Anticipatory Behavior: Exploiting Knowledge About the Future to Improve Current Behavior

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Abstract. This chapter is meant to give a concise introduction to the topic of this book. The study of anticipatory behavior is referring to behavior that is dependent on predictions, expectations, or beliefs about future states. Hereby, behavior includes actual decision making, internal decision making, internal preparatory mechanisms, as well as learning. Despite several recent theoretical approaches on this topic, until now it remains unclear in which situations anticipatory behavior is useful or even mandatory to achieve competent behavior in adaptive learning systems. This book provides a collection of articles that investigate these questions. We provide an overview for all articles relating them to each other and highlighting their significance to anticipatory behavior research in general.

1 Introduction

Intuitively, anticipations are an important and interesting concept. Looking ahead and acting according to our predictions, expectations, and aims seems helpful in many circumstances. For example, we say that we are in anticipation, we are looking forward to events, we act goal-oriented, we prepare or get ready for expected events, etc.

Several recent theoretical approaches have been put forward in an attempt to understand and formalize anticipatory mechanisms. Despite these important approaches, though, it is still hardly understood why anticipatory mechanisms are necessary, beneficial, or even mandatory in our world. Therefore, this book addresses the following questions:

- When and in which circumstances are anticipations beneficial for behavior and life?
- Which types of anticipatory behavior are important to distinguish?
- Which environmental properties or rather which fundamental characteristics of our environment make which types of anticipatory processes useful?
- How can the different anticipatory processes be modeled and implemented in artificial adaptive systems?

Over the last few decades, experimental psychology research gradually started to accept the notion of anticipations beginning with Tolman's suggestion of "expectancies" [29, 30] due to his observation of *latent learning* in rats (learning of environmental structure despite the absence of reinforcement). More recently an outcome devaluation procedure [1, 9, 19] has been employed that provides definite evidence for anticipatory behavior in animals. Even more recently, cognitive psychology provides further evidence of distinct anticipatory mechanisms in, e.g., learning [14, 15], attentional processing [18], or object recognition tasks [22].

In theoretical biology [20, 21] and physics [21, 10] anticipations have been suggested to contribute to the essence of complexity and life itself as well as to the stabilization of chaotic control processes. Robert Rosen puts forward one of the first definitions of an anticipatory system:

> [...] a system containing a predictive model of itself and/or of its environment, which allows it to change state at an instant in accord with the model's predictions pertaining to a later instant.[20, p.339]

In Rosen's definition a *system* might be any entity in an environment, such as an animal, a human, or any other living being as well as inanimate physical entities such as machines, robots, or even weather systems. A predictive model is a model that provides information about the possible future state(s) of the environment and/or the system. The system becomes an anticipatory one when it has such a model and when it uses the model to change behavior according to the predictions in this model. For Rosen, anticipation is the fundamental ingredient to distinguish living from non-living systems.

Several recent attempts have been made in artificial intelligence to integrate anticipatory mechanisms into artificial learning systems in the framework of reinforcement learning [27, 16], learning classifier systems (as online generalizing reinforcement learners) and related systems [24, 4, 12, 31], as well as neural networks [8, 11, 28, 2]. So far, research in artificial intelligence has included anticipatory mechanisms wrapped in model learning systems such as the model-based reinforcement learning approach. Anticipatory processes were never analyzed on their own.

This book suggests the investigation of the characteristic properties and enhanced capabilities of anticipatory behavior in a distinct framework. We are interested in when anticipatory behavior is useful, which environmental properties enable effective anticipatory behavior, what types of anticipatory behavior can be distinguished, and what are the distinct behavioral impacts of anticipatory behavior processing. This introduction takes a general approach to these questions clarifying what we mean by anticipatory behavior and related questions. More concrete treatments of the questions, as well as first implementations and application studies of anticipatory behavioral adaptive learning systems, can be found in the successive articles. The provided overview to each article is meant to give guidance to the reader and relate the articles to the big picture of anticipatory behavior put forward herein.

2 What is Anticipatory Behavior?

Without a conceptual understanding of what anticipatory behavior is referring to, scientific progress towards more elaborate and competent anticipatory behavior systems is impeded. The term “anticipation” is often understood as a synonym for prediction or expectation—the simple act of predicting the future or expecting a future event or imagining a future state or event. Merriam-Webster online provides the following definitions for anticipation [17]:

1. a) a prior action that takes into account or forestalls a later action
   b) the act of looking forward; especially : pleasurable expectation
2. the use of money before it is available
3. a) visualization of a future event or state
   b) an object or form that anticipates a later type
4. the early sounding of one or more tones of a succeeding chord to form a temporary dissonance

