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Diagnosing the Quantum Workforce: **The Hardware Skills Bottleneck**

Author: **DOMINIC LENNON**
Co-founder and Director of Product, QuantrolOx



Executive Summary

Every quantum hub, research park and national programme is competing for the same thing: people who can build and run quantum hardware. Scientists, engineers and technicians with hands-on hardware skills. Those skills can't be learned from a textbook, any more than a pilot can learn to fly from one. They come from time at the bench, beside an expert, on real equipment: learning why a system that worked yesterday fails today, and what to do about it.

This is the constraint. **It takes skilled people and expensive hardware to train skilled people.**

Every hour an expert spends teaching is an hour not spent advancing the hardware. Every hour a novice spends on a multi-million-dollar system puts it at risk. So the field can only train new people as fast as its few experts and scarce machines allow.

We call this workforce development constraint the **hardware skills bottleneck**: a structural limit on the rate at which hands-on hardware skills can be developed, set by the interlocking scarcity of the experts who can teach and the hardware they must teach on.

For most of the field's history, this bottleneck was simply a fact of life.

It no longer has to be.

Simulation can now carry the first layer of training: a "flight simulator" for the quantum lab, where one expert can put fifty students through realistic, hands-on practice with an hour of their time and no hardware at all. Students learn how real systems behave, and misbehave, before they touch one.

The next layer needs real hardware, but not a full research lab. Turnkey, open-architecture systems act as a "quantum breadboard": working hardware from day one that trainees can open up and learn from, without first needing experts to design and build it.

QuantrolOx did not set out to solve this. We build software to accelerate quantum hardware development for quantum labs, and the problem reached us from three directions at once: learners asking to use our demonstration simulator just to feel how real systems behave, a group lead who couldn't pass the skill through his team, and an institution in India trying to build a quantum hardware programme from a standing start.

Today, Quantum EDGE Academy is in paid use at institutions including Brown University, and together with VIDYAQAR it anchors Quantum-Hub@MAHE at Manipal Academy of Higher Education (MAHE) in Bengaluru, training the engineers and technicians the industry needs to grow. At MAHE, our first train-the-trainer programme took 11 trainers (seven students and four faculty, from computer science to mechanical engineering) through to real system operation in one summer, not years. In September 2026, QuantrolOx opened its first US office at UC Berkeley's Roger Herst Quantum Nexus, where we are developing methods to train hardware scientists, engineers and technicians at scale, for research labs and industry alike.

Even with our efforts, the bottleneck is larger than any one company's products. This paper sets out the bottleneck's structure, and recommends specific actions. Among these actions we ask funding bodies to offset the demand they create. Any programme that increases demand for quantum hardware should also fund the training in the hardware skills needed to build and maintain it.

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Introduction

Constrained by Hardware

Quantum computing is no longer a scientific novelty; it's a strategic priority. Governments have now committed an estimated $56.7 billion to quantum technologies, $12.7 billion of it in 2025 alone[1], and the field is projected to create over $1.3 trillion in economic value by 2035[2].

All of that value sits behind one technological constraint: no current system is mature enough to deliver a useful quantum computer, and reaching one depends on maturing every component in the hardware stack. This part of the quantum computing stack is built and run by a small population of trained experts. The supply of which is the industry's most scarce resource. This supply is limited by something more structural than funding or enthusiasm.

Quantum Hardware **Skills**

Throughout this whitepaper we use the term "hardware skills" broadly to refer to anyone who works on the hardware stack. Their competence is built through a slow feedback loop with real hardware. This can include activities such as: designing, fabricating, measuring, debugging, or interpreting real devices. Their skills are tacit, slow to acquire, and are developed iteratively.

This term applies even if the individual doesn't directly run experiments themselves. A device designer who never touches a lithography machine, but whose layout judgment is trained by rounds of fabrication and measurement feedback, faces the same learning problem as the engineer at an electronics work bench.



The Hidden Bottleneck

Regardless of quantum computing modality, the components that make up quantum computing systems are immature. Improving these requires an entire R&D process and tooling.

This process doesn't run itself and the tooling doesn't build itself. It requires hard-to-learn skills ranging from measurement, cryogenics, RF electronics, lithography, CAD, software engineering, and optics, to name a few.

