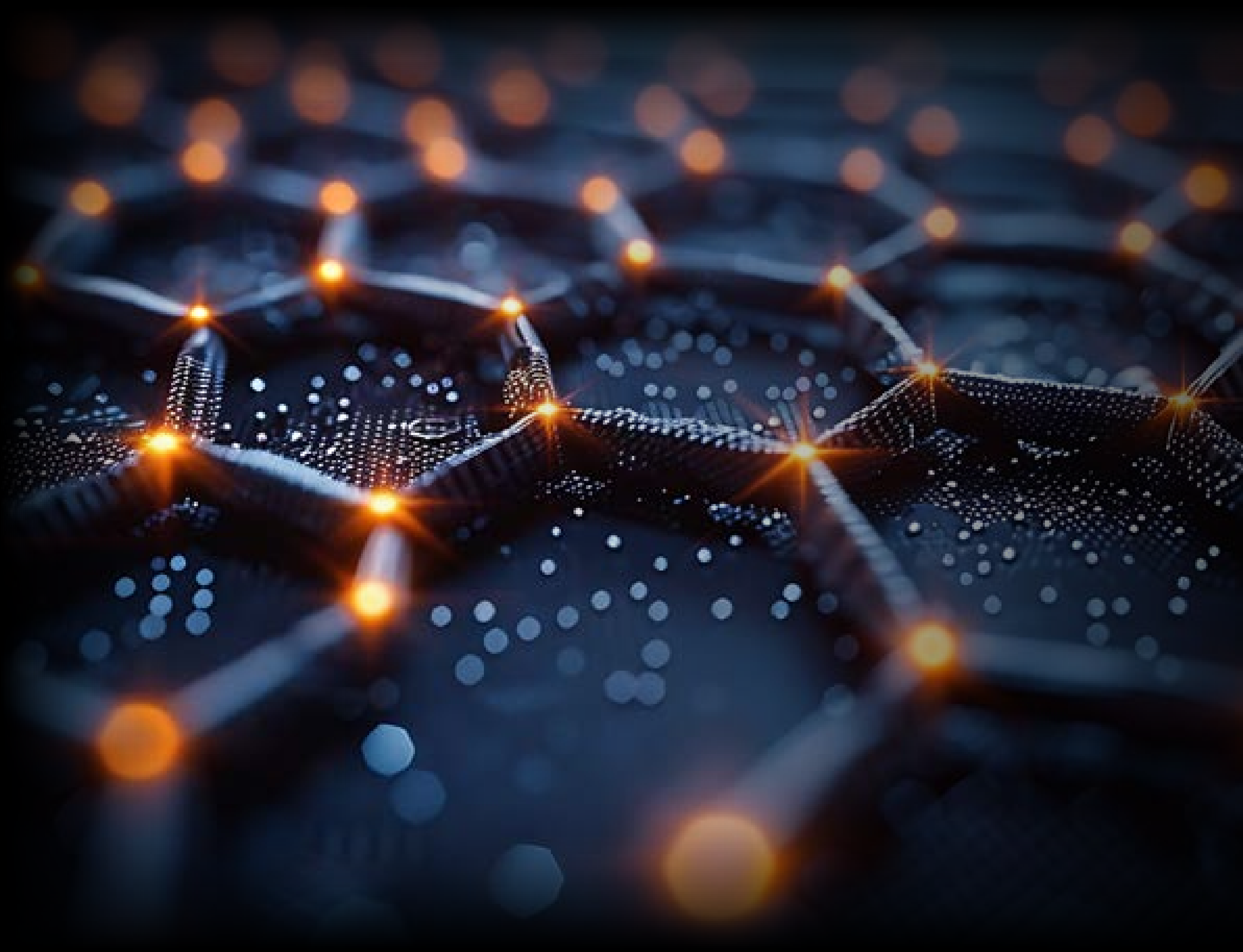
Design Automation for Field-Coupled Nanotechnologies

Computing at the limit of scaling.



