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Horizontal and Vertical Knowledge Transmission in Experimental Cultural Knowledge Evolution

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Abstract

Theories of evolution introduce the replicator/interactor model, as a generalization of the genotype/phenotype in biology, to model biological evolution. Another field of evolution, in which evolutionary theories also apply, is cultural evolution. Moreover, cultural knowledge evolution, which is our main interest, is the study of the evolution of the knowledge component, and comprises an important part in the experimental field. The replicator/interactor model is a way to apply evolutionary theory to cultural knowledge evolution. This is done by making an instantiation of the replicator/interactor in cultural knowledge evolution, using the knowledge/behavior components of culture. By this, we are able to specify the mechanisms that knowledge and behavior are subject to, which are: knowledge's adaptation, the behavior's interaction, and the implicit and explicit transmission of knowledge. Experimental cultural knowledge evolution study knowledge evolution using the mechanisms that knowledge is subject to but do not offer the study of explicit knowledge transmission. To do this, we extend the experiments in cultural alignment repair using the knowledge/behavior instantiated model. This extension allowed to propose the two mechanisms of explicit knowledge transmission. The first mechanism is the horizontal transmission of knowledge which represents the communication and knowledge exchange between individuals in culture. The second mechanism is the vertical transmission of knowledge which represents the inheritance of knowledge from parents to their offspring in culture. We designed the two mechanisms in an attempt to apply them in the experiments in cultural alignment repair. We implemented the first mechanism, an experimental design plan was built for it, several hypotheses were formulated, and experiments were performed. This resulted in confirming some of the hypotheses and opening the discussion for further work and more experiments.

Résumé

Les théories de l'évolution introduisent le réplicateur/interacteur, comme une généralisation du génotype/phénotype en biologie, afin de modéliser l'évolution biologique. L'évolution culturelle est un autre domaine d'évolution où nous appliquons également les théories d'évolution. La connaissance, le comportement et d'autres traits sociaux constituent les composants de la culture. L'évolution de la connaissance culturelle étudie l'évolution de la composante de la connaissance et constitue une partie importante du domaine expérimental. Le modéle réplicateur/interacteur est une méthode d'appliquer la théorie de l'évolution à l'évolution des connaissances culturelles. Nous pouvons appliquer ce modèle en faisant une instanciation du réplicateur / interacteur dans l'évolution des connaissances culturelles, en utilisant les composants connaissances/comportements de la culture. D'aprés ce qui précède, nous sommes capable de spécifier les mécanismes auxquels la connaissance et le comportement sont soumis : l'adaptation de la connaissance, l'interaction du comportement et la transmission implicite et explicite de la connaissance. L'évolution des connaissances culturelles expérimentales étudie l'évolution des connaissances à l'aide des mécanismes auxquels la connaissance est soumise, mais elle ne peut pas étudier la transmission explicite de la connaissance. Dans ce but, nous allons développer les expériences de la réparation de l'alignement de la culture par l'intermédiaire du modèle instancié du connaissance/comportement. Cette extension nous permet de proposer les deux mécanismes de transmission explicite de la connaissance. Le premier est la transmission horizontale des connaissances, qui représente la communication et l'échange de la connaissance entre les individus de même culture. Le deuxième mécanisme est la transmission verticale de la connaissance représenté par l'héritage de la connaissance des parents à leur progéniture. Nous avons concu les deux mécanismes pour tenter de les appliquer aux expériences de réparation de l'alignement culturel. Une méthode expérimentale est développée dans le but d'implémenter le premier mécanisme, formuler plusieurs hypothèses et effectuer des expériences. Cette étude nous a permis de confirmer certaines hypothèses et d'ouvrir la discussion à des études et des expériences précédentes .

Acknowledgment

I would first like to express my deep gratitude to my supervisors Professors Jérôme Euzenat and Manuel Atencia for their continuous support and perfect guidance. They consistently ensured that I acquire knowledge and be the own person in charge of my own work, but guided me in the right direction whenever I needed. Their office were always open whenever I needed to discuss, ran into a trouble, or had a question about my research or writing. I would also like to thank Professor Jérôme David for his technical support whenever needed.
And last, to my main, first and last support, to the dearest of all; my family. A great overwhelmed "thank you" to my parents, for being beside me all the time, pushing me forwards whenever I stepped back, and giving me all the tender, love, and care. Without you and your support, I would not have reached here and neither have done this, thank you.

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Introduction

1.1 Context

Modern theories of evolution introduce the replicator/interactor model as a generalization of the notions of genotype/phenotype in biology. A replicator represents the generalized concept of an individual's genome. It undergoes replication which is a mechanism representing the transmission of genes across individuals, and it is done via reproduction. Moreover, the replicator generates an interactor, which in turn represents the generalized concept of the phenotype. The interactor is subject to natural selection in the same manner as phenotypes are. So, the replicator/interactor was created to model biological evolution. It may also be applied in other evolutionary fields.

Cultural evolution is the application of evolution theory to culture, thus forming a field in which evolutionary theory applies. Culture involves knowledge, behavior, artifacts, beliefs and other forms of social traits. Cultural knowledge evolution is the study of the evolution of the knowledge component of culture. Knowledge is an adaptable variable which is subject to repair. It is also transmitted across individuals via mechanisms of cultural transmission, which include communication and exchange, and inheritance. Moreover, knowledge generates behavior which is in turn subject to outer environmental and individual pressure.

1.2 Problem Statement

The problem is to apply the replicator/interactor model to cultural evolution, and more precisely to cultural knowledge evolution. This means indicating the components and the mechanisms which are in the replicator/interactor model, and use them to form an instantiation of the model in the field of cultural knowledge evolution. Moreover, experiments in cultural knowledge evolution study knowledge evolution using the mechanisms that knowledge is subject to. But, these experiments only take into consideration knowledge being an adaptable component, and behavior being a tool of interaction subject to natural selection, but do not offer explicit knowledge transmission mechanisms. Thus, we will have to extend it.

1.3 Approach

Our approach involves two phases. The first is to make an instantiation of the replicator/interactor model in cultural knowledge evolution using the knowledge and behavior concepts in culture. The instantiation of a knowledge/behavior model involves that the mechanisms of knowledge and behavior will be instantiated in the model too. These mechanisms include knowledge's transmission and adaptation, behavior's generation, and natural's selection impact in culture. The second phase goes deeper into experimental cultural knowledge evolution where we attempt to extend the current experiments in cultural alignment repair by the instantiated model.

This means applying the knowledge/behavior instantiated model to the experiments in cultural alignment repair by adding the mechanisms that have not been studied there yet which concern knowledge's transmission. So, we proposed knowledge's horizontal and vertical transmission which represent, respectively, the mechanisms of knowledge's communication and inheritance in cultural knowledge evolution.

1.4 Contribution

We instantiated a knowledge/behavior model for cultural knowledge evolution from the replicator/interactor model. We then proposed an extension of experimental cultural knowledge evolution in order to suit the proposed knowledge/behavior model. In particular we introduced knowledge's horizontal and vertical transmission mechanisms of the knowledge/behavior model to the current experiments in cultural alignment repair. So, we designed the extension proposed (of the current experiments in cultural alignment repair) for the new mechanisms (regarding agents, their knowledge structure, and knowledge mechanisms) and implemented it. We then planned experiments to test properties of these extensions. Finally, we performed and analyzed the planned experiments.

Due to lack of time, we only implemented the horizontal knowledge transmission mechanism and run its planned experiments.

1.5 Report Outline

We first provide some basic technologies and the necessary background that the reader will find helpful to carry out the full understanding of the work done in Chapter 2. This is done by illustrating in biological evolution some of the needed biological concepts and the corresponding generalized replicator/interactor model. Also, a background part for cultural evolution: an introduction to knowledge evolution, and the previous experimental work done in cultural alignment repair. Then, we make our theoretical proposal of applying the model to cultural knowledge evolution, and extending the experiments in cultural alignment repair in Chapter 3. After that, we delve deeper in Chapter 4 into the designing and the carried implementation of the proposed two mechanisms of knowledge's vertical and horizontal transmission. In Chapter 5, we provide our experimental design plan: the hypotheses, the framework and the expected results of the experiments that we carry out. Results are shown in 6 and interpreted, each results with respect to their corresponding experiment. Finally, we conclude in 7 with the expected impact.

— 2 —

Context and State-of-the-Art

In this chapter, we first explain some evolutionary theory basics in the biological field in order to understand the following discussion. This is followed by presenting the replicator/interactor model as being inspired from biological evolution. We then provide another evolutionary field which addresses knowledge: cultural knowledge evolution. After that, we illustrate some of the experiments done in the domain of cultural knowledge evolution which the are experiments in cultural alignment repair.

2.1 Theory of evolution

Evolution is the process by which different factors acting in an environment lead to changes, over time, in the heritable traits of the species living in it.

2.1.1 Biological Evolution

In biological evolution, changes are seen at the level of the frequencies of alleles in a population over time. Factors that make evolutionary changes in biology are the mechanisms of evolutionary change. These mechanisms include natural selection. Natural selection is the process whereby organisms better adapted to their environment tend to survive and produce more offspring. The theory was first fully expounded by Charles Darwin, and it is now regarded as the main process inducing evolution. However, in order for evolution by natural selection to occur in an environment, certain conditions must be present, they are:

- Variation in the traits of the individuals, which are due to variations in their genes. It is the reason that certain individuals are better adapted than others. Otherwise, if all individuals in the population had the same genomes, natural selection would be random since the offsprings will carry the same genome.

- This variation is heritable by means of reproduction where offspring inherit their traits from their parents.

- This heritable variation leads to differential fitness which is variation in the degree of adaptation of each individual in its environment.Thus, fitter individuals tend to survive more and reproduce more, hence the term differential reproduction.

Genetics

The field of research in genetics mainly focuses on the study of what really happens, and how, in the transmission of hereditary traits from parents to their offspring. And the basic two components involved are:

- **Genotype:** is the gene patrimony of an individual, i.e. its heritable genetic identity. It is the genetic information carried in an individual and encoding it traits.

- **Phenotype:** is the result of the manifestation of genes, that is the set of physical characteristics describing their corresponding encoded genes. Variation at the level of the phenotype is caused by genetic variation it is mainly what causes natural selection to occur.

2.1.2 Replicator/Interactor: generalization of biological evolution

Inspired from biological evolution, the notions of replicator and interactor were introduced as the generalized concepts of genotype and phenotype respectively [1, 5]. And so, under the same mechanisms that genes and their corresponding phenotypic traits act, so do replicators and interactors.

- **Replicator:** the concept of replicator refers to the basic unit of which copies are made of just like a gene where genes are the replicated molecules of biology [2]. Replicators function in replication in the same way that genes replicate during the mitosis phase of reproduction. During reproduction, the genomes of the parents are inherited to their offspring. It means that genes are being transmitted. This transmission takes a vertical direction seen as from parents to their descendants and across generations. Thus, a generalization of gene through the replicator concept, gives the following: replicators replicate to pass themselves to new individuals through transmission.

- **Interactor:** the concept of the interactor refers to the corresponding entity generated by the replicator in the same manner a phenotypic trait is generated by a certain gene. The interactor is then the entity revealed in the environment and the tool by which an individual interacts with other individuals in the environment.

Hence, the relation between the two notions is a causal relation where one entity causes the existence of the other. Replicators generate the interactors which are, in turn, interacting in the environment. Variations in the interactor, resulting from variations of the replicator, causes variation in the degree of fitness of individuals in the environment. This induces natural selection to act affecting later on, the frequencies of the inherited replicators, i.e. resulting in differential reproduction.

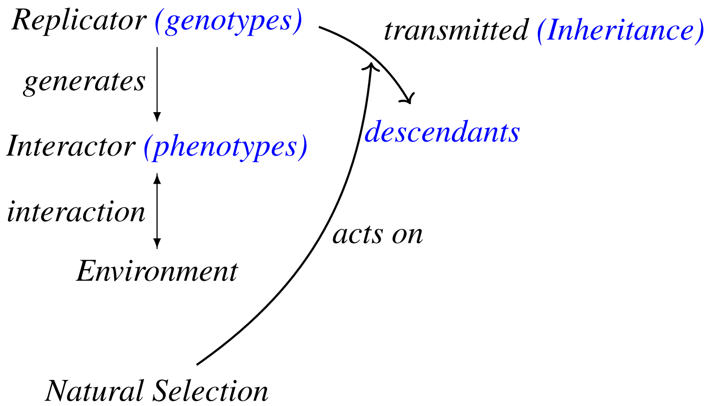


Figure 2.1: Replicator/Interactor: a generalization of genotype/phenotype.

The mechanisms involved in the replicator/interactor model and shown in the figure 2.1 are:

- Replication of the replicator through transmission.
- Generation of the interactor by the replicator.

- Interaction of the interactors in the environment.
- Natural's selection impact on the replicator's transmission due to the interactor's differential fitness.

