Natural Selection Simulation

Computer-Aided Simulations - Main Lab G7

I. Problem overview

Our goal here is to develop a simulator for natural selection. Following what was developed on the previous lab, we now consider S species and try to answer the following questions: How competition between species affects their survivability? Is it possible for them to coexist or will one always eliminate the others?

II. Proposed approach

A. Input parameters

Our model consider S different species, each one described by the following characteristics:

- Initial population size $P_0(s)$;
- Initial population lifetime bound $LF_0(s)$: interval between which the remaining lifetime of the initial population is uniformly distributed;
- Reproduction rate $\lambda(s)$;
- Probability of improvement $p_{imp}(s)$;
- Improvement factor $\alpha(s)$;
- Speed $v(s)$: maximum number of moves an individual can make per time unit;
- Strength $f(s)$: combined with speed, influences result of fights between individuals.

Besides the species characteristics, we also consider as input parameters the map size and the maximum simulation time.

As made on the previous lab, the theoretical lifetime $LF(k)$ of an individual k whose parent is $d(k)$ follows the distribution to which the inverse CDF is presented on Figure 1.

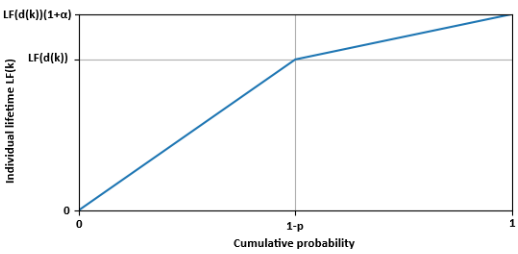

Fig. 1: Inverse CDF for individual k lifetime

In order to avoid overloading the Future Event Set, we try to identify species whose population grows exponentially. This is made arbitrarily by considering an species has reached exponential growth when its population size is 100 times greater than its initial population. New individuals cannot be born under this condition, functioning as a ceiling for the population size, a sort of basic resources limitation model.

B. Output measures

As output metrics of the simulation, we analyse the **average lifetime** of individuals $\overline{LF}$ and the **extinction probability** $p_{extinct}$ of each species. We can further plot the population size of different species along time and an animation of the simulation map for single runs.

C. Mobility model

We consider the map as a discrete hexagonal grid, in a way the map size parameter represents the number of tiles at each side of the map. The hexagonal grid allows individuals to move in 3 different directions (more freedom of movement than standard cartesian), while a discrete map allows a simpler definition of the encounter between individuals, i.e. individuals meet if they are on the same tile at the same instant. The hexagonal map implementation is inspired by [1], using axial coordinates (r, q).

The initial $P_0(s)$ individuals of species s are instantiated on the same tile, different for every species (usually on one of the map corners or on the center). When a child is born, it assumes the same position of its parent.

At the beginning of each time unit (t), we schedule the movements of each individual. The number of moves per time unit (n_{moves}) is an integer randomly chosen between 0 and the individual's speed. These moves are uniformly distributed between t and $t+1$. For each move $m \in \{0, 1, ...n_{moves}\}$, one of the available directions is randomly selected for the individual to follow at instant: $t_m = t + (m/n_{moves})$.

D. Fight model

At the scheduled time of a round of movements, the individuals assumes their new position. If the individuals on a single tile belong to different species, a fight occurs.

Each fight involves 2 species, and individuals of the same species cooperate. If more than 2 species are found on the same position, pairs of species are randomly selected to fight. If there is an odd number of species on the considered tile, one is left out of the fight.

The fight score (FS) consists in a weighted sum of the difference between three aspects of each species: (i) speed v; (ii) strength f and; (iii) number of individuals n of the species involved in the fight, with weights (w_v, w_f, w_n) respectively (Equation 1). With the described equation, we define that $FS > 0$ means advantage for species 1, while $FS < 0$ means advantage for species 2.

This score is then mapped to a value between 0 and 1 by a sigmoid function, that represents the probability of survival (p_{surv}) of each species in this fight (Equation 3).

Furthermore, if the individual survives, a penalty (pen) is applied to its remaining lifetime based on its p_{surv}. The penalty is uniformly distributed between 0 and $1 - p_{surv}$ if the individual won the fight, and between p_{surv} and 1 if it lost (Equation 4). That means lower penalties for winners and greater penalties for losers.

$$FS = (v_1 - v_2)w_v + (f_1 - f_2)w_f + (n_1 - n_2)w_n \quad (1)$$

$$p_{surv,2} = \frac{1}{1 + \exp(FS)} \quad (2)$$

$$p_{surv,1} = 1 - p_{surv,2} \quad (3)$$

$$pen \sim \begin{cases} U(0, 1 - p_{surv,i}) \ , & \text{if } p_{surv,i} \geq 0.5 \\ U(p_{surv,i}, 1) \ , & \text{otherwise} \end{cases} \quad (4)$$

Finally, we fix the values of the weights (w_v, w_f, w_n) as $(1, 1, 2)$, which means speed and strength are equivalent, while each extra individual gives double advantage for its species. We additionally define the one-on-one advantage adv^1 of a species in a fight as $adv^1(s) = w_v v(s) + w_f f(s)$ (or $adv^1(s) = v(s) + f(s)$ with the fixed weights). In a fight with the same number of individuals at both sides, the species with the higher adv^1 will win. This will help us when comparing the species after the simulations.

