Abstract: Group evasion behavior is the evasion pattern of numerous agents, one kind of the most frequently observed behavior patterns in nature. However, there appears to be rather little research about human crowd evasion behavior. In this paper, I introduce a new model for simulating group evasion behavior based on biological and sociological models for the purposes of simulating the crowd animation in evasion situations.

In biology, fish school group evasion behavior is well studied and it has a possibility that the human crowd evasion behavior in emergency is similar to fish school group evasion patterns. I take this biologically inspired model and seek to extend it by integrating sociological factors found in human groups. For the immediate dangers, bio-inspired model could simulate human evasion movement. With sociological factors, I can simulate more complex evasion patterns with considering sociological factors. With this model, I would be able to simulate crowd evasion behavior in emergency situations.

Introduction: The collective behavior of human crowds is one of the most interesting topics for numerous researchers and research areas such as sociology, virtual reality, computer graphics, robotics, psychology, politics, transportation, etc. However, it is difficult to simulate crowd behavior with a good mathematical model because many factors influence how each individual will behave and affects the overall crowd behavior. The factors that induce a variation of a person’s behavior are physical attributes, personality, social status, relations with other individuals, etc. These factors make scientific experiments very hard, and generate difficulties for validation. There are various models to explain human crowd behavior in sociology and psychology [27, 28, 29, 32], but none of them is proven because of the previously mentioned difficulty in the modeling and the validation. Moreover, we cannot experiment on human crowds to produce collective evasion patterns, so it is difficult to retrieve relevant data. Also, collective evasion patterns are usually expressed in emergency situations, so few pieces of video data for this behavior are available.

1. Previous works in crowd simulation and motion planning

Crowd simulation and multi-agent motion planning have been studied by many researchers. One of the main research topics in robotics is to enable multi-robot agents to navigate autonomously and collision-free in various environments. In computer graphics, motion planning with autonomous agents could be used for digital actors, which can react and adapt to high level directives in dynamic environments. Navigating in dynamic environments [2, 3, 4, 6, 8] and efficient collision avoidance [1, 5] for numerous agents are main topics for multi-agent motion planning.

Crowd simulation is very difficult not only for the multi-agent motion planning problem, but for the inherent complexity in the behavior of each human individual. For the purpose of handling very large number of agents,
there are two major approaches for crowd simulation modeling; considering the crowd as particles or considering the crowd as a large group of agents.

The particle approach for the crowd modeling is based on a continuum perspective for the crowd, which considers crowd as some continuous material. It considers crowd motions as per-particle energy minimization \[5, 8, 14\]. Because the system controls all the particles entirely, all the individual motions could be guided easily by global motion planning. Also, it is quite efficient for computation, because increasing the number of agents is just condensing the density of particles. However, because it is based on continuum perspective, the motions of individuals are similar to fluid and not quite realistic \[5, 14\].

The multi-agent approach for crowd modeling is much more complex than the particle approach. The complexity of the multi-agent motion planning increases exponentially with the number of agents and their degree of freedom. However, with this model, each agent can react with some intelligence, similar to the real world, so we can control each agent’s movement more precisely with more details and with autonomous navigation capabilities \[2, 3, 4, 6, 8\].

Within various group behaviors, the crowd evasion behavior is useful for numerous applications: animation, simulation, social science, virtual reality for various situations: evacuation, police chasing to arrest the riot or protester situation, minimizing damage in terror situation, escaped animals from zoo, controlling disorder situation, or video games. There is some good research on crowd evasion situations - evacuation \[9\], and suicide bombing terrorist \[11\]. Helbing presents collective crowd behavior of evacuation, induced by panic, using a simulation based on a social force model. He considered the social force with psychology information, and simulates group evasion patterns resulting jamming in life-threatening situations. Zeeshan shows that running to an exit exposes a person to death threatening situation when the suicide bomber attacks the crowd. However, we are not aware of any works in crowd simulation about use of evasion behaviors based on biological models.

