des poids synaptiques IV

plot_brain.py

```
for i in range(256):
    brain = restore_brain(i)
    frames = []
    for j in range(3):
        frame1 = axes[0, j].imshow(brain.weights[j], cmap='viridis',
        ↪  interpolation='nearest', animated=True)
        frame2 = axes[1, j].imshow(brain.biases[j], cmap='viridis',
        ↪  interpolation='nearest', animated=True)
        frames.extend([frame1, frame2])
    ims.append(frames)  # Add frames for the current brain to the list

ani = animation.ArtistAnimation(fig, ims, interval=500, blit=True,
↪  repeat_delay=1000)
plt.show()
```

Jeu intéractif I

playable_game.py

```python
# un seul serpent

from random import randrange
import pygame

class Game:
    WIDTH = 20
    HEIGHT = 15
    snake_body = [
        (int(WIDTH / 2), int(HEIGHT / 2)),
            (int(WIDTH / 2) + 1, int(HEIGHT / 2)),
            (int(WIDTH / 2) + 2, int(HEIGHT / 2))
        ]
    apple = (randrange(0, WIDTH), randrange(0, HEIGHT))

    direction = (-1, 0)

    def step(self) -> bool:
        keys = pygame.key.get_pressed()
        if keys[pygame.K_RIGHT]:
            self.direction = (1, 0)
        elif keys[pygame.K_UP]:
            self.direction = (0, -1)
        elif keys[pygame.K_LEFT]:
            self.direction = (-1, 0)
```

Jeu intéractif II

playable_game.py

```
        elif keys[pygame.K_DOWN]:
            self.direction = (0, 1)
        return self.move_snake(self.direction)


    def move_snake(self, incrementer: (int, int)) -> bool:

        moved_head = (self.snake_body[0][0] + incrementer[0],
        ↪   self.snake_body[0][1] + incrementer[1])
        # vérification de la présence de la tête dans la grille
        if not (0 <= moved_head[0] < self.WIDTH and 0 <= moved_head[1] <
        ↪   self.HEIGHT):
            return False

        # sauvegarde de la fin de la queue
        end_tail = self.snake_body[-1]

        # déplacement du serpent
        for i in reversed(range(1, len(self.snake_body))):
            self.snake_body[i] = self.snake_body[i - 1]

        self.snake_body[0] = moved_head

        #collisions avec la corps
        for bit in self.snake_body[1:]:
```

Jeu intéractif III

playable_game.py

```
        if bit == self.snake_body[0]:
            return False

    #collisions avec la pomme
    if self.snake_body[0] == self.apple:
        self.snake_body.append(end_tail)
        self.apple = (randrange(0, self.WIDTH), randrange(0,
        ↪  self.HEIGHT))

    return True
```

Programme principal du jeu intéractif I

playable_main.py

```python
# Example file showing a circle moving on screen
import pygame
from random import randrange
from playable_game import Game

game = Game()

SIDE = 50

# pygame setup
pygame.init()
screen = pygame.display.set_mode((game.WIDTH * SIDE, game.HEIGHT * SIDE))
clock = pygame.time.Clock()
running = True
dt = 0

# player_pos = pygame.Vector2(screen.get_width() / 2, screen.get_height()
↪  / 2)

"""apple = (randrange(0, game.WIDTH), randrange(0, game.HEIGHT))

snake_body = [(int(game.WIDTH / 2), int(game.HEIGHT / 2)),
            (int(game.WIDTH / 2) + 1, int(game.HEIGHT / 2)),
            (int(game.WIDTH / 2) + 2, int(game.HEIGHT / 2))]"""
```

Programme principal du jeu intéractif II

playable_main.py

```
direction = (-1, 0)


while running:
    # poll for events
    # pygame.QUIT event means the user clicked X to close your window
    for event in pygame.event.get():
        if event.type == pygame.QUIT:
            running = False

    # fill the screen with a color to wipe away anything from last frame
    screen.fill("darkolivegreen3")

    for (x, y) in game.snake_body:
        pygame.draw.circle(screen, "darkolivegreen4", (x * SIDE + SIDE/2,
        ↪  y * SIDE + SIDE/2), SIDE / 2)

    (x, y) = game.snake_body[0]
    pygame.draw.circle(screen, "black", (x * SIDE + SIDE/2, y * SIDE +
    ↪  SIDE/2), SIDE / 4)

    (a, b) = game.apple
    pygame.draw.circle(screen, "brown3", (a * SIDE + SIDE/2, b * SIDE +
    ↪  SIDE/2), SIDE / 2)
```

Programme principal du jeu intéractif III

playable_main.py

```
    # pygame.draw.circle(screen, "red", player_pos, 40)

    # update your game state here

    running = running and game.step()

    # flip() the display to put your work on screen
    pygame.display.flip()

    # limits FPS to 60
    # dt is delta time in seconds since last frame, used for framerate-
    # independent physics.
    # dt = clock.tick(60) / 1000
    clock.tick(3)

pygame.quit()
```