These definitions stress the look into the future rather than the actual effect of this look. The verb definition stresses the effect of the look into the future much more: [17]:

transitive senses

1. to give advance thought, discussion, or treatment to
2. to meet (an obligation) before a due date
3. to foresee and deal with in advance : FORESTALL
4. to use or expend in advance of actual possession
5. to act before (another) often so as to check or counter
6. to look forward to as certain : EXPECT

intransitive senses

- to speak or write in knowledge or expectation of later matter

In the understanding of this book, anticipation is really about the impact of a prediction or expectation on current behavior. Thus, anticipation means more than a simple lookahead into the future. The important characteristic of anticipation that is often overlooked or misunderstood is the impact of the look into the future on actual behavior. We do not only predict the future or expect a future event but we alter our behavior—or our behavioral biases and predispositions—according to this prediction or expectation. To make this fundamental characteristic of “anticipation” clear, we decided to call this book “*Anticipatory Behavior* in Adaptive Learning Systems” and not merely “Anticipations in Adaptive Learning Systems”. To be even more concrete we define anticipatory behavior as follows:

> **Anticipatory Behavior:** *A process, or behavior, that does not only depend on past and present but also on predictions, expectations, or beliefs about the future.*

The definition is kept fairly general not only to give the reader a feel of what this book is concerned with but also to immediately raise questions and point out the need for further distinctions.

In fact, any “intelligent” process can be understood as exhibiting some sort of anticipatory behavior in that the process, by its mere existence, predicts that it will work well in the future. This implicit anticipatory behavior can be distinguished from explicit anticipatory behavior in which current explicit future knowledge is incorporated in some behavioral process.

To give more intuitive understanding of the concept of anticipation we end this section with a great intuitive example, derived from Sjölander [23], that distinguishes different levels of anticipatory behavior and their resulting impacts. The example addresses the difference in the hunting habits of snakes and dogs. Essentially, a snake is not able to predict future movement of its prey. If the prey disappears, the snake’s hunting behavior remains ’activated’ meaning that it may actively start searching for the prey. However, it does not search for the prey where it should be by now but searches at the spot where the prey was sensed last. On the other hand, a dog hunting a hare (or rabbit) does not need to sense the hare continuously. If the hare, for example, disappears behind a bush the dog predicts the future location of the hare by anticipating where it is going to turn up next and continues its hunt in this direction. This behavior clearly indicates that the dog employs some kind of predictive model of the behavior of the hare predicting the movement of the hare and adapting its behavior accordingly. The snake, on the other hand, does not exhibit any predictive capabilities and consequently does not have a predictive model of the prey that it can employ. Thus, the best thing to do for the snake is to search for the prey where it was sensed last—in (implicit) anticipation to re-sense the prey and eventually catch it.

3 Overview of the Book

The book basically starts from the general and ends with the very concrete. First, philosophical considerations of and reflections on anticipations outline the complexity of the topic. Next, psychological observations of anticipatory behavior are provided which lead to early theories on anticipatory behavior characteristics and properties of anticipatory behavior systems. The following section regarding “Formulations, Distinctions, and Characteristics” develops several mathematical and computational frameworks of anticipatory behavior. Finally, “Systems, Evaluations, and Applications” investigates and develops concrete systems, elaborates on their behavior, and discusses their potentials. The following paragraphs introduce the contributions in somewhat further detail.

3.1 Philosophical Considerations

Seeing our intuitive belief that anticipatory behavior is present in many forms, it is important to investigate the impacts of anticipation on cognition and behavior. Why is anticipatory behavior useful in our world? Which are the cognitive consequences of anticipatory behavior?

This question reaches far back into history and is related to many interesting considerations. The philosophical part of this book provides important thoughts on the impact of anticipatory behavior. The interested reader is also referred to Ernst von Glasersfeld's thoughts on anticipations [13].

Riegler addresses the questions raised by the distinctions between implicit and explicit anticipations used in this book from a constructivist standpoint. He first stresses the importance of anticipations in our cognitive abilities and in our culture, before arguing that unconscious processes are playing a fundamental role in our anticipatory capabilities. Then, from a detailed exposition of the philosophical controversy raised by Libet's ideas on the so-called "readiness potential" and its implication on the possibility of free will, he concludes first that explicit anticipations cannot be equated with the kind of anticipations that a conscious subject actually feels and second that anticipations can only "canalize" our future cognitive processes at a level which is inaccessible to the subject.

Nadin takes a rather different stance on anticipation by regarding guessing, expectation, prediction, and planning as a counter-distinction to anticipation. He argues that anticipatory behavior can only be considered in conjunction with reactive behavior. Further, since anticipation is not reducible to deterministic sequences it is possible to improve predictions and forecasts but it is impossible to accurately predict the future according to past and present.