2.1.3 Cultural evolution

Cultural evolution is the study of changes in the culture. Culture is the group of social behaviors and norms found in human societies [7]. Cultural change is thus, any altering or adaptation in the social behavior and relations of a certain culture. Social behavior comprises the acts of interaction, communication, exchange and other forms of cultural transmission which characterize a certain species.
Cultural transmission is the process by which information is passed from one individual to another via social learning mechanisms such as imitation, teaching or language [6].

Human culture, for example, encompasses knowledge, behaviors, and artifacts that can be learned and transmitted between individuals, and can change over time. Knowledge is variable, communicated and selected among populations. It is variable because variations in knowledge do exist among different individuals. This can be seen through their different social behavior, where behavior is a reflection of what an individual has from knowledge, beliefs, and other social norms. Moreover, human beings are able to communicate their knowledge through several forms of cultural transmission, thus knowledge is communicated. This is the way by which human culture evolves and expands rather than learning the knowledge each time from the environment from zero. However, different environments have different conditions under which humans living in it -forming a population- adapt to. This adaptation of humans towards their environment involves selecting the part of their culture (knowledge, behavior, traits, traditions...) which best fit their environment, hence knowledge is selected.

Moreover, cultural knowledge evolution which is the study of the evolution of the knowledge component in culture forms a main category in the field of cultural evolution. Cultural knowledge evolution experiments attempt to study, design, implement, and perform experiments in the sake of monitoring knowledge evolution.

2.2 Experiments in Cultural Alignment Repair

Experiments in cultural alignment repair [3, 4] study cultural knowledge evolution and specifically cultural alignment repair. Culture, in these experiments, is taken as an intellectual artifact shared among a society of agents and it is represented by their knowledge. Agents react and behave according to the knowledge they have. Cultural repair is the action of adapting knowledge and leading to its evolution. This repair of knowledge is done by agents in response to their interaction with other agents.

2.2.1 Ontology:

An ontology is the conceptualization of objects. It provides a formal model of the concepts and relationships used to describe a certain knowledge domain. It has a certain structure which is a hierarchy of classes. Ontologies can be used to classify objects (instances) according to classes.

- A class represents a general concept.
- A relationship represents the semantic relation that relates two classes. We present the possible relations between two classes C and C' and their corresponding denotations in description logic:
  - a subclass relation: C is subclass C' if all instances belonging to C also belong to C', denoted $C \sqsubseteq C'$.

– a superclass relation: C is a superclass of C' if all instances belonging to C' also belong to C, denoted $C \sqsupseteq C'$.
– a disjoint relation: C and C' are disjoint if they cannot have common instances i.e. any instance belonging to C cannot be an instance of C' and vice versa. It is denoted $(C \perp C')$.
– an equivalence relation: C is equivalent to C' if they are the same class, denoted $C \equiv C'$.

- A top class denoted top which is a superclass of all classes in the ontology i.e. for every instance belonging to any class, it also belongs to the top class.

In the context of the experiments in cultural alignment repair, ontologies are used to represent agents' knowledge. Agents have different ontologies. This aims at making the experiments realistic where agents would have different perspectives from which they see the world, just like humans do. So, different ontologies mean different knowledge representations of the same world where these agents are.
However, an ontology, in the context used in the experiments and that will be used in our following work, is a more special case of the explained concept of ontology. It is a simple decision tree modeling the characteristics of objects present in the world. It is used to classify objects having certain characteristics. To help the reader understand more, we provide the following:

- Objects are characterized by features.
- Features are considered to be boolean i.e. two possible disjoint values for each feature. An example of 3 boolean features is shown in figure 2.2 where we have: color={white | black}, shape={triangle | square} and size={small | large}.

Figure 2.2: Features used to represent objects, figure taken from [3].

- An ontology representing boolean features has the structure of a binary tree. It consists of classes representing the features where classes have names corresponding to names of the features that they represent. The root node of the tree represents the top class of the ontology. Other classes form the intermediate and leaf nodes of the tree. If we have an ontology representing n features, then it has 2^{n-1} size in which each level corresponds to a feature and classes of the level are disjoint. We provide an example of an ontology in figure 2.3 representing two features: size={small | large} and shape={triangle | square} denoted O_{SF} in which S corresponds to size and F to shape, and thus O_{SF}.

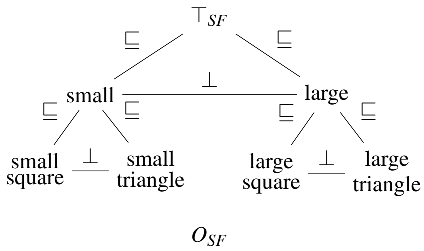


Figure 2.3: An ontology describing the size and shape features denoted SF.

2.2.2 Alignments

Agents having different ontologies interact with each other. This interaction needs common features in the world to be semantically linked. Ontology alignment provide a technique by which the classes of two ontologies can be semantically related. Thus we need alignments to link ontologies of agents, where agents use these alignments to interact with other agents having other ontologies.
An alignment is the set of correspondences linking the classes of one ontology to the classes of another using semantic relations. A correspondence links a class C in ontology O to another class C' in ontology O' using a relation R, and it is denoted $\langle C,R,C'\rangle$. R depends on the semantic relation between C and C'. Thus, a correspondence can be:

- An equivalence correspondence denoted $\langle C,\equiv,C'\rangle$ relating the two classes C and C' if they are semantically equivalent ($C \equiv C'$).
- A subsumed-by correspondence denoted $\langle C,\leq,C'\rangle$ relating the two classes C and C' if C is a subclass of C' ($C \sqsubseteq C'$).
- A subsume correspondence denoted $\langle C,\geq,C'\rangle$ relating the two classes C and C' if C is a superclass of C' ($C \sqsupseteq C'$).

However, alignments used in the experiments include: equivalence correspondences used to link the top classes of two ontologies, and subsumed-by and subsume correspondences used to link other classes. Figure 2.4 shows an example of two ontologies: *SF* representing the size and shape, and *CS* representing the color and size, and the corresponding alignment that relates the classes of both ontologies. For example; the class *small* of ontology O_{SF} is a superclass of the class *blacksmall* of ontology O_{CS}, thus a subsume correspondence $\langle small,\geq,black\ small\rangle$ between them is made.

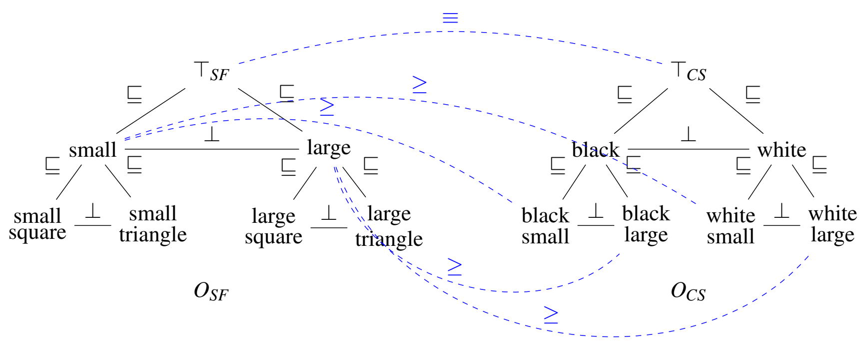


Figure 2.4: An example of two ontologies with an alignment (i.e. set of correspondences) connecting them.

Alignments are typically generated using ontology matching tools and these tools may output incorrect and incomplete alignments. On the one hand, an incorrect alignment is an alignment that includes a false correspondences. Figure 2.5 shows an example of an incorrect alignment where it includes false correspondences shown in red color: $\langle small,\geq,black\ large\rangle$ and $\langle large,\geq,black\ small\rangle$. These correspondences are false because the classes *small* and *black large* are disjoint, and so are the classes *large* and *black small*. On the other hand, an incomplete alignment is an alignment that does not contain all the possible correspondences that relate two ontologies. Figure 2.6 shows an example of an incomplete alignment that misses the correspondences $\langle small,\geq,black\ small\rangle$ and $\langle large,\geq,black\ large\rangle$.

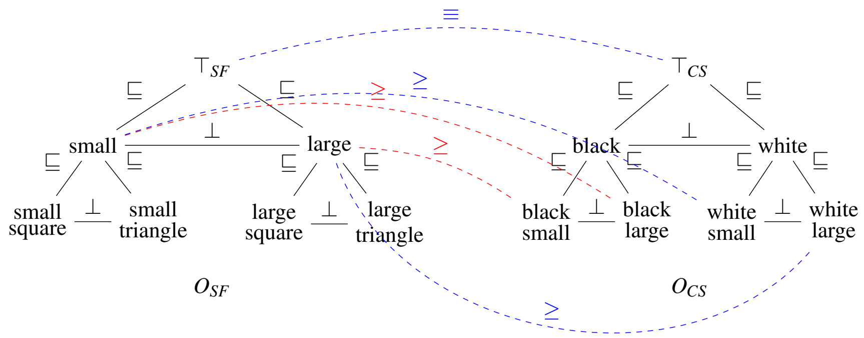


Figure 2.5: An example of an incorrect alignment.

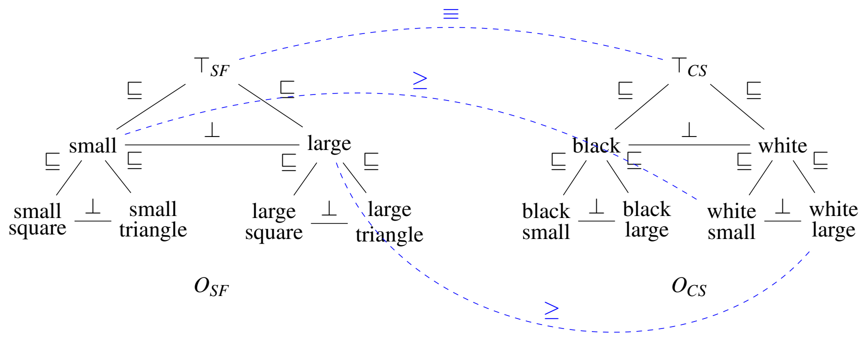


Figure 2.6: An example of an incomplete alignment.

Alignment properties:

Alignments, in the context of our experiments, have to preserve two important properties:

- Equivalence between top: equivalence relations between all top classes of different ontologies. Thus we have an equivalence correspondence in each alignment linking a pair of ontologies between the top classes of these two ontologies.

- Injectivity: injectivity means that from the same class of ontology O, from which the alignment is issued to O', there cannot exist more than one class in relation with the same class of O'. An example of an alignment which does not satisfy the injectivity property is shown in figure 2.7 where the two correspondences shown in red: $\langle \textit{black small}, \leq, \textit{small} \rangle$ and $\langle \textit{white small}, \leq, \textit{small} \rangle$ are linking different classes in O_{CS} to the same *small* in O_{SF}. This property is important to preserve in order for agents to interact well because the interaction of an agent A having the ontology O_{CS} with another agent A' having the ontology O_{SF} is based on the alignment L between both ontologies.

Reference alignment networks:

A reference alignment network is a network of alignments and ontologies where all the possible alignments between the present ontologies are included and are correct. It contains all correct

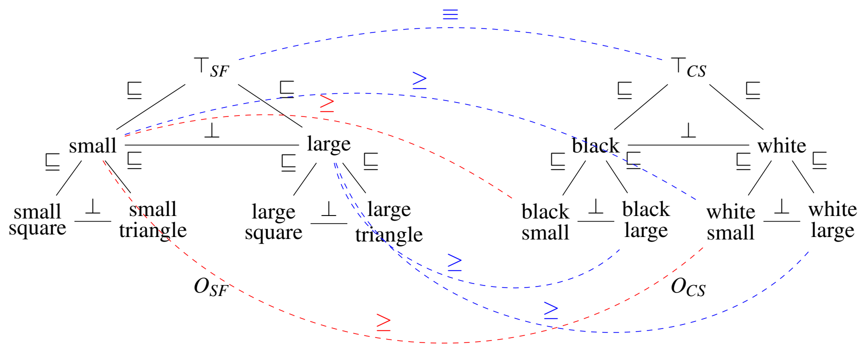


Figure 2.7: An example of an alignment not satisfying the injectivity property.

and complete alignments. In the experiments, the reference alignment network is generated automatically at the beginning of the experiments and it is used for measuring the quality of the alignments of agents by comparison with it. Consider having three boolean features mentioned above, and three ontologies each based on two of the three features: *CS* (color and size), *FC* (shape and color), *SF* (size and shape). Figure 2.8 shows the reference alignment network between these three ontologies where we have: equivalence correspondences between all top classes, and complete and correct alignments between each pair of ontolgies *CS* and *FC*, *CS* and *SF*, and *FC* and *SF*.