Even more importantly the knowledge needs to be context aware. Understanding how to use a signal generator is a good skill, but it isn't enough to know how to construct a measurement routine to optimize a TWPA pump signal. These skills must be learnt from experts in laboratory environments where the context can be taken onboard by mentorship and doing. If you are an aspiring quantum engineer looking to bring the quantum computing revolution meaningfully closer your best option is to embark on a PhD in an established lab with expertise in the area of the hardware stack that is the current biggest bottleneck.



This solution to training does not scale for one critical reason: you need hardware skills and expensive equipment to develop hardware skills. The skills are not possible to gain from textbooks alone, just like how a pilot can't learn to fly an aircraft safely from a textbook. To train others, teachers must create material, mentor, procure hardware, establish processes and maintain equipment.

This leads to the bottleneck; every hour of an existing expert's time is valuable to the quantum industry and so training via mentorship competes directly with progress. Hardware is scarce and mistakes are costly so learning by doing cannot be scaled. These constraints reinforce each other. Cheap hardware would enable students to self learn through trial and error. On the other hand an abundance of teachers could extract far more value from the little hands-on time available. Neither is true, so the problem persists.

With this we can define the problem . . .

The hardware skills bottleneck:
a structural limit on the rate at which new hardware skills can be trained, set by the interlocking scarcity of the experts who can teach and the hardware they must teach on. This limits the supply of trained experts available to accelerate the progress of the quantum hardware stack.

Identifying Solutions to the Bottleneck

Stumbling Across the Problem

A year ago, over the course of a few months, the same problem resurfaced from three completely different directions. It took a while for us to recognise it was the same problem, because each came from a different source.

1

The first sign came at a conference, where QuantrolOx Director of Product Dominic Lennon was presenting our product platform for accelerating quantum hardware development, Quantum EDGE, using an in-house simulator we'd built to give realistic demonstrations. What stuck with us was how many people asked whether they could use the software with just the simulator, with no hardware at all, simply to get a feel for how these systems behave.



A learner who didn't know where to start due to lack of hardware.

2

At a different conference QuantrolOx CTO Juha Seppa scheduled a lunch with one of our key customers of Quantum EDGE. Over lunch the customer articulated the difficulty they had in training new masters students to characterise new superconducting qubit based devices. The problem: they kept getting stuck when responding to common issues, like using too few shots, having poorly calibrated readout, or incorrectly choosing what to measure. The underlying issue was they didn't have a well established mental model about how the system behaved and how to respond to the problems they had.



A group lead who was struggling to get skill to pass through their group due to lack of mentorship.

3

The largest version of the problem came from India, where QuantrolOx CEO Vishal Chatrath met a prospective customer trying to do the hardest thing of all: establish a centre for talent and innovation in quantum hardware R&D from a standing start. They had no prior institutional experience in the area, no existing hardware, and no courses. Building the expertise and apparatus to train students would be a multi-year undertaking before a single student could be brought up to speed. They were, in effect, trying to start the engine of hardware skills training with none of the parts.



An institution that couldn't begin.

When Juha and Dominic compared notes after the conference season, and set them beside what Vishal had heard, the problem became obvious. We immediately started a project to look into the magnitude of the problem.

The quantum workforce shortage is well recognized. US government witnesses told a January 2026 House Science Committee hearing that the field is in "a workforce shortage — plain and simple," with training pipelines failing to keep pace with demand. Industry interview studies in both the US and Europe report the same pattern[3].

However, "workforce" obscures what the problem is. Skills surveys of the quantum industry consistently find that hands-on hardware competency dominates demand. In the largest quantitative survey to date, "experimental physicist" was amongst the most commonly cited hiring needs across 57 companies. In the same survey skills cluster empirically into distinct hardware, software, and business segments. Depending on how you assign roles the hardware segment leads with software (including generic roles such as Software Developer) a close second[4].

Recent analysis of job postings across the quantum industry indicates that one in two roles require PhD or Masters level education with one in three requiring PhD level[5]. The most dominant training mechanism for these roles takes at least ten years of higher education and is only available at the select few institutions in the world with a research group working with quantum hardware.

Given all this evidence we decided to start developing and identifying approaches that could offer solutions.