E. Events

1) `birth`:

This event describes the birth of a new individual. It only takes place if: (i) child's parent is alive or child belong to generation 0; (ii) child's species does not configure exponential growth (as defined previously).

It is responsible for scheduling the following events:
- birth of next individual's brother (if it has a parent);
- birth of first individual's child;
- individual's death.

2) `death`:

This event sets the individual as dead and remove it from the list of individuals. It also set the individual's species as extinct if it was the last of its kind.

3) `movement_scheduler`:

At the start of each time unit, this event schedules the movements to be performed by each individual for the following time unit. It is also responsible for scheduling the next `movement_scheduler` after one time unit.

4) `movement`:

Performs the movements scheduled by `movement_scheduler` and calls the `encounter` event if different species meet on the same tile.

5) `encounter`:

This event describes the encounter of individuals of different species. It executes the fight(s) between species as described previously and updates the death event time of the individuals involved.

6) `map_animation`:

If the animation is to be shown at the end of the simulation, this event generates a frame with the individuals at their current position.

Finally, the simulation will stop when the maximum simulation time is reached or when each species is either extinct or growing exponentially.

III. Experiments and Results

We now run the simulator for different input parameters and analyse how the populations behave. For all instances of the simulator we consider the maximum simulation time equals to 100 and map size equals to 10.

A. Validation

First, we perform some simulations for validating our model, for which we visualize the species population size evolution plot and the animation.

1) $S = 6$ species (similar): On our first scenario, we consider 6 species, all sharing the same characteristics, except for speed and strength, which are set as shown in Table I. Each species start with $P_0(s) = 5$ individuals whose lifetime is uniformly distributed in $LF_0(s) \in [5, 10]$; on average, each individual produces 1 offspring every 4 time units ($\lambda(s) = 0.25$) and their improvement parameters are $p_{imp}(s) = 0.15$ and $\alpha(s) = 0.50$.

Species s	A	B	C	D	E	F
Speed $v(s)$	4	3	4	4	4	6
Strength $f(s)$	1.32	3.57	2.48	4.82	2.85	3.50
Advantage $adv^1(s)$	5.32	6.57	6.48	8.82	6.85	9.50

TABLE I: Speed and strength of species simulated on first scenario

This simulation is shown in Figure 2 and the animation is displayed here.

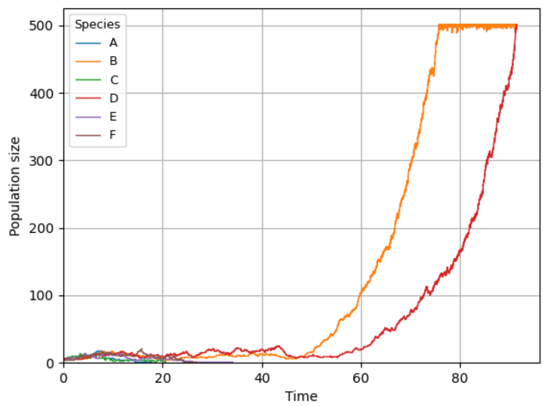

Fig. 2: Population size evolution of species in first scenario.

As we can see, for this simulation, Species B and D reached the exponential growth stage around $t = 70$ and $t = 90$ respectively, while the others were extincted (between $t = 15$ and $t = 35$). This is a possible outcome, since species B had space in the map to grow after the extinction of C and E and species D have an advantage in a fight against species A, C and E, and by the time F was to fight against D, it was already outnumbered and therefore went extinct despite its adv^1 being higher than D's.

2) $S = 3$ species (different): For our second scenario, we then consider 3 species now with different characteristics, as presented by Table II. We use the same parameters $P_0(s)$, $\lambda(s)$ and $\alpha(s)$ as before, while varying the other parameters

Species s	A	B	C
$P_0(s)$	5	5	5
$LF_0(s)$	[6, 8]	[8, 10]	[10, 12]
$\lambda(s)$	0.25	0.25	0.25
$p_{imp}(s)$	0.30	0.20	0.10
$\alpha(s)$	0.50	0.50	0.50
Speed $v(s)$	5	4	6
Strength $f(s)$	2	3	4
$adv^1(s)$	7	7	10

TABLE II: Speed and strength of species simulated on second scenario

across the species. The size of the populations are shown in Figure 3 and the animation is displayed here.

