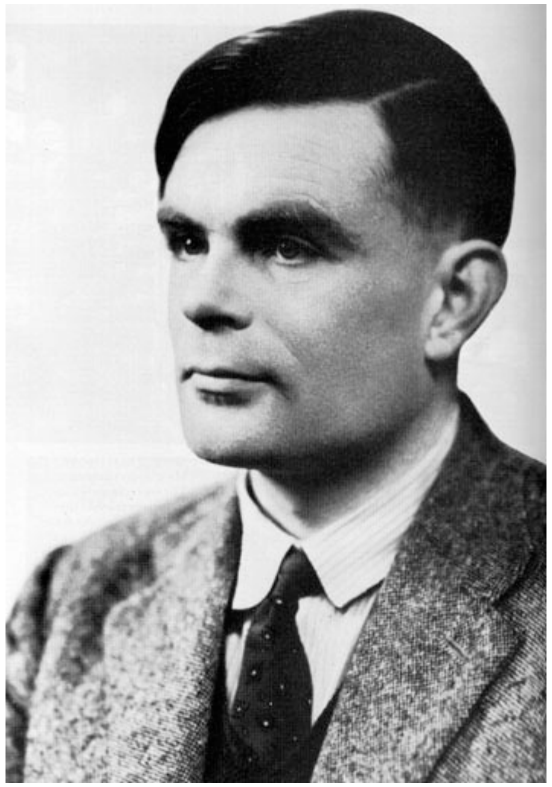
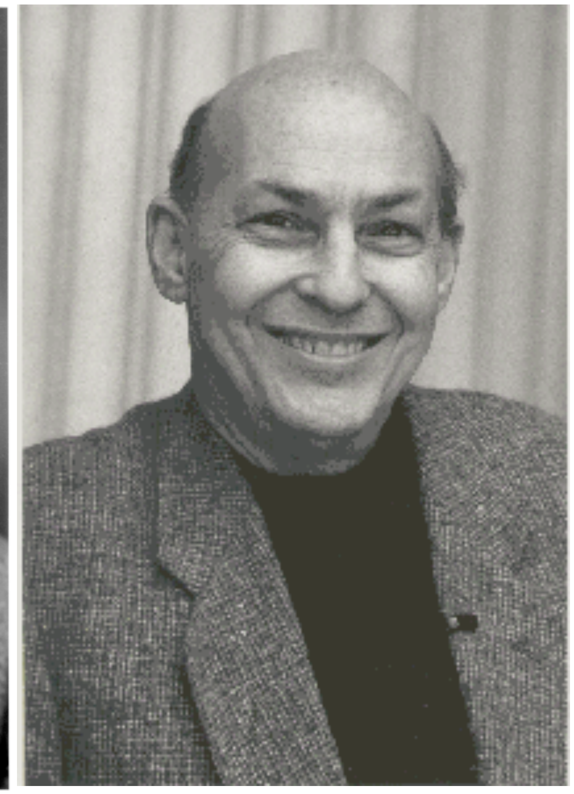
Computing with high-dimensional vectors

