TIPE 2024

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

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June 5, 2024

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.

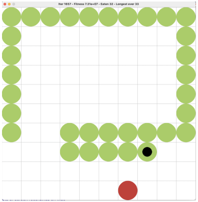
Le jeu de Snake

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 ← ↑ ↓ →.

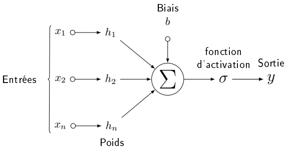
Modélisation d'un neurone: somme pondérée des entrées par un poids synaptique auquel on ajoute un biais. Sortie générée par une fonction d'activation non linéaire.

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

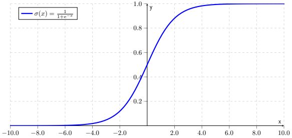
Généralisation à un réseau multicouches: modélisation matricielle avec fonction vectorielle σ

$$\begin{pmatrix} y_1 \\ y_2 \\ \vdots \\ y_m \end{pmatrix} = \sigma\left[\begin{pmatrix} h^{(2)}_{1,1} & h^{(2)}_{1,2} & \cdots & h^{(2)}_{1,k} \\ h^{(2)}_{2,1} & h^{(2)}_{2,2} & \cdots & h^{(2)}_{2,k} \\ \vdots & \vdots & \ddots & \vdots \\ h^{(2)}_{m,1} & h^{(2)}_{m,2} & \cdots & h^{(2)}_{m,k} \end{pmatrix} \sigma\left(\begin{pmatrix} h^{(1)}_{1,1} & h^{(1)}_{1,2} & \cdots & h^{(1)}_{1,n} \\ h^{(1)}_{2,1} & h^{(1)}_{2,2} & \cdots & h^{(1)}_{2,n} \\ \vdots & \vdots & \ddots & \vdots \\ h^{(1)}_{k,1} & h^{(1)}_{k,2} & \cdots & h^{(1)}_{k,n} \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{pmatrix} + \begin{pmatrix} b^{(1)}_1 \\ b^{(1)}_2 \\ \vdots \\ b^{(1)}_k \end{pmatrix}\right) + \begin{pmatrix} b^{(2)}_1 \\ b^{(2)}_2 \\ \vdots \\ b^{(2)}_m \end{pmatrix}\right]$$

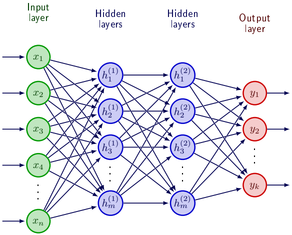
Décision de direction: celle qui a la plus grande valeur de sortie.



Fonctionnement d'un neurone



Fonction d'activation sigmoide



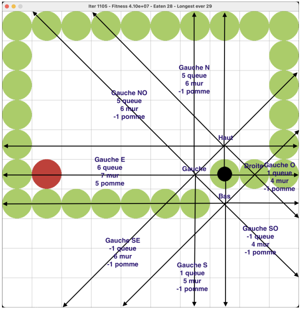
Réseau de neurones multicouches

Stratégies de vision

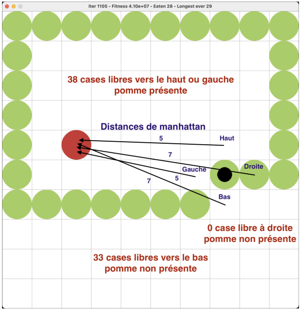
Paramètres en entrée du réseau de neurones

- **Stratégie n°1:** dans les 8 directions de mouvements, 3 informations par direction (distance à la pomme, distance aux murs, distance à la queue), et la taille du serpent
  $\rightarrow$ 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.

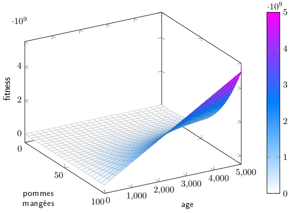
Paramètres: taille du serpent (pommes mangées) et âge (mouvements effectués) à la fin du jeu.

