Vector Symbolic Architectures as a Computing Framework for Emerging Hardware

Denis Kleyko, Mike Davies, E. Paxon Frady, Pentti Kanerva, Spencer J. Kent, Bruno A. Olshausen, Evgeny Osipov, Jan M. Rabaey, Dmitri A. Rachkovskij, Abbas Rahimi, and Friedrich T. Sommer

Abstract—This article reviews recent progress in the development of the computing framework *Vector Symbolic Architectures* (also known as *Hyperdimensional Computing*). This framework is well suited for implementation in stochastic, emerging hardware and it naturally expresses the types of cognitive operations required for Artificial Intelligence (AI). We demonstrate in this article that the field-like algebraic structure of Vector Symbolic Architectures offers simple but powerful operations on high-dimensional vectors that can support all data structures and manipulations relevant to modern computing. In addition, we illustrate the distinguishing feature of Vector Symbolic Architectures, "computing in superposition," which sets it apart from conventional computing. It also opens the door to efficient solutions to the difficult combinatorial search problems inherent in AI applications. We sketch ways of demonstrating that Vector Symbolic Architectures are computationally universal. We see them acting as a framework for computing with distributed representations that can play a role of an abstraction layer for emerging computing hardware. This article serves as a reference for computer architects by illustrating the philosophy behind Vector Symbolic Architectures, techniques of distributed computing with them, and their relevance to emerging computing hardware, such as neuromorphic computing.

Index Terms—computing framework, hyperdimensional computing, vector symbolic architectures, emerging hardware, distributed representations, data structures, Turing completeness, computing in superposition

I. INTRODUCTION

The demands of computation are changing. First, Artificial Intelligence (AI) and other novel applications pose a host of computing problems that require a search over an immense space of possible solutions, with many approximately correct answers, but rarely a single correct one. Second, future emerging hardware platforms, operating at ultra-low voltages to reduce energy consumption and to support continued process scaling, are destined to be noisy and, hence, operate stochastically [1]. These observations expose the need for a computing framework that supports both deterministic computation in the presence of noise as well as the approximate and parallel nature of algorithms used in AI.

By emerging hardware, we refer to the broad class of new hardware designs that are highly parallel, fabricated at ultra-small scales, utilize novel components, and/or operate at ultra-low voltages, thus consisting of unreliable, stochastic computational elements.

The conventional (à la von Neumann) computing architecture is not well adapted to these demands, as it was designed assuming precise computational elements for tasks that require exact answers. Conventional computing architectures will continue to play an important role in technology, but there is a growing amount of computational demands that are better served by new computing designs. Thus, hardware engineers have been looking at distributed and neuromorphic computing as a way of meeting these demands.

Many of the emerging computational demands come from cognitive or perceptual applications found within the realm of AI. Examples include image recognition, computer vision, and text analysis. Indeed, large-scale deep learning neural network modelling dominates discussions about modern computing technology, pushing innovations in hardware design towards parallel, distributed processing [2]. While widely used, deep learning neural networks still have limitations, such as lacking the transparency of learned representations and the difficulties in performing symbolic computations. In order to support more sophisticated symbolic computations, researchers have

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   The Architecture of Symbolic Computers Peter M. Kogge,1991 Focuses on the design and implementation of two classes of non von Neumann computer architecture those designed for functional and logical language computing   **A RISC architecture for symbolic computation** Richard B. Kieburtz,1987   *Fifth Generation Computer Systems* T. Moto-Oka,2012-12-02 The Japan Information Processing Development Centre JIPDEC established a committee for Study and Research on Fifth Generation Computers Beginning in 1979 this Committee set out on a two year investigation into the most desirable types of computer systems for application in the 1990 s fifth generation computers and how the development projects aimed at the realization of these systems should be carried forward This book contains the papers presented at the International Conference on Fifth Generation Computer Systems Included among these papers is a preliminary report on the findings of the Committee   **Parallel Processing and Applied Mathematics** Roman Wyrzykowski,2008-05-26 This book constitutes the thoroughly refereed post conference proceedings of the 7th International Conference on Parallel Processing and Applied Mathematics PPAM 2007 held in Gdansk Poland in September 2007 The 63 revised full papers of the main conference presented together with 85 revised workshop papers were carefully reviewed and selected from over 250 initial submissions The papers are organized in topical sections on parallel distributed architectures and mobile computing numerical algorithms and parallel numerics parallel and distributed non numerical algorithms environments and tools for as well as applications of parallel distributed grid computing evolutionary computing meta heuristics and neural networks The volume proceeds with the outcome of 11 workshops and minisymposia dealing with novel data formats and algorithms for dense linear algebra computations combinatorial tools for parallel sparse matrix computations grid applications and middleware large scale computations on grids models algorithms and methodologies for grid enabled computing environments scheduling for parallel computing language based parallel programming models performance evaluation of parallel applications on large scale systems parallel computational biology high performance computing for engineering applications and the minisymposium on interval analysis   Parallel Symbolic Computing: Languages, Systems, and Applications Robert H. Halstead,Takayasu Ito,1993-11-03 Parallel and distributed computing are becoming increasingly important as cost effective ways to achieve high computational performance Symbolic computations are notable for their use of irregular data structures and hence parallel symbolic computing has its own distinctive set of technical challenges The papers in this book are based on presentations made at a workshop at MIT in October 1992 They present results in a wide range of areas including speculative computation scheduling techniques program development tools and environments programming languages and systems models of concurrency and distribution parallel computer architecture and symbolic applications   **Parallel Computing** D.J Evans,C.N Sutti,1989-05-01 Parallel Computing Methods Algorithms and Applications presents a collection of original papers presented at the international meeting on parallel processing methods