Artificial Intelligence

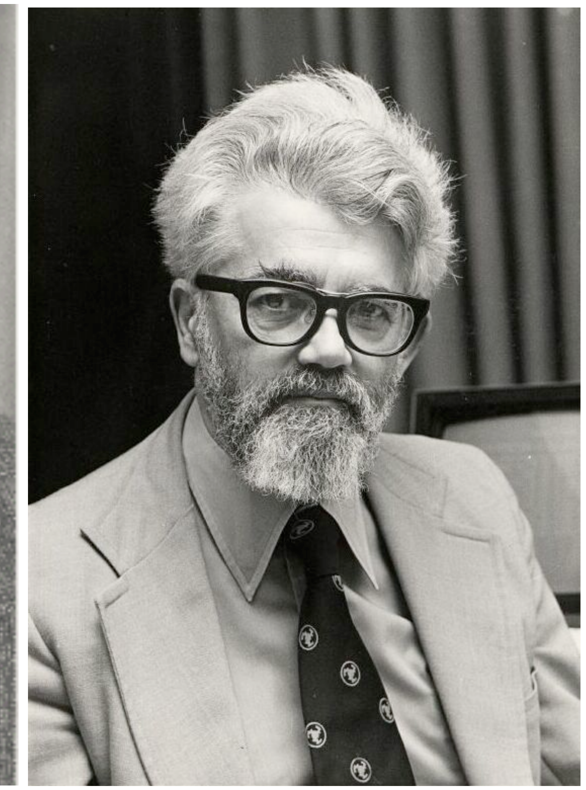


Alan Turing

John von Neumann



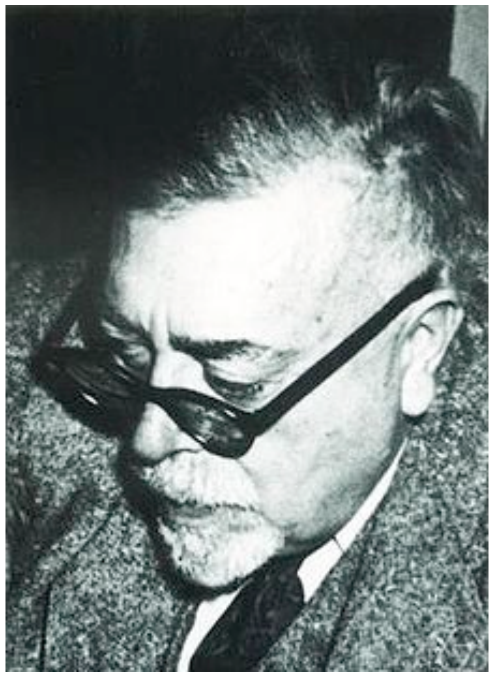
Marvin Minsky



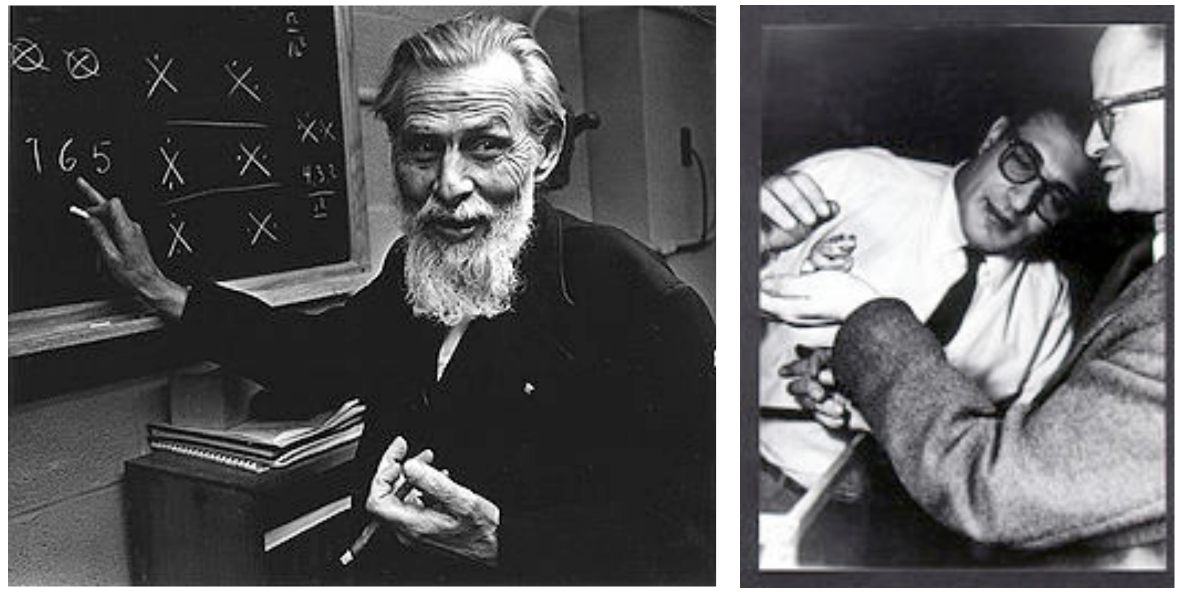
John McCarthy

Among the most challenging scientific questions of our time are the corresponding analytic and synthetic problems: How does the brain function? Can we design a machine which will simulate a brain?
-- *Automata Studies*, 1956

Cybernetics/neural networks



Norbert Wiener



Warren McCulloch & Walter Pitts

Frank Rosenblatt

“The theory reported here clearly demonstrates the feasibility and fruitfulness of a quantitative statistical approach to the organization of cognitive systems. By the study of systems such as the perceptron, it is hoped that those fundamental laws of organization which are common to all information handling systems, machines and men included, may eventually be understood.” -- Frank Rosenblatt

The Perceptron: A Probabilistic Model for Information Storage and Organization in the Brain. In, *Psychological Review*, Vol. 65, No. 6, pp. 386-408, November, 1958.