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

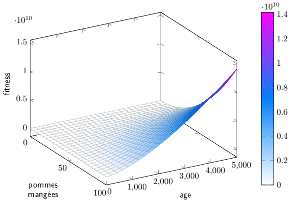
- $f_1(\text{taille}, \text{age}) = \text{taille}^3 \times \text{age}$
- $f_2(\text{taille}, \text{age}) = (2 \times \text{taille})^2 \times \text{age}^{1.5}$

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

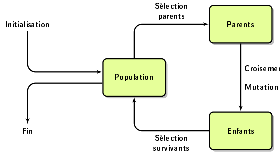
Entrainement du réseau de neurones par algorithme génétique

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

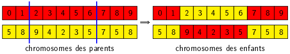
- **Sélection** des individus les plus adaptés pour la reproduction, basée sur leur score de fitness (ici 20%).
- **Croisement** des serpents sélectionnés par paires aléatoire (parents) en K points (ici K=2) pour recomposer la population totale en générant des enfants.
- **Mutation** par ajustement mineur 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



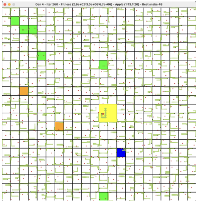
Croisement 2 points (2 points crossover)

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

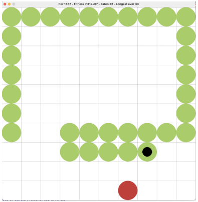
Algorithme d'optimisation

Entrainement du réseau de neurones par algorithme génétique

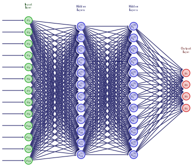
Population $\mathcal{P} \leftarrow 484 = 22^2$ **serpents**
for all serpent $s \in \mathcal{P}$ **do**
  cerveau c **de** $s \leftarrow$ **réseau neurones** $[13, 12, 12, 4]$, **poids & biais aléatoires**
end for
génération $g \leftarrow 0$
while $g < 2000$ **do**
  for serpent $s \in \mathcal{P}$ **do**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



Population de serpents

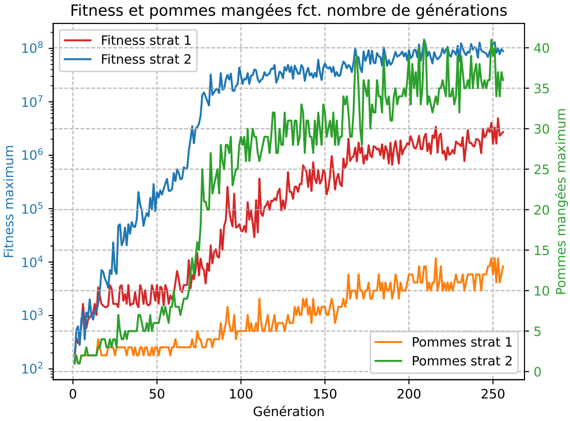


Le jeu pour un serpent



Cerveau du serpent stratégie n°2

Résultats de convergence



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.

Conclusion

- Deux outils mathématiques 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 du serpent sur son environnement.
  - Des algorithmes génétiques pour optimiser les poids et biais des réseaux de neurones.
- 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.
- 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.
- La totalité du projet est disponible en annexes et sur github: `https://github.com/marilabs/tipe-2024`

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 = False # 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 = 0.4 # chance of mutation for the genetic algorithm
MUTATION_COEFF = 0.4 # 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

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

```
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

```
# 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:
    """
    The genetic algorithm was run many different times with many
    ↪ different fitness functions.
    Formulaically, the first fitness function was:
    ((score^3)*(frame_score)
    Score is equivalent to the length of the snake minus 1 (since
    ↪ the snake always starts at length 1),
    and frame_score is the amount of frames that the snake was
    ↪ alive. However, originally this fitness
    function resulted in many snakes that looped in circles
    ↪ endlessly without eating any fruit to maximize
```

Un jeu VIII

game.py

```
    the frame_score component of the function. Thus, the training
    ↪  was modified such that all snakes are
    killed off if they do not eat a fruit in 50 frames. Also, if a
    ↪  snake died due to not eating any fruit
    for 50 frames, 50 points were subtracted from the frame_score
    ↪  to discourage the behaviour.
    """
    # 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
        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
```

Un jeu IX

game.py

```
        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
    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
```

Un jeu X

game.py

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

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

Un jeu XI

game.py

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

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

Un jeu XII

game.py

```python
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
    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:
```

Un jeu XIII

game.py

```
                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] +
    ↪  c.eight_directions[i][1])))

    for (i, incrementer) in enumerate(c.eight_directions):
```

Un jeu XIV

game.py

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

Un jeu XV

game.py

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

Un jeu XVI

game.py

