Building the bridge to molecular technologies

A. Ardavan, 4 December 2025

The vision:

Imagine a world where information processing consumes 100 or 1000 times less energy, so computation can be *embedded wherever the work is* — in every vehicle, tool, habitat, and instrument — without heat sinks, server rooms, or megawatt data centres. Picture *learning machines that respond continuously to their environments*, not by shipping petabytes to cloud farms but by adapting on-device, in situ, for pennies of energy. Envision *solid-state quantum technologies* with rich, local component function and seamless integration.

This programme starts from first principles: if we seek orders-of-magnitude leaps, silicon is not the substrate to deliver them. We go to the ultimate limit permitted by physics. Molecules are the smallest objects whose structures can be engineered for function; they are intrinsically quantum mechanical, naturally enabling quantum functionality. Leveraging advances in synthetic biology and programmable self-assembly, we will develop a technological framework in which the functional components are individual molecules. The results: radically lower power, richer component-level function than transistors**,** inherent quantum capabilities, and three-dimensional architectures rather than intrinsically two-dimensional fabrication. In a literal sense, this is the *final* industrial revolution in miniaturization: there is no smaller technological building block available in our universe.

To make this vision concrete, the programme will (i) demonstrate the *basic building block for spin-based quantum technologies* and (ii) deliver a *biosensor operating at the single-molecule limit*. In parallel, we will establish the *technology enablers*, *generalised assembly strategies* and *a comprehensive patent strategy*, to help drive broad adoption and deployment across industries.

The problem:

We want to build practical devices out of individual molecules, the smallest structures in nature that can be designed for function.

Currently, molecular devices are predominantly made and tested one molecule at a time in highly specialized lab setups. Methods like scanning tunnelling microscopy and break junction experiments can show what is possible, but they are slow, inefficient, and unsuitable for high yield manufacture at industrial scale. Fabrication approaches like electron-beam or ultraviolet lithography can pattern features down to about 10 nanometres, but this is too coarse: building with molecules requires control at the nanometre scale. As a result, despite decades of research, molecular devices have not yet moved beyond lab demonstrations.

To deliver this technological revolution requires adoption of a new manufacturing paradigm: self-assembly.

What is new in our approach:

Recent research advances have shown a way to solve the nanoscale assembly problem by using engineered polymers as scaffolding. DNA self-assembly allows us to design and build structures with nanometre precision, and we can use it to organize both functional molecules and gold nanoparticles into larger structures that connect with existing electronics. This method is:

- scalable – it allows many molecular components to be integrated into a single device;
- controllable – it produces consistent device yields far higher than legacy techniques;
- compatible – it bridges the gap between the molecular scale and established lithography tools.

DNA self-assembly is now a deployable technology, which, over the past 15 years, has been proven as a powerful and reliable tool for construction at the molecular scale. The Oxford University team has already demonstrated the key steps in deploying DNA to assemble electronic devices, validating the results in a recent preprint [arXiv:2503.13642]. They hold a patent [WO2019234427A1] on quantum spin devices, and are in the process of filing a patent on molecular biosensors. This combination of proof-of-concept, published results, and intellectual property means that with appropriate resource this breakthrough is ready to be scaled into working prototypes.

The programme strategy is simultaneously:

- to develop a molecular assembly infrastructure (the "plumbing") underpinning all applications;
- in collaboration with commercial partners, to pursue near-term technology demonstrators that can generate sustainable industrial development within 3 to 5 years;
- to facilitate both *basic science* and *industrial* research in domains with longer-term transformative potential, including, for example, quantum technologies and machine learning.

The payoff:

This project will reshape how we build technology. Crucially, semiconductor-based microelectronics, while enormously successful, is unsuited to some pressing current problems, such as quantum information and machine learning. These challenges demand new hardware paradigms that more directly embody the relevant information and algorithms in their physical architecture. Molecular devices offer this hardware richness, allowing us to tackle opportunities that today's silicon-based technologies cannot.