algorithms and applications at Verona Italy in September 1989 **Scaffolded Minds** Somogy Varga,2025-02-04 A comprehensive account of cognitive scaffolding and its significance for understanding mental disorders In Scaffolded Minds Somogy Varga offers a novel account of cognitive scaffolding and its significance for understanding mental disorders The book is part of the growing philosophical engagement with empirically informed philosophy of mind which studies the interfaces between philosophy and cognitive science Varga draws on two recent shifts within empirically informed philosophy of mind the first toward an intensified study of the embodied mind and the second toward a study of the disordered mind that acknowledges the convergence of the explanatory concerns of psychiatry and interdisciplinary inquiries into the mind Varga sets out to accomplish a dual task theoretical mapping of cognitive scaffolding and the application calibration of fine grained philosophical distinctions to empirical research He introduces the notion of actively scaffolded cognition ASC and offers a taxonomy that distinguishes between intrasomatic and extrasomatic scaffolding He then shows that ASC offers a productive framework for considering certain characteristic features of mental disorders focusing on altered bodily experience and social cognition deficits With Cognitive Scaffolding Varga aims to establish that shifting attention from mental symptoms to fine grained sensorimotor aspects can lead to identifying diagnostic subtypes or even specific sensorimotor markers for early diagnosis *Cognitive Science* Harald Maurer,2021-07-08 The Mind and Brain are usually considered as one and the same nonlinear complex dynamical system in which information processing can be described with vector and tensor transformations and with attractors in multidimensional state spaces Thus an internal neurocognitive representation concept consists of a dynamical process which filters out statistical prototypes from the sensorial information in terms of coherent and adaptive n dimensional vector fields These prototypes serve as a basis for dynamic probabilistic predictions or probabilistic hypotheses on prospective new data see the recently introduced approach of predictive coding in neurophilosophy Furthermore the phenomenon of sensory and language cognition would thus be based on a multitude of self regulatory complex dynamics of synchronous self organization mechanisms in other words an emergent flux equilibrium process steady state of the total collective and coherent neural activity resulting from the oscillatory actions of neuronal assemblies In perception it is shown how sensory object informations like the object color or the object form can be dynamically related together or can be integrated to a neurally based representation of this perceptual object by means of a synchronization mechanism feature binding In language processing it is shown how semantic concepts and syntactic roles can be dynamically related together or can be integrated to neurally based systematic and compositional connectionist representations by means of a synchronization mechanism variable binding solving the Fodor Pylyshyn Challenge Since the systemtheoretical connectionism has succeeded in modeling the sensory objects in perception as well as systematic and compositional representations in language processing with this vector and oscillation based representation format a new convincing theory of neurocognition has been developed which bridges the neuronal and the cognitive analysis level The

book describes how elementary neuronal information is combined in perception and language so it becomes clear how the brain processes this information to enable basic cognitive performance of the humans   *Proceedings* ,1991   *Design and Implementation of Symbolic Computation Systems* ,1990   **Optical and Hybrid Computing** Harold H. Szu,Roy F. Potter,1987   *Laboratory for Computer Science Progress Report* Massachusetts Institute of Technology. Laboratory for Computer Science,1987   Government Reports Announcements & Index ,1988   **OOPSLA '87** Norman Meyrowitz,1987   **An Introduction to Expert Systems** Robert J. Mockler,Dorothy G. Dologite,1992   **Peterson's Annual Guides to Graduate Study** ,1982-12   Architectural Alternatives for Exploiting Parallelism David J. Lilja,1991 Graduates advanced undergraduates and practicing engineers of computer architecture or system design may find interest in the survey of various architectures within which a computer can be induced to walk and chew gum at the same time The 37 reprinted journal articles and conference presentation   **12th IMACS World Congress, July 18-22, 1988, Paris, France** Robert Vichnevetsky,Pierre Borne,J. Vignes,1988   Computers for Artificial Intelligence Processing Benjamin W. Wah,C. V. Ramamoorthy,1990-10-12 The present book supports the increasing complexity and the growing need for computational power of artificial intelligence AI by providing comprehensive treatments of new hardware and software engineering met in AI language design and applications The book is a collection of 16 substantial papers chapters the contributors being 51 well known researchers in the AI fields The papers are grouped into the following five sections Section 1 represents a well documented survey on symbolic processing computers Section 2 Language based AI Architectures supports the design and implementation of AI language oriented computers Three 2 4 chapters are devoted to computer architecture concerning sequential Lisp processing architectural features of Lisp computers Symbolics Lisp computer architecture memory management and performance evaluation of a Lisp machine system Other three 5 7 chapters discuss multiprocessing and parallel processing of Lisp and general functional programs The last two chapters of section 2 are presenting architectures supporting object oriented programming Smalltalk and production systems Section 3 Multiprocessor AI Architecture contains two 10 11 chapters dealing with Connection Machine architecture and its applications and with the design of data knowledge base machines for AI processing Section 4 Connectionist Architectures and Applications include two 12 13 chapters illustrating the connectionist model architecture design and learning Section 5 Software Architectures for AI Applications is made up of three 14 16 chapters analysing the relationship between AI and software engineering the development tools for AI programs and the problem of AI hardware and software reliability This book addresses a wide range of AI readers from beginners to professionals It carries forth doubtless qualities compact and well dimensioned chapters comprehensively written by AI remarkable professionals covering up to date AI topics and trends   **Optical Engineering** ,1989 Publishes papers reporting on research and development in optical science and engineering and the practical applications of known optical science engineering and technology

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