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Descriptional Complexity

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Descriptional Complexity

Dagstuhl-Seminar
May 3 - 7, 1993

Report

on Dagstuhl Seminar Nr. 9318 on

Descriptional Complexity: A Multidisciplinary Perspective

Descriptional complexity is a highly multidisciplinary field, with contributions being made in theoretical computer science, artificial intelligence, statistics, information theory, physics, perceptual psychology, and neurophysiology. However, research efforts in these areas have historically been isolated from each other by disciplinary boundaries. There has been relatively little interdisciplinary interaction and exchange of results despite the fact that the origins of descriptional complexity date back over 30 years.

The purpose of this seminar was to improve interdisciplinary interaction by encouraging such interaction among a small group of leading scientists from several disciplines. The seminar programme included tutorial presentations on the issues each group is addressing, presentations of recent research results, moderated discussions, and many informal discussions as are customary in the conducive Dagstuhl atmoshpere. Through stimulating interactions among the participants we hope to have promoted future interdisciplinary interactions in the field as a whole.

The midterm and longterm goals of this Dagstuhl seminar can thus be summarized as follows:

GOALS:

(1) To promote research in all aspects of descriptional complexity through conferences, publications, and more informal means of scientific interaction;

(2) To promote interaction and the exchange of information across traditional discipline boundaries;

(3) To provide a point of contact for all researchers in all disciplines interested in descriptional complexity and its applications.

In order to achieve the above goals, this Dagstuhl seminar focussed on the following

SCIENTIFIC SCOPE:

The scope of this seminar encompassed many aspects of descriptional complexity, both theory and application. These aspects included but were not limited to:

(1) Generalized descriptional complexity measures and their properties, including resource-bounded complexity, structural complexity, hierarchical complexity, trade-offs in succinctness and the complexity of sets, languages, grammars, automata, etc.;

(2) Algorithmic and other descriptional theories of randomness;

(3) The use of descriptional randomness and associated descriptional complexity measures in computational complexity, economy of description, cryptography, information theory, probability, and statistics;

(4) Descriptional complexity measures for inductive inference and prediction and the use of these measures in machine learning, computational learning theory, computer vision, pattern recognition, statistical inference, and neural networks.

Frankfurt/Main, August 1993 Detlef Wotschke

Participants:

José L. **Balcázar**, Universidad Politècnica de Cataluna

Andrew R. **Barron**, Yale University

Ronald V. **Book**, University of California at Santa Barbara

Alexander **Botta**, Adaptive Computing Inc.

Imre **Csiszár**, Hungarian Academy of Sciences

Carsten **Damm**, Universität Trier

Jürgen **Dassow**, Technische Universität Magdeburg

Joachim **Dengler**, Vision Systems

Josep **Díaz**, Universidad Politècnica de Cataluna

Peter **Gács**, Boston University

Làszló **Gerencsér**, Hungarian Academy of Sciences

Jozef **Gruska**, Universität Hamburg

Juris **Hartmanis**, Cornell University

Günter **Hotz**, Universität Saarbrücken

Tao **Jiang**, McMaster University

Helmut **Jürgensen**, University of Western Ontario

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Jack H. **Lutz**, Iowa State University

Christoph **Meinel**, Universität Trier

Pekka **Orponen**, University of Helsinki

Edwin **Pednault**, AT&T Bell Laboratories

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P. **Gács**: *The Boltzmann Entropy and Randomness Test*

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T. **Jiang**: *k-One Way Heads Cannot Do String Matching – a Lower Bound by Kolmogorov Complexity*

H. **Jürgensen**: *Randomness of Number Representations*

H. **Leung**: *Separating exponentially ambiguous NFA from polynomially ambiguous NFA*

M. **Li**: *Average-case Complexity of Heapsort*

J. H. **Lutz**: *The Utility and Depth of Information*

Ch. **Meinel**: *Frontiers of Feasible Boolean Manipulation*

P. **Orponen**: *Instance complexity*

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P. **Vitányi**: *Thermodynamics of Computation and Information Distance*

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Abstracts:

The Complexity of Algorithmic Problems on Succinct Instances

José L. Balcázar, Universidad Politècnica de Cataluna

(Joint work with A. Lozano and J. Torán)

Highly regular combinatorial objects can be represented advantageously by some kind of description shorter than their full standard encoding. A natural scheme for such succinct representations is by means of Boolean circuits. The complexity of many algorithmic problems changes drastically when this succinct representation is used. Results quantifying exactly this increase of complexity are presented, and applied to show that previous results in the area can be interpreted as sufficient conditions for completeness in the logarithmic time and counting hierarchies.