2. **Bio-inspired algorithms**

It is a well developed approach to introduce biological algorithms in various fields: optimization, robotics, networking, social organization, etc. In particular, robotics researchers are mainly focused on an emergent behavior of a biological swarm, which is a high-level goal-driven group behavior resulting from the cooperation of simple individual patterns. Emergent group behavior patterns are easily found as insect swarm and animal herd behaviors in nature. Biological individuals only have limited sensing capability, and use simple and robust decentralized algorithms. Biological algorithms are easily applied to simple autonomous robots for these properties, so there are numerous bio-inspired research studies in robotics \[17, 18, 20, 23, 24\]. Because the biological algorithms or procedures have survived the evolutionary process, they are shown by natural selection to be effective, robust and efficient. Bio-inspired approaches are often used when dealing with overly complex problems, or when there exist similar problems in nature.

Many researchers have used biological inspirations. Reynolds \[15\] simulates the flocking behavior inspired by flock of birds. Svennebring and Koenig introduce ant pheromones for their terrain covering robots. Schwager et al. bring in the ladybugs’ algorithm to solve terrain coverage problem with distributed agents \[20\]. Halasz et al. introduce the quorum sensing for the redistribution of swarm robots, which is inspired by ants’ house hunting algorithm \[18\]. Stafford et al. utilize the locust vision system in the collision detection mechanism for cars \[24\]. Barrows adopts the optic flow to UAV flight control, which is used by insects’ vision to avoid collision \[23\].
genetic algorithm and the ant colony optimization are used in numerous fields: game theories, NP complete optimization problems, etc [19]. However, there are few papers [15] in computer animations for group behaviors which are biologically inspired.

In emergency situations, human crowd reactions are similar to animal group behavior in a high level perspective, because of the urgency to react -- "Individuals start pushing, and interactions among people become physical in nature" [9]. The reactions of people vary at the different levels of danger and situations [29]. However, with immediate dangers for primitive sensors, people usually have no time to think about the complex environmental information, so I believe that there should be some linkages between the crowd evasion behavior and the animal group evasion behavior. Therefore, adopting animal group evasion models should be useful to simulate the crowd evasion patterns.

Animal group evasion behaviors are well studied because it is one of the most important behaviors for animal researchers. Unlike the human crowd evasion behaviors cases, the experiment for the animal group evasion behaviors easily controls variables, and generates repeatable situations. Therefore, animal researchers have developed good mathematical models for animal group evasion cases. Especially, fish group evasion patterns are one of the best developed behaviors and have some good mathematical models with relevant evidence data [21, 22].

Among the fish group evasion behavior models, Inada et al. [21] suggest a good mathematical model with the validation of simulation and proper proof. Its basic model is based on Aoki’s and Huth & Wiseel’s model. This model is based on individual behaviors, so it is proper to generate emergent behaviors. It is two-dimensional model based on velocity and angular change with decision time delay also being considered. The decisions of fish individuals are based on motions of neighborhood, with some tendency value. The basic strategy for grouping is similar to Reynolds’ flocking [15]. Fish individuals move during building a group with motions of approaching, parallel orientation, and repulsion. With this model, the authors could simulate all reported evasion patterns of real fish schools, except for the ball pattern. It is a good model with reliable validation data, but has some limitations. Their model only considers free field with no obstacles, and only one predator. Also, they do not think about the factor of domains of danger [25] or the speed change for urgent evasions.

There is numerous predator-prey research but only a little of the research is about predators and does not have convincing results. Zheng et al. [22] suggests more realistic predator behaviors than [21], but they also assume unrealistic predator parameters for focusing on evasion patterns.

For my robot motion planning project in autumn 2007, the pursuit for an evader in crowded situation, I used the probabilistic pursuit-evasion approach [13]. It shows pursuers search for evaders effectively and cooperatively using shared information, so this approach could be applied to make the group evasion project produce more realistic results.

3. Sociological models

Fish school evasion patterns give us good insight to simulate crowd evasion simulation. Nevertheless, a human individual is not as simple as the fish. Although fish school evasion patterns have evolved with long genetic history, human individuals can sense information from the environments and conclude different decisions for different situations, and communicate and influence each other. There must be differences between the human crowd and the fish school, so I applied sociology factors to simulate more human like behavior.
There are many theories about crowds and collective behaviors in sociology. “Social impact theory” [26] is a modeling of social influence at the individual level. Its assumption is one’s behaviors, attitudes, moods, and other attributes will change as a function of the strength, immediacy, and cardinality of sources and targets. It seems that this theory is a dominant one for the individual behavior modeling. This model is frequently used for simulations and predictions of emergent behaviors with computer, so there are various simulation results based on this model. Other considerable sociological theories – “Social identity theory” [28], “Emergent norm theory” [32] - and factors would be considered in my model.