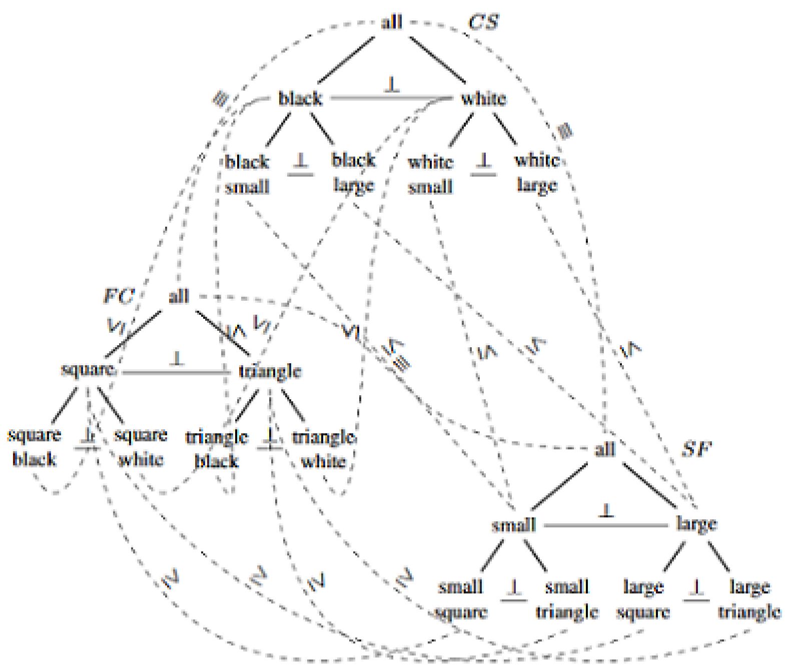


Figure 2.8: Example of a reference alignments network between three ontologies *CS*, *SF* and *FC*, figure taken from [3].

2.2.3 Description of the experiments

Experiments in cultural alignment repair observe a society of agents evolving their culture through a defined protocol. Agents perform repeatedly and randomly a task called "game" and their cultural evolution is monitored. The protocol aims to experimentally discover the common state that agents may reach and its properties.
Agents use their knowledge to play the games and adapt it in consequence. The context of knowledge used here consists of two components: the ontology and the alignments from this ontology towards other ontologies. Ontologies are agents' knowledge representation and they cannot be adapted. Alignments are generated randomly and may be incorrect and incomplete. Thus, agents repair their alignments in an attempt to correct and complete them, and this is what is meant by knowledge adaptation.

Environment:

An environment contains objects characterized by m features, and n agents with as many ontologies as agents. Each ontology is based on $m-1$ of these features and is assigned to an agent. Ontologies are linked using alignments. Agents know about their ontologies which are private to each and they use it to do their task which is playing games, and they also have access to the set of shared alignments between their ontologies. Initially, alignments are randomly generated between ontologies to form random network.

Game:

A game is an interaction between two random agents towards a random object. It consists of the two agents (A) and (A') having ontologies O and O' respectively, and the object (i) to be classified.

Step 1: Agent A asks the other agent A' about its most specific classification C' of the object i. So, C' is a class in O' for which the object i belongs to i.e. i is an instance of C'.

Step 2: Agent A checks the corresponding classification C of the object i, in its ontology O, based on the alignment from O to O' linking a class C of the agent A to the target class C' of agent A.

Step 3: Agent A checks the class D belonging to its ontology O to which it classifies object i to i.e. i instance of D.

Step 4: Agent A compares its real classification D of i to the one that the correspondence of the alignment resulted with which is C. Different cases ensue according to which the result of the game is decided as *Success* meaning that the existing correspondence is not false, or *Failure* meaning that it is false:

- if C and D are equivalent classes, then *Success*.
- if C is a superclass of D, then *Success*.
- if C is a subclass of D, then *Success*.
- if C and D are disjoint, then *Failure* and A attempts to repair the alignment.

Alignment repair:

Alignments are taken to be the repairable component of knowledge addressed in these experiments. Thus cultural repair is the repairing of an agent's alignment linking his ontology to another ontology. This repair is due to *Failure*. Repairing depends on the adaptation operator used by the agent, which according to it, the agent will repair his alignment. Adaptation operators are:

- delete: the correspondence $\langle C, r, C' \rangle$ is discarded from the alignment.

- replace: the equivalence correspondence ($\equiv$) is replaced by a subsumption ($\leq$) from C to C'.
- add: in addition to the previous correspondence, a new subsumption relation ($\leq$) is added from C' to a superclass of C.
- addjoin: states that the argument provided for add is still the same.
- refine: this operator will add ($\geq$) to the subsumees of C' not subsuming D' where $D' \in O'/D'(i)$.
- refadd: this operator implements refine and add.

Evaluation metrics:

Evaluation metrics are the measures, according to which, the experiments of agents repairing their alignments are evaluated. They depend on the alignments and specifically: their correctness and completeness as explained previously.

- Success rate: **??** it is the ratio of *Success* over the number of games played, and it is the main measure.
- Semantic precision and recall: **??** they measure the degree of correctness and completeness, respectively, of the resulting alignments of agents with respect to the reference alignments network.They are denoted P and R respectively.
- Semantic Fmeasure: it is a quality measure that tests the accuracy of agents' alignments. It has the formula:
  $F_m = \frac{2 \times P \times R}{P + R}$
- Convergence: **??** is the number of games at which Fmeasure converges. It is an observed maximum, not an average when the process converges.

Experiments:

Series of experiments were performed to illustrate how each adaptation operator works, and the convergence of agents' knowledge. Experiments have been run with 4 agents playing 2000 games over 10 runs, and results were averaged over these runs [4]. We present three main experiments:

- Convergence: In spite of the random initial settings taken (random initial alignments, random agents and random instances in each games), experiments converge towards a uniform success rate. With 4 agents, several runs converge at 400.
- Repair operators comparison: To test the behavior of the six modalities of the six repair strategies, results of experiments were collected in terms of the mentioned evaluation metrics, where out of 10000 runs, only the first 2000 games are displayed. Results showed different behaviors of the different operators and can be seen in figure **??**.
- Baseline comparison: The results obtained by these operators were then compared to baseline repairing algorithms. These algorithms also use repair strategies and are available to to compare to. Comparison is done in terms of the number of correspondences, success rate, incoherence degree, precision, F-measure and recall, shown in figure **??**. Figure 2.9 shows the evaluation metrics of the results of different experiments run with the different operators and in comparison with the baseline repairing algorithms.

Experimental results showed that cultural repair is able to converge towards successful communication -a state in which no mistake occur- through improving the objective correctness of alignments.

Network and operator	Size	Success rate	Incoherence degree	Semantic Precision	Semantic F-measure	Semantic Recall	Convergence
reference	86	1.0	0.0	1.0	1.0	1.0	-
initial	54	0.24	0.34	0.11	0.20	0.89	-
Alcomo	28	0.43	0.0	0.21	0.26	0.33	-
LogMap	29	0.51	0.0	0.24	0.26	0.29	-
delete	6	0.99	0.0	1.0	0.13	0.07	445
replace	11	0.99	0.01	0.99	0.21	0.12	1478
add	33	0.98	0.14	0.80	0.52	0.39	1396
refine	20	0.99	0.02	0.96	0.37	0.23	1133
addjoin	23	0.99	0.10	0.84	0.43	0.29	1004
refadd	41	0.99	0.09	0.86	0.62	0.48	1266

Figure 2.9: Measures with the reference and initial network on ontologies, the initial network repaired with Alcomo and LogMap, those obtained by the six operators(delete/replace/add/refine/addjoin/refadd), table taken from [4]

2.3 Conclusion

In this chapter, we provided the existing work. On one side, we explained some of the evolutionary theory concepts, some genetic notations, demonstrated the replicator/interactor model as the generalized theory of genotype/phenotype in biological evolution, and presented the study of cultural knowledge evolution which is our main interest. On the other side, we moved to the experimental cultural knowledge evolution field and illustrated the previous experiments in cultural alignment repair. Finally, we presented the problem statement. The next chapter will introduce our theoretical proposal for the extension of experimental cultural knowledge evolution.

— 3 —

Theoretical proposal of extending experimental cultural knowledge evolution

In this chapter, on the one hand, we show how the replicator/interactor mode, explained in Section 2.1.2, will be applied to the study of cultural knowledge evolution, explained in Section 2.1.3. On the other hand, we propose our extension of experimental cultural knowledge evolution. This extension is in terms of the mechanisms that will be added to the previous experiments in cultural alignment repair, that were illustrated in Section 2.2. These mechanisms are mainly from the instantiated replicator/interactor model to cultural knowledge evolution.

3.1 Applying replicator/interactor to cultural knowledge evolution

Based on their functions as entities and the mechanisms they are subject to, the replicator and interactor can be applied to the study of cultural knowledge evolution and specifically on the knowledge/behavior components of culture. We illustrate in this section how the replicator/interactor notions fit knowledge/behavior concepts, and the corresponding mechanisms and structure of the model's application to cultural knowledge evolution.

3.1.1 To which components do replicator and interactor fit?

The replicator and interactor notions, in their informational means, are found to perfectly fit the knowledge and behavior concepts in cultural evolution. We illustrate this as follows:

Knowledge:

Knowledge is considered as a basic entity of human culture. Since knowledge is variable and transmitted across individuals through communication, then it forms a main component in cultural transmission. Moreover, knowledge is also selected and adapted among individuals based on its degree of fitness in the corresponding environment in which the individual carrying this knowledge lives.

Behavior:

Behavior is the result of the corresponding knowledge of an individual, that is knowledge generates behavior. It is the tool by which individuals interact with each other, during encounters, and with their environment. The variations present in knowledge across different individuals lead to variations in the generated behavior. Thus, the differential degree of fitness of knowledge is translated into a differential adaptation of the corresponding generated behavior in the environment. This results in some individuals being more adapted to their environment than others. Eventually, natural selection affects the frequencies of knowledge in the corresponding environment and thus knowledge's inheritance. Due to natural selection and differential fitness, an individual tends to adapt his knowledge in order to fit more in its environment.

Hence, knowledge acts as the replicator and behavior acts as the interactor with their mechanisms as follows:

- Replication of knowledge (i.e. the replicator) through cultural transmission.
- Generation of the behavior (i.e. the interactor) by knowledge.
- Interaction of the behavior in the environment.
- Adaptation of knowledge through behavior.
- Natural's selection impact on the inheritance of the knowledge due to the differential fitness of the behavior.

3.1.2 Different forms of cultural transmission

Cultural transmission can take two different directions regarding the individuals from whom it is transmitted, the individuals to whom it is transmitted, and the mechanism by which it is transmitted.

On the one hand, individuals are able to communicate with each other in order to exchange their knowledge and transmit it to others. This is **knowledge's horizontal transmission** across individuals. Thus, a horizontal form of cultural transmission is done through communication and exchange from living individuals having a certain knowledge to other living individuals having a different knowledge, within the same time interval.

On the other hand, knowledge is inherited from parents to their descendants, while teaching them how to behave, eat, learn, and adapt. This is regarded as **knowledge's vertical transmission**. It is thus due to inheritance and occurs from parents to their newborns who live in different time intervals.

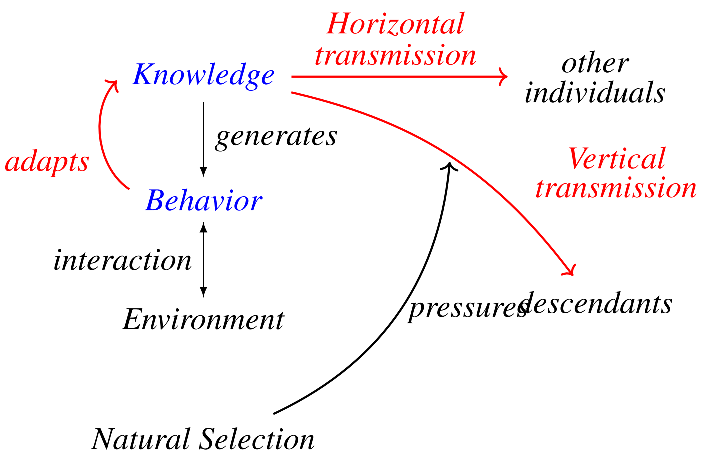


Figure 3.1: The replicator/interactor model for knowledge/behavior components.

As preceding, the application of the replicator/interactor on knowledge/behavior in cultural knowledge evolution shows a perfect fit. This can be seen in Figure 3.1 where we show the two components, knowledge and behavior, and their corresponding mechanisms of generating and interaction of the behavior, adapting knowledge, natural selection, and the horizontal and vertical transmission of knowledge.

3.2 Extending experimental cultural knowledge evolution

After applying the replicator/interactor model to cultural knowledge evolution, we get the instantiated knowledge/behavior model, and thus we aim at experimenting with it. In order to that, we extend the previous experiments in cultural knowledge evolution, specifically the experiments in cultural alignment repair that we illustrated in section 2.2, with the replicator/interactor model. That is to design, implement, and experiment the mechanisms of the knowledge/behavior model, instantiated from the replicator/interactor, model in cultural alignment repair. In order to so, we present in this section the main difference between the previous experiments, what they had, and what we want to add to them, in terms of our proposed mechanisms: knowledge's horizontal transmission and knowledge's vertical transmission

What previous experiments studied

- Interaction between agents by means of the game itself.
- Knowledge adaptation as a result of agents' interaction with other agents. It is done through alignments repair where an agent corrects mistakes in its alignments, its way of thinking towards other agents. This mechanism is considered a source for introducing variations to the initial knowledge of agents.
- Convergence towards a unified state of knowledge after several games.

