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Dipartimento di Ingegneria dell'Informazione, Elettronica e Telecomunicazioni

Novel Quantum Approaches to Hyperdimensional Computing for Neural Networks

Leonardo Lavagna, Andrea Ceschini, Antonello Rosato and Massimo Panella

Department of Information Engineering, Electronics and Telecommunications (DIET)

Sapienza University of Rome

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Motivation & Context

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- The role of hypervectors in HDC can be interpreted as distributed activation patterns across an abstract set of neurons, in which each bit represents the activation state at a particular time so we can associate to HDC architecutres a role analogue to Neural Networks

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- The role of hypervectors in HDC can be interpreted as distributed activation patterns across an abstract set of neurons, in which each bit represents the activation state at a particular time so we can associate to HDC architecutres a role analogue to Neural Networks
- HDC acts through a set of well-defined operations that enable the encoding, manipulation, and comparison of data, and these operations can be defined with different approaches.

Motivation & Context

- Despite its promise, HDC's reliance on specialized hardware imposes inherent limitations

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- Despite its promise, HDC's reliance on specialized hardware imposes inherent limitations
- Quantum computing, which leverage principles such as entanglement and superposition, enable the management of information in fundamentally distinct ways from classical systems, yielding remarkable speedups

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- Quantum computing, which leverage principles such as entanglement and superposition, enable the management of information in fundamentally distinct ways from classical systems, yielding remarkable speedups
- Quantize the components of HDC architectures!

Mmmh…. How…

Methodology

- Stop making cat memes

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- Quantize one element at a time: first the associative memory (i.e. a dictionary of hypervectors), then the operations

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- Quantize one element at a time: first the associative memory (i.e. a dictionary of hypervectors), then the operations
- Theorem 1 (informal): For every HDC architecture it is possible to quantize both the associative memory and the operations, but
  - If you start by quantizing the memory you automatically get quantized operations (e.g. binding)
  - If you start by quantizing the operations you can keep the memory classical

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Example

- I'll show you only the first process...

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- I'll show you only the first process...
- There exists a quantum version of the associartive memory (Martinez & Ventura ~2000) that uses only the superposition principle

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Example

- I'll show you only the first process...
- There exists a quantum version of the associartive memory (Martinez & Ventura ~2000) that uses only the superposition principle
- You start by encoding each hypervector in the dictionary into a quantum state, by "carving out one amplitude at a time".

$$|\psi\rangle = \frac{1}{2}(|00\rangle + |01\rangle + |10\rangle + |11\rangle)$$

Example

- Use Grover's algorithm (Grover ~1996) to perform inference and retrieval

$$U_{z^*} := \begin{cases} -|z\rangle & \text{if } z = z^* \\ |z\rangle & \text{otherwise} \end{cases} \quad \rightarrow \quad U_{g(f(\cdot))} := \begin{cases} -|z\rangle & \text{if } z = f(\cdot) \\ |z\rangle & \text{otherwise} \end{cases}$$

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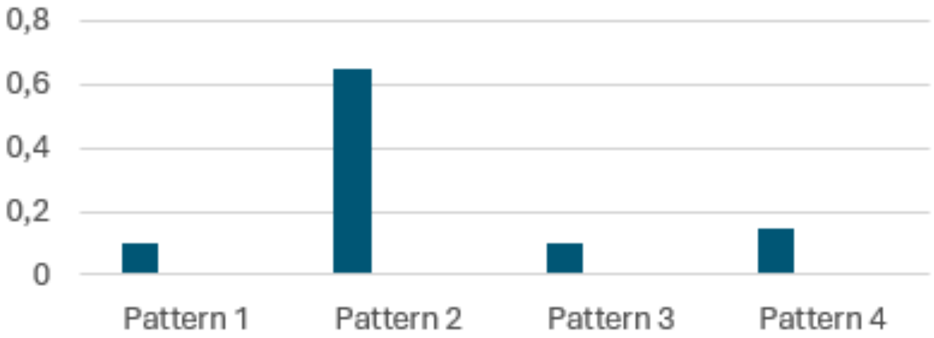

github.com/leonardoLavagna/qhdc

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IT. COULD. WORK!
Laff

Some results

- Consider the pattern completion problem summarized below

Let $y \in \{0,1\}^{n-k}$ be a partially observed binary sequence of length $n-k$, and let $\omega \in \{0,1\}^k$ be an unknown binary suffix of length k. The goal is to find a completed sequence $z = y\omega \in \{0,1\}^n$ that satisfies a set of constraints C.

