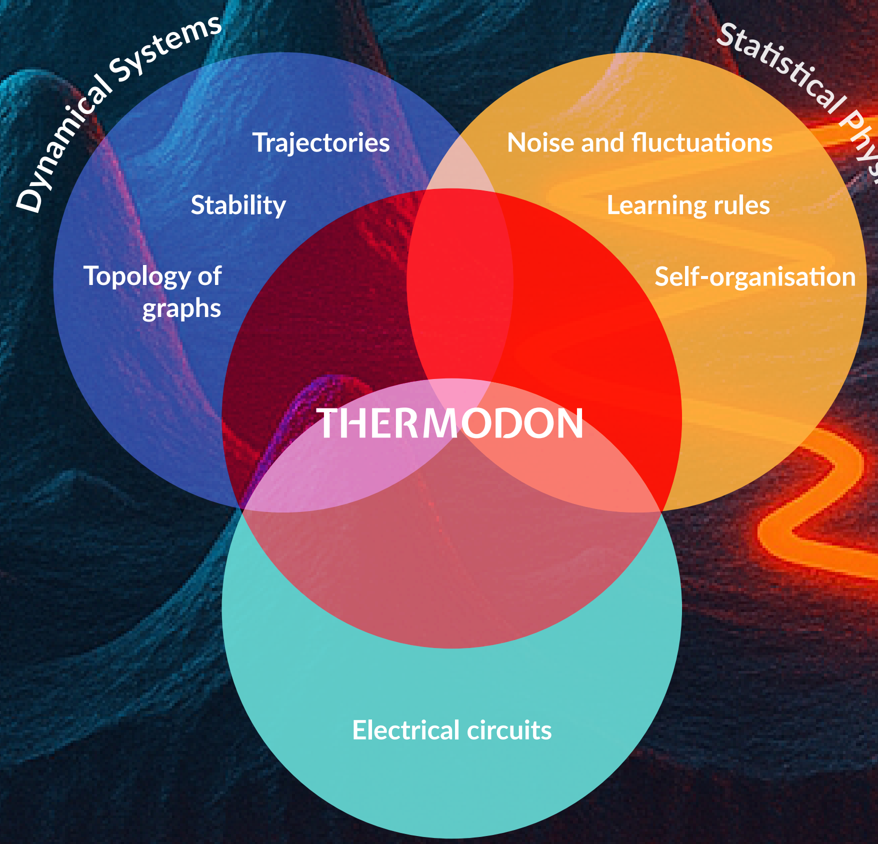
How to build a thermodynamic computer?

What would a thermodynamic computer look like?
What are its building blocks?
What can you do with it?
What technology would you build it with?

These questions are becoming more prominent in bringing innovation to computing hardware as there is a pressing need to address the power consumption of computing, which keeps rising to the point that it has become an environmental concern.



Despite the remarkable progress in semiconductor technology, computing architectures are still energy inefficient, engineered for deterministic tasks, and susceptible to noise, heat and variations. Instead of massively over-designing architectures to compute with acceptable reliability, we take an alternative path. In our THERMODON project, we 'let physics do the computing', which harnesses noise, heat and variabilities for energy-efficient computing.

At the heart of this emerging computing paradigm is the thermodynamics of open systems entwined with neuromorphic computing. In THERMODON, we are developing an unconventional neuromorphic architecture to thermodynamically compute and self-organise ('learn').

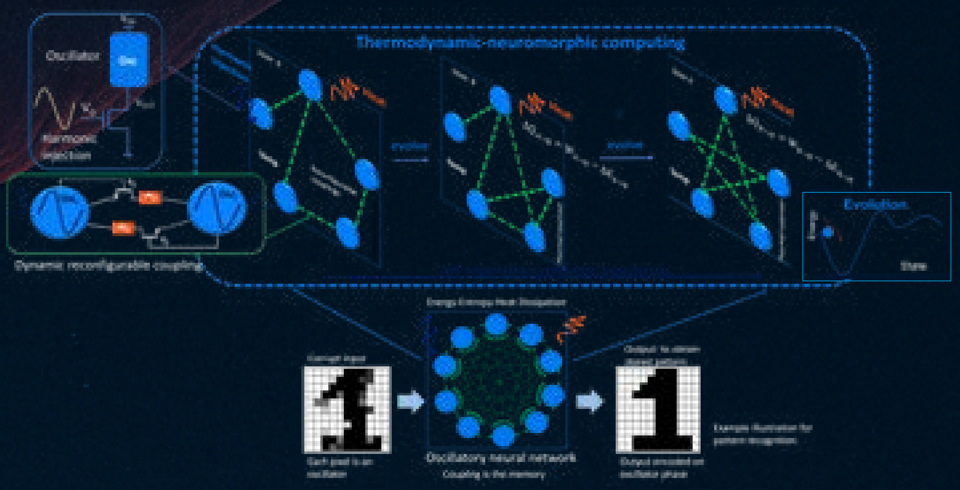
How would a thermodynamic computer compute?