Single neuron recording ⇒ Single neuron thinking

1940 PROCEEDINGS OF THE IRE November

What the Frog's Eye Tells the Frog's Brain*

J. Y. LETTVIN†, H. R. MATURANA‡, W. S. McCULLOCH‖, SENIOR MEMBER, IRE, AND W. H. PITTS‖

Perception, 1972, volume 1, pages 371-394

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Single units and sensation: A neuron doctrine for perceptual psychology?

H B Barlow
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Received 6 December 1972

Abstract. The problem discussed is the relationship between the firing of single neurons in sensory pathways and subjectively experienced sensations. The conclusions are formulated as the following five dogmas:

1. To understand nervous function one needs to look at interactions at a cellular level, rather than either a more macroscopic or microscopic level, because behaviour depends upon the organized pattern of these intercellular interactions.
2. The sensory system is organized to achieve as complete a representation of the sensory stimulus as possible with the minimum number of active neurons.
3. Trigger features of sensory neurons are matched to redundant patterns of stimulation by experience as well as by developmental processes.
4. Perception corresponds to the activity of a small selection from the very numerous high-level neurons, each of which corresponds to a pattern of external events of the order of complexity of the events symbolized by a word.
5. High impulse frequency in such neurons corresponds to high certainty that the trigger feature is present.

The development of the concepts leading up to these speculative dogmas, their experimental basis, and some of their limitations are discussed.

Holographic Reduced Representations

Tony Plate

Vector Symbolic Architectures

Ross Gayler

Hyperdimensional Computing

Pentti Kanerva

Plate, T.A. (1995). Holographic reduced representations. *IEEE Transactions on Neural networks, 6(3)*, 623-641.

Gayler, R.W. (2004). Vector symbolic architectures answer Jackendoff's challenges for cognitive neuroscience. arXiv:cs/0412059.

Kanerva P (2009) Hyperdimensional Computing: An Introduction to Computing in Distributed Representation with High-Dimensional Random Vectors. *Cognitive Computing, 1*: 139-159.

