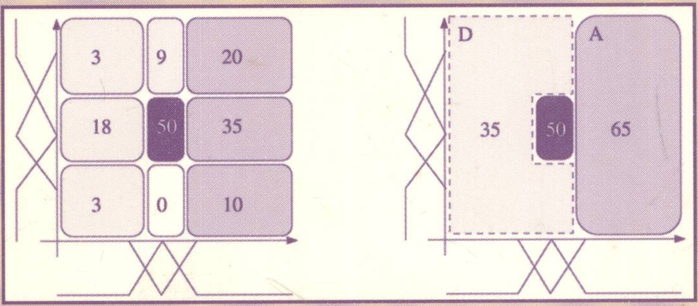
Carlos Andrés Peña Reyes

LNCS 3204

Coevolutionary Fuzzy Modeling



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Library of Congress Control Number: 2004113303

CR Subject Classification (1998): F.1, F.4, I.2

ISSN 0302-9743
ISBN 3-540-22994-9 Springer Berlin Heidelberg New York

Springer is a part of Springer Science+Business Media

springeronline.com

Printed in Germany

Typesetting: Camera-ready by author, data conversion by Boller Mediendesign
Printed on acid-free paper SPIN: 11312918 06/3142 5 4 3 2 1 0

Lecture Notes in Computer Science 3204

Commenced Publication in 1973
Founding and Former Series Editors:
Gerhard Goos, Juris Hartmanis, and Jan van Leeuwen

Lecture Notes in Computer Science

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with love...

to Sandra, my wife, for being there

to Paula, my daughter, for having arrived

Foreword

As we all know only too well, computers are rigid, unbending, unyielding, inflexible, and quite unwieldy. Let's face it: they've improved our lives in many a way, but they do tend to be a pain ... When interacting with them you have to be very methodical and precise, in a manner quite contrary to human nature. Step outside the computer's programmed repertoire of behavior, it will simply refuse to cooperate, or—even worse—it will "crash" (what a vivid term computing professionals have coined to describe a computer's breaking down!). Computers are notoriously bad at learning new things and at dealing with new situations. It all adds up to one thing: At their most fundamental computers lack the ability to *adapt*.

Adaptation concerns a system's ability to undergo modifications according to changing circumstances, thus ensuring its continued functionality. We often speak of an environment, and of the system's adjustment to changing environmental conditions. The archetypal examples of adaptive systems are not among Man's creations, but among Nature's: From bacteria to bumblebees, natural organisms show a striking capacity to adapt to changing circumstances, a quality which has not escaped the eyes of computing scientists and engineers. The influence of the biological sciences in computing is on the rise, slowly but surely inching its way toward the mainstream. There are many examples today of systems inspired by biology, known as *bio-inspired* systems.

Adaptation comes in many guises and forms. For one, computers are *crisp* creatures whereas we humans are *fuzzy*. So can we (beneficially) narrow this gap? There are two possible ways to go about this. The first is by forcing humans to behave more crisply—to be precise and unambiguous; this is exactly the stance that computer programmers must assume: Since they converse in the computer's tongue, they must be very "mechanic," avoiding the use of imprecise concepts. There is another way to narrow the human-computer gap, though, which is much less "painful" to us: having the computer behave in a fuzzier manner. Can this be done—can we "fuzzify" computers? Yes—by using so-called *fuzzy logic*.

Fuzzy logic made its appearance in 1965, when Lotfi Zadeh, then at the University of California, Berkeley, published a paper entitled *Fuzzy Sets*. The field has gained prominence over the past two decades, finding its way beyond academic circles into industry: Many successful commercial applications—fuzzy systems—have been built to date, ranging from washing machines to medical diagnostic systems.

Perhaps the biggest obstacle in the field is that of design: How does one go about designing a fuzzy system, with all of its multifarious, interdependent parameters? In this book, Carlos Andrés Peña-Reyes presents a highly efficient methodology to overcome this debilitating obstruction, by resorting to Nature's modus operandi for designing complex systems: Evolution.