In conclusion, I would adopt biological models to human evasion patterns for imminent dangers, and utilize sociological models for distant dangers. In this paper, I only apply biological models to my simulation model.

Methods:

1. Fish collective evasion model

   The main model for fish collective evasion patterns in my research is based on [21], because it requires relatively simple numerical calculations and produces reliable results. However, it does not consider some important factors: obstacles in the space, increasing speed of the prey in the situation of urgent evasion, and existence of many predators.

   For collision avoidance for objects in space, using “Reciprocal Velocity Obstacle” [1] for collision avoidance framework enables resolving most collision problems. For the speed changes in the situation of evasions, I adapt the speed increasing factor from [22]. [22] also considers the energy expenditure effect, but I applied fish evasion patterns to human crowd evasion patterns only in the case of imminent dangers, so I thought energy preserving evasions are not realistic for human individuals in urgent situations.

   For predator behaviors, there appears to be no realistic complex model for predators in biological research, because the evasion pattern for animal herd is a much more important topic for biologist. As I described before, to produce more realistic hunting behaviors, I plan to use my motion planning project research, which is based on probabilistic pursuit-evasion approach of [13]. I injected predator visibility checking for this framework, and it works successfully in the crowded situation for my motion planning project. With this approach, I can simulate the case where the predator loses sight of the fish school by obstacles and gives up attacking, and also simulate the multi-predator situation. Both cases occur frequently in the real world [22], so it should be considered properly.

   Natural predators should align themselves for easy sight-tracking and attacking with a specific individual prey fish. However, in the human crowd evasion situation, like a suicide bomber attacking situation, predator might be aiming to maximize the density of the crowd. Therefore, predator strategies should change for different scenarios, but as a preliminary test for first stage, I just consider biological predators to adapt biological evasion model.

   In [21], Aoki’s individual behavior model is based on three orientation fields: repulsive-orientation, parallel-orientation, and attractive-orientation fields. The motion of an individual in a school is computed in the two dimensional plane, with the speed and the moving direction. This model considers only the visual sensor, which is a main sensor for almost all high-level creatures. In this model, each individual fish has a blind region located at its backside, whose range is 60 degree wide. Figure 1 shows reaction regions of Aoki’s model.

   However, Zheng et al. suggests another model, which has different reactive regions from Aoki’s model for
predator detections. Figure 2 shows reaction regions of Zheng’s model. It is more natural to apply Zheng’s model for human and fish individual, because human and fish individual can sense predators or dangers of proximity using other sensors; sound, flow and tremor of water or ground. Therefore, I integrate Zheng’s model to original Aoki’s model with more plausible motion patterns. I merged the region 4 with region 5 in Figure 2, because I applied fish evasion model only for the imminent situation.

In Aoki’s model, there are five motion rules based on the region and the angle between the predator and individuals.

1. **Approach:** When the \( j^{th} \) individual of a school is in the attractive-orientation field (a region between \( Ra \) and \( Rp \)) of the \( i^{th} \) individual, \( i^{th} \) individual moves toward to \( j^{th} \) individual.

2. **Parallel orientation:** When the \( j^{th} \) individual of a school is in the parallel-orientation field (a region between \( Rr \) and \( Rp \)) of the \( i^{th} \) individual, the \( i^{th} \) individual moves in the same direction as \( j^{th} \) individual.

3. **Repulsion:** When the \( j^{th} \) individual of a school is in the repulsive-orientation field (a region from an individual to \( Rr \)) of the \( i^{th} \) individual, the \( i^{th} \) individual moves away from the \( j^{th} \) individual to avoid a collision. This rule is automatically achieved by local collision avoidances of RVO, including obstacles existing in the space.

4. **Search:** When no other individuals are found in the reaction field, the individual moves in a random direction until other individuals are found in the reaction field. For human individual case, this would be related to movement for searching goal positions (like exits, regions of interest), and more complex than the fish individual case.

5. **Escape:** When a predator is in any region of the reaction field of the \( i^{th} \) individual, the \( i^{th} \) individual moves in the direction exactly opposite to that of the predator to escape.