Asymptotic Optimality of Minimum Complexity Estimation

Andrew R. Barron, Yale University

The minimum description length principle estimates a probability density function from a random sample by minimizing the total description length over a class of candidate probability densities (for each candidate density, data are described by first giving a preamble to specify the density, then giving the Shannon code for the data based on the candidate density). As shown in [1], an index of resolvability characterizes the best trade-off between complexity and accuracy of approximations to the true density. This resolvability bounds both the redundancy of the codes and the accuracy of the estimated density. In cases popularized by Jorma Rissanen, the class of candidate densities for description is a sequence of finite-dimensional smooth parametric families with parameter vectors restricted to a grid spaced at width proportional to $1/\sqrt{n}$ in each coordinate, where n is the sample size. The dominant term in the codelength for the candidate densities is $m/2 \log n$, where m is the dimension of the parameter vector. This codelength provides the minimum redundancy when the true density is in such a family. In contrast, when the families provide approximation to the true density (as in the case of series expansion of the log-density [2]), the redundancy and the statistical convergence rate of the model selected by the criterion with penalty $m/2 \log n$ is of order $(\log n/n)^{2s/(2s+1)}$ (where s is the

number of derivations of the log-density assumed to be square integrable) compared to the optimal statistical convergence rate of order $1/n^{2s/(2s+1)}$ achievable by models selected by Akaikes' information criterion, which uses a penalty of just m. This discrepancy leads us to ask whether it is necessary to abandon the data compression framework to achieve optimal inference. However, by restricting the candidate parameters Θ_k in the series expansion to a grid contained in the ellipse $\sum_{n=1}^{m} \Theta_k^2 k^{2s} \leq r^2$ for some radius $r > 0$, the codelength can be taken to be order m (instead of $m/2 \log n$) for codes that provide the best resolvability. In this case we have a minimum description length criterion that achieves the statistically optimal rate of convergence.

[1] A.R. Barron, T.M. Cover, *Minimum complexity density estimation*, IEEE IT 31, 1991.

[2] A.R. Barron, C.H. Shen, *Approximations of densities by sequences of exponential families*, Ann. Statist. 19, 1991

Complexity Classes and Randomness

Ronald V. Book, University of California Santa Barbara

Let $\mathcal{R}$ be a reducibility. Let ALMOST-$\mathcal{R}$ denote the class

$$\text{ALMOST-}\mathcal{R} \quad := \quad \{ A \mid \text{for ALMOST every } B,\ A \in \mathcal{R}(B) \}.$$

It is known that

$$\begin{aligned}
\text{ALMOST-} \leq_M^P &= \text{ALMOST-} \leq_{BTT}^P = \mathcal{P}, \\
\text{ALMOST-} \leq_T^P &= BPP, \\
\text{ALMOST-} \leq_T^{NP} &= AM, \\
\text{ALMOST-} \leq_T^{PH} &= PH.
\end{aligned}$$

Book, Lutz, and Wagner proved that for suitable $\mathcal{R}$, ALMOST-$\mathcal{R} = \mathcal{R}(\text{RAND}) \cap$ REC, where RAND denotes the class of languages whose characteristic functions are algorithmically random in the sense of Martin-Löf, and REC denotes the class of recursive languages. Thus, ALMOST-$\mathcal{R} = (\bigcup_{B \in \text{RAND}} \mathcal{R}(B)) \cap \text{REC}$.

The new result presented here is the random oracle characterization: for suitable reducibility $\mathcal{R}$, ALMOST-$\mathcal{R} = \mathcal{R}(B) \cap$ REC for **every** $B \in$ RAND.

Using the random oracle characterization the following can be shown: if there exists $B \in \mathsf{RAND}$ such that the polynomial time hierarchy relative to B collapses, then the (unrelativized) polynomial-time hierarchy collapses.

Basic Regularities

Alexander Botta, Adaptive Computing Inc.

We present an approach to unsupervised concept formation based on accumulation of partial regularities. Using an algorithmic complexity framework, we define regularity as a model that achieves a compressed coding of data. We discuss induction of models. We present induction of finite automata models for regularities of strings and induction of models based on vector transitions for sets of points. In both cases we work on structures that accept a decomposition into recurrent, recognizable parts. These structures are usually hierarchical and suggest that a vocabulary of basic constituents can be learned before focussing on how they are assembled. We define basic regularities as algorithmically independent building blocks for structures with reference to a particular model class. We show that they are identifiable as local maxima of the compression factor as a function of model complexity. We illustrate stepwise induction that consists of finding a basic regularity model, using it to compress and encode the data, then applying the same procedure on the code.