Breaking the Cycle

Pilots aren't trained via textbook, they are trained via a comprehensive program of studying, shadowing, instructor led training and most importantly simulated flight hours. The quantum lab had no analogue to most of this. So, we set out to build the "flight simulator" for the quantum lab.

This approach is powerful precisely because it can provide the system level context about how an experiment feels to perform, allowing them to build intuition about how things behave. All in a safe, low risk environment where failure is cheap and most critical of all, in a way that can be easily replicated without expert time or expensive hardware.

With a solution like this, an expert can spin up 50 instances of the product, hand them out to incoming students and teach them what a continuous wave measurement is and why it's useful, all with a small time investment.

A "flight simulator" on its own isn't a complete solution, it only provides a solution that enables learning by doing. Because these skills are multidisciplinary, the simulator provides one more important educational channel, with vital context and support provided both by mentorship and by strong supporting materials and assets. A multifaceted approach like this can reduce the coupling between training and the hardware skills bottleneck, providing a much more comprehensive first line of education for students aspiring to work in the quantum industry.



A Purpose-Built Tool: Quantum EDGE ACADEMY

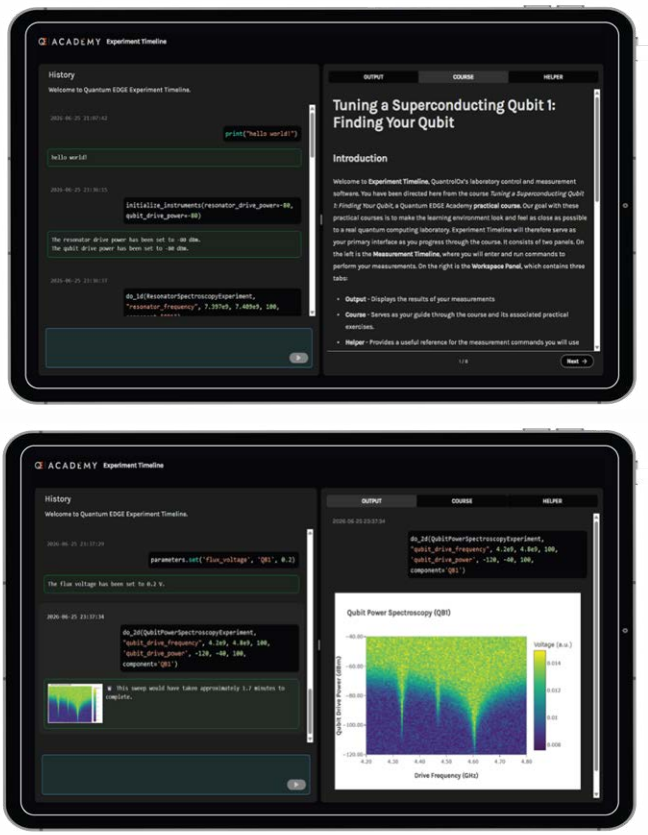
This became Quantum EDGE Academy. We were able to repurpose features of our measurement and automation platform Quantum EDGE Team to create an interactive environment.

The flight simulator for the quantum lab

The most important feature taken from Quantum EDGE was our realistic simulator. We originally developed this simulator as a tool for testing and demonstrating Quantum EDGE when hardware was unavailable. Its entire job was to be a realistic stand-in for a superconducting qubit based device under measurement.

> This is different from most other simulators precisely because it isn't trying to simulate the device as if it is behaving like a quantum computer. Instead it tries to simulate to a reasonable approximation what it is like to measure the device with numerous different inputs and schemes that are far more common in real world R&D like when characterizing devices. In other words a virtual lab.