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**Figure 1.** Aoki’s fish individual model. The regions within \( Rr \) represents repulsive-orientation field, the region between \( Rr \) and \( Rp \) represents parallel-orientation field, the region between \( Rp \) and \( Ra \) represents attractive-orientation field. An image from [21]
The motion rules from 1 to 3 are based on location and direction of other individuals in the school, so there could be many individuals who affect the result direction calculated by these rules. Inada et al. adopts the maximum number of neighbors which accounts to individual interactions. Introducing maximum number of interacting neighbors is plausible because the attention of each individual to neighbor individuals has limitations for both fish and human individuals. If there are more individuals in the reaction fields than the maximum number of neighbors, individuals at the front should be chosen to consider front priority of natural fish schools [22]. The motion rule 4 is used only there is no other individual or predators in any reaction field of individuals.

The rule 5 represents the selfish evasion behavior, so this rule is not able to be exclusive of other rules for schooling behaviors. Therefore, the final motion is to be considered as a summation of the selfish evasion behavior and schooling behaviors with some ratios. Inada et al. introduces the obedience level to represent tendency of an individual to follow the motion of its neighbors or the selfish evasion movement, because original Aoki’s model does not consider the influence of predators. This obedience level can be used to simulate changes of the attention to self behaviors or environmental conditions. Therefore the obedience level should change according to the situation. I integrate new term called the goal-obedience level for the human individual cases. Because the human individuals usually move to some goal positions, so I add the tendency of an individual to follow the motion of its neighbors or the movement toward goals.

In [21], the speed of each individual is determined stochastically by a gamma distribution, which is observed in biological groups. The speed of the predator is also based on this distribution with the speed ratio greater than one. As I described before, [21] does not consider the increase in the speed of the prey fish in evasion situations, so I adapt the speed increasing factor value – the ratio of maximum speed and normal speed from [22]. I did not consider the energy expenditure effect of the [22], because I thought the energy preserving evasion is not so plausible for human individuals. The moving direction is determined by the Gaussian distribution, where the mean value is the angular change computed by five motion rules. The angular change is calculated by unit vector summation, which is reasonable because the neural command of animal body is determined based on the vector averaging model [22]. The Gaussian distribution perturbation prevents same motions for all the individuals in similar environment situations.
These biology papers [21, 22] used unrealistic predator parameters, especially in the range of sensory field. Because they focus on only collective evasion patterns, they assume unlimited sensor ranges for the predator, and only consider one predator. However, my model should consider realistic values of them and variations of predator patterns to produce realistic crowd evasion simulations. As I described before, I adapted the predator model from my motion planning course project research, which is based on a probabilistic pursuit-evasion approach, to make it more extensible for various situations and more plausible simulations. The basic model of [13] is based on robots’ false positive and false negative probability of the sensor detection, which only use adjective sensors. They assume a Markov random model for motions of the evader, which determines avoidance motions with the equal probability for all adjunct grid cells. In this course project of motion planning, I modeled a visual sensor detection model using a two-dimensional view-frustum to apply this approach for human pursuers. Figure 3 shows the view frustum detection model of my course project research. It is very simple two-dimensional view frustum model, which calculates the visible portion of the target occluded by other agents. I used this portion value to calculate the probability.

In biology, schooling is a defensive strategy for prey to confuse their predator. In [21], a predator determines its direction similar to the prey, using only the attractive rule and considering a limited number of the prey with the front priority. In [22], the predator finds a first target and pursues it, without the confusing probability. However, the predators should find another target if it missed the first target which is occluded by other individuals or obstacles. I use the same view-frustum model of course project to find this missing probability of predators. However, it has no meaning that I consider false positive or false negative in this case because predators do not need to distinguish the target individual from other individuals. If cooperating predators who
share the detection information are targeting the highest density area of the prey - like suicide bomber situation, we should estimate all prey locations by proper probability models.

Dynamic constraints for motions of agents are very important. The angular speed constraint is omitted in [21], but it is one of the most important constraints to reproduce plausible motion simulation. In [22], the authors used angular speed limitation of 30 degree. For human individual case, the human body dynamic constraint should be considered.

The purpose of my project is to visualize realistic movement of crowd evasion situation, so the most important validation for

2. Sociology evasion model

Currently, I integrated my biological model to sociological model from [33]. The system of [33] has a good computational modeling for emergency egress case, and be validated its precision of the simulation by the comparison between the results from other crowd simulation tool and NIS survey data of the Rhode island nightclub fire case.