Redundancy rates for universal coding

Imre Csiszár, Mathemathical Institute, Hungarian Academy of Sciences

Given a finite alphabet $\mathbf{X}$, a **code** is a mapping $\phi : \mathbf{X}^* \to \{0,1\}^*$ such that for every fixed n, the codewords $\phi(x), x \in \mathbf{X}^n$ satisfy the prefix property. The goodness of a code ϕ for a stochastic model P (a consistent probability assignment to the strings $x \in \mathbf{X}^*$) can be characterized by the behaviour of the (per letter) mean or max redundancy, viz.

$$\frac{1}{n} \sum_{x \in \mathbf{X}^n} P(x)\,(\mid \phi(x) \mid + \log_2 P(x)) \tag{1}$$

or

$$\frac{1}{n} \max_{x \in \mathbf{X}^n} (\mid \phi(x) \mid + \log_2 P(x)) . \tag{2}$$

A code is called **strongly universal** for a model class, in the mean or max sense, if we have $\overline{R_n} \to 0$ or $R_n^* \to 0$, respectively, where $\overline{R_n}$ and R_n^* denote the suprema of the redundancies (1) and (2) as P ranges over the given model class. For several model classes involving a finite number of parameters, such as the class of the i.i.d. models or the Markov models, the best possible $\overline{R_n}$ and R_n^* are known (up to a constant), and are of order $\log n/n$. Very little is known, however, about universal codes for non-parametric model classes. Several preliminary results, obtained jointly with P. Shields (University of Toledo, Ohio) are stated below.

A **renewal model** corresponding to a distribution $\{Q(k)\}$ on $\mathbb{N}$ is a model P with alphabet $\mathbf{X} = \{0, 1\}$ such that if $x = u_0 u_1 \ldots u_m$ with u_i being a string of $j(i)$ zeros followed by a one then $P(x) = P(u_0) \prod_{i=1}^{m} Q(j(i))$.

Theorem 1. For the class of renewal models, there exist strongly max-universal codes with $R_n^* = O(\sqrt{n})$, and there do not exist strongly mean-universal codes with $\overline{R_n} = O(n^{1/3})$.

Now let $\mathbf{X}$ be any finite set, and consider the models P such that if $x = u\,v\,w$, $|\,v\,| \geq l$, then $P(x) \leq kP(u)P(w)$, where l and k are fixed.

Theorem 2. For the above mentioned class, there exist strongly max-universal codes with $R_n^* = O(1/\log n)$.

Symmetric Functions in $AC^0[2]$

Carsten Damm, Universität Trier

Katja Lenz, Universität Frankfurt

We consider symmetric Boolean functions computable by $AC^0[2]$-circuits – polynomial size, constant depth circuits with AND-, OR-, and PARITY-gates. If the depth is restricted to 2 or if PARITY-gates are disallowed, characterizations of these functions are already known (see [1] and [2]). Also for related models similar characterizations are known (see [3]). All these characterizations exhibit one interesting phenomenon: if the depth of the circuits is restricted to be 2, the symmetric functions computable by this type of circuits are all those that have a constant bound on a certain complexity measure. If arbitrary constant depth is allowed, the functions are characterized by having a polylogarithmic bound on that same measure. The question arises if that *magic* polylog bound holds also in the case of $AC^0[2]$. In the depth-2-case the properties of a certain transformation (the well known *Reed-Muller*-transformation) played a central role. Under the assumption that these properties continue to hold in the general constant depth

case, we can give a complete characterization also for $AC^0[2]$: any symmetric Boolean function in $AC^0[2]$ is "in essential" 2^t-periodic with $2^t = \log^{O(1)} n$ - thus completing the above drawn picture of constant and polylogarithmic bounds.

[1] C. Damm, *The complexity of symmetric functions in parity normal forms*, Mathematical Foundations of Computer Science, Vol. 452 of Lecture Notes on Computer Sciences, Springer 1990, 232-238

[2] R. Fagin, M.M. Klawe, N.J. Pippenger, L. Stockmeyer, *Bounded depth, polynomial size circuits for symmetric functions*, Theoretical Computer Science 36, 1985, 239-250

[3] Z.L. Zhang, D.A. Mix Barrington, J. Tarui, *Computing symmetric functions with AND/OR circuits and a single MAJORITY gate*, in: Symposium on Theoretical Aspects of Computing, 1993.