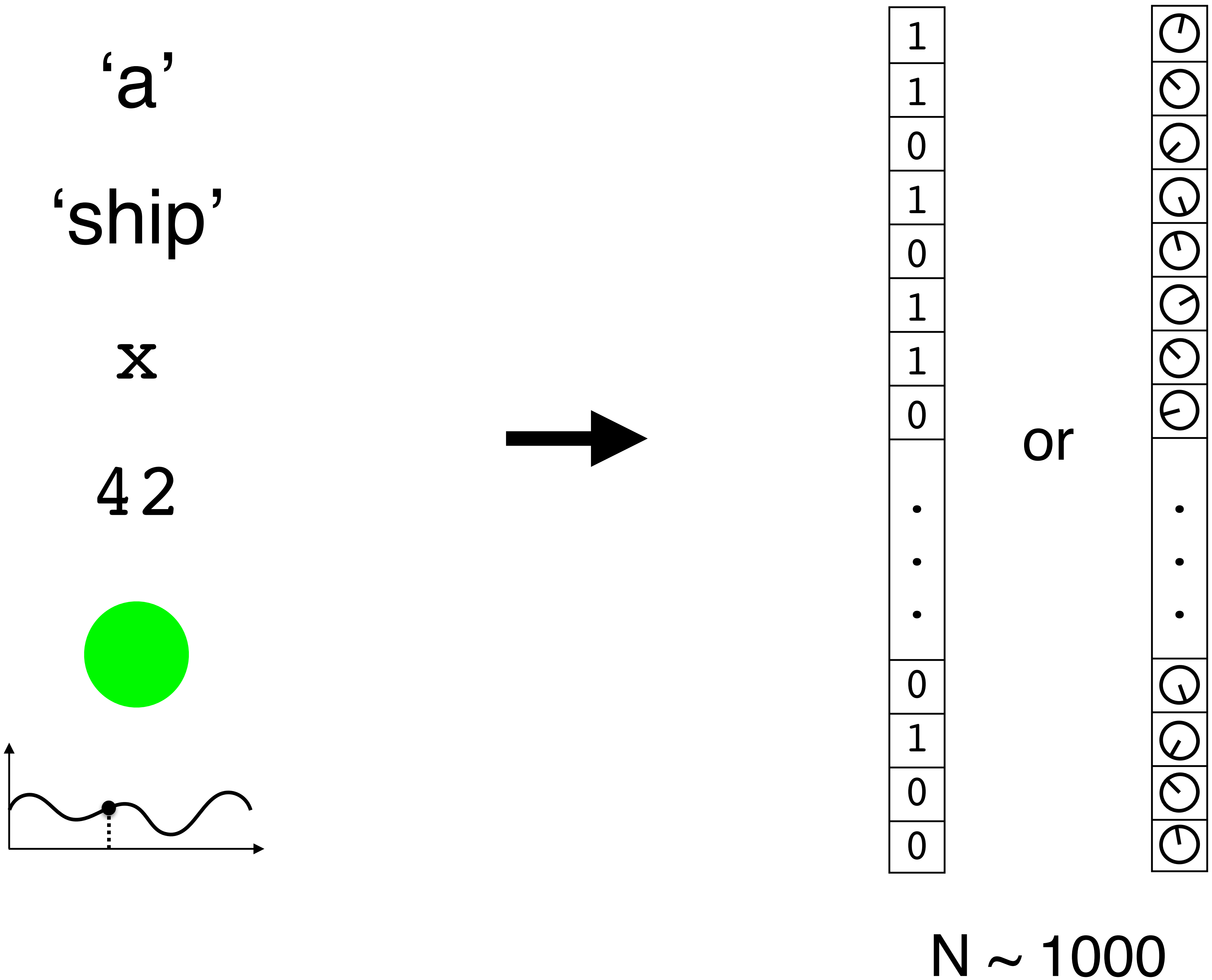
- Everything represented as a high-dimensional vector.
- Algebra over vectors (instead of numbers).

Hyperdimensional Computing

Pentti Kanerva

- The brain’s circuits are high-dimensional.
- Computing elements are stochastic, not deterministic.
- No two brains are alike, yet they exhibit the same behavior.
- Learns from data/example, learns by analogy, or even “one-shot.”
- Integrates signals from disparate senses.
- Allows high degree of parallelism.

Computing with High-Dimensional Vectors (aka ‘HD computing’)



