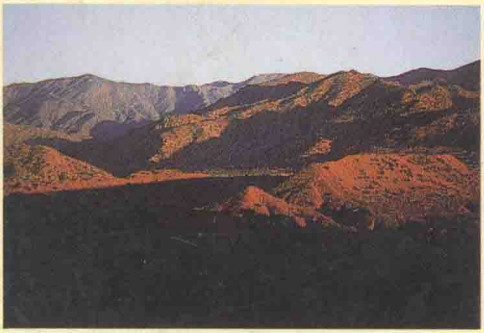
SØREN BRUNAK
BENNY LAUTRUP

NEURAL NETWORKS
COMPUTERS WITH INTUITION



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World Scientific
Singapore • New Jersey • London • Hong Kong

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1. edition, 1. printing, 1990
Layout: Kitte Fennestad
Cover photo: © Kitte Fennestad
Illustrations: Jesper Tom-Petersen
Translation: Andrew Cameron-Mills

Published by

World Scientific Publishing Co. Pte. Ltd.
P.O. Box 128, Farrer Road, Singapore 9128
USA office: 687 Hartwell Street, Teaneck, NJ 07666, USA
UK office: 73 Lynton Mead, Totteridge, London N20 8DH, England

Original Danish edition published by
Munksgaard International Publishers, Copenhagen

Library of Congress Cataloging-in-Publication Data
Brunak, Søren
[Neurale Netværk. English]
Neural Networks: Computers with Intuition/
Søren Brunak and Benny Lautrup
p. cm.
Translation of: Neurale Netværk: Computere med Intuition.
Bibliography: p.
Includes index.
ISBN 9971-50-938-5. – ISBN 9971-50-939-3 (pbk)
1. Neural computers. 2. Neural circuitry. I. Lautrup, Benny. II. Title.
QA76.5.B78513 1990 006.3 – dc20 89-14671

Printed in Singapore

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FOREWORD

Understanding the human brain is the greatest scientific and intellectual challenge ever faced by man. It has always provoked wonderment, how that lump of nerve cells can produce art and science, war and peace, hate and love. Science is no longer in any doubt that the human spirit has a physical origin in the brain, but nobody has yet made the connection between mind and matter.

In this book we try to describe a new field of knowledge which lies in the borderland between the natural and the synthetic. Natural phenomena have the reputation of being honest, strong and not to be circumvented. Synthetics smack of trickery, "artificial" is a pejorative, and all are viewed with the deep mistrust that we reserve for those things we have ourselves invented. This book also examines the relationship between man and machine and what possibilities these uneasy partners have of ever understanding each other.

With the advent of the computer, machines have attained a degree of complexity which makes it possible to study intelligence in a completely new way. We can now simulate the behavior of small and greatly simplified versions of the neural networks with which Nature has equipped advanced, living beings. These networks have a structure radically different from that of the conventional computer and have shown themselves to be much better

at carrying out calculations of a cognitive character.

One of the main themes is therefore the relationship between calculation and intelligence, both artificial and natural, and it is a theme which involves such fundamental existential relationships as language and reality, intuition and symbolism, body and soul. The book is not packed with quotations leaving the responsibility for the arguments to others, but presents our views in a way which makes it possible for the reader to disagree.

Verbal communication is a very restricted channel. We have tried to widen it by evoking in the reader some of the images which have been a part of our thinking. We have not, however, included lots of complicated diagrams of either brains or computers, but have put the emphasis on the principal matters behind computation and on that backdrop of concepts which lies behind the physics in the behavior of the computer.

We thank Johanne Brunak, Wibeke Fonnesberg, Grete Henius, John Hertz, Jørn Hounsgaard, Steffen Petersen, Henrik Oxvig and Morten Olesen for criticism and comment which has helped us greatly with the Danish edition which appeared in October 1988. Special thanks go to our Danish editors Tor Nørretranders, Jørgen Steen Nielsen and Joachim Malling for support and encouragement. For the English edition we owe thanks to Johanne Brunak, John Hertz and Choy Kam Luen.

SØREN BRUNAK AND BENNY LAUTRUP
Copenhagen, August 1989

PROFESSION: COMPUTER

Dutchman Wim Klein was a computer.