Descriptional Complexity of Grammar Systems

Jürgen Dassow, Technische Universität Magdeburg

Motivated by the blackboard architectures of Artificial Intelligence we introduce grammar systems which consist of some sets of productions and rewrite a common sentential form. The investigations concern the following measures of description:

- number of components,
- number of productions in a component,
- number of active symbols in a component,
- degree of nondeterminism.

We present the hierarchies which are obtained by the restriction of one or two of these parameters.

Moreover, we show that descriptions of context-free languages by grammar systems are more succinct than descriptions by context-free grammars.

Stochastic Complexity of Orthonormal Function Systems and Applications in Image Analysis

Joachim Dengler, Vision Systems

The concept of stochastic complexity eliminates all possible redundancy of a coding system, thus approximating closely the Kolmogorov complexity.

One practical problem of stochastic complexity is the fact that it cannot be calculated analytically in closed form for most model classes. It is shown in this presentation that for the regression problem with orthonormal regressor variables and the traditional conjugate priors, the stochastic complexity can indeed be determined in closed form. The result is a very simple formula, where the stochastic complexity only depends on the number of parameters and the ratio of the explained to the total variance.

The system of the eigenfunctions of the 2D quantum mechanical harmonical oscillator are shown to be extremely useful for early vision, not only due to their variance properties with respect to scaling and rotation, but also due to their biological relevance.

As an example a high level segmentation problem of fingerprint images is presented. The intuitive understanding of good quality is translated into the local concept of a ID wave with local support. By comparing the stochastic complexity of an oriented model with a general model the quality of a fingerprint quantified and the "good" areas are labelled reliably.

The Query Complexity of Learning DFA

Josep Díaz, Universidad Politècnica de Cataluna

(Joint work with J. L. Balcázar, R. Gavalda, O. Watanabe)

It is known that the class of deterministic finite automata is polynomial learnable by using membership and equivalence queries. We investigate the query complexity of learning deterministic finite automata (number of membership and equivalence queries made during the process of learning). We extend a known lower bound on membership queries to the case of randomized learning algorithms, and prove lower bounds on the number of alternations between membership and equivalence queries. We also show that a trade-off exists, allowing us to reduce the number of equivalence queries at the price of increasing the number of membership queries.

The Boltzmann Entropy and Randomness Test

Peter Gács, Boston University

Description complexity is known to be related to Shannon entropy. The relation to thermodynamical entropy is less understood. Here we introduce a quantity called algorithmic entropy which is defined via payoff functions, and is close to the negative of Martin-Löf's test. The approximations to this quantity have the form $K(\omega^n) + \log_2 \mu(\Gamma_{\omega^n})$, where K is the prefix description complexity, ω is an element of the "phase space", ω^n are the first n bits of a binary description of ω, μ is the phase space volume measure, and Γ_{ω^n} is the set of those elements with first bits ω^n. This quantity is interpreted as the desirable correction of Boltzman's entropy, related to a similar expression introduced by Zurek. Its properties will be discussed, and several relations among the abovementioned quantities will be established.

Stochastic Complexity and Optimal Misspecification

Làszló Gerencsér, Computer and Automation Institute, Hungarian Academy of Sciences

We present a problem in signal processing, which can be solved using ideas of the theory of stochastic complexity. The problem is the so-called change point detection, where the change in the dynamics of a stochastic process has to be detected. Stochastic complexity in its predictive form due to Rissanen is generalized to allow for the description of time-varying processes. The idea is to forget past information at an exponential rate. This way the estimation algorithm also becomes more robust. Moreover misspecification i.e. the use of simple models which may not contain the true model becomes desirable, and thus the problem of increasing model complexity is avoided. In the context of change point detection the encoding procedure is tailored to the assumed moment of change. Thus the number of model classes is equal to the number of observations, but the associated codelengths can be reduced to the partial sums of a signal sequence. An extensive computer simulation has shown the viabiltiy of the method. In addition a number of beautiful mathematical problems can be formulated in connection with these methods, some of them which have been answered.

Some Observations related to Kolmogorov Complexity

Günter Hotz, Universität Saarbrücken

The lecture discusses some critical statements to the state of the theory.

- The Kolmogorov complexity of finite theory is finite.