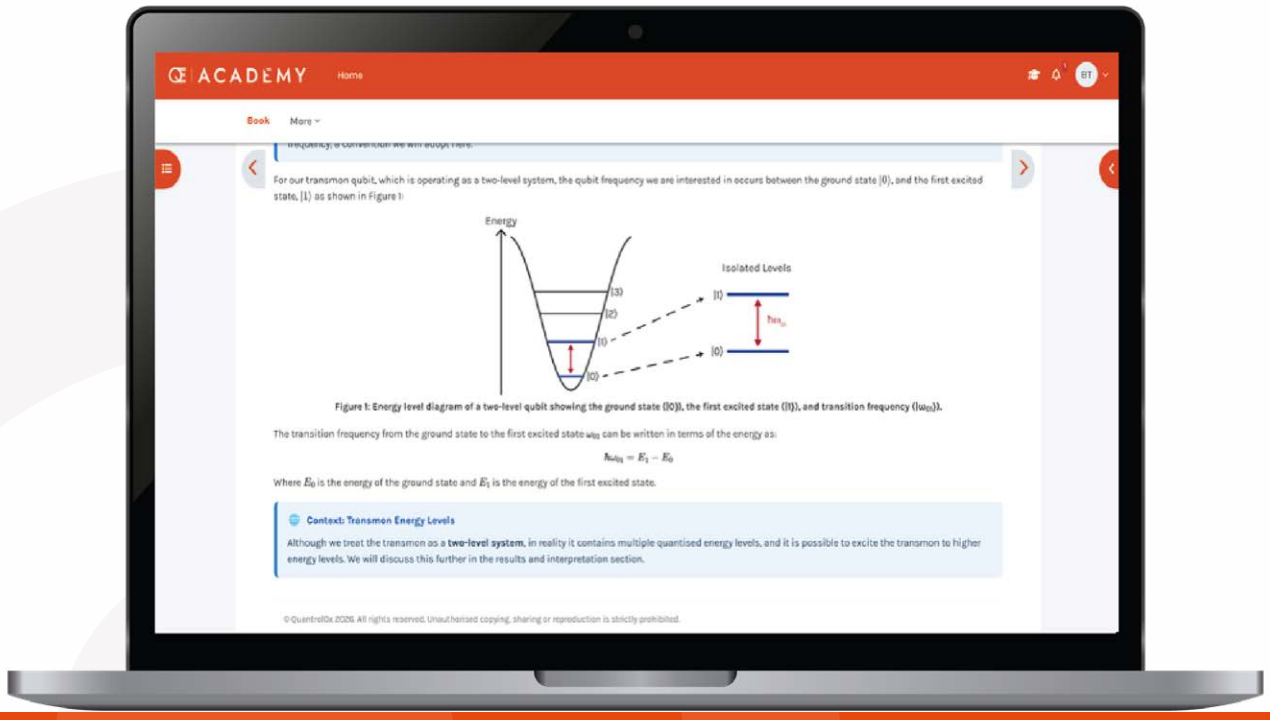
The simulator alone is not a complete solution, we also need an environment the user can use to measure it. The solution to this is the Experiment Timeline. An interactive measurement environment that allows the user to control Quantum EDGE and interact with the simulator using its Python based Software Development Kit (SDK).



Inside of the Experiment Timeline, the user is presented with course material that guides them through the steps of performing experiments. On the left-hand side, they are presented with the timeline itself where they can execute commands in Python and the entire history of their experiments is available for them. This includes interactive visualisations.

The supporting material

To support the user as they learn how to perform experiments, we have included course and concept material. This provides the user with theoretical knowledge and context that is needed for them to understand the practicals that take place in the interactive environment. This includes content like diagrams, plots, text, quizzes, callouts and equations.



"Quantum EDGE [Academy] allows our students to acquire, within two years, all the skills that the industry needs. [It] is really allowing us to provide practical training without having to run the labs and pay the overhead of things not working in a real lab."

VESNA MITROVIC
Chair and Professor of Physics and Engineering,Brown University

Going Beyond the First Line of Education: VIDYAQAR

A scalable first line training is a significant improvement that opens the door to a completely new way of training quantum lab skills.

However, it is not a complete solution. Just like how a pilot must perform real flight hours while training, more comprehensive training is best accompanied by real hardware or alternative experiences. The community as a whole must start to consider training of the quantum workforce as a pipeline of different solutions, all with the aim of lowering the barrier to entry while protecting the time of the existing workforce.

We've started building toward this ourselves, with integrated turnkey hardware and education solutions specifically to enable this next level of training.

A Breadboard for the Quantum Era



Our first offering is VIDYAQAR which you can think of as a breadboard for understanding quantum computing hardware. The most important feature for an educational system like this is that it is based on open architecture components. These must be interchangeable, used in industry and individually evaluatable. This allows transferable learning across the full stack. Another critical feature is that it is turnkey. Because it is turnkey, it requires no upfront procurement and system-design effort, which typically has to be performed by an expert.