- For industry, it provides a practical platform for developing approaches better suited to today's priorities, as well as faster, smaller, and more energy-efficient devices. Potential applications include molecular quantum processors, machine learning hardware, low-energy information processing, and biomedical sensors.
- For science, it opens a new frontier where quantum and molecular effects can be reliably harnessed, in turn helping to realise further applications and devices.
- For society, engineering devices at the nanoscale will accelerate advances in a range of technologies impacting fields across sensing, communications, medicine and security.

The impact will be comparable to the shift from vacuum tubes to transistors, ushering in a new technological era built from molecules. Just as semiconductor integration enabled a revolution in information technologies, molecular device integration will open revolutionary opportunities in a complementary technology ecosystem. Developing and protecting this richer engineering landscape now will position the UK and Europe at the forefront of the next wave of industrial and scientific innovation.

The programme:

This 5-year programme is designed to drive molecular technologies from compelling laboratory demonstrations to credible, reproducible, and integrable *engineering componentry*. It does so in layers: first, by building *two near-term demonstrators* that build ecosystem confidence; second, by industrialising the *platform and tooling* that deliver those demonstrators and enable manufacture of a broader range of technologies; third, by *a programme for market and business development* so results translate into adoption; and finally, by broadening the *self-assembly foundations* beyond DNA so the platform extends viability across chemistries and environments. While maximum impact depends on the whole programme, the parallel work streams (WSs) can be assembled to match opportunities over a range of finance scales.

WS1: Demonstrators (prove the thesis; create pull)

After 50 years of promise but little significant progress, the field faces scepticism from industry and parts of academia. An effective way to build confidence is by *demonstrating devices that work*, with high yields, and *measured performance* that matters to real applications. The two demonstrators below were chosen because they (i) require the core assembly capabilities the programme must master, (ii) have clear, quantifiable proof points, and (iii) open conversations with "problem-holders" across multiple markets.

- **WS1A: Molecular quantum building block (three-terminal molecular quantum device)**
  We will implement a quantum dot in a porphyrin with a magnetic ion (a spin qubit), with a porphyrin ribbon as electrostatic gate. The central capability to show is *projective measurement of the spin qubit state via itinerant current*, with integrated microwave control for coherent manipulation. The first tranche of results will report performance metrics (i) lifetimes T_1 and T_2, (ii) readout time, and (iii) readout fidelity, from devices fabricated at meaningful yield. A second tranche extends to a four-terminal double-quantum-dot two-qubit device, demonstrating scale-up and positioning the platform against established solid-state approaches (e.g., superconducting transmons, lithographic quantum dots).
- **WS1B: Single-molecule electronic biosensor**
  We will deliver *single-molecule sensitivity with electronic readout*, overcoming two challenges which have historically blocked the technology: high channel resistance and low yield in assembling the molecular element. (A patent is in progress.) Primary performance metrics are (i) yield of molecular integration, (ii) transduction efficiency ($\Delta R/R$ on binding/unbinding), (iii) bandwidth of the electronic signal, and (iv) selectivity to the target analyte.

WS2: Platform and tooling (make it manufacturable)

To facilitate translation, we will establish the assembly infrastructure and protect intellectual property so that third parties can build with molecules the way they build with silicon blocks today.

- *Surface docking & placement.* Scalable strategies to register molecular subsystems to pre-patterned substrates, drawing on established methods while adapting them for higher yield and device-class robustness.
- *In-molecular multiplexing.* Techniques that reduce mesoscale I/O and enable complex intra-device architectures, analogous to how a silicon die exposes only dozens of pins despite billions of internal elements.
- *A component interface "API."* Define a practical electrical/physical abstraction (analogous to TTL in semiconductor logic) so heterogeneous molecular functions can be combined without bespoke engineering each time; where necessary, specify a hierarchy of interfaces to accommodate differing operating modalities.
- *Architecture, design libraries and standards.* Publish and maintain reusable electrode motifs, pinouts, test vectors, data schemas, and packaging conventions: the ingredients for replication, benchmarking, and fast iteration, informed by a coherent intellectual property strategy.
- *End-to-end assembly pipelines.* From design → simulation → scaffold/component functionalisation → placement → metallisation/contacts → encapsulation → test, with standard operating procedures and yield metrics that a manufacturing partner can adopt.
- *Open call to "performers".* Invite component creators to align their molecular functions (e.g., neuromorphic primitives) with the assembly and interface standards so the platform rapidly accumulates capability.

