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Modeling Higher-Order Adaptive Evolutionary Processes by Multilevel Adaptive Agent Models

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Abstract. In this paper a fourth-order adaptive agent model based on a multilevel reified network model is introduced to describe different orders of adaptivity of the agent's biological embodiment, as found in a case study on evolutionary processes. The adaptive agent model describes how the causal pathways for newly developed features affect the causal pathways of already existing features. This makes these new features one order of adaptivity higher than the existing ones. A network reification approach is shown to be an adequate means to model this.

1 Introduction

In the literature many examples can be found of first-order adaptive agent models, in different (e.g., cognitive, mental, social) domains. The current paper focuses on a case study of an adaptive agent model with biological embodiment to describe evolutionary processes, and the orders of adaptation that are recognized in them; e.g., [3, 4]. The case study addresses how the existence of pathogens has led to the adaptation of developing a defense system with an internal immune system and an external behavioural immune system [1]. Pregnancy led to the adaptation of temporary suppression of the internal defense system to give the (half-foreign) conceptus a chance to get embedded. Moreover, above that, as another adaptation, for the first trimester of pregnancy a strong feeling of disgust was developed to still strengthen the overall defense system by strengthening, in particular, the external component of it; see [1].

The case study is analysed in some depth and modeled by a fourth-order adaptive agent model making use of a multilevel reified network model. For this model different scenarios were simulated. In Sect. 2 the case study itself is briefly discussed. In Sect. 3 reified network models are briefly summarised. Section 4 introduces the fourth-order adaptive agent model, and Sect. 5 the simulations with it. An Appendix addresses mathematical analysis of the model's emerging behaviour and verification of the model based on that; see https://www.researchgate.net/publication/335473231.

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2 Higher-Order Adaptation in Evolutionary Processes

Viewed from a distance, an evolutionary process is an adaptation process that is changing the physical world by creating new causal pathways or blocking existing causal pathways. This can be described as changing the causal connections in such causal pathways from 0 or very low to high, or conversely. The adaptive aspect is exerted by the selection pressure, which makes that for given circumstances organisms with more favourable causal pathways for these circumstances become more dominant. Then they determine more the average causal pathways of the population: this leads to a shift in the average pathways by changes in the causal connections in these pathways. From [9] it is suggested that three levels of adaptation might be considered applicable for the first trimester of pregnancy. However, also the occurrence of pathogens can be considered a form of adaptation for the wider ecological context. Therefore, the following four adaptation orders can be distinguished:

First-Order Adaptation. Pathogens occur, with causal pathways negatively affecting the causal pathways for good health.

Second-Order Adaptation. An internal defense system occurs, with causal pathways which negatively affect the causal pathways used by pathogens.

Third-Order Adaptation. For pregnancy, causal pathways are added to make the defense system's causal pathways less strong as the half-foreign conceptus might easily be identified as a kind of parasite and attacked.

Fourth-Order Adaptation. Disgust during (first trimester) pregnancy adds causal pathways by which potential pathogens in the external world are avoided so that less risks are taken for entering of pathogens while the internal defense system is low functioning. This strengthens the overall defense system by strengthening the external defense system (the behavioural immune system) by which the pathogens are addressed outside the body. this makes the causal pathway from (first trimester) pregnancy to suppress the causal pathways of the overall defense system less strong as the external component of the defense system strengthened by disgust is not addressed by it.

So, can this be used as a basis for a fourth-order reified adaptive network model? This will be addressed in Sect. 4.

3 Reified Adaptive Temporal-Causal Network Models

The designed adaptive agent model to model these evolutionary processes makes use of a Network-Oriented Modeling approach. The Network-Oriented Modeling approach used is based on reified temporal-causal network models [7, 8]. A temporal-causal network model in the first place involves representing in a declarative manner states and connections between them that represent (causal) impacts of states on each other, as assumed to hold for the application domain addressed. The states are assumed to have (activation) levels, usually in the interval [0, 1], that vary over time. The following three main characteristics *connectivity*, *aggregation*, and *timing* of a network structure define a conceptual representation of a temporal-causal network model [6, 9]:

- **Connectivity** Each connection from a state X to a state Y has a connection weight value $\boldsymbol{\omega}_{X,Y}$ representing the strength of the connection.
- **Aggregation** For each state a combination function $\mathbf{c}_Y(..)$ is chosen to combine the causal impacts of other states on state Y.
- **Timing** For each state Y a speed factor $\boldsymbol{\eta}_Y$ is used to represent how fast state Y is changing upon causal impact.