3.2.1 Knowledge's horizontal transmission:

Knowledge's horizontal transmission is the transmission of knowledge between agents, by means of communication, for knowledge exchange. It can be done by permitting agents, after a certain time, to stop, communicate and exchange their acquired knowledge towards other ontologies during the games. In order for a group of agents to communicate with each other and exchange some knowledge, they need to have the same knowledge representation. This need can be explained with a realistic example from human culture: if we have two individuals with different knowledge illustrated with two languages let's say C and F, C knows only Chinese and F knows only French, and they want to exchange their knowledge towards a third individual E who knows only English. C and F will not be able to communicate in the first place, neither exchange any knowledge. So, to study this horizontal transmission, we have to introduce first a structure that describes a group of agent sharing the same knowledge representation i.e. the same ontology. This structure will be represented by the notion of a *population* which describes a group of agents sharing the same ontology.

Moreover, knowledge's horizontal transmission will be presented as the synchronization of agents' knowledge. And since agents' knowledge comprises their ontology and their alignments, and since their alignments are the acquired repairable component of knowledge, then synchronization will address their alignments. The synchronization of several alignments is the synchronization of the correspondences contained in them. Synchronization will take place between several agents within the same population, towards the other ontologies of other populations.

The result of knowledge's horizontal transmission would be an alignment that is agreed about between the communicating parties. Thus, the output of a population's synchronization is a new alignment (i.e. knowledge towards the ontology that they are synchronizing towards) which includes synchronized correspondences that are agreed about between agents in the population. This alignment will be represented using the notion *Consensus alignment*. The *Consensus alignment* is given then to the agents of the synchronizing population in order to make use of them.

Agents are autonomous and will have several possibilities: replace their old alignment, merge their old alignment with the consensus one (according to disjunction, conjunction, entailment) or even discard the returned consensus alignment. Figure 3.2 presents the synchronization mechanism of the alignments of agents (Ag_1,Ag_2,Ag_3,Ag_4) having the ontology O, towards other present ontologies O' and O''.

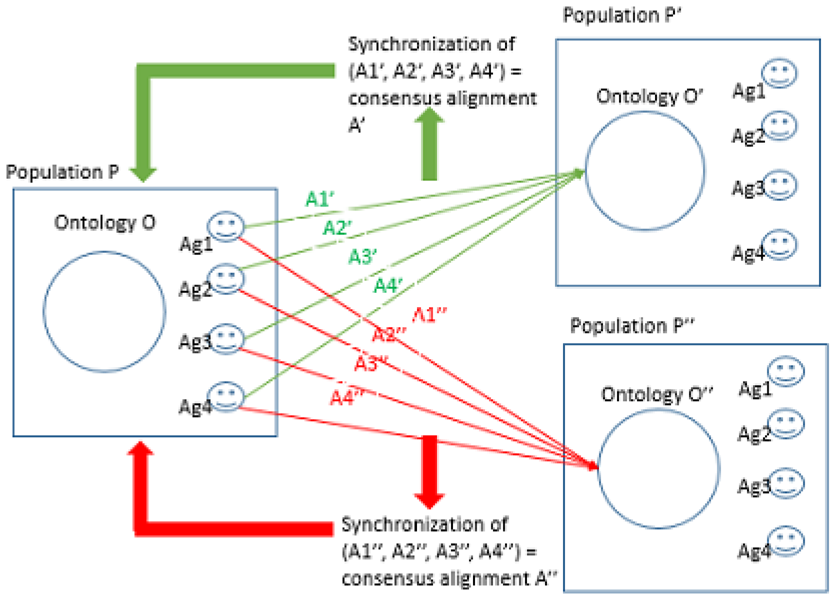


Figure 3.2: Knowledge's horizontal transmission: alignments synchronization.

3.2.2 Knowledge's vertical transmission:

Knowledge's vertical transmission is the transmission of knowledge across agents, in an upcoming time interval, by means of differential inheritance of the fittest knowledge. It can be done by inheriting agents' fittest knowledge, i.e. fittest alignments, after a certain time to another group of agents who would replace the present ones. Differential inheritance is occurs across time and thus is related to a time interval according to which inheritance is seen and would be differential. In order to talk about different time interval, we need to introduce a notion that describes a group of agents in a certain time interval and which is different than another group of agents in another time interval. This will be represented using the term *generation* which represents a group of living agents within the same time interval (regardless of having same or different ontologies, it rather describes agents in the whole environment).

A new generation of agents is generated depending on the fittest knowledge that was there in the previous generation. A fit knowledge depends on the alignments contained in this knowledge rather than on the ontology. This means, for a group of agents having the same knowledge (i.e. a population), the fittest alignments are alignments of the agents who made more successful communications, with other agents of other ontologies, than other agents in their population. Thus, the fitness measure to be used is the function according to which certain alignment is decided to be better adapted than other alignments towards a certain ontology depending on successful communication.

Moreover, knowledge's vertical transmission which provides a new generation of agents concerns all the agents of all different populations. Thus, if we have have n ontologies, that is n populations, the mechanism will generate n populations with transmitting to each population the fittest $n-1$ alignments which the population had before.

Figure 3.3 presents the new generation mechanism of the alignments of agents (Ag_1,Ag_2,Ag_3,Ag_4) having the ontology O, towards other present ontologies O' and O'', which results in the selected alignments: Ax'' which is one of the alignments $A1''$, $A2''$, $A3''$, or$A4''$ according to the fitness function, and Ay' which is one of the alignments $A1'$, $A2'$, $A3'$, or$A4'$ according to the fitness measure used.

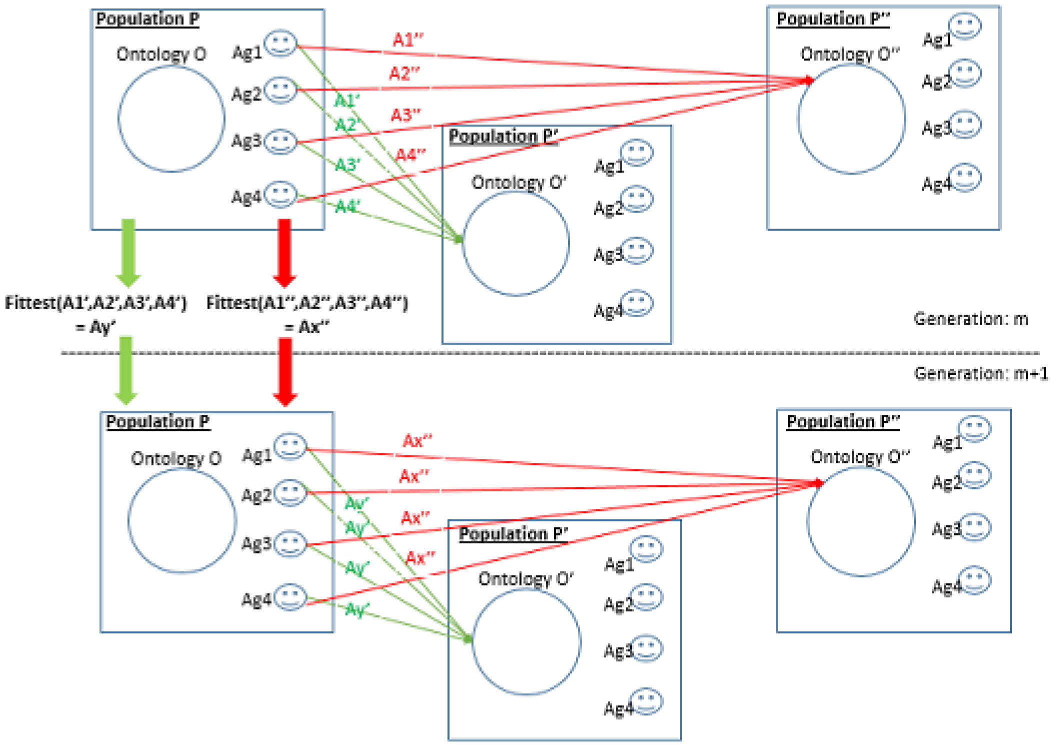


Figure 3.3: Knowledge's horizontal transmission: alignments synchronization.

3.3 Conclusion

Contrary to genes in biological evolution, in current cultural knowledge evolution experiments, there is no explicit transmission of knowledge. Knowledge is only evolved implicitly within each agent through games as seen in Section 2.2.

We thus attempt to introduce explicit knowledge transmission to enhance knowledge evolution. As explained in Section 3.2, this transmission may be vertical or horizontal. We proposed a design of both knowledge transmissions, but our following work will focus on designing, implementing and experimenting the first proposal of knowledge's horizontal transmission via alignments synchronization. However, the second proposal will be designed and described also but without implementation and experimenting. The next chapter presents the practical design and implementation of the proposal taken into consideration.

— 4 —
Mechanisms Design and Implementation

In this chapter, we describe more precisely the two mechanisms presented in Chapter 3. We first provide some important information concerning the new proposed mechanisms, we illustrate the modifications made in the structure of alignments of the previous experiments explained in Section2.2. Then, we consider the horizontal transmission of knowledge proposal followed by the vertical transmission of knowledge proposal.

4.1 Design description and alignments modifications

Agents within the same population share the same ontology, but with different alignments, i.e. each agent makes his own specific alignments towards other ontologies. An agent A, for example, in population P knows that the class C, of another agent A' in its same population, is the same as the class C that it has, because they share the same ontology. But they do not know about each others' alignments.

Moreover, agents do not know the ontology of agents in other populations. In order to learn about them, agents interact with other agents outside their population, at random. This interaction between agents is done through a game which is the same as the original game of the previous experiments explained in Section 2.2. After playing several games, each agent will be having as knowledge: his ontology which is the same to all agents in the same population, his new own alignments which represent new (or the same) knowledge that he gained towards the ontologies of other agents he interacted with.

Modified alignments structure

It is important to notice a main difference in the experimental settings of the current extended experimental framework compared to the previous settings explained in Section 2.2. This difference is regarding the alignments network that links ontologies.
As explained before, alignments were shared between agents in the environment. Alignments were public and agents had access to all, but each agent actually only used the alignment that he needed between his ontology and the ontology of the other agent whom he is interacting with. So, it is true that alignments were public, but each alignment was never accessed by, at least , the one agent who was not concerned by the two ontologies that this alignment relates. Figure 4.1 shows an example of a shared alignments network structure. Each of the alignments A_{12}, A_{13}, and A_{23} included all types of correspondences, that is: equivalence between the tops of all three ontologies, and subsume and subsumed by correspondences. They are considered as bidirectional alignments since they were accessed in both directions. For example, A_{12} which links O_1 to O_2 includes correspondences of the form:

- $\langle \top_1, \leq, \top_2 \rangle$ which is between the top class $\top_1$ and $\top_2$ of O_1 and O_2 respectively.

- $\langle C_1, \leq, C_2 \rangle$ which is made by agent X having O_1 when he interacted with agent Y having O_2 regarding his class C_1, where $C_1 \in O_1$, towards the class C_2 where $C_1 \in O_2$.

- $\langle C'_1, \geq, C'_2 \rangle$ which is made by agent Y having O_2 when he interacted with agent X having O_1 regarding his class C'_2, where $C'_2 \in O_2$, towards the class C'_1 where $C'_1 \in O_1$.

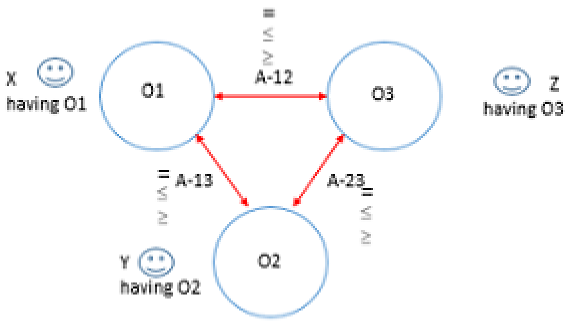


Figure 4.1: An example previous alignments structure

However, the current alignment network linking ontologies has a different structure. This goes back to the fact that ontologies are no more specific to agents, but they are specific to populations instead. Each ontology corresponds to a population and there are several agents in a population. Each agent can interact with randomly chosen agents from other populations. So, each agent might have interacted with certain agents, which are different from the agents whom his friend in his population interacted with. Using figure 3.2, which shows the structure of the current alignment network, we can give an example to make it clear. Three ontologies O, O' and O'' exist in the environment specified for the three populations P, P' and P'' respectively, and the shown agents in each population. Suppose that agent Ag_1 having ontology O has interacted with Ag'_1 and Ag'_2 from P', and thus made an alignment A'_1 relating his ontology O to O' according to what he has learned. Suppose now that, agent Ag_2, his friend in P, has interacted during the games with agents Ag'_3 and Ag'_4 from P' and thus made another alignment A'_2 relating O to O', according to what he has learned. So, A'_1 and A'_2 can be different because alignments' adaptation is dependent on agents.