The advantage of species C with higher LF_0 and adv^1 than species A and B is not enough to prevent its early extinction ($t = 30$), which is reasonable, since it has a lower p_{imp} parameter. Meanwhile species B starts growing and reaches exponential growth stage around $t = 50$, and species A is almost extinct, but with a greater p_{imp}, its individuals live long enough to produce its offspring and also reaches exponential growth stage later at $t = 75$.

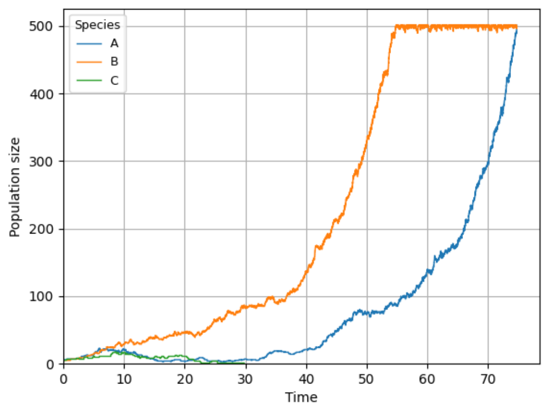

Fig. 3: Population size evolution of species in second scenario.

Again, this is a reasonable outcome, but we must evaluate other possibilities, which will be made on the following section.

B. Confidence intervals

Now that we have seen how single runs of the simulator are executed, we are able to run it multiple times and analyse confidence intervals for the average lifetime and extinction probability. We repeat the two previous sets of input parameters, performing 1000 runs of the simulation, compute confidence intervals with a confidence level of 98% and the accuracy of each output measure.

1) $S = 6$ species (similar): For the scenario with 6 similar species, differing only on speed and strength (Table I), the output obtained is as shown in Table III. The accuracy obtained at each output metric was at least 95%.

First we see that the average lifetime is lower than the input lifetime interval of the initial individuals $LF_0(s) = [5, 10]$, not only because of the fights reduce the individual's lifetime, but also because of the lower chance o improvement p_{imp}.

Species	$\overline{LF}$	$p_{extinct}$
A	3.835 ± 0.060	0.931 ± 0.019
B	4.083 ± 0.077	0.865 ± 0.025
C	3.977 ± 0.068	0.895 ± 0.023
D	4.434 ± 0.088	0.724 ± 0.033
E	4.064 ± 0.075	0.864 ± 0.025
F	4.357 ± 0.082	0.751 ± 0.032

TABLE III: Output measures for the first scenario

Further, we see that both metrics are sorted according to the species one-on-one advantage. Species D and F have the higher advantage, so the average lifetime of its individuals are the highest and the probability of extinction the lowest. It is followed by species B and E with alike metrics, since their one-on-one advantage are similar, then species C. Finally, species A has the lowest value ($adv^1(A) = 5.32$), resulting in the lowest lifetime and the highest probability of extinction.

2) $S = 3$ species (different): Now we analyse the output obtained in Table IV for the 3 species considered on the second scenario (presented in Table II). The accuracy obtained at each output metric was at least 92%.

Species	$\overline{LF}$	$p_{extinct}$
A	6.549 ± 0.212	0.504 ± 0.037
B	5.057 ± 0.118	0.638 ± 0.035
C	4.447 ± 0.058	0.622 ± 0.036

TABLE IV: Output measures for the second scenario

At a first look, we already see that these species had a better outcome than the ones considered before, with higher average lifetime and lower probability of extinction. This can be explained by the fact that the number of species decreased while the map size was kept the same, reducing the number of fights and allowing an easier survival of the individuals.

This time, the higher initial lifetime interval and the one-on-one advantage of species C were not enough to benefit it among species A and B. Species C had almost the same chance of being extinct as species B (both higher than species A) and the lowest average lifetime. In fact, it was also the greatest decrease in the average lifetime if compared it with $LF_0(s)$. We are led to conclude that the p_{imp} parameter plays a crucial role in the survival of individuals and species, since species A, even in disadvantage and starting with lower lifetimes, had a higher chance of surviving and a higher average lifetime than the other 2 species, due to its higher chance of improvement in the offspring lifetimes.

IV. Conclusion

Therefore, we were able to develop an simulator and analyse species lifetime and extinction chance based on their characteristics. We could also answer the questions stated previously, as we saw that competition in fact affects the survivability of species and that species can coexist on the same environment.

References

[1] A. Patel. (2013) Hexagonal grids. [Online]. Available: https://www.redblobgames.com/grids/hexagons/