WS3: Market activation and partnerships (convert proof into demand)

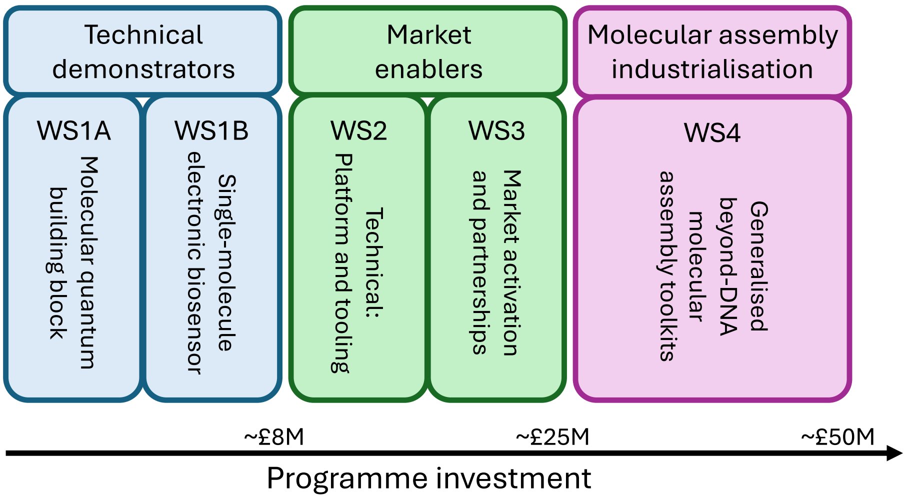
This workstream turns technical credibility into commercial momentum. It will:

- Run a targeted *industry education and business development programme* anchored on WS1 data, transforming demonstrations into *problem-class narratives* and solution templates.
- Use *demand-pull instruments* (e.g., advance market commitments) to accelerate translation and create sustainability in the research-deployment loop.
- Progress *pre-engagements* with customers, and cultivate partners in diagnostics and quantum who can absorb WS1 devices into pilots and product roadmaps.
- Develop and execute an *IP strategy* designed to protect and commercialise core inventions, delivering opportunities for economic development and return on investment.

WS4: Generalised self-assembly frameworks (de-risk the next substrate)

We use DNA now because it is reliably programmable and available, but it also brings constraints (e.g., operation in warm, salty aqueous media, structural helicity, and compatibility issues with some component chemistries). In parallel with WS1-3, WS4 will establish molecular self-assembly technologies that are not burdened with DNA's biological evolutionary history:

- Set *performance targets* for alternative scaffolds (e.g., PNA/xNA and related frameworks) driven by *real WS1/WS2 needs*: chemical stability, geometric freedom, operating environment, and interfacing rules.
- Build a *compatibility layer* so next-generation scaffolds can be adopted in the WS2 pipeline and WS1 device classes without re-engineering the stack.



The structure of a programme kick-starting adoption of molecular device technologies. Dependencies move to the right: WS1A and WS1B could be stand-alone, but inclusion of WS2 and WS3 drives translation and sustainability. WS4 enables the ambition of a generalised molecular technologies industry framework.

Milestones and decision gates (illustrative)

- **M18: Platform readiness.** WS1A shows spin readout signal; WS1B shows single-molecule binding events with electronic transduction; WS2 pipeline producing repeatable placement and yield
- **M30: Demonstrator credibility.** WS1A coherence and fidelity benchmarks to spec; WS1B ΔR/R, bandwidth, and selectivity to spec; v1 standards pack published; at least one advance market commitment or pilot LoI (WS3).
- **M48: Scale and adoption.** Two-qubit double-dot path defined and initial integration run; biosensor pilot in an external lab; third-party performer components validated via the interface API; beyond-DNA options down-selected on evidence.