Ingenious research and engineering work throughout the first half of the 20th century led to the invention of transistors, the fundamental electronic components that can amplify or switch electronic signals. These enabled the digital revolution and initiated the beginning of the information age. The following decades were characterised by an exponential increase in the transistor density in such circuits, making them increasingly powerful.

However, any exponential growth must eventually arrive at an impassable barrier due to its inability to exceed the limitations imposed by physics. One of the main limiting factors of the flattened scaling in recent years is, in fact, energy dissipation. Intuitively speaking, each operation happening on a chip dissipates some energy in the form of heat. The smaller transistors become, the denser they can be packed. Consequently, in terms of thermal density, modern processors are comparable to the cores of nuclear power plants, just a lot smaller. Thus, even with excessive cooling, this fact strictly limits frequency scaling and also prevents the simultaneous utilisation of certain chip regions to avoid overheating. Estimates suggest that, for upcoming transistor technologies at most 50 per cent of a chip's area can be used simultaneously, or it might burn up.

Nonetheless, more powerful computational systems will be continuously needed to enable technologies such as artificial intelligence, autonomous driving, or immersive virtual reality. However, due to the discussed effects and the increasing ubiquity of digital systems, worldwide energy consumption allotted to information and telecommunication is growing rapidly. Some scenarios predict that the sector could reach as much as 51 per cent of global electricity usage by 2030, contributing up to 23 per cent of the globally released greenhouse gases. This alarming estimation has not yet been factored into the recent large-scale deployment of Large Language Models (LLMs) and their respective power-hungry training processes.

Therefore, current research aims to establish new materials and building blocks that enable extremely low-power computational paradigms, facilitating further miniaturisation and large-scale integration by reducing on-chip thermal density while reducing overall worldwide power consumption to engage climate change.

Rethinking Computation

Hence, a radically new concept of computation is required. One promising idea is to conduct computation via the interactions of physical fields instead of the flow of electric current. This concept is called **Field-Coupled Nanotechnologies (FCN)**, which is an umbrella term for a class of post-CMOS candidates (see: Technological Implementations below) that share similar properties, e.g. the aforementioned field-based interactions as well as logic-in-memory capabilities and tremendously low energy dissipation. To this end, FCN does not utilise transistors but elementary devices called **cells**. Which are nanometer-sized building blocks that rely on quantum-mechanical effects to transmit signals and conduct computation. Furthermore, some FCN implementations promise energy dissipation below the **Landauer limit**—the lower theoretical bound of energy consumption of non-reversible computation—or clock frequencies in the terahertz range. These can, thus, be integrated much denser than conventional transistors while requiring only a fraction of their power. Recent breakthroughs in fabrication have even led to the founding of Quantum Silicon Inc., a research startup in Edmonton, Alberta, Canada, solely concerned with revolutionising computation in this green and powerful way.

But how exactly is the FCN concept conducting computation? It is all about arrangement. The way FCN cells interact with each other highly depends on their positioning. Different spatial structures make them interact in different ways. Many arrangements have been investigated, both in simulation and in experimentation. To this end, cell arrangements have been found that behave in accordance with common Boolean functions, e.g. AND, OR, NOT, etc. True to the established term in the conventional domain, these cell arrangements that conduct Boolean functions are called **gates**.

The task of assembling FCN gates or individual cells by arrangement in the plane and, thereby, realising desired functionality defined by a specification is called 'physical design'. *At the end of this process, an FCN* 'layout' is obtained, which contains notions of clocking, timing, delay and data synchronisation by possessing information about the precise positioning of all cells.

Design Challenges

However, in the FCN domain, many novel design challenges arise that differ from those enforced in most conventional technologies.