Natural evolution is a powerful force: It has brought about a plethora of complex machines—such as eyes, wings, and brains—the construction of which are still well beyond our current engineering capabilities. If natural evolution is so successful a designer, why not simulate its workings in an engineering setting, by using a computer to evolve solutions to hard problems? Researchers pursuing this idea in the 1950s and 1960s gave birth to the domain of evolutionary computation. Four decades later, the domain is flourishing—both in industry and academia— presenting what may well be a new approach to optimization and problem-solving.

Marriage, as discovered by social designers long ago, is a powerful force, able to bring about genius, ingenious, and heterogenous (albeit sometimes arsenious) offspring. Harnessing this unifying force of nature, Dr. Peña-Reyes has produced a winning offspring by marrying evolutionary computation and fuzzy logic. And, most propitiously, the marriage certificate itself—this book you know hold—is a joy to read!

Enjoy...

April 2004 Moshe Sipper

Preface

> Anything is one of a million paths. [...] I warn you. Look at every path closely and deliberately. Try it as many times as you think necessary. Then ask yourself, and yourself alone, one question: [...] Does this path have a heart? [...] A path without a heart is never enjoyable. You have to work hard even to take it. On the other hand, a path with heart is easy; it does not make you work at liking it. **For my part** there is only the traveling on paths that have heart, on any path that may have heart. There I travel, and the only worthwhile challenge is to traverse its full length. And there I travel looking, looking, breathlessly.
>
> *Don Juan Matus,*
> *quoted by Carlos Castaneda in* The Teachings of Don Juan

Human thinking and in particular our capacity to make decisions has long interested scientists: philosophers, physiologists, psychologists, mathematicians, engineers. Philosophers are interested in the motivations and the implications of decisions, physiologists and psychologists in the different mechanisms leading to them, and mathematicians and engineers in obtaining a model that permits the reproduction of this capacity. The research presented in this book goes in this latter direction: it proposes a methodology for modeling and reproducing human decision-making processes.

Rather than seeing this research as the culmination of an effort, I prefer to see it like a landmark in a path ... my path with heart. This book exists thanks to the support and the teachings of many people. In particular, five people had direct effect on its contents and on its form: Sandra Parra, Moshe Sipper, Andrés Pérez-Uribe, Daniel Mange, and Eduardo Sánchez. To them, my most sincere and grateful acknowledgment. Each person we cross in our life modifies a little the course that our path can take. My gratitude goes to all those people—teachers, friends, and family—whose presence has modeled my path.

This book introduces *Fuzzy CoCo*, a novel approach for system design, conducive to explaining human decisions. Based on fuzzy logic and coevolutionary computation, Fuzzy CoCo is a methodology for constructing systems able to accurately predict the outcome of a decision-making process, while providing an understandable explanation of the underlying reasoning. Fuzzy logic provides a formal framework for constructing systems exhibiting both good numeric performance (precision) and linguistic representation (interpretability). From a numeric point of view, fuzzy systems exhibit nonlinear behavior and can handle imprecise and incomplete information. Linguistically, they represent knowledge in the form of rules, a natural way for explaining decision processes. Fuzzy modeling—meaning the construction of fuzzy systems—is an arduous task, demanding the identification of many parameters. This book analyzes the fuzzy-modeling problem and different approaches to coping with it, focusing on evolutionary fuzzy modeling—the design of fuzzy inference systems using evolutionary algorithms—which constitutes the methodological base of my approach.

The central contribution of this work is the use of an advanced evolutionary technique—cooperative coevolution—for dealing with the simultaneous design of connective and operational parameters. Cooperative coevolutionary fuzzy modeling succeeds in overcoming several limitations exhibited by other standard evolutionary approaches: stagnation, convergence to local optima, and computational costliness.