The notion of *network reification* [7] is a means to model adaptive networks in a more transparent manner within a Network-Oriented Modelling perspective. This concept is used in different scientific areas in which it has been shown to provide substantial advantages in expressivity and transparency of models, and, in particular, within AI; e.g., [2, 5, 13]. Specific cases of reification from a linguistic or logical perspective are representing relations between objects by objects themselves, or representing more complex statements by objects or numbers.

For network models, reification can be applied by reifying network structure characteristics for connectivity, aggregation and timing (e.g., $\boldsymbol{\omega}_{X,Y}$, $\mathbf{c}_Y(..)$, $\boldsymbol{\eta}_Y$ indicated above) in the form of additional network states (called *reification states*, indicated by $\mathbf{W}_{X,Y}$, $\mathbf{C}_Y$, $\mathbf{H}_Y$, respectively) within an extended network. According to the specific network structure characteristic represented, *roles* **W**, **C**, **H** are assigned to reification states: *connection weight reification*, *combination function reification*, *speed factor reification*, or values, respectively. Also a role **P** for *combination function parameters* is used. For more details, also see [10, 11], or the forthcoming book [12]. Multilevel reified networks can be used to model networks which are adaptive of different orders [8]. As discussed in Sect. 4 (see Box 1), a format based on *role matrices* **mb** (for base role), **mcw** (for connection weight role **W**), **mcfw** (for combination function weight role **C**), **mcfp** (for combination function parameter role **P**), and **ms** (for speed factor role **H**), is used to specify a reified network model according to these roles.

4 An Agent Model for Fourth-Order Adaptive Processes

Inspired by the information in Sect. 2 but abstracting from specific details, a fourth-order reified adaptive network for these evolutionary processes has been designed. As pointed out in Sect. 2, evolutionary adaptation usually concerns affecting existing causal pathways by adding new causal pathways that weaken or strengthen the existing causal pathways. This makes that levels of adaptation are created where the causal pathways at one adaptation level are adapted by the causal pathways at the next level. The adaptation of a causal pathway can be done by strengthening or weakening one or more causal connections within such a causal pathway. This fits well in a reified network architecture where for each level, for connection weights in causal pathways at that level, reification states are introduced at the next level. The general pattern then becomes in a simple form (for the main example, see Fig. 1):

Base level: causal pathway by a causal connection from a to b

First adaptation level: causal pathway by a causal connection from a_1 to $\mathbf{W}_{a,b}$; this $\mathbf{W}_{a,b}$ represents the causal connection from a to b from the base level

Second adaptation level: causal pathway by a causal connection from a_2 to $\mathbf{W}_{a_1}$, $\mathbf{W}_{a,b}$; this $\mathbf{W}_{a_1,\mathbf{W}_{a,b}}$ represents the causal connection from a_1 to $\mathbf{W}_{a,b}$ from the first adaptation level

Third adaptation level: causal pathway by a connection from a_3 to $\mathbf{W}_{a_2,\mathbf{W}_{a_1,\mathbf{W}_{a,b}}}$; this $\mathbf{W}_{a_2,\mathbf{W}_{a_1,\mathbf{W}_{a,b}}}$ represents the connection from a_2 to $\mathbf{W}_{a_1,\mathbf{W}_{a,b}}$ from the second adaptation level

Fourth adaptation level: causal pathway by a causal connection from a_4 to $\mathbf{W}_{a_3,\mathbf{W}_{a_2,\mathbf{W}_{a_1,\mathbf{W}_{a,b}}}}$; this $\mathbf{W}_{a_3,\mathbf{W}_{a_2,\mathbf{W}_{a_1,\mathbf{W}_{a,b}}}}$ represents the causal connection from a_3 to $\mathbf{W}_{a_2,\mathbf{W}_{a_1,\mathbf{W}_{a,b}}}$ from the third adaptation level

This general pattern for hierarchical adaptation processes for causal pathways will be used to obtain a more specific reified network model for the multilevel adaptation processes described in Sect. 2.

