

# Inferring Hierarchical Clustering Structures by Deterministic Annealing

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## Abstract

The unsupervised detection of hierarchical structures is a major topic in unsupervised learning and one of the key questions in data analysis and representation. We propose a novel algorithm for the problem of learning decision trees for data clustering and related problems. In contrast to many other methods based on successive tree growing and pruning, we propose an objective function for tree evaluation and we derive a non-greedy technique for tree growing. Applying the principles of maximum entropy and minimum cross entropy, a deterministic annealing algorithm is derived in a meanfield approximation. This technique allows us to canonically superimpose tree structures and to fit parameters to averaged or ‘fuzzified’ trees.

## Introduction

Clustering is one of the fundamental problems in exploratory data analysis. Data clustering problems occur in pattern recognition, statistics, unsupervised learning, neural networks, data mining, machine learning and many other scientific fields. The wide range of applications is explained by the fact that clustering procedures are important tools for an automated or interactive detection of structure in data sets. Especially for large data sets grouping data and extracting typical prototypes is important for a compact representation and is a precondition for further symbolic processing stages. In the context of data clustering the detection of hierarchical structures is an essential goal of data analysis. In this paper we consider binary trees with stochastic transition nodes, (Breiman *et al.* 1984) applied to vector-valued data.

We will formulate data clustering as a stochastic optimization problem to be addressed in the *maximum entropy framework*. Maximum entropy methods have been introduced as a stochastic optimization method, called *simulated annealing* in a seminal paper of Kirkpatrick *et al.* (Kirkpatrick, Gelatt, &

Vecchi 1983). To overcome the computational burden of Monte Carlo sampling, efficient *deterministic annealing* variants have been derived for a number of important optimization problems (Yuille 1990; Kosowsky & Yuille 1994; Buhmann & Hofmann 1994; Gold & Rangarajan 1996), including unconstrained clustering and vector quantization. (Rose, Gurewitz, & Fox 1990; Buhmann & Kühnel 1993). Maximum entropy methods have recently been successfully applied to the case of tree-structured vector quantization in (Miller & Rose 1994; 1996). Similar methods have also been used in the context of regression (Jordan & Jacobs 1994) and for unsupervised learning problems (Dayan, Hinton, & Zemel 1995). The key idea in simulated and deterministic annealing is to reformulate a given combinatorial optimization problem as a stochastic optimization problem. A temperature parameter  $T$  is introduced to control the amplitude of the induced noise. In the zero temperature limit,  $T \rightarrow 0$ , the combinatorial problem is recovered, while for high temperatures the objective function is smoothed. Tracking solutions from high temperatures thus helps us to avoid unfavorable local minima.

The major novelty of our approach is an *explicit* treatment of the topology of binary trees in the maximum entropy framework, which results in a systematic and well-founded ‘fuzzification’ of binary tree topologies. At a finite computational temperature different trees are superimposed resulting in an average tree structure. An average tree is not a single tree but a tree mixture. The proposed algorithm optimizes the tree topology jointly with all other relevant parameters, e.g. data assignments to clusters and decision node parameters.

## Unconstrained Data Clustering

We restrict our attention to the case of real-valued data vectors  $\mathcal{X} = \{\mathbf{x}_i \in \mathbb{R}^d : 1 \leq i \leq N\}$ , and a corresponding set of prototypes  $\mathcal{Y} = \{\mathbf{y}_\nu \in \mathbb{R}^d : 1 \leq \nu \leq K\}$ ,  $K \ll N$ ,  $\mathbf{y}_\nu$  representing a group  $G_\nu$ . To describe the mapping of data vectors to prototypes we introduce an indicator function representation by Boolean assignment matrices  $M \in \{0, 1\}^{N \times K}$  obeying the con-

\*Supported by the Federal Ministry for Science and Technology (BMFT) under grant # 01 M 3021 A/4. The LANDSAT data have been provided by D. Klaus.

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