Designing interpretable systems is a prime goal of my approach, which I study thoroughly herein. Based on a set of semantic and syntactic criteria, regarding the definition of linguistic concepts and their causal connections, I propose a number of strategies for producing more interpretable fuzzy systems. These strategies are implemented in Fuzzy CoCo, resulting in a modeling methodology providing high numeric precision, while incurring as little a loss of interpretability as possible.

The application of Fuzzy CoCo is validated by modeling the decision processes involved in three problems: Fisher's iris data, a benchmark problem, and two breast-cancer diagnostic problems, the WBCD problem and the Catalonia mammography interpretation problem. Several aspects of Fuzzy CoCo are then thoroughly analyzed to provide a deeper understanding of the method. These analyses show the consistency of the results. They also help derive a stepwise guide to applying Fuzzy CoCo, and a set of qualitative relationships between some of its parameters that facilitate setting up the algorithm. Finally, this work proposes and explores preliminarily two extensions to the method: Island Fuzzy CoCo and Incremental Fuzzy CoCo, which together with the original CoCo constitute a family of coevolutionary fuzzy modeling techniques.

Morges, Switzerland
June 2004

Carlos Andrés Peña-Reyes

Table of Contents

1 Introduction

Human thinking and in particular our capacity to make decisions has long interested scientists from many disciplines: philosophy, medicine, psychology, mathematics, and engineering, among others. Philosophers are interested in the motivations and the implications of decisions, physicians and psychologists in the different mechanisms leading to them, and mathematicians and engineers in obtaining a model that permits the reproduction of this capacity. The central aim of this research is to propose a methodology to attain this latter goal: modeling and reproducing human decision making processes.

1.1 General Context

1.1.1 Problem Description

The general problem that motivates the research is the development of an approach to automatically construct systems which predict, as accurately as possible, the outcome of a human decision-making process while providing an understandable explanation of a possible reasoning leading to it. Such systems should, as much as possible, deal with the features of the information involved in human decisions: imprecise, incomplete, ambiguous, and subjective.

Human decision-making processes involve many factors, from factual information to intuitionistic relations, that are hard to explain, even for the person making the decisions (whom we call the *expert*). Acquiring, or transmitting expertise (i.e., the knowledge required to make decisions in a given domain) involves one or more of the following knowledge-processing tasks: formalization, ordered presentation, experiment-driven verification and validation, and continuous actualization based on experience. This is a long process, and a human can take up to several years to reach a satisfactory level of expertise in critical domains. Nowadays, with the increasing amount of available information and the development of new technologies, many domains require the shortening of acquiring, transmitting, and updating knowledge. Computer-based systems may provide the tools necessary to do this.

Present-day databases contain a huge amount of data concerning human decisions that should be used to model decision-making processes. These data are, however, just a collection of recorded facts that do not contain by themselves any information or knowledge useful to explain or to predict the decisions. There exist many methods that, based on these data, can build systems to predict the outcome of a given decision. Albeit useful and widely used, these methods and systems lack the explanatory power required to transmit knowledge to humans.

It thus becomes necessary to produce systems that, besides proposing accurate predictions, also provide human-understandable explanations of the decisions made. Note that the goal herein is not to model the actual human reasoning process, but only to express the knowledge behind a decision in a manner conducive to human understanding. As with many other human activities, decision-making involves information that is inherently imprecise, often ambiguous, and sometimes incomplete. The systems developed should be able to deal with such information, and still provide accurate predictions and understandable explanations.

Many human tasks may benefit from, and sometimes require, decision explanation systems. Among them one can cite client attention, diagnosis, prognosis, and planning. In client attention, the person or system in charge usually requires vast knowledge to answer simple questions. Diagnostic tasks involve the interpretation of many facts to identify the condition of a system. Prediction implies the analysis of actual conditions to predict the future development of a system. Planning tasks involve deciding on actions that, once performed, would drive a system to a desired condition. There exists a domain that concerns all these tasks and several others, where decisions must be made and accompanied by explanations: medicine. Indeed, in medical practice it is customary to perform patient examination, diagnosis of risks and diseases, prognosis of a disease development, and treatment planning. Medicine is thus a domain where explanatory systems might bring many advantages.