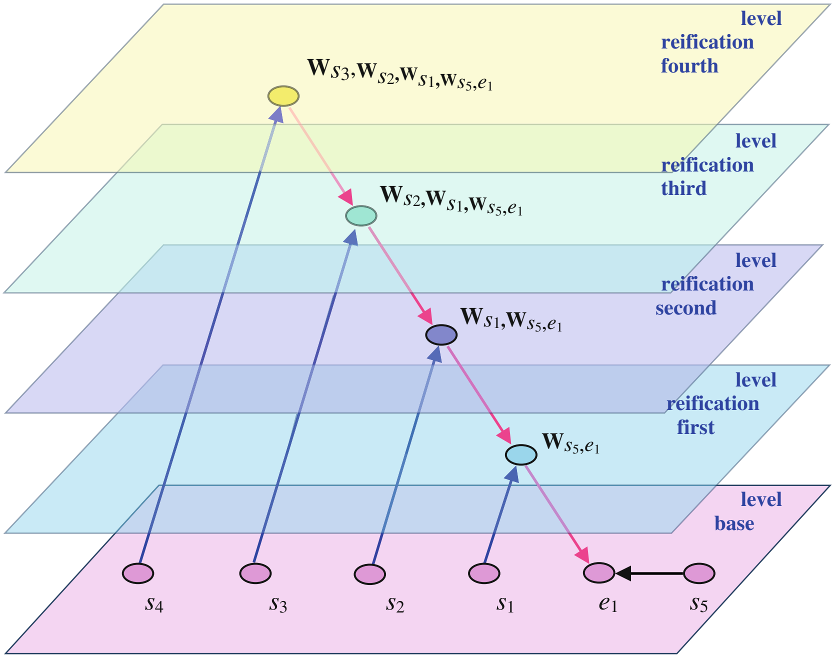

Fig. 1. Reified network model for fourth-order adaptation in an evolutionary context

In the considered reified network model four levels are considered, where for each level its causal pathway can be changed by causal pathways at one level higher. To limit the complexity of the overall model, the causal pathways at each level are kept simple, modeled by just one causal connection covering the whole pathway. Table 1 explains the states of the network model. Figure 1 shows a picture of the conceptual graphical representation of the reified network model. It includes four reification states at four levels which each reify the connection weight of the causal pathway one level lower:

- $\mathbf{W}_{s_5,e_1}$ first reification level state representing the causal connection from s_5 to e_1 from the base level
- $\mathbf{W}_{s_1,\mathbf{W}_{s_5,e_1}}$ second reification level state representing the causal connection from s_1 to $\mathbf{W}_{s_5,e_1}$ from the first reification level
- $\mathbf{W}_{s_2,\mathbf{W}_{s_1,\mathbf{W}_{s_5,e_1}}}$ third reification level state representing the causal connection from s_2 to $\mathbf{W}_{s_1,\mathbf{W}_{s_5,e_1}}$ from the second reification level
- $\mathbf{W}_{s_3,\mathbf{W}_{s_2,\mathbf{W}_{s_1,\mathbf{W}_{s_5,e_1}}}}$ fourth reification level state representing the causal connection from s_3 to $\mathbf{W}_{s_2,\mathbf{W}_{s_1,\mathbf{W}_{s_5,e_1}}}$ from the third reification level

Box 1 shows the role matrices **mb** (base connectivity), **mcw** (connection weights), **ms** (speed factors), **mcfw** (combination function weights), **mcfp** (combination function parameters). Each role matrix has a format in which in each row for the indicated state it is specified which other states (red cells) or values (green cells) affect it, and according to which role. In particular, in role matrix **mcw** the red cells indicate which states X_i play the role of the reification states for the weights of the connection indicated in that cell in **mb**.

Table 1. The states and their explanations

state		explanation	level
X_1	s_1	Occurrence of pathogens	Base level
X_2	s_2	Occurrence of interrnal defense system	
X_3	s_3	Occurrence of pregnancy	
X_4	s_4	Occurrence of disgust	
X_5	s_5	Contextual circumstances	
X_6	e_1	Health level, on a causal pathway with a connection from s_5 for context	
X_7	$\mathbf{W}_{s_5,e_1}$	Reification state for the weight of the base level connection from s_5 for context to $e1$ for health level, on a causal pathway with a connection from s_1 for pathogens	First reification level
X_8	$\mathbf{W}_{s_1,\mathbf{W}_{s_5,e_1}}$	Reification state for the weight of the first reification level connection from s_1 for pathogens to $\mathbf{W}_{s_5,e_1}$, on a causal pathway with a connection from s_2 for internal defense system	Second reification level
X_9	$\mathbf{W}_{s_2,\mathbf{W}_{s_1,\mathbf{W}_{s_5,e_1}}}$	Reification state for the weight of the second reification level connection from s_2 for internal defense system to $\mathbf{W}_{s_1,\mathbf{W}_{s_5,e_1}}$, on a causal pathway with a connection from s_3 for pregnancy	Third reification level
X_{10}	$\mathbf{W}_{s_3,\mathbf{W}_{s_2,\mathbf{W}_{s_1,\mathbf{W}_{s_5,e_1}}}}$	Reification state for the weight of the third reification level connection from s_3 for pregnancy to $\mathbf{W}_{s_2,\mathbf{W}_{s_1,\mathbf{W}_{s_5,e_1}}}$, on a causal pathway with a connection from s_4 for disgust	Fourth reification level