  This theorem is not at all consistent with our feeling: K.C. cannot be a measure of information, for it's absurde that a theory has only a finite information content or the concept of a theory in logic is not what we expect to be a theory.

- Resource bounded K.C. could be an approximation to information understanding.

- Learning from ergodic sources seems to be hard; teaching seams to be extremely non-ergodic.

- Describing Galileis experiment by minimal programs never will lead to his laws. We miss in such constructconstructions the very essential concept of "ideal elements"; in Galileis case the "vakuum".

- Nature description is essentially based on the language of differential calculus.

- Prediction of events in Natural Science is a two stage process:

  1. Understanding by use of ideal elements
  2. Prediction by approximation of ideal behaviour.

- Real numbers and the Ackermann function don't differ in reality. One should extend the theory of computation such that operations as $x := \lim_{n\to\infty} a_n$ and operations on power series are included.

Historical remark: The concept of collectives from von Mises appears 17 years before the publication of von Mises in a paper of Helm "Bd.1 Naturphilosophie 1902, 364-381".

Resource bounded K.C. were first studied in Schnorr: "Zufälligkeit und Wahrscheinlichkeit", Lect.Not.Math. Vol.218 (1971).

k-One Way Heads Cannot Do String Matching – a Lower Bound by Kolmogorov Complexity

Tao Jiang, McMaster University, Hamilton, Ontario, Canada

(Joint work with Ming Li)

We settle a conjecture raised by Galil and Seiferas twelve years ago: k-head one way DFA cannot do string matching, for any k. The proof uses Kolmogorov complexity and the concept of incompressibility.

Randomness of Number Representations

Helmut Jürgensen, University of Western Ontario, London/Ontario

We show that randomness of the natural positional presentation of a real number is invariant under base transformations.

Average-case Complexity of Heapsort

Ming Li, University of Waterloo

Heapsort is a commonly used sorting algorithm with both worst-case and average-case running time $O(n \log n)$, no extra space (*in situ*-sorting), and comparison based. Due to J. Williams (1965), there is an improved version by R. Floyd (1968?). The problem of determinig the lower bound on the average-case running time is mentioned by D.E. Knuth (1973, in Sorting and Searching), and was left open until the solution by R. Schaffer (Ph.D. Thesis 1992, see also a paper of Schaffer and Sedgewick). Ian Munro subsequently gave a short and simple proof using Kolmogorov complexity in the incompressibility method. The lower bound (exact) on the number of comparisons is $n \log n$ (Floyd's) and $\kappa n \log n$ (William's).

Separating exponentially ambiguous NFA from polynomially ambiguous NFA

Hing Leung, New Mexico State University

We prove that exponentially ambiguous NFA is "separated" from polynomially ambiguous NFA. Specifically, we show that there exists a family of NFAs $\{A_n \mid n \geq 1\}$ over a two-letter alphabet such that, for any positive integer n, A_n is exponentially ambiguous and has n states, whereas the smallest equivalent DFA has 2^n states and any smallest equivalent polynomially ambiguous NFA has $2^n - 1$ states.

The Utility and Depth of Information

Jack H. Lutz, Dept. of Computer Science, Iowa State University

(Joint work with David W. Juedes and James I. Lathrop)

A DNA sequence and the UNIX operation system contain far less information than random coin-toss sequences of comparable length. Nevertheless, DNA and UNIX appear to be more useful than random coin-toss sequences. Clearly, a data object derives its usefulness not only from the amount of information it contains, but also from the manner in which this information is organized. Recently, Bennett has defined computational depth (also called logical depth) to quantify the amount of "computational work" that has been "added" to the information in an object and "stored" in its organization.

This talk gives an overview of computational depth and its fundamental properties. Two new results on the computational depth of infinite binary sequences are also presented. Roughly speaking, the first says that a sequence must be deep in order to be useful. The second says that, in the sense of Baire category, almost every infinite binary sequence is somewhat deep.

Frontiers of Feasible Boolean Manipulation

Christoph Meinel, Universität Trier

(Joint work with J. Gergov)

A central issue in the solution of many computer aided design problems is to find concise representations for circuit design and their functional specification. Recently, a restricted type of branching programs (so called OBDDs) proved to be extremely useful for representing Boolean function for various CAD applications. Unfortunately, many circuits of practical interest provable require OBDD-representation of exponential size. We systemmatically study the question up to what extend more concise branching program-descriptions can be successfully used in symbolic Boolean manipulation, too. We prove in very general settings

- the frontier of efficient Boolean manipulation on the basis of BP-representations are FBDDs (i.e. real-once-only braching programs),
- the frontier of efficient probabilistic Boolean manipulation with BP-based data structures are MOD-2-FBDDs.