On August 27, 1976 he extracted in 2 minutes and 43 seconds the 73rd root of a 500-digit number — in his head! In the field of mathematical wizardry, normally regarded as the exclusive realm of the electronic computer, Wim Klein was an impressive magician. Unlike electronics, his performances were not entirely silent, but were accompanied by a muttered mixture of Dutch numerals and profanities.

The term *computer* was originally the name given to someone who performed calculations for a living. Computers typically worked for banks or insurance companies, where loans and insurance policies required extensive calculations. When this work was taken over by machines, they also took over the name.

Calculating is not just juggling with figures. When the human brain constructs, in a tenth of a second, a three-dimensional experience from two-dimensional images imposed on the retinas of the eyes, a very complex calculation is taking place. Such calculations are, in fact, so complex that it would take a supercomputer several hours just to sort out the spatial relationships which occur in traffic at an ordinary intersection. What is more, the human brain's calculations are so certain that it is possible, for example, for many people to drive simultane-

ously in traffic at speeds far higher than those we are actually designed for.

The brain can process formidable amounts of information. Through the eyes, ears, nose, mouth and skin, information pours into our brains. The so-called "five senses" are not the brain's only input channels. Information about the state of the body and its internal organs is constantly being transmitted to the brain. Various parts of the brain are incessantly sending each other messages: memories, status reports, decisions, alarms and what not.

This colossal amount of information is processed and transformed partly as output observable to the outside world in the form of muscle movements and partly to the brain itself in the form of thoughts. A pianist carries out highly organized muscular activity, largely governed by input from the senses. Conversely, the passive experience of listening to piano music is an inner mental process whereby input from the senses is translated to thoughts and feelings.

Calculation is not just mathematical work in the ordinary sense, but includes all forms of information processing. A calculation is a process that transforms one set of data, the input, into another set of data, the output, which is the result of the calculation. Today, machines which perform this function are called computers.

Contrary to what might generally be supposed, these processes never *create* information. Normal information processing actually works on a principle of forgetting, or more accurately, discarding information. The tricky thing is, of course, to do it in the correct way. Consequently, these processes cannot normally work backwards, just as it is usually impossible to reconstruct a question on the basis of an answer.

In the brain, the end product of a computation is the focusing on a particular piece of information. The famous "cocktail party effect" is an example of the brain's incredible ability to focus and discard information. When a person is standing in the middle of a large group of talking people, his brain can single out a particular conversation from all the others, for example that between his wife and some sexy-looking Jack Nicholson type. All the rest of the incoming information — the other conversations — is discarded and there is no way of reconstructing it from the conversation between the wife and the satanic satyr.

All forms of cognition are based on *reduction* of information. Without the use of such rough concepts of classification as truck, contract, temperature, or politician, one would never be able to make coherent associations and would experience the world as a swirling chaos of isolated details. The brain boils all these details down to an understandable form which can be both comprehended by oneself and communicated to others.

During the '40s and '50s Wim Klein, the computer, performed in French and Dutch circuses. In 1958 he finally got a steady job at the European Nuclear Research Centre, CERN, in Geneva. His function was to perform complex calculations for theoretical physicists, using his phenomenal numerical ability. However, within a few years he was outsmarted by a new generation of computers, the speed of which had vastly increased and which, unlike Wim, could run nonstop 24 hours a day. But, for special types of calculation, he was still supreme and later gained a place in the *Guinness Book of Records* for the incredible ability to extract roots mentioned at the beginning of the chapter.

Today, machines have outdistanced us all in the domain of "number crunching" and related symbol manipulation. Wim Klein and his colleagues have now been transferred to other types of work, and his 1958 "victor's crown" has been taken over by the electronic computer and will never again be won by human brains. The digital computer is, however, hopelessly inferior to humans in almost all other respects.

Human intuition rapidly solves complex problems which conventional computers and their programmers are quite powerless to deal with. To recognize someone from a mere glimpse of his face involves data processing of such speed and extent as to make the fastest computer seem like a snail. When we recognize a face, it occurs almost momentarily, and it is remarkable that we are completely unable to consciously halt the process.