Moreover, each alignment has a certain direction from an ontology O to O'. A unidirectional alignment is an alignment having one direction only i.e. accessed in one direction. For example, using Figure 4.2, if an alignment links O to O' then this means it belongs to an agent having O and is always under his, and only his, modification while interacting with any other agent having O', and it includes correspondences of the form:

- $\langle \top_O, \equiv, \top_{O'} \rangle$ which is between the top class $\top_O$ and $\top_{O'}$ of O and O' respectively.

- $\langle C, \leq, C' \rangle$ which is made the agent X having O, who has this alignment, when he interacts with any agent having O' during the game. Depending on the game, the agent adapts his alignment by putting a subsumed by correspondence $\leq$. That is why we say that now, all correspondences, have the form $\langle C, \leq, C' \rangle$ because they are seen in one direction.

In an attempt for agents to communicate, exchange their new acquired knowledge towards others, and transmit their knowledge to upcoming generations, the following two mechanisms are taken into consideration.

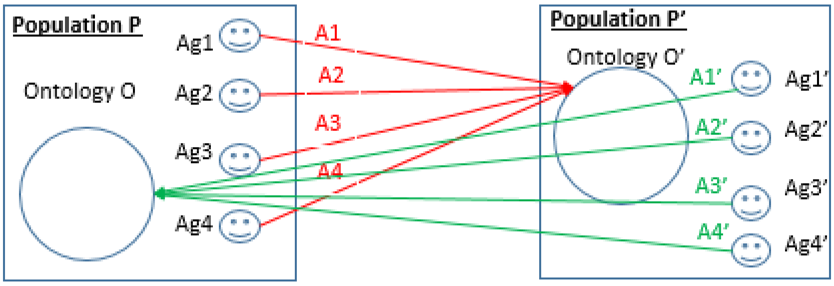


Figure 4.2: An example of the previous alignments structure

4.2 Horizontal transmission of knowledge

4.2.1 Description

A first proposal, is to design and implement knowledge's horizontal transmission between agents within the same population. In order for agents to exchange their acquired knowledge towards others, this mechanism is proposed. It addresses agents' knowledge towards other ontologies, i.e. the agents' alignments.

Populations represent agents having the same ontology. Agents within the same population, after a certain number of games, will synchronize their alignments towards every other ontology. Synchronizing alignments means synchronizing the correspondences of the alignments of these agents within a population. The number of games after which synchronization will occur is called the synchronization rate. Different rates will be considered, based on the population size, to differentiate between different synchronization times and conclude with the best rate. The strategy according to which alignments will be synchronized is called the synchronization mode. We study different synchronization modes in order to depend either on the ontology of the population itself i.e. the hierarchy of classes in it, or on the agents of the population themselves.

Considering a population of n agents, the process of alignments' synchronization consists of two main phases:

- At the population level: computing a consensus alignment is the first phase in which agents give the population their alignments, and the population synchronizes them according to the specified synchronization mode. The result is thus a consensus common alignment, denoted $Cons(A_1, \ldots, A_n)$ for $i = 1, \ldots, n$ where n is the population size i.e. the number of agents in it.

- At the agent level: integrating the result which is updating the old alignments. It is the second phase in which the result of the first is returned to the agents to update their alignment A_i, denoted $Update(A_i, Cons(A_1, \ldots, A_n))$ for $i = 1, \ldots, n$.

Figure 4.3 shows the phases of the synchronization process.

4.2.2 New features of synchronization

Population:

A population is a group of n agents sharing the same ontology. So we have as many ontologies as populations.

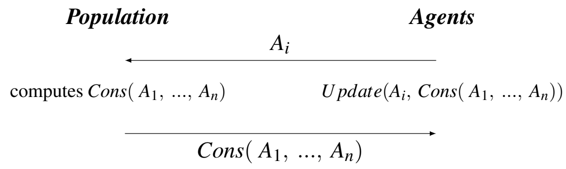


Figure 4.3: Synchronization process phases.

Synchronization rate:

The number of games after which agents would stop to synchronize their alignments and afterwards they continue playing games if more iterations are yet to be played.

Synchronization modes:

Different strategies of synchronization called synchronization modes will be taken into account in order to synchronize a group of agents' alignments. And since synchronizing alignments is synchronizing the correspondences in them, this means that for every class, of the other ontology to synchronize towards, we take the set of classes which agents in the synchronizing population have correspondences with. Consider two populations P and P' with ontologies O and O' respectively. Assume that P is the synchronizing population who is synchronizing its agents' alignments towards ontology O'. This means: for every class C' in O', we get a multi-set of classes S which agents in P have made correspondences from them towards C'. S contains redundant elements. The synchronization of S is done according to one of the three possible modes:

- **majority:** It uses a majority score according to which it returns the class whose frequency in S, denoted $C\#S$, is the highest among all classes in S depending on the size of S, denoted $|S|$. Thus, it gives more importance to the population itself than to the ontology where it depends on the alignments of agents of the synchronizing population. However, if two classes have the same frequency in S, then one is randomly selected. Majority is the default mode in case no mode is specified. It can be translated as follows:

$$Cons(\ A_1,\ ...,\ A_n)_{majority} = \begin{cases} C, & \text{if } C\#S > \frac{|S|}{2} \\ \varnothing & \text{otherwise} \end{cases}$$

- **general:** It chooses the least common subsumer of the classes in S (with condition of not being the top class of the ontology) as the result. That is the most specific class which subsumes all the elements in S. Thus, it gives more importance to the ontology itself than to the population where it depends on the hierarchy of classes in the ontology of the synchronizing population. It can be translated as follows:

$$Cons(\ A_1,\ ...,\ A_n)_{general} = \begin{cases} C, \text{ if } \forall\, C_j \in S,\ 1 \leqslant j \leqslant |S|,\ (C_j \leq C) \\ \qquad \wedge\ (\ \exists!\, D \in O\ /\ \forall\, C_j \in S,\ C_j \leq D\ \wedge\ D \leq C\ ) \\ \qquad \wedge\ (C \neq top(O)) \\ \varnothing \text{ otherwise} \end{cases}$$

- **specific:** It chooses the greatest common subsumee of the classes in S as the result. That is the most general class which is subsumed by all elements in S. It gives more importance to the ontology itself than to the population where it depends on the hierarchy of classes in the ontology of the synchronizing population. It can be translated as follows:

$$Cons(\, A_1,\ ...,\ A_n)_{specific} = \begin{cases} C, \text{ if } \forall\, C_j \in S,\ 1 \leqslant j \leqslant |S|;\ (C \leq C_j) \\ \quad \wedge\ (\ \exists!\, D \in O \,/\, \forall\, C_j \in S,\ C \leq D \\ \quad \wedge\ D \leq C_j\ ) \\ \varnothing \text{ otherwise} \end{cases}$$

To illustrate using an example, the different proposed synchronization modes, consider the following binary tree in Figure 4.4 representing classes where H is the top class.
Assume that we have the set $S = \{\, B,\, A,\, A,\, A,\, A,\, F,\, C\,\}$ containing classes of O from which

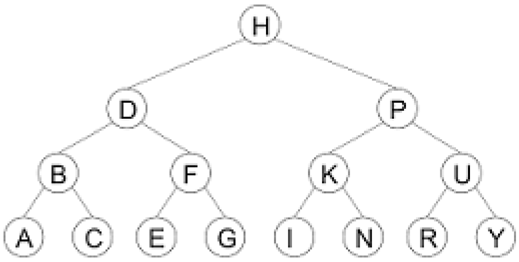


Figure 4.4: A binary ontology.

agents of P have made correspondences with, towards the class X of ontology O'. Thus, the synchronization of S will be as following:

- in case majority mode: the class A having the frequency $(A\#S = 4) > \frac{|S|}{2} = 3$ will be returned as the result
- in case general mode: the most specific class which subsumes all classes is D where $D \leq D$ and $B \leq D$ and $F \leq D$ and $C \leq D$ because they are all subclasses of D.
- in case specific mode: there is no greatest specific class which is subsumed by all the classes in S, thus nothing will be returned in this case.

4.2.3 Implementation

Computing a consensus alignment

We will consider a correspondence of an agent A, in population P having ontology O, towards an ontology O' to have the general form: $\langle C, \leq, C' \rangle$ where $C \in O$ and $C' \in O'$ (*). The ontology towards which an agent synchronizes his alignment with agents of its population, i.e. O', will be referred to as *target ontology*. And moreover, during the synchronization of correspondences towards every class of O', the class C' taken into consideration will be referred to as *target class*. The process of synchronizing the alignments of agents in P towards every other ontology O' involves the following steps:

- Retrieving all the alignments of all agents in P towards all agents in O'.
- Grouping the retrieved correspondences of the alignments according to the target classes of the other ontology. This means, for every target class $C' \in O'$ found in the agents' alignments, we make the set of correspondences $SC = \{\langle C_1, \leq, C' \rangle, \langle C_2, \leq, C' \rangle, ...\}$. Thus SC contains the correspondences issued from different classes in O towards the same class C' in O'. This means that this set will have a maximum number of elements, correspondences, in it equal to the number of agents in P.

- For each entry C', synchronizing the correspondences set SC that is synchronizing the multi-set S containing classes of O from which correspondences in SC are made. The synchronization of S is carried out according to the specified synchronization mode, and returns a result class C.

- Generating the resulting class C into a new correspondence $\langle C, \leq, C' \rangle$, and adding it to the alignment $Cons(A_1, ..., A_n)$. Thus, the consensus alignment will have the results of all synchronizations of P.

- Giving back to the agents of P the resulting consensus alignment.

Integrating the result

In order for agents to integrate the resulting consensus alignment with their current one, two main steps are taken into consideration by agents:

- Updating their old alignment based on a logical merging they decide. They have several possibilities to integrate the new consensus alignment to their old one. Considering that for every agent in P, his alignment is A_i is a set of correspondences $\langle C, \leq, C' \rangle$, and the new consensus alignment has the same structure too, we will suppose that agents will take the following action of integration:

  $Update(A_i, Cons(A_1, ..., A_n)) := \{ \langle C, \leq, C' \rangle \; \forall C' \in O' \; / \; (\langle C, \leq, C' \rangle \in Cons(A_i, \forall i)) \vee (\langle C, \leq, C' \rangle \in A_i \text{ if } \exists! \; \langle C, \leq, C' \rangle \in Cons(A_i, \forall i)) \}$

- Preserving the injectivity property of alignments. Consider now that the new set of correspondences that an agent has (after merging) is S. For every correspondence $Co = \langle C, \leq, C' \rangle$ in S, check if there is any other correspondence which has the same class C, i.e. if S contains more than one correspondence issued from the same class C of O towards different classes in O', the agent then checks other agents in P who have already modified their alignment and asks them about their correspondence towards the target C' if present, or chooses randomly one of them if not.

4.3 Vertical transmission of knowledge

4.3.1 Description

A second proposal, is to design and implement knowledge's vertical transmission across agents over several generations. This mechanism is proposed in order for agents to transmit their fittest knowledge to upcoming generations due to natural selection's effect. It addresses agents' knowledge towards other ontologies, i.e. the agents' alignments.

To do so, the interval of time, i.e. the number of games, which agents will be involved in will be called the generation. Agents within the same generation, after a certain number of games, will transmit their fittest alignments, to a next generation.

4.3.2 New features of generation

Generation:

A new generation is the evolution of its prior one after a certain time. It is the replacement of the agents of a population with new ones haing the fittest knowledge with respect to the fitness measure proposed. It comprises all the populations with their agents.

Generation rate:

The number of games (as the time interval) after which a new generation of agents is generated and replaces the previous one.

Fitness measure:

Depending on the success rate of the chosen settings of of the played games. This goes back to the fact that the agents' degree of adaptation in the environment depends on the interactions that it made, how they revealed the state of its alignments, and consequently pushed him to repair the false alignments. Thus this is related to the agents' knowledge convergence towards a state of success compared to the reference alignments. Hence, the success rate measure is used.

4.4 Conclusion

We have designed two mechanisms to be added to experimental cultural knowledge evolution. However, we only implemented the first one, in the LazyLavender platform. In order to test and experiment with our implemented mechanism, we designed an experimental plan which is presented in the next chapter which is Chapter 5.

— 5 —
Experimental Plan

In this chapter, we provide the experimental design plan in order to test the proposal of knowledge's horizontal transmission mechanism which is explained in Section 3.2, and designed and implemented in Section 4.2.