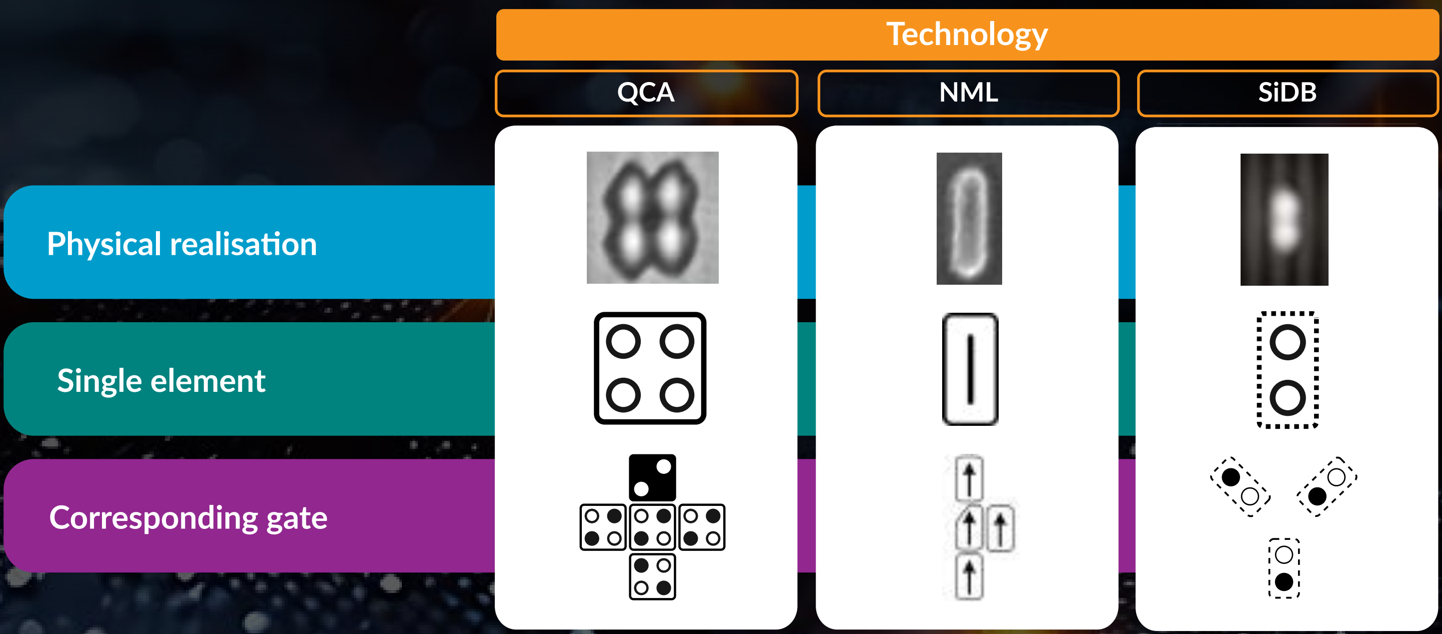
- Clocking is necessary for combinational and sequential FCN circuits because it stabilises signals and directs the information flow.
- FCN systems work in a pipeline-like fashion that leads to the emergence of data synchronisation issues, i.e. all paths throughout a layout must be balanced to ensure that information arrives synchronously at every gate. This circumstance requires careful attention so as not to induce unintended, or worse, undefined, behaviour accidentally.
- Wire segments and gates are created from the same elementary devices and, thus, share the same area requirements and signal delay properties, i.e. in conventional technologies, wire costs can be neglected on many abstraction levels, and FCN layout costs are heavily dominated by interconnections.
- FCN technologies are considered planar with limited and expensive wire-crossing capabilities, which also quickly convolutes placement and routing.

- Technology-specific fabrication constraints must be obeyed to ensure that any designed system can be physically realised.
- Eventually, the question arises whether an obtained layout is functionally equivalent to its original specification under all clocking, timing and data synchronisation constraints.
- Finally, the obtained FCN layout is to be physically simulated to ensure that the logical correctness is retained even when taking quantum-mechanical effects into account, which inevitably play an important role at the limit of scaling.

Due to their peculiarity in terms of design constraints, conventional physical design and simulation algorithms cannot be applied to the FCN domain to solve these problems. Thus, sophisticated novel algorithmic methods are required to facilitate the composition and verification of atomic structures for this of green and powerful computational devices.

Technological Implementations

Over the last decades, multiple technological implementations for the FCN paradigm have been proposed. They all share similar properties but work fundamentally differently. The most common FCN technologies are described below.