3.2 From Cognitive Psychology to Cognitive Systems

After comprehending what anticipatory behavior means and why anticipatory behavior can exist in our world, we want to know when and where anticipatory behavior is useful. That is, which environmental properties give rise to beneficial anticipatory behavior?

To approach these questions it is helpful to look at manifestations of anticipatory behavior in real life as well as experimental investigations that show the usefulness of anticipatory behavior in experimental and theoretical scenarios. The psychological section of this book provides many insights in how anticipatory behavior was (re-)discovered by psychology and how it is experimentally assessed in animal and human behavior. Moreover, two psychological-based anticipatory behavior models are derived.

Hoffmann stresses the impact of anticipations on behavioral execution and learning. Similar thoughts had been put forward already in the 19th century in the *ideomotor principle* but were then neglected by the behaviorist movement in the early 20th century. His theory of anticipatory behavioral control emphasizes the primacy of action-effect relations and the secondary conditioning on important contextual information. Behavior is triggered by a representation of its behavioral consequences, making it inherently anticipatory. The proposed mechanisms are supported by a large variety of experimental investigations. A first implementation of the anticipatory behavior control theory was realized in the anticipatory classifier system [24–26].

Witkowski distinguishes four psychological learning theories, integrating them into a dynamic expectancy model of behavior. The model distinguishes between four essential capabilities of anticipatory animats: (1) action independent future predictions; (2) action dependent future predictions; (3) reinforcement independent action ranking; and (4) guided structural learning by detecting unpredicted events (that is, biased learning of a predictive model). Five rules are put forward that guide the generation of predictions and the prediction-dependent action execution. The implementation of the framework in the SRS-E system shows many interesting behavioral properties.

3.3 Formulations, Distinctions, and Characteristics

Next, further frameworks of anticipatory behavior are put forward. In "Internal Models and Anticipations in Adaptive Learning Systems" we postulate further distinctions of anticipatory behavior suggesting (1) implicitly anticipatory behavior, in which predictions are only done implicitly in the control structure, (2) payoff anticipatory behavior, which compares expected payoff before action execution, (3) sensory anticipatory behavior, which alters sensory processing due to predictions, expectations, and/or intentions, and (4) state anticipatory behavior, in which the behavioral component is biased explicitly on future predictions, expectations, and/or intentions. Examples of all types are provided in a literature review on previous adaptive learning systems.

Dubois develops a mathematical theory of strong and weak anticipations. He defines a strong anticipatory system as a system whose predictive model is essentially represented by itself, whereas a weak anticipatory system is a system in which the model is an approximation of the system. Furthermore, he distinguishes between incursive and hyperincursive control. While hyperincursion allows the mathematical formulation of multiple possible outcome scenarios, incursive control results in system stabilization much like *model predictive control* [7] but in a more fundamental way.

Bozinovski sketches a framework of personality based on anticipatory behavior. He addresses the questions of what motivation and what emotion are in an anticipatory system. Motivations for anticipatory behavior are characterized by the anticipation of future emotional consequences. Thus, emotions are seen as the internal reinforcement mechanisms that shapes motivational driven behavior. This is a somewhat controversial but interesting view. In fact, other researches proposed rather the opposite in that emotions are designed to influence current activity selection by, for example, shaping current motivations in an implicitly anticipatory fashion [5, 6]. Further thoughts and elaborations on this matter are necessary.

Davidsson introduces the concept of preventive state anticipation. In this form of anticipation the agent continuously predicts future states. Behavior is altered only if a future state is undesirable. Experimental investigations show the efficiency of the simplest form of preventive state anticipation (i.e. linear anticipation) in a single agent world, cooperative multi-agent world, and a competitive multi-agent world.

Tani puts forward the dynamical systems perspective in terms of anticipatory behavior. He suggests that dynamical systems can prevent the curse of re-representation in the predictive model by learning an implicit dynamic representation of the world in the form of a recurrent neural network. Tani shows that the dynamic predictive model can be used efficiently to predict future states, even conquering the problem of non-Markov states. He explains that the dynamic representations form fractal attractors where each attractor represents a possible state, whereas the fractal structure of each attractor provides information about the past.

3.4 Systems, Evaluations, and Applications

With several concepts of the characteristics of anticipatory behavior and the most important distinctions in mind, this section looks at actual studies of anticipatory behavior in several frameworks including neural network systems, evolutionary computation models, as well as rule-based approaches. Useful characteristics of anticipatory behavior are identified. First applications are suggested.