Our main hypothesis is that the natural thermodynamics of appropriately engineered architecture can harness noise, heat and variations to self-organise toward energy-efficient 'solutions' to 'problems' posed by external potentials.

What would a thermodynamic computer look like?

We are developing such architecture based on coupled oscillatory neural networks that we master in our NanoComputing lab. Over the years, we have developed networks of coupled oscillators, or oscillatory neural networks (ONNs), to perform simple tasks such as associative memory and pattern retrieval. In THERMODON, we are embarking on a research path to understand how thermodynamic principles can be applied to ONNs to derive learning rules that are unsupervised, continuously adapting and transforming the architecture into a dynamic 'self-organising' and 'open interactive' system that learns, infers and interacts with the environment.

Originating from Hopfield neural networks (HNNs) (Hopfield, 1982; Hoppensteadt and Izhikevich, 2000; Izhikevich, 2003), recurrent neural networks can store and retrieve information while minimising their energy (Ising, 1924). A primary candidate



for their physical implementation is the oscillatory neural network we are working with. Notably, this research area has gained renewed attention following the recent Nobel Prize awarded to Hopfield for his seminal contributions (Nobel Prize Outreach, 2025). HNNs inspired Hoppensteadt and Izhikevich to conceive the idea of computing with oscillators in the early 2000s (Hoppensteadt and Izhikevich, 1997; Hoppensteadt and Izhikevich, 2000; Izhikevich and Kuramoto, 2006). Since there have been many efforts to engineer, design and implement such neural networks for performing simple AI/ML algorithms (Endo and Takeyama, 1992; Wu, 1998; Izhikevich and Kuramoto, 2006; Nikonov *et al.*, 2015; Nikonov *et al.*, 2020; Wang *et al.*, 2021). These developments serve as a solid foundation for our work in THERMODON to exploit the energy minimisation property of ONNs for implementing a thermodynamic computer.

Some of the key questions that we are delving into are to investigate how thermodynamics in thermodynamic computing models and AI-specialised hardware can enable online training and inference for intelligent systems. The interdisciplinary research in this project between neuromorphic computing and thermodynamics opens a new and exciting area in computer architecture, triggering a paradigm shift in edge AI computing and having an immediate impact as a hardware accelerator platform.

Based on these hypotheses and research questions, we are investigating the complex dynamics of coupled oscillators and developing the analytical framework for studying such dynamics. The key building blocks in the thermodynamic computer based on ONNs are the oscillator and the coupling elements between them. Over the years, we have explored and developed many ways to design such building blocks—digital, analogue or mixed signal among them (Corti *et al.*, 2018; Delacour and Todri-Sanial, 2021; Carapezzi *et al.*, 2021; Abernot *et al.*, 2021; Abernot, Gil and Todri-Sanial, 2022; Todri-Sanial *et al.*, 2022; Núñez *et al.*, 2021; Abernot *et al.*, 2023; Luhulima *et al.*, 2023; Todri-Sanial *et al.*, 2024). However, the question of how to make such a system robust and scalable for computing is the focus of the THERMODON project. Hence, we are developing both the computing architecture design and implementation along with the algorithms for solving different tasks such as inference, online learning and combinatorial optimisation problems.

The team currently has three members, including Professor Todri-Sanial as PI, and several open positions to be filled during the first two years. The team is divided into two sub-groups: one focused on computing hardware design, and the other on algorithm development and benchmarking.

PhD student Jelle Verest leads the computing hardware design sub-group, while algorithm development and benchmarking are led by PhD student Federico Sbravati.