5.1 Hypotheses

Based on our theoretical proposal and its corresponding mechanisms' implementation, we propose the following hypotheses:

- **H1:** Alignment synchronization leads to faster evolution of agents' knowledge, i.e. a least convergence value is reached with synchronization compared to without synchronization.
  Since synchronization allows agents to exchange their acquired knowledge that they gained through interaction, it is then seen as a cooperation between agents which enhances the evolution their knowledge. Thus, a faster knowledge evolution.

- **H2:** Alignment synchronization provides more accurate alignments, i.e. higher Fmeasure with synchronization compared to without synchronization.
  Since synchronization occurs between several agents regarding their knowledge towards one ontology, it is thus giving importance to the number of agents which agree on this knowledge, or to the relation between their different knowledge, rather than depending on the interaction itself, which can result in a *Failure* communication.

- **H3:** Different synchronization rates lead to different results of convergence, accuracy and success. Taking the synchronization rates (100 ,500, 1000), the rate of 500 provides the least convergence value and the highest Fmeasure, at which it converged compared to the other two rates.
  This is because a low rate is not sufficient yet for agents to have played and adapted their knowledge, and a high rate might not give importance to synchronization because games would be approaching towards convergence already.

- **H4:** Majority synchronization mode converges faster than general and specific.
  This is because majority takes into consideration that an agreement between several agents about a piece of knowledge enhances its possibility to be a true knowledge agreed on.

- **H5:** General synchronization mode gives similar results to those of majority mode but with higher convergence value and a lower Fmeasure at which it converged, with a lower success rate too .
  This is because the general mode takes the most specific common subsumer of all the agents knowledge, which makes all agents satisfied by the result which is always consistent with their previous knowledge on one side. But, on the other side, leading to a decrease in the accuracy of the alignment because of taking a general result.

- **H6:** Specific synchronization mode has the highest convergence values compared to majority and general modes with lower Fmeasure at which it converged, and lower success rate and recall, but higher precision.
  This is because, choosing the greatest common subsumee which is subsumed by what the agents already had, can either lead to an incorrect answer which will decrease recall, Fmeasure, and success rate, or the correct answer that will increase recall. Thus, the result is not always convenient with agents' previous knowledge.

5.2 General experimental setup

All experiments are run using LazyLavender, a framework which provides a simulation tool for cultural knowledge evolution. To carry out the experiments, we need an environment including m populations, each population consisting of n agents. A population P of n agents is characterized by the common ontology that all agents in it would have, and a number of alignments linking resources from this ontology to other ontologies. P can have a maximum of $n \times (m-1)$ alignments connecting it to the other $m-1$ ontologies, of the $m-1$ other populations, in this environment. This goes back to the fact that all the n agents in P would have interacted with at least one agent from all other $m-1$ populations, and thus $n \times (m-1)$ alignments.

However, with the new experimental setup which added the population component, we will use the least possible value that can be taken as the number of populations which is 4. Four populations means 4 different ontologies in the environment. The choice of at least 4 populations is interpretable as follows: In previous experiments [3, 4] where each agent had a different ontology (and no populations), with the setting of 3 agents, some operators derived the convergence of alignments towards a trivial alignment. And according to this, 4 agents, as the minimum number, were considered to be used then. Thus, if we now have the populations as the structures holding distinct ontologies, then we would rather test with at least 4 populations in order to avoid such incompatibility to our main study. Moreover, n will be taken to be 4 also i.e. 4 agents in population. We will use the basic setting for running our experiments, that is running them with no modalities added.

In order to compare our experimental results, we will not use the previous values of the evaluation metrics of the previous experiments [3, 4]. This is because, as explained in Section 4.1, the new alignments structure and the new increased size of the number of agents in the environment, we will have different results. Thus, for comparison, we first get the results of experiment that is without synchronization (i.e. with populations but no synchronization), and we then use these results to evaluate the hypotheses of our synchronization proposal. Each experiment will be run for the six adaptation operators that we have, and results of convergence will be compared in an individual manner, i.e. each operator at once.

5.2.1 Replaying games

In order to make a fair comparison between several game settings (different synchronization modes, different synchronization rates with different operators in each), we attempt to replay the same games with the same initial settings regarding agents' knowledge. Thus, to replay games, a first run is made in which its setting is saved. Then it is used for other runs of different experiments. This helps providing more comparable results.

5.2.2 Controlled variables

The controlled variables in which our experiments address and test for several values are:

- synchronization rate: tested for values equal to 100, 500 and 1000.
- synchronization mode: tested for the possible values which are: majority, general and specific.

5.2.3 Observed variables

Results of the 10 random runs will be averaged, and we will observe the same evaluation metrics presented in 2.2.3 which are:

- Success Rate of an operator op with the condition c, denoted $SRate(c, op)$.
- Semantic Precision and Recall representing the measures of qaulity (correctness) and quantity (completeness), respectively, of an operator op with the condition c, denoted $Prec(c, op)$ and $Rec(c, op)$.
- Semantic F-measure it represents the accuracy, computed in terms of precision and recall, of an operator op with the condition c, denoted $Fmeasure(c, op)$.
- Convergence value, it represents the least game at which the Fmeasure value of an operator op with the condition c converged, i.e. became constant, and it is denoted $ConvTime(c, op)$.

5.3 Experiments

In order to test the validity of the proposed hypotheses and to show how the proposed mechanism of synchronization impacts agents' knowledge evolution with respect to time, we designed three experiments. The following experiments are tested with only the basic setting mentioned in 5.2. Thus, we use 4 populations of 4 agents with 20000 iterations over 3 runs.

5.3.1 Convergence using synchronization

This experiment addresses **H1** and **H2**. It aims at studying agents' knowledge evolution using synchronization and comparing the results of this evolution to the case of no synchronization. To do so, despite the synchronization mode used, we run the following:

- with synchronization, denoted S: using a synchronization rate equal to 500 and majority mode.
- without synchronization, denoted $\overline{S}$ i.e. a synchronization rate equal to 0.

The results of the two runs will test the following:

- **H1** is false if there exits an operator op whose convergence without synchronization is earlier than its convergence with synchronization, i.e.
  $\exists\ op$ such that $Convtime(\overline{S}, op) < Convtime(S, op)$.
- **H2** is false if there exists an operator op whose Fmeasure, at which the iterations converge, without synchronization is greater than its Fmeasure with synchronization, i.e.
  $\exists\ op$ such that $Fmeasure(\overline{S}, op) > Fmeasure(S, op)$.

5.3.2 Synchronization rates comparison

This experiment addresses **H3**. It aims at studying how different synchronization rates affect agents' knowledge evolution and what rate best suits their evolution. It is independent of the synchronization mode, so we choose majority. To do so, we record the results of the following runs:

- using 100 synchronization rate, denoted S_{100}.
- using 500 synchronization rate, denoted S_{500}.

- using 1000 synchronization rate, denoted S_{1000}.

The choice of the preceding numbers for synchronization rates is dependent on the size of the population i.e. the number of agents, where as the size increases greater synchronization rates will be needed and this can be tested later. The results of the three runs will test the following: **H3** is false if **one** of the following ensues:

- there exists an operator op whose convergence time with a synchronization rate of 100 is less than that of its convergence time with a synchronization rate of 500 and its Fmeasure with a 100 synchronization rate is greater than that with a 500 synchronization rate, i.e. $\exists\ op$ such that $(Convtime(S_{100}, op) < Convtime(S_{500}, op))$ $\wedge\ (Fmeasure(S_{100}, op) > Fmeasure(S_{500}, op))$.
- there exists an operator op whose convergence time with a synchronization rate of 1000 is less than that of its convergence time with a synchronization rate of 500 and its Fmeasure with a 1000 synchronization rate is greater than that with a 500 synchronization rate, i.e. $\exists\ op$ such that $Convtime(S_{1000}, op) < Convtime(S_{500}, op)$ $\wedge\ Fmeasure(S_{1000}, op) > Fmeasure(S_{500}, op)$.

5.3.3 Synchronization modes comparison

This experiment aims at testing the behavior of the three synchronization modes: majority, general, and specific. It is independent of the synchronization rate used, so we will choose a synchronization rate of 500 games. To do so, we record the results of the following runs:

- using majority synchronization mode, denoted S_{maj}.
- using general synchronization mode, denoted S_{gen}.
- using specific synchronization mode, denoted S_{spec}.

The results of the four runs will test the following:

- **H4** is false if **one** of the following ensues:
  - there exists an operator op whose convergence time with general mode is less than that of its convergence with majority mode, i.e. $\exists\ op$ such that $Convtime(S_{gen}, op) < Convtime(S_{maj}, op)$.
  - there exists an operator op whose convergence time with specific mode is less than that of its convergence with majority mode, i.e. $\exists\ op$ such that $Convtime(S_{spec}, op) < Convtime(S_{maj}, op)$.
- **H5** is false if **one** of the following ensues:
  - there exists an operator op whose convergence time with general mode is less than that of its convergence with majority mode, i.e. $\exists\ op$ such that $Convtime(S_{gen}, op) < Convtime(S_{maj}, op))$.
  - there exists an operator op whose success rate with general mode is greater than that with majority mode, i.e. $\exists\ op$ such that $SRate(S_{gen}, op) > SRate(S_{maj}, op)$.
  - there exists an operator op whose Fmeasure with general mode is greater than that with majority mode, i.e. $\exists\ op$ such that $Fmeasure(S_{gen}, op) > Fmeasure(S_{maj}, op)$.
- **H6** is false if **one** of the following ensues:

- there exists an operator op whose convergence time with a specific mode is less than that of its minimum convergence time reached with general or majority, i.e. $\exists\, op$ such that $Convtime(S-spec, op) < min(Convtime(S_{maj}, op), Convtime(S_{gen}, op))$.
- there exists an operator op whose Fmeasure with a specific mode is greater than or equal to that of its maximum reached with general or majority, i.e. $\exists\, op$ such that $Fmeasure(S_{spec}, op) > max(Fmeasure(S_{maj}, op), Fmeaure(S_{gen}, op))$.
- there exists an operator op whose SRate with a specific mode is greater than or equal to that of its minimum reached with general or majority, i.e. $\exists\, op$ such that $SRate(S_{spec}, op) > max(SRate(S_{maj}, op), SRate(S_{gen}, op))$.
- there exists an operator op whose Recall with a specific mode is greater than or equal to that of its minimum reached with general or majority, i.e. $\exists\, op$ such that $Rec(S_{spec}, op) > max(Rec(S_{maj}, op), Rec(S_{gen}, op))$.
- there exists an operator op whose Precision with a specific mode is less than or equal to that of its maximum reached with general or majority, i.e. $\exists\, op$ such that $Prec(S_{spec}, op) < min(Prec(S_{maj}, op), Prec(S_{gen}, op))$.

5.4 Conclusion

In this chapter, we provided the experimental design plan that we made in order to carry out the experiments to test our proposed approach. We first stated the hypotheses, then the required experimental setup, and at last, the corresponding experiments. In the next chapter, we will present the results and the necessary interpretation of each of the experiments.

— 6 —

Experimental Results and Discussion

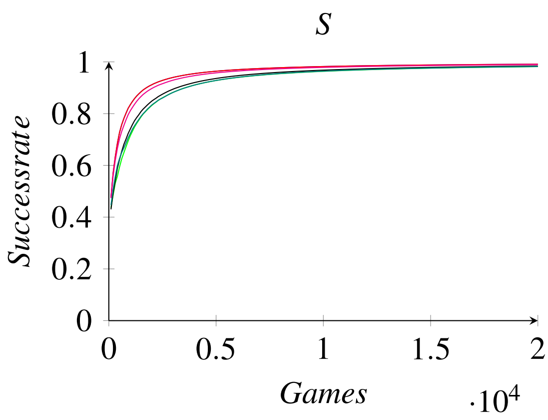
So far, we presented an experimental plan to test the benefits of the proposed alignment synchronization mechanism. In this chapter, we present the results of the experiments that are proposed in Chapter 5. For each experiment, we report the measures of the evaluation metrics that it addresses, and we check the invalidity of each hypothesis, in correspondence to the results of the experiment. We then open a discussion of the obtained experimental results.