Baldassarre introduces feed-forward neural net planners and reinforcement-learning based planners. The system can be regarded as a neural net extension of Sutton's Dyna-PI model [27] with additional goal representations (the "matcher") and goal dependent planning algorithms. Reactive and anticipatory behavior are integrated in one framework choosing either one according to current confidence measures. This confidence measure reflects the animat's belief in its own predictions and results in a controlled "thinking before acting". The paper highlights the noise-robust stability of the resulting predictive ANN. Forward and backward planning are applied.

Fleischer, Marsland, and Shapiro introduce a landmark detection mechanism that is based on anticipatory behavior, particularly sensory anticipatory behavior. The anticipatory landmark detection mechanism is shown to clearly outperform pure stimulus-based landmark detection. Moreover, it is shown that the established landmark categories improve behavior when used in a goal-oriented route-following task, pointing out the importance of efficient learning and representation of a predictive environmental model.

Hülse, Zahedi, and Pasemann base their investigation on an evolved minimal recurrent controller. They form macro-action maps to represent the encountered environment exploiting the structure of the recurrent controller. Although the discretization approach departs from Tani's dynamical system perspective, interesting behavior patterns are realized such as exploration, homing, and navigation behavior. Although no truly anticipatory behavior is shown, the discretization approach seems to have great anticipatory behavior potential.

Laaksolahti and Boman provide an interesting application scenario proposing the anticipatory guidance of plot. As anticipations can be seen as stabilization mechanisms as well as guidance down an inevitable path, it is only natural that this property may be extended to plot guidance in an interactive narrative scenario. In its wider sense, the idea of plot guidance is derived from Davidsson's idea of preventive state anticipation.

Edmonds investigates the usefulness of predictive information in an artificial stock market scenario. Both the predictive system as well as the trading system are learned by the means of genetic programming methods. The extensive experimental analysis provides an unclear picture of which scenarios actually benefit from predictive knowledge. As expected, though, predictive knowledge is not sufficient by itself to improve behavior. The study strongly points out the need for further structured investigations of when, where, and how anticipatory behavior is beneficial.

Butz and Goldberg enhance the anticipatory classifier system ACS2 with further state-anticipatory mechanisms. The paper addresses the online generalization of state values while learning a predictive model. State values reflect the utility of reaching a state given a current problem (in the form of a partially observable Markov decision process (POMDP)). For ungeneralized states, the values are identical to values that can be determined by the dynamic programming algorithm approximating the Bellman equation [3]. The resulting system, XACS, implements a predictive model learning module and a separate reinforcement learning module generalizing the representations of both modules online. Behavior is state-anticipatory in that future predictions and the values of those predicted states determine actual behavior. The interaction of multiple reinforcement modules is suggested, allowing for the design of a motivational or even emotional system .

4 Conclusions

Although the concept of anticipatory behavior has been appreciated over many decades, explicit research on anticipatory behavior began only recently. This book provides philosophical considerations, psychological manifestations, formal and conceptual foundations, and first investigations and applications of anticipatory mechanisms. Advantages, as well as possible drawbacks, of anticipatory behavior are revealed. Although none of the questions addressed in this book are answered completely at this point, the large variety of scenarios and examples presented herein are an important step towards a proper understanding and utilization of anticipatory mechanisms.

Anticipatory behavior appears useful in many situations allowing for previously impossible behavioral patterns. First, anticipatory processes can stabilize behavioral execution. Second, anticipations may guide, or canalize, behavioral flow. Third, anticipatory mechanisms can bias attentional processes enabling goal-directed focus and faster reactivity. Fourth, anticipatory behavior may result in advantages in hunting and other competitive scenarios. Fifth, anticipatory behavior may result in faster adaptivity in dynamic environments by the means of internal reflection and planning. Sixth, cooperative behavior may be improved and suboptimal behavior may be overcome by preventive state anticipatory behavior. Finally, anticipatory behavior appears to be an important prerequisite for social interaction.

In conclusion, anticipatory mechanisms can be beneficial in many different areas and in many different forms. Despite this strong diversity, the basic concept of anticipatory behavior is the same in all areas. Thus, the unified investigation of these systems in terms of their anticipatory properties and capabilities may enable prosperous interdisciplinary research advancements effectively sharing new ideas and insights. In particular, future research on anticipatory behavior may lead to (1) significant improvement of the behavior of adaptive learning systems; (2) further understanding of the function of anticipatory mechanisms in animals and humans; (3) the creation of social interactive systems with human-like anticipatory features; (4) the discovery of the processes underlying motivations and emotions; (5) the development of truly cognitive systems that do not only reactively move through the world but learn about important resemblances, contiguities, and causes of effects, and efficiently exploit this knowledge by anticipatory behavior mechanisms. We hope that this first survey on anticipatory behavior in adaptive learning systems will hold its promise and lead to an insightful and rewarding new research direction.

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