[33]'s model shows good results and it considers a perception process for each agent, so it is suitable for this project. However, it only shows concepts and elements of the model, and does not show the model’s details. It was not able to figure out how to compute the stress level from three cues, which are perceived urgency, perceived importance, and perceived uncertainty, process model and decision tree has some confictions between them. Also, there is no model in [33] that explains how the perceived cues are distributed and communicated between agents.

I firstly tried to extract importance factors and cues from this model like social behaviors, and make my own reasonable but simple model for my model. I would simulate with same scenarios of [33] like the Rhode Island nightclub fire case, and compare my result with same criterions which used in environmental and civil engineering.

Currently, I implemented the queuing behavior, competitive behavior, leader-following behavior, and herding behavior except for the altruistic behavior. I do not have enough clues for build up altruistic behavior from [33], because it shows different behavior depends on the situation.

(1) Queuing behavior: My implementation for queuing behavior is based on simple but efficient algorithm. When an individual is in queuing behavior status, find the nearest agent between nearest perceived exits and the individual, and follow the agents. The nearest agent should be closer with more than some distance. With this simple algorithm, I could represent queuing behavior without deadlock between agents.

(2) Herding behavior: If perceived exits are more than one, the individual would go to exits with more agents are waiting. The number of agents for each exit is calculated by the closest exit for each perceived agent.

(3) Competitive behavior: The individual move toward close exit with urgency.

(4) Leader-following behavior: The leader candidate should have some social authorities like police or firefighter, and if the stress level becomes over the stress threshold, the individual becomes a leader. If there are perceived leader for an individual, the individual would follow him with some decision tree.
I used the perceived urgency and the perceived uncertainty for my model. Most difficult portion for this modeling is the propagation of the urgency and uncertainty. The information by communication is also very hard topic for simulation, and main communication would be physical in emergency cases. Obedience level and goal-obedience level also changes with the urgency level. Therefore, there are more sociology factors to integrate with my simulation model. The candidate theories would be the “social impact theory” [26], and considerable candidates are “social identity theory” [28] and “emergent norm theory” [32]. It is possible to generalize this model to other group behavior models.

**Preliminary results:**

These are preliminary results to consider and observe the changes of the fish model’s reaction with different variables. Each person is different in his sensory capacity and maneuverability, so my model should reflect those differences. I focused on the possibility of fish model to be applied in human crowd evasion model within the imminent danger escaping. The base testing framework is RVO library [1], and test with integrated fish evasion model with local collision avoidance of RVO. The biology papers [21, 22] only focus on the order or survivability of the prey group, which is different from this project goal, so I should observe simulations focusing on my purpose.

The vision angles of each individual affects school shape and rate of survival. The fish has about a 300 degree vision angle, and human has about 180 degree wide for a visual angle. With a small visual angle, the school shape becomes more elongated to its moving direction as shown in Figure 4, and the survival rate of the prey decreases. Human’s visual sight angle might be extended to more than 180 degree with considering eye and head movements, so 60 degree is too small for human individual. Also, there are other sensors to detect dangers besides visual sensors.

The integrated model with two reaction region models of [21] and [22] produces plausible motions. Without backside urgent field of [22], the evasion patterns are not created reasonably to the approaching predator from backside.
Introducing urgent mode to my model generates more realistic motion without breaking the stability of the school. The speed factor in urgency mode is derived from the observation of real fish school. I found the measured human average speed and maximum speed from [33]. It is interesting that the ratio of average speed to maximum speed of human individual is almost same as fish individual case. The predator also increases its speed if the prey is in its urgent region, which is larger than the prey’s region. However, if urgent rate is too high, motions of individuals become unrealistic, and the survival rate of prey decreases sharply [22]. The value from [22], which is used for fish, might be reasonable for human simulation in my observation.