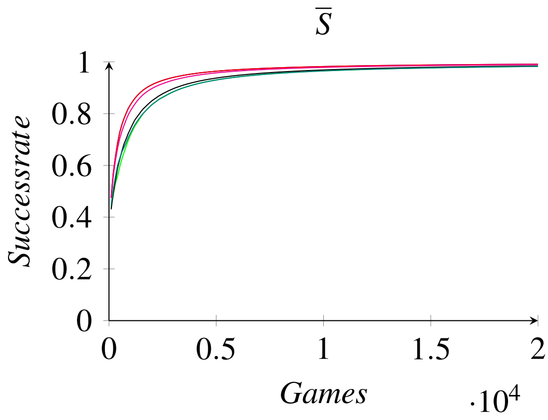
6.1 Experiment of convergence

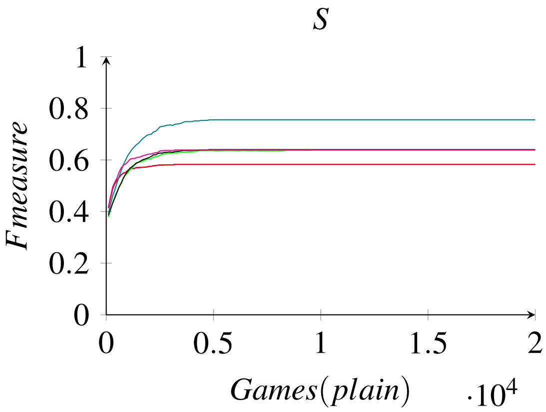
6.1.1 Results with and without synchronization

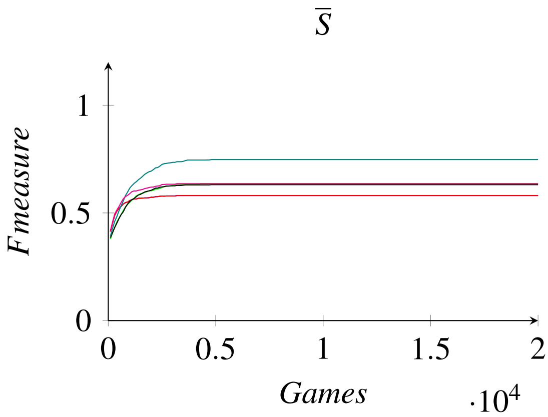
?? We first provide a graphical representation of the obtained results. Below, we show the graphs of the first experiment provided in Section 5.3.1 where we run two experiments: with and without synchronization. We report the values of Fmeasure and Success rate.

replace: delete: add: refine: refadd: addjoin:









Below, Table 6.1 provides a summary of the data shown in the preceding graphs. For each operator, we report its Success rate, Fmeasure, and Convergence value with and without synchronization.

operator	condition	Success Rate	Fmeasure	Convergence
delete	S	0.99	0.58	3174
	$\overline{S}$	0.99	0.58	3174
replace	S	0.99	0.58	3174
	$\overline{S}$	0.99	0.58	3174
refine	S	0.98	0.64	4759
	$\overline{S}$	0.98	0.64	4759
add	S	0.98	0.64	9577
	$\overline{S}$	0.98	0.63	4298
addjoin	S	0.99	0.64	3174
	$\overline{S}$	0.99	0.64	3174
refadd	S	0.98	0.76	5025
	$\overline{S}$	0.98	0.75	4759

Table 6.1: Table showing the results of the evaluation metrics of the six operators with and without synchronization

6.1.2 Hypothesis 1

Alignments synchronization provides least convergence values

Hypothesis is not valid. This is because the convergence value of some operators which are add and refadd are higher with synchronization than their values without synchronization. This means there existed an operator which converged faster without synchronization, and can be seen in Table 6.1 which showed:
$Convtime(\overline{S}, add) = 4298 < Convtime(S, add) = 9577.$
$Convtime(\overline{S}, refadd) = 4759 < Convtime(S, refadd) = 5025.$
We notice the invalidity of the hypothesis H1 with the two operators add and refadd only. This can be interpreted in correspondence to the behavior of these two operators. Add and refadd opeartors add anew correspondence in case of failure, in addition to the previous false one. Thus if half of the agents, at least, in the synchronizing population did not have the chance to play a game that corresponds to this false correspondence and add the new correct one, then majority will always choose the current false one that they gave. Thus, in order for majority to

have better results with these two operators, it needs a higher synchronization rate which gives more chance to a greater number of agents (i.e. more than half the population) to correct their correspondence.

6.1.3 Hypothesis 2

Alignments synchronization provides more accurate alignments

Hypothesis 2 is not invalidated, and thus it still holds. Table 6.1 shows that for all operators, the value of Fmeasure with synchronization is either equal or higher than its value without synchronization. This means that the quality of the obtained knowledge with synchronization is more accurate than that obtained without synchronization. Since the obtained observed effect of synchronization on the quality of the alignments is relatively small, it would require more precise investigation with further significant tests.

6.2 Experiment of Synchronization rates comparison

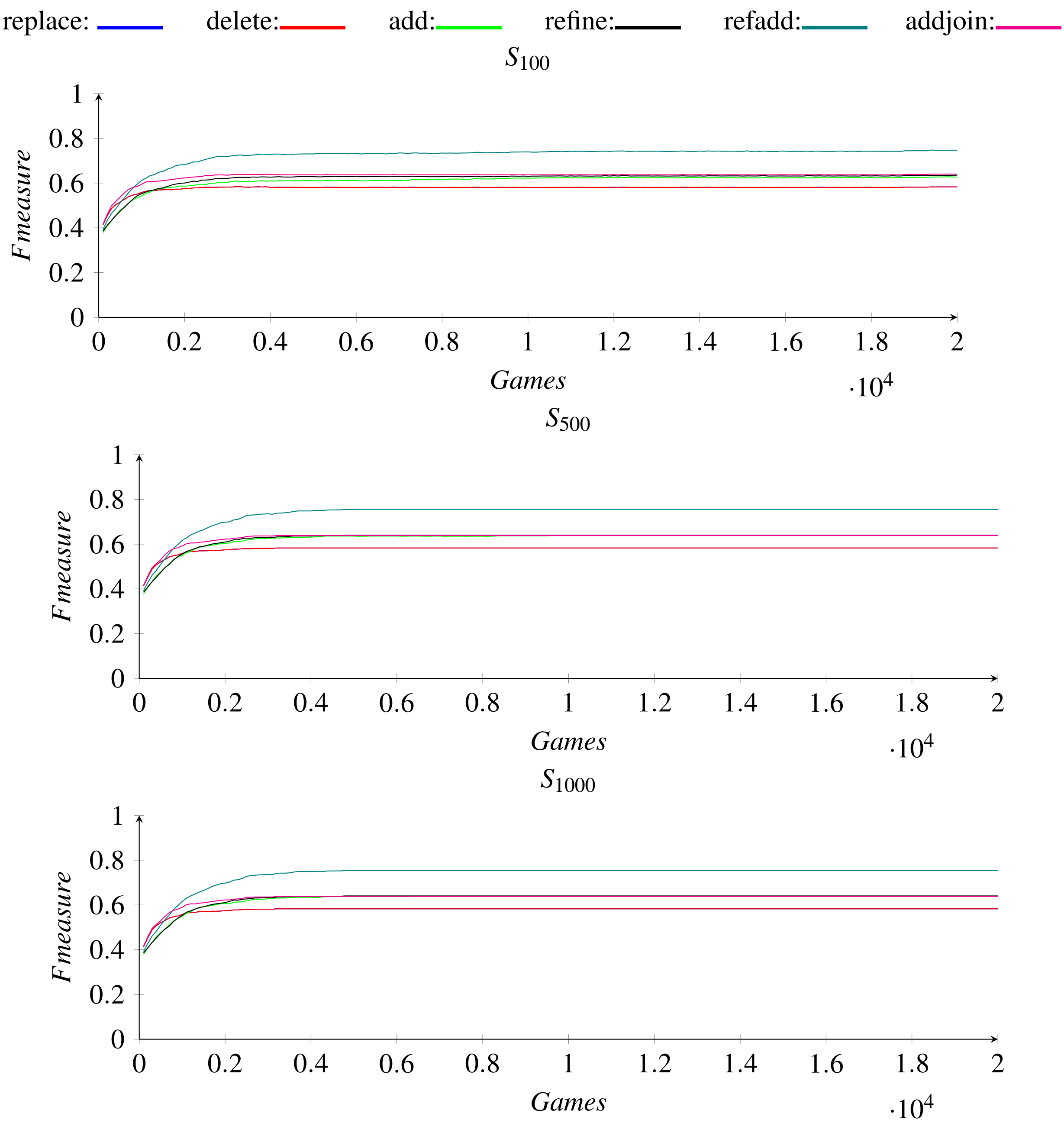
6.2.1 Results of different synchronization rates

We first provide a tabular representation in Table 6.2 of the output results, of the experiment in Section 5.3.2, in terms of Success rate, Fmeasure and Convergence value of the different tested synchronization rates.

operator	condition	Success Rate	Fmeasure	Convergence
delete	S_{100}	0.99	0.58	19302
	S_{500}	0.99	0.58	3174
	S_{1000}	0.99	0.58	3174
replace	S_{100}	0.99	0.58	19302
	S_{500}	0.99	0.58	3174
	S_{1000}	0.99	0.58	3174
refine	S_{100}	0.97	0.64	19975
	S_{500}	0.98	0.64	4759
	S_{1000}	0.98	0.64	4759
add	S_{100}	0.97	0.63	19908
	S_{500}	0.98	0.64	9577
	S_{1000}	0.98	0.64	6272
addjoin	S_{100}	0.99	0.64	19302
	S_{500}	0.99	0.64	3174
	S_{1000}	0.99	0.64	3174
refadd	S_{100}	0.97	0.75	19975
	S_{500}	0.98	0.76	5025
	S_{1000}	0.98	0.75	4759

Table 6.2: Table showing the results of the evaluation metrics of the six operators with different synchronization rates

Below, we show a graphical representation of the Fmeasure values (to show convergence) of the three experiments: with 100 synchronization rate, with 500 synchronization rate and with 1000 synchronization rate.



6.2.2 Hypothesis 3

A 500 synchronization rate provides better results than a 100 or 1000 synchronization rate

Hypothesis 3 is confirmed, and hence it could not be invalidated. Table 6.2 shows that no operator was able converge with a synchronization rate of 100 or 1000 faster than with a rate of 500 with a condition of reaching an accuracy better than majority. On the one hand, a synchronization rate of 100 games shows the highest values in convergence, thus confirming the first part of the hypothesis which concerns a 500 rate being better than a 100 rate. On the other hand, a synchronization rate of 1000 has close results to that of 500 with some operators (as seen with refine, addjoin and refadd) but none of them had better results in terms of lower convergence value and higher Fmeasure. This confirms the second part of the hypothesis which concerns a 500 rate being better than a 1000 rate.

6.3 Experiment of synchronization modes comparison

6.3.1 Results of different modes

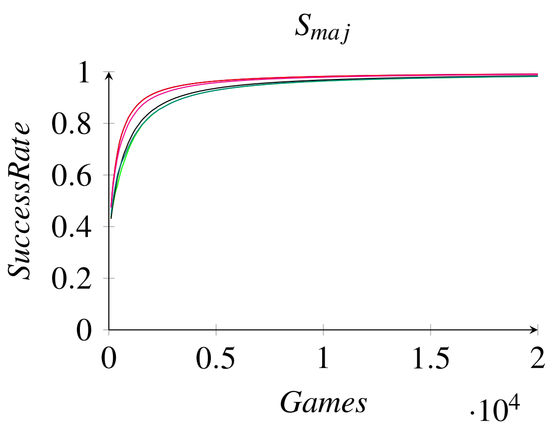
We first provide a tabular representation in Table 6.3 of the output results, of the experiment in Section 5.3.2, in terms of Success rate, Fmeasure and Convergence value of the different tested synchronization rates.