Paired with a programme to train-the-trainers — bringing a customer's own people up to speed on the system as it's deployed — it means ...

> An institution with no prior hardware experience can begin with working, investigable hardware on day one, and grow its own teaching expertise from there, rather than waiting years to assemble both the apparatus and the people.

An education program built around VIDYAQAR goes through multiple stages:

stage 1 — **Learning the relevant concepts using Quantum EDGE Academy.**
It then moves on to stage 2

stage 2 — **Purpose built laboratory practicals on components the student will be working with.**
Finally it then moves on to stage 3

stage 3 — **Real system operation and performing characterization experiments on real quantum relevant hardware.**

This is precisely the shape of our first VIDYAQAR engagement — Quantum-Hub@MAHE at Manipal Academy of Higher Education, Bengaluru, announced in March 2026 and inaugurating this October. Our first VIDYAQAR train-the-trainer program ran over the summer following this model.

"Access to real quantum hardware, cryogenic systems, and RF infrastructure ensures that our students and researchers are not merely technology users but system builders. This is essential for developing India's next generation of quantum engineers through the Manipal House of Quantum."

PROF. IVEN JOSE
Director,
MIT MAHE Bengaluru

> We showed in one summer 11 prospective trainers consisting of 7 students and 4 faculty with a variety of backgrounds ranging from computer science to mechanical engineering can be trained to stage 3, real system operation. The trainer team at MAHE has now received its first dilution refrigerator with the team's goal to operate the lab smoothly. All in an institution with no prior quantum hardware courses, faculty or laboratories.

Recommendations for funders, educators, employers and providers

The bottleneck is a single structural problem experienced across the whole industry; the solution to it requires action beyond one single company, government, or institution. All the necessary actors exist for the industry to be able to directly remove it, but they need to pull together to open up the bottleneck rapidly



Educators

Educators sit upstream of the bottleneck: every scientist, engineer and technician passes through them, which is why the actions of every other actor ultimately converge on education. But educators need not wait for others to act; they have levers of their own.

- **Treat integrated hardware as scarce.** Full quantum systems are the scarcest resource but necessary as cloud access and purchased turnkey computers train users not builders. Educators should identify precisely which skills can only be learnt on an integrated system and move everything else elsewhere. Foundational measurement practice can move to simulation, and component-level skills to purpose-built laboratory practicals. Time on real systems should then go only where nothing else will do.
- **Run short, measurable cycles.** Academic timelines are slow, and a training pipeline will not be right on the first attempt. Rather than committing to multi-year programmes up front, educators should trial new tools and approaches in engagements of a few months. That is long enough to produce measurable results and short enough to iterate. MAHE's first train-the-trainer programme ran in a single summer.
- **Measure outcomes.** Without shared measures, no one can tell which approaches work. Industry can propose candidates, such as time to autonomous system operation (how long until a trainee can run a system unsupervised). Ultimately, though, educators should agree among themselves on the metrics that best reflect the skills the quantum workforce needs, and report against them.



Employers

Employers sit downstream of the bottleneck: they feel its cost directly, in roles that stay unfilled and hardware progress that stalls. They also shape it, through who they hire, what they ask for, and how they spend their experts' time.

- **Hire on demonstrated competence.** One in three quantum roles requires a PhD, yet many cryogenic, RF and characterisation roles need proven lab competence rather than research training. Employers should separate the roles that genuinely need a doctorate from those that don't, and assess the latter through practical evidence such as hands-on assessments, documented lab work, or completed training programmes.
- **Specify the skills you need.** Educators can only design meaningful programmes and measure outcomes if they know what a competent employee looks like. Employers should describe their needs at the level of skills and tasks, not just job titles, so education targets what industry actually requires.
- **Invest in productivity.** Automation and tools that make each existing expert more productive don't remove the bottleneck, but they soften its effect. Every expert-hour saved is one that can go into training the next cohort.

Funding bodies

Funding bodies set the incentives for every other actor. Where money flows decides what educators teach, whom employers can hire, and which tools get built. That makes funders the actors best placed to remove the bottleneck and shape the quantum workforce.