The three predator patterns are tested on testing framework.
1. Inada et al.’s model [21], which uses vector summation of the direction of detected prey
2. Zheng et al.’s model [22], following one target fish, with a sight occlusion

Currently, my preliminary results are tested on open space, so it does not include a complex environment. Without considering the complex environment, these three predator patterns represent no significant difference in their behaviors. Because the preys are always dispersed by the approach of the predator, there is no visual occlusion by other individuals, so the pattern 1 and 2 are similar. For biological predators, the pattern 1 and 2 are more reasonable than the pattern 3, because natural predators are not intelligent enough to adapt complex pursuit patterns. Predator pursuit patterns are various with human evasion situations, so pattern 3 would be more suitable and extensive for complex and intelligent predator situations.

The predator speed factor only affects the survivability of prey, not the evasion pattern of prey. Varying initial conditions - position, orientation, and velocity - of the prey and the predator does not affect the stability and evasion motions of the group. The range of the parallel-orientation field affects the schooling density of the prey, and using a fish model express motions similar to human crowds from the evasion scenes. The obedience level affects evasion patterns of prey, as simulated in [21]. The evasion pattern of natural fish schools is successfully simulated by their model, and the three variables are related to the frequency of the evasion patterns: the angular deviation, the number of influential agents, and the obedience level. Figure 6 shows these simulated behaviors, which is from [21]. The obedience level and goal-obedience level could be related to the tendency of a human individual to follow group decisions, so it is able to be used effectively in sociological models.

![Figure 6: The simulated fish school evasion patterns. (a) herd, (b) split, (c) hourglass, (d) vacuole, (e) flash expansion, (f) flash turn, (g) fountain effect. An image from [21]](image)

With the simple algorithm for the sociological behaviors, it produces similar movement to the [33]. Currently,
I simulated with an evacuation scenario, because [33] only focused on evacuation cases. After validating my model with evacuation and free space cases, I should make more complex evasion scenarios.

**Discussion:**

The most important and difficult problem for this project is how to evaluate result; why this result is convincing and realistic. Similar to other crowd simulations, there is no relevant data extracted from real human situations. Because the data driven methodologies are not available, the plausible modeling for real crowds is most important. The biology papers focus on the stability of the group and the efficiency of evasion patterns, so they validate the result with the fish school’s angular deviation, the internal collision frequency, and the survival time of individuals. My model also satisfies the stability and the efficiency of evasion because I applied fish model to my models. It is able to estimate human crowd evasion patterns with some relevancy, but more convincing evaluation methods are needed to show the model is realistic.

Human locomotion dynamics is one of the most difficult problems to simulate. The angular velocity limitation according to the speed is one of the most important constraints of human gait motion. There are many researches about human gait motion constraints for joints, but there appears to be no experimental data for the maximum angular velocity value of total human body.

For the future work, my model with sociological factors will be able to emulate more realistic attributes of human individuals: panic, grouping with similar properties – similar social identity, or similar social group – or social influences. Therefore, integrating social models with the fish evasion model is most important for realistic and flexible human crowd evasion simulations. Moreover, sociological model could be generalized for other group behaviors of human crowds.

Apart from simple sensors and reaction patterns of animal individuals, human individuals can react with adaptive evasion patterns according to predator patterns. Without previously learned information, human cannot respond to powerful predators, like vehicles or terrorists. In biological papers, using an overly large speed factor for the predator breaks down all the evasion strategies. However, humans can evade vehicle predators - like in *Homicidal Chauffeur* game situation, in which vehicles attack pedestrians - with the knowledge of vehicle’s dynamic constraints – the non-holonomic constraint (usual cars cannot move to left or right directly), the limited angular speed at the high speed. Predator patterns are not the goal of this project, but the predator pattern has an intimate relation with evasion patterns. Therefore, various and complex predator patterns should be considered.

The performance is another consideration, because real-time applications provide a convenience for the evaluation and the observation for results. RVO can simulate hundreds of agents with just local collision avoidances in real time, but it requires an exponentially increasing computing power with complex behavior models.

The sociological model has numerous things to do for future work. I should find a good detailed computational model for communication of information and group identity. Especially for the altruistic behavior, I should consider the social group like a family or companions, where the altruistic behavior frequently observed.

The most important thing for validation of my model is the good real situation video clip. I also need some video clips from other simulation cases, and compare it with my results. However, finding the video clips of real situation is quite difficult, so I should search for various research areas. For the biological model, finding video clips of the human group evasion patterns similar to fish school evasion patterns can reinforce my arguments.
Reference:

[Multi Agent/Crowd]
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[ Biological]