For the specific context described in Sect. 2, these elements are associated to the following:

- in environmental context s_5 a causal pathway from s_5 leads to a good health e_1
- pathogen state s_1 leads to disturbing the causal pathway to a good health effect (e_1)
- well functioning internal defense system (s_2) blocks the causal pathway for the effect of pathogens s_1 on the health pathway to e_1

- pregnancy in the first trimester s_3 needs less blocking of the effect of pathogens
- disgust s_4 is needed to compensate for the less blocking of foreign material

Box 1 Role matrices for the fourth-order adaptive network model

mb	base connectivity	1
X_1	s_1	X_1
X_2	s_2	X_2
X_3	s_3	X_3
X_4	s_4	X_4
X_5	s_5	X_5
X_6	e_1	X_5
X_7	$\mathbf{W}_{s_5,e_1}$	X_1
X_8	$\mathbf{W}_{s_1,\mathbf{W}_{s_5,e_1}}$	X_2
X_9	$\mathbf{W}_{s_2,\mathbf{W}_{s_1,\mathbf{W}_{s_5,e_1}}}$	X_3
X_{10}	$\mathbf{W}_{s_3,\mathbf{W}_{s_2,\mathbf{W}_{s_1,\mathbf{W}_{s_5,e_1}}}}$	X_4

mcw	connection weights	1
X_1	s_1	1
X_2	s_2	1
X_3	s_3	1
X_4	s_4	1
X_5	s_5	1
X_6	e_1	X_7
X_7	$\mathbf{W}_{s_5,e_1}$	X_8
X_8	$\mathbf{W}_{s_1,\mathbf{W}_{s_5,e_1}}$	X_9
X_9	$\mathbf{W}_{s_2,\mathbf{W}_{s_1,\mathbf{W}_{s_5,e_1}}}$	X_{10}
X_{10}	$\mathbf{W}_{s_3,\mathbf{W}_{s_2,\mathbf{W}_{s_1,\mathbf{W}_{s_5,e_1}}}}$	1

mcfw combination function weights		1 alo-gistic	2 comp id
X_1	s_1	1	
X_2	s_2	1	
X_3	s_3	1	
X_4	s_4	1	
X_5	s_5	1	
X_6	e_1	1	
X_7	$\mathbf{W}_{s_5,e_1}$		1
X_8	$\mathbf{W}_{s_1,\mathbf{W}_{s_5,e_1}}$		1
X_9	$\mathbf{W}_{s_2,\mathbf{W}_{s_1,\mathbf{W}_{s_5,e_1}}}$		1
X_{10}	$\mathbf{W}_{s_3,\mathbf{W}_{s_2,\mathbf{W}_{s_1,\mathbf{W}_{s_5,e_1}}}}$		1

mcfp combination function parameters	function	1 alogistic		2 compid	
	parameter	1 σ	2 τ	1	2
X_1	s_1	18	0.2		
X_2	s_2	18	0.2		
X_3	s_3	18	0.2		
X_4	s_4	18	0.2		
X_5	s_5	18	0.2		
X_6	e_1	8	0.5		
X_7	$\mathbf{W}_{s_5,e_1}$				
X_8	$\mathbf{W}_{s_1,\mathbf{W}_{s_5,e_1}}$				
X_9	$\mathbf{W}_{s_2,\mathbf{W}_{s_1,\mathbf{W}_{s_5,e_1}}}$				
X_{10}	$\mathbf{W}_{s_3,\mathbf{W}_{s_2,\mathbf{W}_{s_1,\mathbf{W}_{s_5,e_1}}}}$				