```
        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)
    # 9 inputs in total
    neural_network_input = []
    (hx, hy) = self.snake_body[0] # head of the snake body
```

Un jeu XVII

game.py

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

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

Un jeu XVIII

game.py

```
    # 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

#! todo: understand why changing fitness it is nok for previous
↪ brains...
#! todo: play with fitness and understand the impact on the game

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
```

Un jeu XIX

game.py

```
        space = 0
        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 - 50 *
        ↪  self.died_bc_no_apple)
```

Un jeu XX

game.py

```
def fitness2(self):
    return (self.apples_eaten ** 3) * (self.age - 50 *
    ↪   self.died_bc_no_apple)

def fitness3(self):
    return ((self.apples_eaten * 2) ** 2) * ((self.age - 50 *
    ↪   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 XXI

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

```python
# 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)
        game_brains = [game.brain for game in self.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

```
    @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

```
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

```
"""
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

```
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

```
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)

"""
# Set the y-axis limits from 0 to max_fitness_value
plt.plot(range(len(max_fitness)), max_fitness, color='blue', label='Max
↪  Fitness')
plt.plot(range(len(max_fitness)), avg_fitness, color='green',
↪  label='Average Fitness')
plt.plot(range(len(max_fitness)), max_apple_eaten, color='red', label='Max
↪  Apples Eaten')

plt.xlabel('Iteration')
plt.ylabel('Fitness')
plt.ylim(0, max(np.max(max_fitness), np.max(avg_fitness),
↪  np.max(max_apple_eaten)))
plt.title('Fitness vs Iteration')
plt.grid(True)
```

Programme principal XI

main.py

```
plt.legend()
plt.show()
"""

fig, ax1 = plt.subplots()

color = 'tab:blue'
ax1.set_xlabel('Iteration')
ax1.set_ylabel('Max Fitness', color=color)
#x_new = np.linspace(0, len(max_fitness), 300)
#spl = make_interp_spline(range(len(max_fitness)), max_fitness, k=3)
#max_fitness_smooth = spl(x_new)
#ax1.plot(x_new, max_fitness_smooth, color=color)
ax1.set_yscale('log')
ax1.plot(range(len(max_fitness)), max_fitness, color=color)
ax1.tick_params(axis='y', labelcolor=color)

ax2 = ax1.twinx()
color = 'tab:red'
ax2.set_ylabel('Average Fitness', color=color)
ax2.set_yscale('log')
ax2.plot(range(len(avg_fitness)), avg_fitness, color=color)
ax2.tick_params(axis='y', labelcolor=color)

plt.title('Max and Average Fitness vs Iteration')
```

Programme principal XII

main.py

```
plt.grid(True)
fig.tight_layout()
plt.show()


fig, ax1 = plt.subplots()

color1 = 'tab:blue'
ax1.set_xlabel('Iteration')
ax1.set_ylabel('Max Fitness', color=color1)
ax1.plot(range(len(max_fitness)), max_fitness, color=color1)
ax1.tick_params(axis='y', labelcolor=color1)

color2 = 'tab:red'
ax2 = ax1.twinx()
ax2.set_ylabel('Average Fitness', color=color2)
ax2.plot(range(len(avg_fitness)), avg_fitness, color=color2)
ax2.tick_params(axis='y', labelcolor=color2)

color3 = 'tab:green'
ax1.plot(range(len(max_apple_eaten)), max_apple_eaten, color=color3,
↪  linestyle='dashed', label='Max Apples Eaten')

plt.title('Fitness vs Iteration')
plt.grid(True)
```

Programme principal XIII

main.py

```
fig.tight_layout()
plt.show()


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 neural_network import NeuralNetwork
import sys
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 = []
```

Rejouer le meilleur serpent sauvé II

play_snake.py

```
# pygame setup
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

#? VERIFIED
while running:

    iteration += 1
```

Rejouer le meilleur serpent sauvé III

play_snake.py

```
cur_fitness = game.fitness()
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
        if iteration >= c.MAX_ITERATION:
            break
        game = restore_snake(c.SINGLE_SNAKE_BRAIN)

    # 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)
```

Rejouer le meilleur serpent sauvé V

play_snake.py

```
    frames.append(frame_image)
    clock.tick(25)

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

```
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()
```

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()
```