The brain and the run-of-the-mill computer have widely different architectures, and this markedly affects the type of functions each is best able to perform. No matter which computer you buy — from a miniature pocket calculator to a giant supercomputer — they all process information more or less after the same principle: one thing at a time. Although most computers are so fast it seems that many users are served simultaneously, this is actually an illusion. The computer in fact allocates each user a tiny time slice and moves constantly around between them.

In contrast, the human brain can conduct an enormous number of operations simultaneously and in parallel. Information processing is carried out by a network of connected nerve cells called neurons. This network is composed of an astronomical number of neurons and is

vastly more complex in structure than the telephone network of the entire planet.

The work of the conventional computer is fully centralized, whereas that of the brain to a much greater extent is done through decentralized, distributed influence instead of control. The two architectures are as ideologically different as the structures of totalitarian and anarchic states.

These ideological differences in structure are clearly reflected in their different vulnerabilities. Everybody knows just how fragile and sensitive computers are. At the least provocation they go "down", whereas the brain — even under the most wretched conditions — is "up" year after year, without interruption through an entire lifetime.

The dream of artificial intelligence has for many years been based on the centralized structure, but after 40 years of research this dream has not come true. It seems as if imitation of the natural intelligence of living organisms will not succeed without borrowing ideas from the structure of biological neural networks.

For centuries, the heart was supposed to hold the secret of man's divine origin, be the seat of his soul. Modern medical science has destroyed this myth and placed the heart in perspective as being an organ similar to the pump in an ordinary washing machine. The Norwegians, for example, have taken this insight to its logical conclusion in their language and simply call the organ a "bloodpump"!

Having been driven out of the heart, the soul took up residence in the brain. This diminution of the heart's "divine" status has not, however, made it any easier to be unhappily in love. Heartache is still synonymous with the

pain of love, and even if the heart is now no more than a pump, the human emotions have not yet been reduced to the mechanical performance of a washing machine.

The traditional attitude of medical science towards the mind and the brain has been — and still is — marked by the father of modern anatomy, Niels Stensen, in Latin Nicolaus Steno. He died in 1686 and was canonized in 1988 by the Catholic Church because of his ability to operate remotely — after death — as a miraculous healer. Steno held that there were fundamentally two approaches towards understanding the brain. Either one could ask the divine Creator, or one could try to dismantle the brain into its basic parts to see how it worked. He felt that the first approach was rather impractical, as direct communication had been discontinued for some time ("God is alive, but He doesn't want to get involved"), and, therefore, the second approach was the only realistic possibility.

Brain research has not had much success in identifying the exact location of the mind. Regardless of how much the anatomy and physiology of the brain have been studied, nobody has located the mind yet, even though most agree that it must be in there somewhere. The reason for this could, of course, be that the mind is not to be found in any particular place, but is distributed over the entire network of neural calculators that makes up the brain.

It is a common belief that if one understands the functions of the parts in sufficient detail, it is an easy matter to deduce the function of the whole. The fact is, however, that in nature, *collective effects* of many interacting parts often show up, effects that cannot be explained easily in terms of the properties of the

individual parts.

We are alive not because each individual biomolecule in us is alive. Life is not the sum of small lives, but an irreducible property of large molecules interacting collectively with each other and their surroundings, a property which cannot be broken down into corresponding properties of its component molecules. Otherwise detergent with its component of biological enzymes would also be alive.

What we know as consciousness, mind, and intelligence must also be collective effects of the interaction between many neurons, effects that cannot be reduced to similar properties of individual neurons. The construction of artificial neural networks is a modest attempt at understanding collective effects occurring in such networks. It is still an open question whether one will be able to manage with much smaller networks than those provided by Nature. Artificial neural networks are media for knowledge, and the study of them attempts to decipher the enigmatic means by which Nature carries out information processing.

WHOLESALE RIDDLES

Man is a curious creature, possibly the only animal that attempts to acquire a deep understanding of his surroundings. The need to understand is not dictated just by a desire to control one's circumstances, but can be purely esthetic or even religiously motivated. We have a compulsion to understand what the universe is, what we are, and finally why we ask why. We live in a mysterious world full of great riddles.