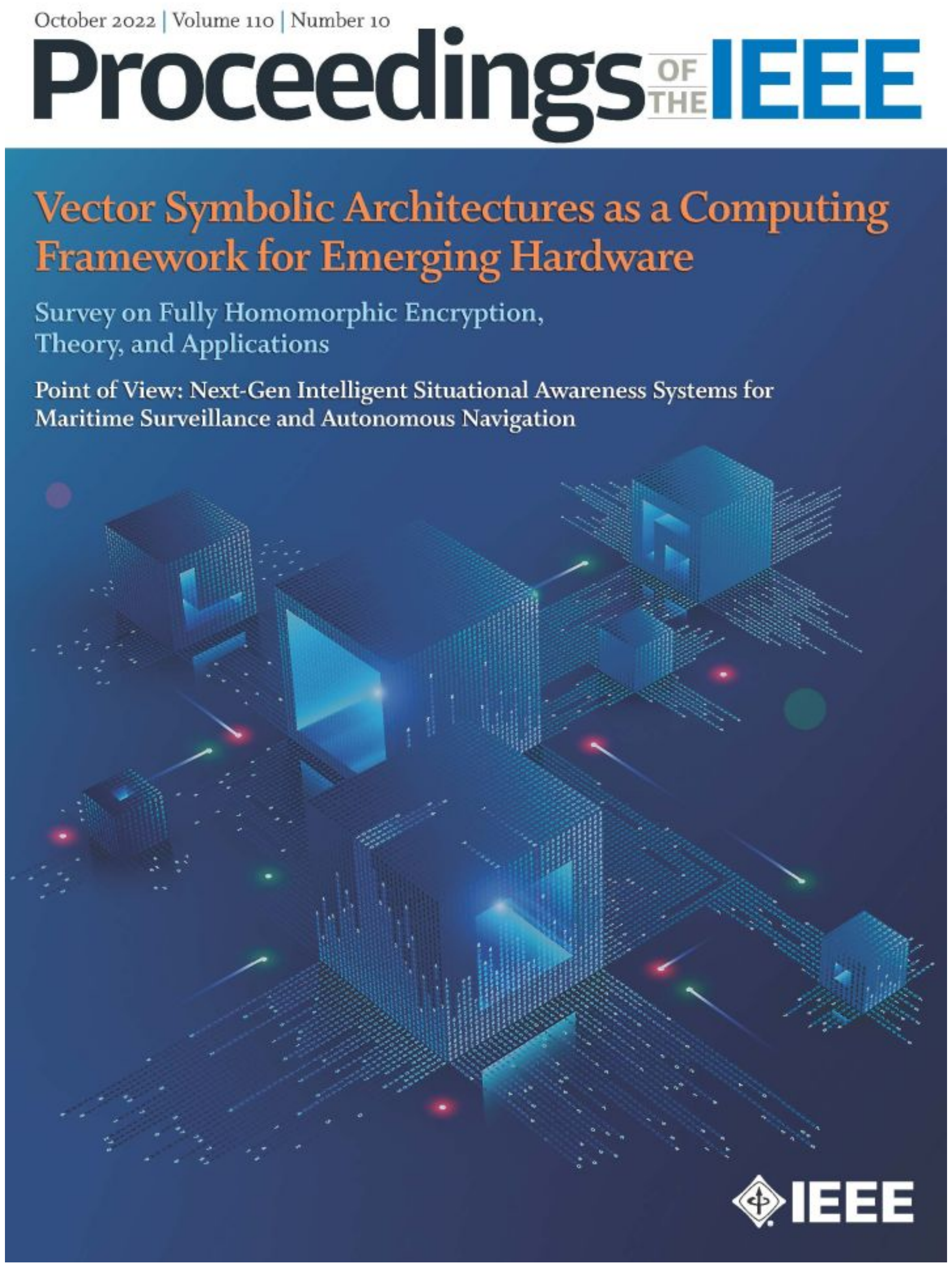
HDC Algebra

Set or **Bundling**	{ a, b, c, … }	**Z**(a) + **Z**(b) + **Z**(c) + ….
Key-Value binding	x ← a	**K**(x) ⊙ **V**(a)
Spatial relations, transformation	'object a' at 'position x' shift by y	**S** = **O**(a) ⊙ **Z**(x) **S_new** = **Z**(y) ⊙ **S**
Sequencing	[a b c …]	**Z**(a) + ρ(**Z**(b)) + ρ^2(**Z**(c)) + ….

Kanerva P (2009) Hyperdimensional Computing: An Introduction to Computing in Distributed Representation with High-Dimensional Random Vectors. *Cognitive Computing, 1*: 139-159.

Kleyko, D., Davies, M., Frady, E. P., Kanerva, P., Kent, S. J., Olshausen, B. A., ... & Sommer, F. T. (2021). Vector symbolic architectures as a computing framework for nanoscale hardware. arXiv:2106.05268.

Menon, A … Rabaey, J (2022) On the Role of Hyperdimensional Computing for Behavioral Prioritization in Reactive Robot Navigation Tasks. ICRA 2022.



Vector Symbolic Architectures as a Computing Framework for Emerging Hardware

This article reviews recent progress in the development of the computing framework referred to as vector symbolic architectures, or hyperdimensional computing.

By Denis Kleyko, *Member IEEE*, Mike Davies, *Member IEEE*, Edward Paxon Frady, Pentti Kanerva, Spencer J. Kent, Bruno A. Olshausen, Evgeny Osipov, Jan M. Rabaey, *Life Fellow IEEE*, Dmitri A. Rachkovskij, Abbas Rahimi, and Friedrich T. Sommer

	Traditional computing/AI	**Neural nets**	**HD computing**
Symbolic computing with variables and binding	✓	✗	✓
Distributed representation	✗	✓	✓
Learn from data	✗	✓	✓
Robust (error-correcting)	✗	?	✓
Transparent	✓	✗	✓