Quantum-dot Cellular Automata (QCA)

As the first proposed FCN implementation, QCA was inspired by and named after the mathematical concept of **cellular automata. Each cell in QCA consists of four (or six) quantum dots**, which are entities able to confine electric charges, and they are grouped together in a quadratically shaped frame on a substrate. With the quantum dots arranged in the corners (and the centre) of the square and two charges inserted into the system, **Coulomb interaction** leads to the emergence of exactly two stable polarisation states and one unexcited state. The stable states are labelled binary 0 and binary 1, respectively. Quantum dots in QCA could be successfully fabricated using, among others, semiconductors and bipolar bis-ferrocene molecules. Both implementations come with their own advantages and drawbacks.

Nanomagnet Logic (NML)

NML relies on single-domain magnets of varying shapes and sizes to realise non-volatile devices operating at room temperature. In contrast to QCA, NML devices interact via magnetic fields instead of electric ones and represent their state via their magnetisation instead of polarisation. NML requires more area overhead than other FCN technologies and is limited to clock frequencies of only several hundred megahertz.

Silicon Dangling Bonds (SiDB)

Hydrogen-passivated silicon surfaces contain discrete sites that can be turned into quantum dots with atomic precision. To this end, the tip of a scanning tunnel microscope is lowered onto a hydrogen site. An applied electric current breaks the H-Si bond and desorbs the hydrogen atom, leaving behind an open valence bond, i.e. a SiDB. Just like the quantum dots in QCA, SiDBs can confine electric charges but can be fabricated with greater flexibility and higher precision.

Additionally, SiDBs could be of benefit in other domains as they allow the implementation of atomic wires that conduct electric current and could enable interoperability between the CMOS domain and quantum computers.

The Munich Nanotech Toolkit (MNT) – a sandbox for nanotechnology

A software toolkit incorporating sophisticated algorithms for the entire FCN design flow has been developed and is publicly available as an open-source project. The Munich Nanotech Toolkit (MNT) offers functionality for obtaining placed, routed and clocked layouts of precise cell locations from logic specifications and allows exact physical simulation thereof.

With ongoing research in the field, it is unclear which FCN technology will eventually compete with CMOS. To be as generic as possible, the MNT is able to perform physical design tasks for FCN circuit layouts on data structures that abstract from particular technologies or cell designs. Using an extensible set of gate libraries, technologies and cell types, these can easily be compiled down to any desired FCN technology for physical simulation. Therefore, the MNT supports numerous state-of-the-art physical simulators and design tools like QCADesigner, ToPoliNano, MagCAD, SCERPA and SiQAD.

The MNT is academic software and aims at researchers and developers in the FCN domain who want to obtain cell-accurate circuit layouts from logical specifications, physically simulate FCN layouts or implement their own physical design algorithms and other experiments.

For these use cases, the MNT contains the framework fiction at its core that offers a header-only C++ library with Python bindings that provide data types and algorithms for recurring tasks, e.g. logic network and layout types on different abstraction levels, clocking schemes, gate libraries, placement, routing, clocking, verification and simulation algorithms, etc. Additionally, fiction comes with an ABC-like CLI-tool that allows quick access to its core functionality.

The fiction framework is publicly available at https://github.com/cda-tum/fiction.

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PROJECT NAME
Design Automation for Nanotechnologies

PROJECT SUMMARY
Nanotechnologies promise alternatives to conventional CMOS-based circuits with enhancements in terms of energy dissipation and feature size. But automated methods and software tools for this technology are still at their infancy. This project aims at developing automatic and efficient methods, e.g., for synthesis, physical design, and simulation of corresponding circuits.

PROJECT LEAD
Prof. Dr Robert Wille is a computer scientist by training. His team and he cover a broad covers a broad spectrum of topics, with a particular focus on the development of automatic methods for the design, simulation, verification, and test of complex systems in hard- and software. They consider conventional technologies (from formal specifications to realisation) and future technologies (including quantum computing, nanotechnologies, or microfluidic biochips).

PROJECT PARTNERS
The project is executed at the Technical University of Munich (Germany) as well as the Software Competence Center Hagenberg GmbH (Austria).

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