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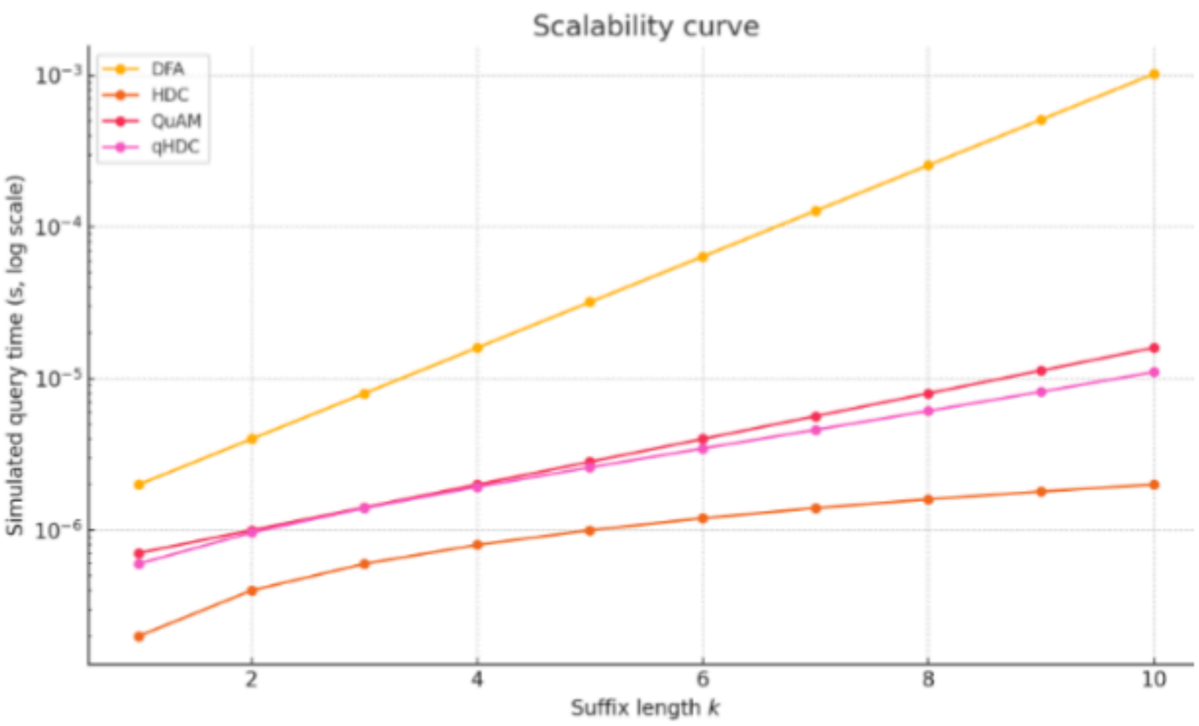
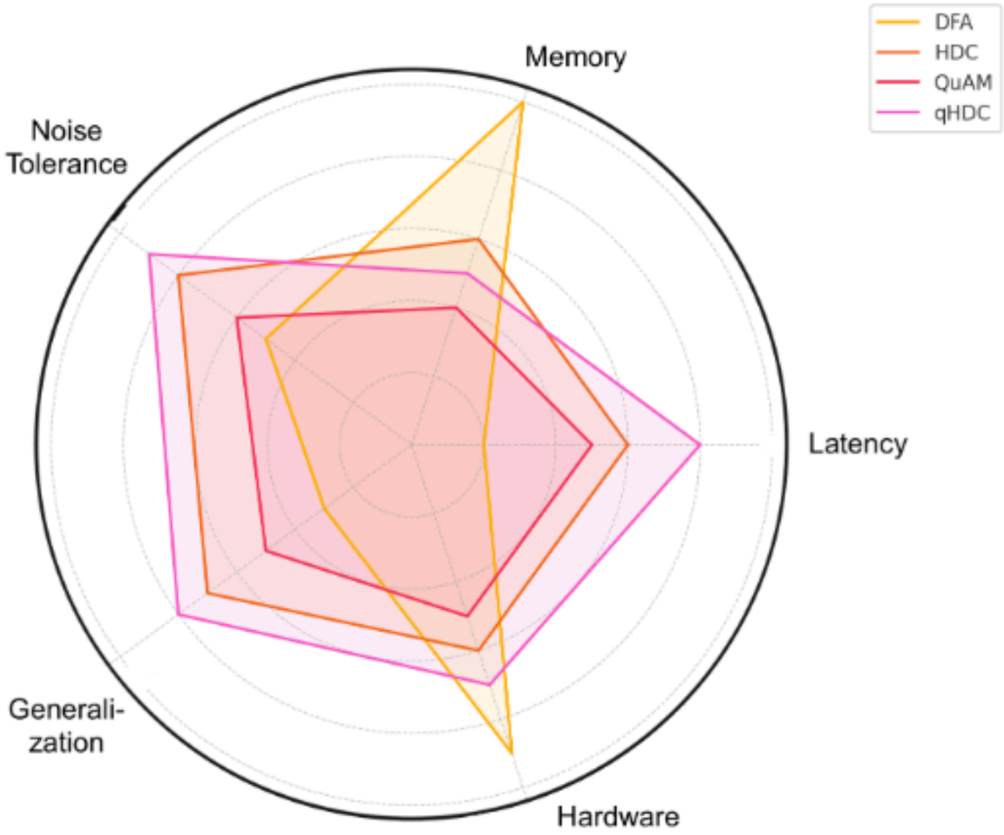
Some results

- Consider the pattern completion problem
- The proposed quantum-HDC architectures
  - show better scaling
  - have a balanced performance in terms of noise tolerance, memory requirements, latency and generalization capabilities


Scalability curve
DFA
HDC
QuAM
qHDC
Simulated query time (s, log scale)
10^{-3}
10^{-4}
10^{-5}
10^{-6}
2
4
6
8
10
Suffix length k


DFA
HDC
QuAM
qHDC
Memory
Noise Tolerance
Latency
Generali- zation
Hardware

Conclusions

- We can do it and there can be some advantages (e.g. an exponential gain in memory size) always subject to tradeoffs (e.g. a slowdown in pattern retrieval)

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Conclusions

- We can do it and there can be some advantages (e.g. an exponential gain in memory size) always subject to tradeoffs (e.g. a slowdown in pattern retrieval)
- We don't have good enough quantum hardware

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- We don't have good enough quantum hardware
- There are "deep" reasons that compell you to limit the applications to "pattern-completion-type" problems

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Conclusions

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- We don't have good enough quantum hardware
- There are "deep" reasons that compell you to limit the applications to "pattern-completion-type" problems
- Theorem 2 (informal): we can solve a machine learning problem with a quantum HDC architecture if and only if we can map it to a pattern completion problem (cf., regular languages and finite automata)

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- https://sites.google.com/view/nesya
- leonardo.lavagna@uniroma1.it