Instance complexity

Pekka Orponen, University of Helsinki

(Joint work with Ker-I Ko, Uwe Schöning, Osamu Watanabe)

We introduce a measure for the computational complexity of single instances of a decision problem and survey some of its properties. The **instance complexity** of a string x with respect to a set A and a time bound t, $ic^t(x : A)$, is defined as the size of the smallest special case program for A that runs in time t, decides x correctly, and makes no mistakes on other strings ("dont't know"-answers are permitted). It can be shown that a set A is in class $\mathcal{P}$ if and only if there exist a polynomial t and a constant c such that $ic^t(x : A) \leq c$ for all x; on the other hand if A is $\mathcal{NP}$-hard and $\mathcal{P} \neq \mathcal{NP}$, then for all polynomials t and constants c, $ic^t(x : A) > c \log_2 \mid x \mid$ for infinitely many x.

Observing that $\mathcal{K}^t(x)$, the time t bounded Kolmogorov complexity of x, is roughly an upper bound on $ic^t(x : A)$, we propose the following "instance complexity conjecture": for all appropriate time bounds t, if a set is not in the class DTIME(t), there then exists a constant c and infinitely many x such that $ic^t(x : A) \geq$

$\mathcal{K}^t(x) - c$. Intuitively, the conjecture claims that if a problem is not decidable in time t, there will be infinitely many problem instances for which the essentially best time t solution method is simple table look-up.

The following partial results on this conjecture have been obtained:

- if $t(n) \geq n$ is a time constructible function and A is a recursive set not in DTIME($t(n)$), there then exist a constant c and infinitely many x such that $ic^t(x : A) \geq \mathcal{K}(x) - c$, where $\mathcal{K}(x)$ is the time-unbounded version of Kolmogorov complexity.
- if A is $\mathcal{NP}$-hard and EXPTIME $\neq$ NEXPTIME, then for any polynomial t there exist a polynomial t' and a constant c such that for infinitely many x, $ic^t(x : A) \geq \mathcal{K}^{t'}(x) - c$.

If the set A is EXPTIME-hard, the latter result holds even without the assumption that EXPTIME $\neq$ NEXPTIME.

Application of Descriptional Complexity to Computer Vision and Machine Learning

Edwin Pednault, AT & T Bell Laboratories, Holmdel, New Jersey, USA

This talk presents an overview of descriptional complexity as applied to computer vision and machine learning. The relevance of descriptional complexity to these areas is illustrated by means of several psychophysical phenomena in human vision. The phenomena are readily explained by assuming that the visual system operates by finding a minimal encoding of retinal images is some sort of visual language. Using the examples as motivation, the information theoretic concepts of Shannon coding and Shannon entropy are introduced, together with the descriptional complexity concepts of Kolmogorov complexity, the Minimum Description-Length (MDL) principle, stochastic complexity, and predictive MDL. Examples drawn from the speaker's work on piecewise-polynomial curve fitting and the work of several other researchers are used to illustrate the application of these descriptional complexity measures to problems in computer vision and machine learning.

An Algebraic Model for Combinatorial Problems

Richard E. Stearns, Dept. of Computer Science, University at Albany

(Joint work with H. B. Hunt III)

A new algebraic model, called the "generalized satifiability problem" or "GSP" model, is introduced for representing and solving combinatorial problems. The GSP model is an alternative to the common method in the literature of representing such problems as language recognition problems. In the GSP model, a problem instance is represented by a set of variables together with a set of terms, and the computational objective is to find a certain sum of products of terms over a commutative semiring. Each Boolean satisfiability problem, each nonserial optimization problem, many $\{0,1\}$ linear programming problems, and many graph problems are directly representable as GSPs.

Important properties of the GSP model include the following:

1. By varying the semiring, a number of complete problems in the complexity classes $\mathcal{NP}$, Co$\mathcal{NP}$, D^P, OPT-$\mathcal{P}$, MAX SNP, MAX Π_1, PSPACE, and #PSPACE are directly representable as GSPs.

2. In the GSP model, one can naturally discuss the structure of individual problem instances. The structure of a GSP is displayed in a "structure tree". The smaller the "weighted depth" or "channelwidth" of the structure for a GSP instance, the faster the instance can be solved by any one of several generic algorithms.