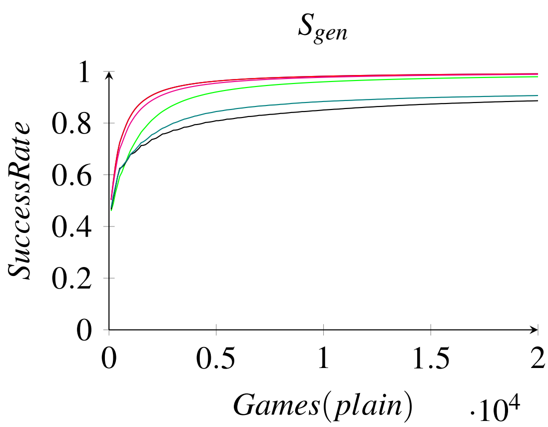
operator	condition	Success Rate	Precision	Fmeasure	Recall	Convergence
delete	S_{maj}	0.99	1.00	0.58	0.41	3174
	S_{gen}	0.99	1.00	0.58	0.41	7502
	S_{spec}	0.99	1.00	0.57	0.40	3156
replace	S_{maj}	0.99	1.00	0.58	0.41	3174
	S_{gen}	0.99	1.00	0.58	0.41	7502
	S_{spec}	0.99	1.00	0.57	0.40	3156
refine	S_{maj}	0.98	0.99	0.64	0.47	4759
	S_{gen}	0.89	0.83	0.65	0.53	20000
	S_{spec}	0.92	0.93	0.65	0.50	19974
add	S_{maj}	0.98	0.95	0.64	0.48	9577
	S_{gen}	0.98	0.96	0.63	0.47	14559
	S_{spec}	0.98	0.96	0.63	0.47	9577
addjoin	S_{maj}	0.99	0.95	0.64	0.48	3174
	S_{gen}	0.99	0.96	0.63	0.47	7502
	S_{spec}	0.99	0.96	0.63	0.47	4054
refadd	S_{maj}	0.98	0.94	0.76	0.63	5025
	S_{gen}	0.91	0.75	0.70	0.65	19994
	S_{spec}	0.94	0.86	0.75	0.66	19969

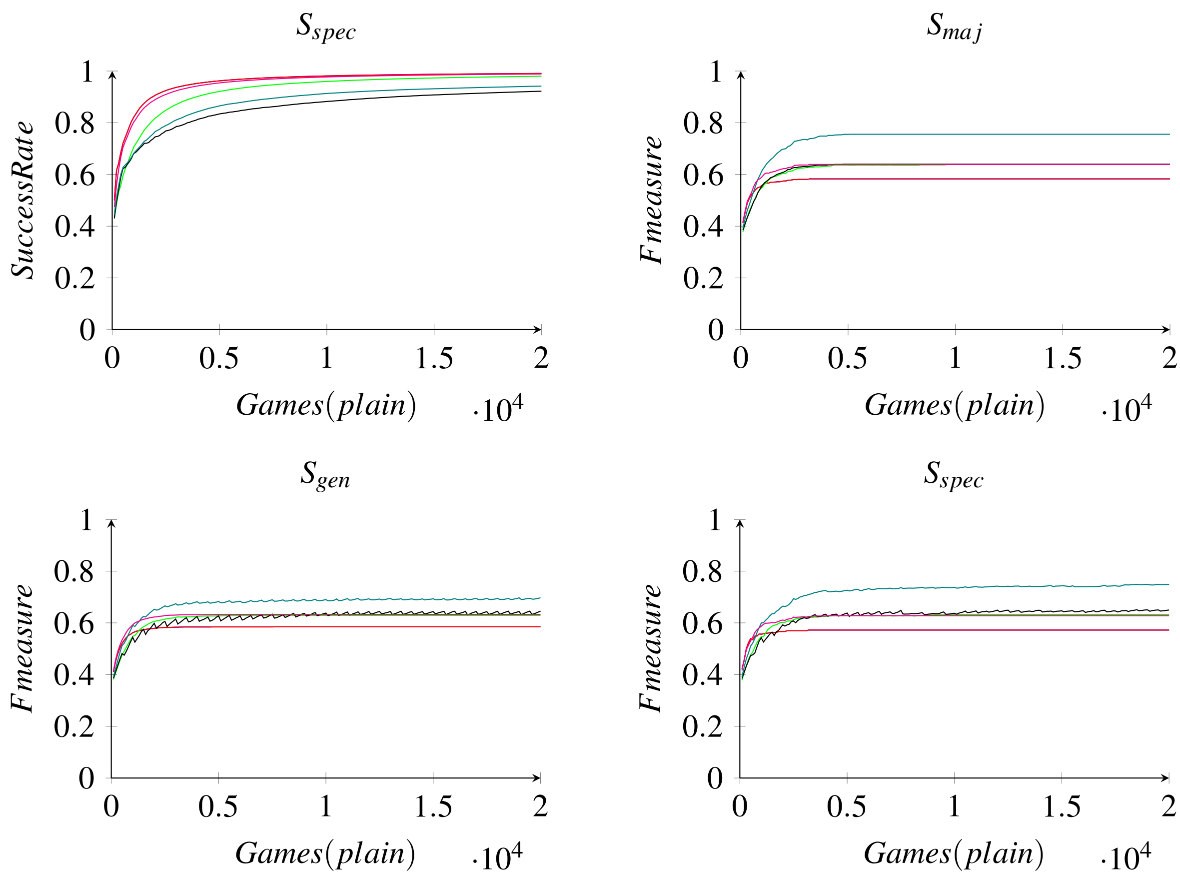
Table 6.3: Table showing the results of the evaluation metrics of the six operators with different synchronization modes

Below, we show a graphical representation of the Success rate and Fmeasure values of the three experiments: with majority synchronization mode, with general synchronization mode and with specific synchronization mode.

replace: delete: add: refine: refadd: addjoin:







6.3.2 Hypothesis 4

Majority provides the least convergence value

Hypothesis 4 is not valid. As seen in Table 6.3, using the specific synchronization mode, the delete and replace operators had less convergence value than that with majority synchronization mode:
$Convtime(S_{spec}, delete) = 3156 < Convtime(S_{maj}, delete) = 3174$
$Convtime(S_{spec}, replace) = 3156 < Convtime(S_{maj}, replace) = 3174$
We notice the invalidity of the hypothesis H4 with the two operators delete and replace only. This can be interpreted in correspondence to the behavior of these two operators with respect to each of majority and specific synchronization modes. The two operators delete or replace the false correspondence. Majority mode, as explained before gives importance to the majority agreement of the agents in the synchronizing population. So, if not, at least, half the agents of the synchronizing population have corrected or deleted the false correspondence, majority will still choose it as its result in the consensus alignment. However, specific synchronization mode, always takes into consideration all the correspondences of the agents, and returns back a new correspodence which least specific one subsumed by all the current correspondences, thus taking into consideration the behavior of delete and replace. Hence, specific seems to be enhancing the behavior of delete and replace operators thus faster convergence. While majority seems to give back the current result each time, and discard the new one that was corrected, unless if a sufficient number of agents have corrected their correspondence already, thus lowering convergence.

6.3.3 Hypothesis 5

General mode converges slower and has less accurate alignments than majority

Hypothesis 5 is not valid since as seen in Table 6.3, using the general synchronization mode, the refine operator had higher $Fmeasure$ than that with the majority synchronization mode: $Fmeasure(S_{gen}, refine) = 0.65 > Fmeasure(S_{maj}, refine) = 0.64$.
However, it is visible that is only the case with the refine operator that it Fmeasure, and only Fmeasure, has higher value than that in majority, but with even no convergence ($Convtime(S_{gen}, refine) =$ 2000). A value of 20000 convergence in an experiment of 20000 iterations means that the corresponding operator did not reach convergence yet. Thus, further experiments should be considered in order to enhance the invalidity or confirm the validity of H5.

6.3.4 Hypothesis 6

Specific mode converges slower and has less complete alignments but more correct ones than majority

Hypothesis 6 is not valid. This is because as seen in Table 6.3, using the specific synchronization mode, the delete and replace operators had less convergence value than that with majority and general synchronization modes :
$Convtime(S-spec, delete) = 3156 < min(Convtime(S_{maj}, delete), Convtime(S_{gen}, delete)) =$ 3174.
$Convtime(S-spec, replace) = 3156 < min(Convtime(S_{maj}, replace), Convtime(S_{gen}, replace)) =$ 3174.
The interpretation of such result has been explained within the result of hypothesis H4.

6.4 Discussion of the results

According to the results that we had, we can draw out the following discussion:

- Synchronization relies highly on the synchronization rate chosen.
  If we compare a synchronization rate of 100, to experiments which do not use synchronization (i.e. synchronization rate = 0), then this will show that synchronization is not a better choice. Since a synchronization rate of 100 games neither converges faster, not has more accurate results in terms of Fmeasure, in comparison to the experiments without synchronization.
  However, a choice of a 500 (or 1000) synchronization rate ensures that experiments with synchronization tend to converge before those without synchronization and thus they show that knowledge evolves faster with synchronization. In addition to faster evolution, knowledge also has higher quality measure with synchronization compared to without synchronization. This can be seen through the values of Fmeasure that show higher values with synchronization (using these rates of 500 or 1000) compared to without synchronization.

- Different synchronization modes affect differently the adaptation operators used by agents. This can be seen through the different values, of each adaptation operator, that we obtained with each synchronization mode.
  Majority and specific modes have close values and higher than those of the general synchronization mode. This can be interpreted by the following: the synchronization general mode always chooses the least common subsumer (i.e. that most specific class that subsumes all the classes) when it want to give agents back a consensus alignment. This contradicts the behavior of some operators which in sake of adapting their knowledge, they go more towards specific classes. The refine operator, for example, corrects *False* correspondences by choosing a more specific class than the previous class that it had in

its correspondence. So if agents, during synchronization, had different specific correspondences, and even maybe true correspondences, the general mode is always trying to give back a common correspondence that is accepted by all the agents. Thus, it is contradicting the behavior of the refine operator. So, convergence would be hardly reached. Thus, in order to compare experiments with and without synchronization, the choice of the mode according to which we synchronize should take into consideration the operator used by the agents in the experiment. The mode should be chosen in a way that, at least, it doesn't contradict the behavior of the adaption operator.

- General and specific synchronization mode have an undesired effect with refine and refadd operators. This can be seen in the two curves representing the Fmeasure values in cases of general and specific mode. The Fmeasure value seems to be in a continuous change of a decrease and increase, thus leading to no convergence. This can be interpreted with what is explained in the preceding point regarding the behavior of refine and that of general mode.
- Knowledge structure, after being modified in comparison with the previous knowledge structure as explained in Section 4.1, showed better results. This can be seen by comparing the following experiments: the experiment without synchronization $\overline{S}$ (i.e. synchronization rate = 0) which we have its results in the first reported experiment in Section **??**, and the previous experiments presented in 2.2.3. But to compare results, we multiply the convergence values of the previous experiments by four, that is because they were performed using an environment of 4 agents, while we now have an environment of 16 agents (4 populations with 4 agents in each).

Thus, further experiments must be performed to study, in a more detailed manner, the synchronization mechanism.

6.5 Conclusion

In this chapter, we provided the experimental performance of the proposed experiments in the previous chapter with the corresponding interpretation in terms of each hypothesis. This was followed by opening a discussion concerning the results, the invalidated hypotheses, and proposing explanations for further work and experiments.

— 7 —
Conclusion

We showed that the replicator/interactor can model cultural knowledge evolution through the knowledge/behavior instantiation. This applicability of the model on the study of cultural knowledge evolution can be seen in two sides. On one side, the components of the model (i.e. the replicator and the interactor) well represent the knowledge and behavior concepts. On the other side, the mechanisms that exist in the model are in par with the knowledge and behavior mechanisms that exist in cultural knowledge evolution. Thus, we succeeded in confirming the applicability of the model in an evolutionary field other than biology which is culture.

We also managed to use this knowledge/behavior instantiated model to extend the previous experiments in cultural alignment repair within two phases.
The first phase was accomplished by modifying the structure of knowledge in the experiments by the ontology component specific for the population concept and the alignments component specific for each agent. Such modification was successful in which it showed better results compared to the results of experiments with the previous knowledge structure.
The second phase concerned the application of the knowledge/behavior mechanisms of the proposed model on the experiments in cultural alignment repair. However, we managed to accomplish studying only one cultural transmission mechanism which is knowledge's horizontal transmission, but not knowledge's vertical transmission due to lack of time. Adding the mechanism of knowledge's horizontal transmission to the experiments was achieved by implementing alignments synchronization according to different synchronization modes and using different synchronization rates. On one side, some results enhanced our proposal of having better knowledge evolution with the presence of knowledge's horizontal transmission mechanism. Other results, which invalidated our hypotheses, give us the base upon which we can build new hypotheses and study with more details the conditions needed for better knowledge transmission. So, these results open a new discussion towards some more complicated restrictions on alignments' synchronization modes that they their improvement of agents' knowledge evolution is dependent on the agents' behavior in the games (i.e. the behavior of the adaptation operator that they use to adapt their knowledge).

We realized that alignments synchronization depends on a combination of the synchronization mode used, the synchronization rate chosen, and the adaption operator used by the agent. Using such a combination, we can be able to push the state of the art towards new hypotheses about knowledge evolution in the experiments of cultural alignment repair, and in particular, to the domain of cultural knowledge evolution. However, depending on the work accomplished in this report, we are able to propose now new hypotheses concerning knowledge evolution.

This work can thus be extended by taking into consideration more complicated conditions in synchronization as in the proposed combination of the synchronization modes, rates and the agents' behavior. For general and specific synchronization mode, we can base on the fact that they were problematic with some operators but well successful with others, and this can be relied on to put more conditions for their usage.

Bibliography

[1] Richard Dawkins. *The Selfish Gene*. New York: Oxford University Press, 1976.

[2] Richard Dawkins. The extended phenotype: The gene as the unit of selection. *Philosophy of Science*, 51(2):357–359, 1984.

[3] Jérôme Euzenat. First experiments in cultural alignment repair. volume 1162, 05 2014.

[4] Jérôme Euzenat. Interaction-based ontology alignment repair with expansion and relaxation. In *Proceedings of the Twenty-Sixth International Joint Conference on Artificial Intelligence, IJCAI-17*, pages 185–191, 2017.

[5] David L. Hull. Interactors versus vehicles. 1988.

[6] Alex Mesoudi and Andrew Whiten. Review. the multiple roles of cultural transmission experiments in understanding human cultural evolution. *Philosophical transactions of the Royal Society of London. Series B, Biological sciences*, 363 1509:3489–501, 2008.

[7] Wikipedia contributors. Culture — Wikipedia, the free encyclopedia, 2019. [Online; accessed 10-April-2019].