Meet the THERMODON team

Federico Sbravati

What's your background?

I studied Engineering Physics at Politecnico di Milano, where I chose the Nanophysics and Nanotechnology track. While studying, I got interested in simulation work and computational physics, which is the microscopic framework in which macroscopic thermodynamic properties of matter are studied. Specifically, my graduation work concerned the Ising Model, which is the foundational model in ONNs and many studies in statistical mechanics.

How/what got you interested in thermodynamic computing?

Since my background is in statistical physics, I already had a vested interest in thermodynamics. The project aims to exploit microscopic physical systems for implementing computing architectures to solve mathematical problems, and it seemed like an exciting project.

What is your involvement and the problem(s) you want to solve?

I am analysing the dynamics of different ONN models and how these transfer to electronic circuits. Specifically, different mathematical models behave differently when coupled together. Additionally, one has to first understand how the ONNs behave prior to trying to embed a problem and solve anything with them.

Jelle Verest

What's your background?

I did all my studies at Eindhoven University of Technology, and now I am a PhD student of Aida in the THERMODON project. My studies were in electrical engineering with a focus on RF integrated circuit design.

How/what got you interested in thermodynamic computing?

I've always been deeply interested not only in my specific area of electrical engineering, but also in entirely different fields. Mathematics, in particular, fascinates me, especially how it shapes our understanding of nature. My perspective on nature was profoundly impacted by a book on Chaos Theory, and how this field has evolved over the last century. And when it came time to search for a PhD project, I found this one where electrical engineering and complex dynamical systems beautifully came together, and so I jumped at the opportunity!

What is your involvement and the problem(s) you want to solve?

For me, the most important aspect of this project is how to implement the theoretical developments into complex systems with my circuit design background. I also analyse the scalability of the systems and develop hardware demonstrations to harness thermodynamics for computing!

Project Lead
Professor Aida Todri-Sanial

What's your background?

A professor in the Integrated Circuits Group at TU/e, and leads the Nano-Computing Research Lab. Her research spans physics-based, neuromorphic and quantum computing. Previously, she held R&D roles at CNRS, STMicroelectronics, Cadence Design Systems and IBM T.J. Watson Research Center.

How/what got you interested in thermodynamic computing?

With over 15 years of experience, she has developed computational models and implemented them using novel devices and circuit designs. She is currently conducting pioneering research on physics-based computing with harmonic oscillators for energy-efficient computing. She has received the prestigious ERC Consolidator Grant, is coordinating a Horizon Europe project, and has coordinated three other major EU Framework projects.

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THERMODON

PROJECT SUMMARY

The growing energy consumption of computing technologies has become an environmental concern, despite advancements in semiconductor technology. Current computing architectures remain energy-inefficient, primarily designed for specific tasks, and are vulnerable to noise, heat and variability. This project embraces the concept of 'Let the physics do the computing' by utilising noise, heat and variabilities for energy-efficient computing.

PROJECT PARTNERS

THERMODON will bring breakthrough innovations in thermodynamic computing models and AI-specialized hardware to enable online training and inference to intelligent systems. The interdisciplinary research in this project between neuromorphic computing and thermodynamics opens a new and exciting area in computer architecture, triggering a paradigm shift in edge AI computing as well as an immediate impact as a hardware accelerator platform.

PROJECT LEAD

Aida Todri-Sanial received the BS degree in electrical engineering from Bradley University, IL in 2001, MS degree in electrical engineering from Long Beach State University, CA, in 2003 and a PhD degree in electrical and computer engineering from the University of California, Santa Barbara, in 2009. She is currently a Full Professor in Electrical Engineering Department at Eindhoven University of Technology, Netherlands and Director of Research for the French National Council of Scientific Research (CNRS). Dr Todri-Sanial was a visiting fellow at the Cambridge Graphene Center and Wolfson College at the University of Cambridge, UK, during 2016–2017. Previously, she was an R&D Engineer for Fermi National Accelerator Laboratory, IL. She has also held visiting research positions at Mentor Graphics, Cadence Design Systems, STMicroelectronics and IBM TJ Watson Research Center. Her research interests focus on emerging technologies and novel computing paradigms such as neuromorphic and quantum computing.

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