3. The GSP model extends easily so as to apply to hierarchically-specified problems and enables solutions to instances of such problems to be found directly from the specification rather than from the (often exponentially) larger specified object.

On a conjecture by Orponen + 3

John Tromp, CWI Amsterdam

This short talk presented two results relating the instance complexity of elements of non-recursive sets to their (simple) Kolmogorov complexity. The first, for any non recursive set A, says that for infinitely many x, $ic(x : A)$ is at least $\log K(x) - O(1)$. The second, for any enumerable non recursive set A, says that for infinitely many x, $ic(x : A)$ is at least $K(x) - ub(x) - O(1)$, where $ub(x)$ is the least number of bits needed to describe an upper bound on x.

An Invitation for Retrospectives and Perspectives

Vladimir A. Uspensky, Moscow State Lomonosov University

The underlying ideas of the Kolmogorov complexity are simple and natural. There are objects and there are descriptions of those objects. Kolmogorov complexity of an object is the size of the best description. Of course, some *description mode*, preferably the best one, should be chosen in advance. (A descpiption mode is a subset E of the cartesian product $X \times Y$, where X is the set of all descriptions and Y is the set of all objects; $\langle x, y \rangle \in E$ means that x is a description of y with respect to E.)

Therefore, the following entities are to be fixed:

1. A class of admissible description modes.
2. A partial ordering "to be better" on that class.
3. A partial ordering "to be better" on X.
4. A *size function*, which is a total function from X to $\mathbb{N}$.

Historically, any ordering on X is determined by the size fuction: for descriptions, to be better means to have smaller size. So a best description is the minimal-size description, and Kolmogorov complexity of an object is the minimal size of its description. Also historically, for modes, to be better means to give smaller complexities: E is better than F if for some C not depending on y and for all y

$$\mathrm{Compl}_E(y) \leq \mathrm{Compl}_F(y) + C.$$

(Here is another possible ordering: E is better than F if there is a polynomial P such that $t_E(y) \leq P(t_F(y))$, where $t_G(y)$ is the running time of producing y from its best description.)

The scheme just exposed gives five well-known versions of Kolmogorov complexity:

- simple entropy KS (A.N. Kolmogorov, 1965);
- decision entropy KD (D.W. Loveland, 1969);
- a priori entropy KA (L.A. Levin, 1970);
- monotonic entropy KM (L.A. Levin, 1973);
- prefix entropy KP (L.A. Levin, 1974).

Remark 1. A best mode is usually called "an *optimal* mode". And according to the Moscow tradition of Kolmogorov scientific school, the word "entropy" is used instead of "Kolmogorov complexity". The term "complexity" is still used when an arbitrary, not necessarily optimal, description mode is considered. So the entropy is the complexity with respect to an optimal description mode.

Remark 2. The first scientific works by Kolmogorov were not in mathematics but in history. Those student papers are to be published in Moscow as a separate book (probably, this year). Some ideas of Kolmogorov complexity can be traced down to those papers. (Namely, in his study of fiscal policies in the medieval state of Novgorod, Kolmogorov heavily leaned on the idea that the regulations should be simple, not complex.)

An Axiomatisation of Randomness

Michiel van Lambalgen, University of Amsterdam

The talk described an attempt to axiomatize a notion of randomness by abstracting an algebraic structure that is implicit in many existing recursion theoretic definitions of randomness, such as those of Schnorr, Martin-Löf, and Gaifman and Snir.

The motivation for this attempt is partly philosophical: a desire to describe directly in a simple language intuitions about randomness, unencumbered by formal details of computability theories. Also, there are other (informal) applications of randomness in mathematics, notably set theory and model theory, which cannot be formalized by the usual recursion theoretic definitions: forcing is a case in point.

The fundamental relation used in the axiomatisation is: a finite sequence of oracles $y_1, \ldots, y_n$ does not contain information about the random sequence x. The axioms proposed for this relation are a combination of axioms for matroids (including the Steinitz-Maclane exchange principle), and Kolmogorov's 0-1 law.

The axioms can be shown to hold for the aforementioned definition of randomness by considering suitable notions of oracle computation. To show the non-triviality of the axioms, we add them to Zermelo-Fraenkel set theory to obtain quick disproofs of the axiom of choice and continuum hypothesis (in its aleph free version). On the other hand, the axioms are consistent with weak choice principles.