- **Fund capability, not just access.** The most successful hubs, such as Delft, have quantum hardware skills and hardware-building capability at their core. Cloud access to quantum processors and purchased turnkey computers train users not the people who build and maintain them. Funders should adopt a builder-not-user strategy. Buying a system to use is not the same as buying one to learn from, and the test of any hardware investment is whether the institution ends up able to operate, maintain and improve it. Every hub grant should include a capability plan that names its trainers and budgets for teaching hardware and trainer time. Building this capability is expensive, but every other hardware investment depends on it.
- **Offset the demand you create.** Funding that targets end technologies or applications increases demand for hardware skills without adding to their supply. Any programme that creates demand for quantum hardware should state how many quantum hardware experts it will need, and fund training sufficient to at least meet that demand.
- **Pay for trainers, not just students.** Scholarships add students to a pipeline whose capacity is set by the number of trainers. Teaching fellowships and funded buy-outs of expert time let existing experts train others without it competing with their research.
- **Fund in short, measured cycles.** Multi-year grants lock in approaches before anyone knows whether they work. Funders should back short pilot programmes, require reporting against shared outcome metrics, and scale what works.

Tools and component providers

Tools and component providers hold much of the knowledge the workforce needs. Understanding how an individual component behaves, and how it interacts with the rest of the stack, is a large part of the tacit skill that makes hardware skills slow to train, and that knowledge sits with the companies that build the components.

- **Teach your components.** Tools and component providers benefit directly when users understand their products deeply. Full-stack providers' incentive is often the opposite: to abstract the hardware away. Providers should turn that advantage into hands-on, cost-effective educational offerings, such as simulators or emulators of their instruments, education licences, and practical exercises. These should be designed to fit the programmes educators run and funders prioritise.
- **Commit to open architecture.** Skills learnt on a closed stack travel poorly; skills learnt on interchangeable components transfer across labs. Providers should support interoperability with the wider family of competing components, through documented interfaces and support for common control stacks. Components can then be swapped, evaluated independently, and learnt once. A larger workforce is a larger market for everyone in it.

> The hardware skills bottleneck has been a constraint on the field for as long as it has existed. That is no longer the whole truth. Parts of this training can now be scaled. And the industry is mature enough to be able to address it.

None of the actions above is radical; what has been missing is a shared understanding of where the constraints actually are and coordinated actions to eliminate the bottleneck.

Conclusion

The field in its current state is heavily constrained by the maturity of the components in its hardware stack. More research and development is required to bring components to the maturity required to achieve a useful quantum computer.

This R&D doesn't run itself and the tooling doesn't build itself. It requires a workforce that has hard to learn skills and an understanding of how to apply those skills in quantum. This cannot be learnt from a textbook. It is presently taught through direct mentorship and doing. This requires a large time commitment from the teacher that scales poorly with the number of students. And it takes years. This produces the hardware skills bottleneck: a structural limit on the rate at which hardware skills can be developed.

For most of the field's history this bottleneck was simply a fact of life. It no longer has to be. The solution to this problem is to think about training the way the aviation industry does. Treat training as a pipeline, and identify alternative scalable ways to deliver the relevant parts of that pipeline. However, establishing meaningful pipelines is an industry wide challenge that can't be solved by any single institution or organization. It requires coordination between the companies, governments and institutions. We provide recommended steps for each actor that we believe will provide a path to alleviating the bottleneck.

The field's progress is set by the maturity of its hardware, and the hardware's progress is set by the people who can build it. Remove the constraint, and the timeline to a useful quantum computer shortens.

"Every quantum roadmap assumes a workforce that doesn't exist yet.

You can't hire your way out of that. You have to train your way out, without pulling experts off the hardware."

VISHAL CHATRATH, Co-Founder and CEO of QuantrolOx.

References

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VIDYAQAR

QuantumEDGE ACADEMY

FINLAND

QuantrolOx Finland Oy,
Keilaranta 10 E,
02150 Espoo
Registration number: 3228548-5

UK

QuantrolOx Ltd.,
Grassroots Coworking Space,
46 Woodstock Road,
Oxford, OX2 6HT
Registration number: 13529974

NETHERLANDS

QuantrolOx Netherlands B.V.,
Delftechpark 1,
2628 XJ Delft
Registration number: 93542747

INDIA

QuantrolOx Quantum Solutions Private Limited,
198, CMH Road,
2nd Road, No. 327,
Indiranagar, 560038
Bengaluru
Registration number: U62011KA2025FTC202453