Building explanatory systems is a difficult task. An extended approach, used to build so-called expert systems, is based on knowledge gathered directly from experts. One applies a process, known as *knowledge engineering*, which starts by collecting raw knowledge from diverse experts, continuing by systematically organizing and formalizing this knowledge, finally producing an explanatory system capable of providing sufficiently accurate predictions. Such knowledge construction is a lengthy task that involves many people from diverse domains, and long sessions of knowledge gathering, formalization, and validation with experts. Despite the fact that it is costly and time-consuming, knowledge engineering is still the best alternative to designing large and hierarchic explanatory systems (i.e., involving hundreds of input variables, and tens of chained, hierarchical decisions).

Other approaches for building explanatory systems take advantage of available data to support many design stages, extracting the knowledge embedded in the data and representing such knowledge in a manner accessible to humans. These approaches render knowledge engineering more automatic, as the role of the expert is reduced to delimiting the problem and validating the soundness and the coherence of the extracted knowledge.

1.1.2 Proposed Solution

The solution I propose, called *Fuzzy CoCo*, is a novel approach that combines two methodologies—fuzzy systems and coevolutionary algorithms—so as to automatically produce accurate and interpretable systems. The approach is based on two elements: (1) a system model capable of providing both accuracy and human understandability, and (2) an algorithm that allows to build such a model from available information.

To represent the knowledge, I chose fuzzy systems, which may attain good numeric performance and provide a scheme to represent knowledge in a way that resembles human communication and reasoning. Fuzzy systems exhibit some characteristics that render them adequate to solving the problem tackled herein:

1. They represent knowledge in the form of rules, a natural way to explain decision processes.
2. They express concepts with linguistic labels, close to human representation (e.g., "high fever" instead of "temperature higher than 39.3 degrees").
3. Such linguistic representation (i.e., concepts and rules) is accompanied by a precise numeric equivalent that is adequate for managing information available in a numeric way.
4. Fuzzy systems are adequate to model nonlinear behaviors, exhibited by almost all natural processes.
5. Fuzzy systems have proven to be universal approximators, meaning that provided enough rules and concepts, they can approximate any numeric behavior with the desired precision level (at the cost of reduced linguistic expressiveness).

The construction of fuzzy models of large and complex systems is a hard task, demanding the identification of many parameters. To better understand this problem—i.e., the fuzzy modeling problem—I propose a classification of fuzzy parameters into four classes: logic, structural, connective, and operational. This classification serves as a conceptual framework to decompose the fuzzy modeling problem, to understand how existing modeling techniques deal with this problem, and to propose novel techniques to solve it efficiently.

As a general methodology for constructing fuzzy systems I use evolutionary computation, a set of computational techniques based on the principle of natural selection. Evolutionary algorithms are widely used to search for adequate solutions in complex spaces that resist analytical solutions. Specifically, I use an advanced evolutionary technique, cooperative coevolution, which deals particularly well with requirements of complexity and modularity, while exhibiting reasonable computational cost.

The search for interpretability in evolutionary fuzzy modeling is represented by several constraints taken into account when designing the evolutionary algorithm. However, there is no well-established definition for interpretability of fuzzy systems serving to define these constraints. Based on some works that have attempted to define objective criteria to reinforce interpretability, I define two groups of criteria—semantic and syntactic—and propose some strategies to satisfy them.

The resulting approach, Fuzzy CoCo, is a fuzzy modeling technique, based on cooperative coevolution, conceived to provide high numeric precision (accuracy), while incurring as little a loss of linguistic descriptive power (interpretability) as