[1] Michiel van Lambalgen, *Independence, Randomness and the Axiom of Choice*, Journal of Symbolic Logic Vol.57, No.4, 1992

Introduction to Kolmogorov Complexity and its Applications

Paul Vitányi, CWI / University of Amsterdam

(Joint work with Ming Li and based on the book of the same title, Springer Verlag 1993)

We survey the basic notions of Kolmogorov complexity and its many applications. Among others:

- inductive reasoning and machine learning,
- the incompressibility method in combinatorics,
- formal languages,
- average case (time) complexity,
- machine models,
- algorithmic entropy and information distance,

and so on.

Thermodynamics of Computation and Information Distance

Paul Vitányi, CWI / University of Amsterdam

(Joint work with Charles Bennett, Peter Gács, Ming Li, W. Zurek in STOC93)

It is widely accepted that the only bit operations that necessarily dissipate energy in the form of heat ($kT \log 2$ Joule, where k is the Boltzmann constant and T the temperature in degree Kelvin) are those operations which are irreversible. This has consequences on the continuing miniaturization of electronic chips and accompanying advance in computing power. It appears that new principles of computing which dissipate no (an arbitrary low) energy need to be found within 20 years. One road, perhaps the most promising one, is to turn to reversible computing. We investigate several notions of absolute information distance:

- $E_1(x,y)$ = length of shortest program to translate x to y and y to x on a normal (irreversible) Turing machine

- $E_2(x,y)$ = the minimum "pattern" distance satisfying some normalization criteria and effectiveness.

- $E_3(x,y)$ = length of shortest program to translate from x to y and y to x by a **reversible** Turing machine. (In E_1 and E_3 the program works in a 'catalytic' manner and is retained before, during and after the computation). It turns out that $E_1 = E_2 = E_3$ up to a log additive factor.

- $E_4(x,y)$ = amount of irreversibility in translating x to y and y to x by an otherwise reversible computation (minimal number of bits consumed at the beginning and reversibility deleted at the end).

Since $E_1(x,y) = \max(K(x|y), K(y|x))$ and $E_4(x,y) = K(x|y) + K(y|x)$ (up to a log additive term), we find $E_1(x,y) \leq E_4(x,y) \leq 2E_1(x,y)$ up to a log additive term.

Economy of Description for Single-valued Transducers

Andreas Weber, Universität Frankfurt am Main

(Joint work with Reinhard Klemm, Pennsylvania State University)

In this talk questions of economy of description are investigated in connection with single-valued finite transducers. The following results are shown.

1. Any single-valued real-time transducer M with n states can be effectively transformed into an equivalent unambiguous real-time transducer having at most 2^n states.

2. Let M be a single-valued real-time transducer with n states and output alphabet Δ which is equivalent to some deterministic real-time or subsequential transducer M'. Then, M can be effectively transformed into such an M' having at most $2^n \cdot \max\{2, \#\Delta\}^{2n^3 l} + 1$ states where l is a local structural parameter of M.

3. For any single-valued transducer it is decidable in deterministic polynomial time whether or not it is equivalent to some deterministic real-time transducer (to some subsequential transducer, respectively).

The results 1. and 2. can be extended to the case that M is not necessarily real time. The upper bound in 1. is at most one state off the optimal upper bound. Any possible improvement of the upper bound in 2. is greater or equal than 2^n.

Descriptional Complexity for Automata, Languages and Grammars

Detlef Wotschke, Universität Frankfurt

This talk is to be seen **primarily** as a survey and an introduction to some of the talks to come.

In Automata, Languages and Grammars we are dealing with rather restricted objects which have a definite place in computer science as description or design models for applications.

Within these restricted and application-oriented models, the 'absolute' minimal length descriptions are very often not desirable, for example in Structured Programming, Finite Automata, Context-Free Grammars, Pushdown Automata. Within these models one looks at organizational measures which seems to capture the **essential** part of the information.

However, this organizational overhead should be kept to a minimum. So, we try to measure and minimize this organizational overhead by measuring organizational components.

We measure parameters such as

- Description length **within** the limited model,
- Number of states,
- Number of productions,
- Number of nonterminals,
- Number of states times number of stack-symbols.

For a given language (set) L, how does L's descriptional complexity change with regard to the underlying descriptive model? Or more specifically:

How short, how succinct, how simple or how economical can the descriptions of automata, grammars and programs be if we allow the usage of concepts such as

- arbitrary or limited nondeterminism,
- arbitrary or limited ambiguity,
- arbitrary or limited delay in error-recovery,
- arbitrary or limited lookahead,
- different notions of acceptance?

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