ms	speed factors	1
X_1	s_1	0.08
X_2	s_2	0.05
X_3	s_3	0.015
X_4	s_4	0.008
X_5	s_5	0.2
X_6	e_1	0.5
X_7	$\mathbf{W}_{s_5,e_1}$	0.05
X_8	$\mathbf{W}_{s_1,\mathbf{W}_{s_5,e_1}}$	0.05
X_9	$\mathbf{W}_{s_2,\mathbf{W}_{s_1,\mathbf{W}_{s_5,e_1}}}$	0.004
X_{10}	$\mathbf{W}_{s_3,\mathbf{W}_{s_2,\mathbf{W}_{s_1,\mathbf{W}_{s_5,e_1}}}}$	0.004

iv	initial values	1
X_1	s_1	0.2
X_2	s_2	0.1
X_3	s_3	0.11
X_4	s_4	0.1
X_5	s_5	0.5
X_6	e_1	0
X_7	$\mathbf{W}_{s_5,e_1}$	0.8
X_8	$\mathbf{W}_{s_1,\mathbf{W}_{s_5,e_1}}$	0.8
X_9	$\mathbf{W}_{s_2,\mathbf{W}_{s_1,\mathbf{W}_{s_5,e_1}}}$	0.8
X_{10}	$\mathbf{W}_{s_3,\mathbf{W}_{s_2,\mathbf{W}_{s_1,\mathbf{W}_{s_5,e_1}}}}$	0.8

5 Simulation Experiments

Simulations have been performed using the dedicated software environment for reified network models described in [10, 11] and in the forthcoming [12]. The scenario considered here focuses on a time period in which subsequently pathogens occur, a defense system against them is developed, pregnancy occurs, and disgust (in the first trimester of pregnancy) occurs. So, there are four orders of adaptation:

- Adaptation 1 Pathogens are introduced — first-order adaptation
- Adaptation 2 Defense system is developed — second-order adaptation
- Adaptation 3 Pregnancy — third-order adaptation
- Adaptation 4 Disgust — fourth-order adaptation

The red line in Fig. 2 indicates the health level. Before adaptation 1 health is good, after adaptation 1 health becomes bad, after adaptation 2 health becomes good again, after adaptation 3 health becomes worse again, and after adaptation 4 health becomes better again. The simulation results for this scenario are shown in Fig. 2.

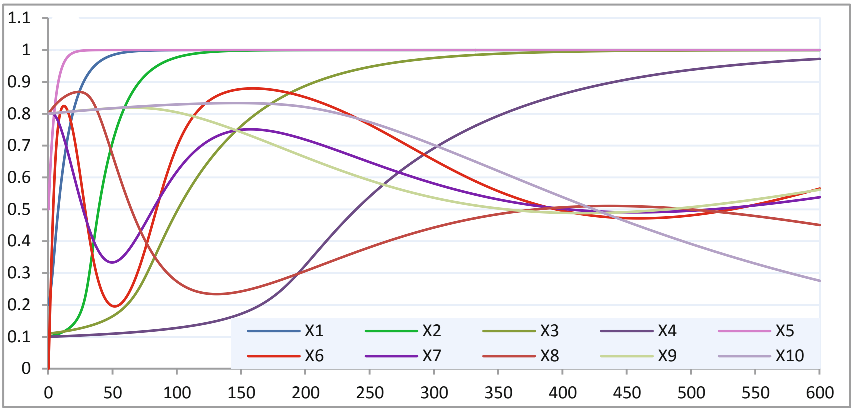

Fig. 2. Simulation with pathogens, internal defense system, pregnancy, and disgust occurring (Color figure online)

6 Discussion

In this paper a fourth-order adaptive agent model based on a multilevel reified network model was introduced to describe different orders of adaptivity found in a case study on evolutionary processes; e.g., [3, 4]. The adaptive agent model describes how the causal pathways for newly developed features in this case study affect the causal pathways of already existing features, which makes the pathways of these new features one order of adaptivity higher than the existing ones, as they adapt the previous adaptation. More details can be found at https://www.researchgate.net/publication/335473231. The network reification approach has shown to be an adequate means to model this in a transparent manner. In future research it can be explored how the adaptive agent model introduced here can be extended and whether this also works for other evolutionary case studies.

From a more general perspective, this paper illustrates how higher-order adaptive agent models can be designed making use of reified network models to specify their functionality and a dedicated Network-Oriented Modeling environment [10, 11]. In the current paper, the agent's embodiment was addressed from a biological perspective. Application for a similar approach to model higher-order adaptive mental and social processes for agents can be found in [8], and in the forthcoming book [12].

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