MIT ASSIGNMENT (Due date 22 June 2026 at 2300UTC)

The Assignment

"From the three historically significant landmark papers on experimental demonstrations of quantum simulations (see section *Reference Papers*), write a critical analysis about one paper of your choice and how you envisage using it in your use case".

I chose the paper on scalable quantum simulation of molecular energies using superconducting qubits for Variational Quantum Algorithm Eigensolver (VQE) modality. My use case is the HSBC experiment of 2023.

VQE is the first algorithm that proved noisy quantum devices can still produce chemically accurate results. This paper uses that insight to argue that hybrid quantum-classical pipelines are the most realistic path forward for finance, chemistry, optimisation and machine learning. It shows that *useful quantum output* can come from imperfect machines.

The HSBC Experiment

Sometime in 2023, HSBC did something groundbreaking. For the first time, a real quantum computer, not a simulator, was used to improve a REAL financial prediction task, showing that quantum noise and sampling can generate features classical models cannot.

Before the HSBC experiment, quantum-finance work fell into three categories:

1. Pure theory (papers proposing quantum algorithms for finance)
2. Toy demonstrations (2–4 qubits, synthetic data, simulators)
3. Classical simulators pretending to be quantum

HSBC's experiment broke that pattern by using IBM's 127-qubit Heron processors, real order-book data, a real trading-signal task, hybrid quantum–classical model and demonstrated performance improvement over a classical baseline (of approx. 34% improvement in predicting order-book fill probability). As a former physicist and a quantitative fund manager who used to manage $800m for very demanding institutional investors, this result really excited me me: until then, most "quantum-finance" experiments lived in sandboxes or simulators, and the IBM experiment was the first time a bank had run a real financial task on a universal quantum processor with more than 100 physical qubits.

The parameter HSBC chose for this groundbreaking experiment was whether using quantum algorithms could give them quantum advantage was order-book fill probability. Now, as a former quant fund manager placing electronic trades worth millions every month, this interested me a lot. In layperson speak, order-book fill probability is the likelihood that your order will actually get executed at the price you want before the market moves away.

It answers a simple but crucial question:

"If I place this order now, what are the chances it gets filled?"

A well-modelled fill probability can materially affect a fund's performance, because it determines execution quality, slippage, and the true cost of implementing trading decisions. Thus, for a quant or execution desk, predicting fill probability is as fundamental as predicting volatility.

In the classical world, and using the classical algorithms I helped build, fill probability depends on the microstructure of the market:

- **queue position** (how many orders are ahead of you)
- **order-book depth** (how much volume is available)
- **order flow** (how aggressively others are buying or selling)
- **price dynamics** (whether the price is drifting toward or away from your level)
- **latency and cancellations**

If the market moves up before your order is reached, you don't get filled. If the market trades through your level, you do get filled. It sounds simple and intuitive, but in actual fact, fill probability is high-dimensional, non-linear, path-dependent and sensitive to microstructure noise. This makes it an ideal target for quantum feature generation, because quantum circuits naturally produce complex, high-dimensional feature spaces, non-linear transformations and noise-rich samples that classical models cannot easily generate.

HSBC saw a 34% improvement because the quantum features captured subtle microstructure patterns that classical models miss. My indulgence would be to use the HSBC-IBM's 127-qubit Heron quantum processor to experiment with the following:

- execution algorithms
- liquidity modelling
- slippage estimation
- market-making
- risk-aware order routing.

Quantum Features of Fill Probability

A central insight of the HSBC–IBM experiment is that quantum noise can act as a constructive feature rather than an error term. This matters because the field has been almost entirely focused on eliminating noise through error correction, yet this experiment showed that, under the right conditions, quantum noise itself can become a useful source of structure rather than something to suppress.

When a quantum circuit prepares a state $|\psi\rangle$on real hardware, the device samples from a noisy distribution`;

$$p_{\text{hardware}}(x) = p_{\text{ideal}}(x) + \varepsilon(x),$$

where $\varepsilon(x)$captures hardware-level stochasticity. Instead of degrading performance, this noise injects high-dimensional, non-linear variability into the feature map:

$$\phi(x) = f_{\text{quantum}}(x, \varepsilon),$$

which the classical model can learn from. This mirrors the behaviour of variational quantum algorithms such as VQE, where noise can enrich the expressive power of the ansatz, smooth optimisation landscapes and reveal correlations inaccessible to classical models.

The second breakthrough is empirical: the hybrid quantum–classical model achieved a 34% improvement in predicting order-book fill probability, a key microstructure quantity defined as:

$$\Pr\,(\text{fill}) = \Pr\,(P_t \leq P_{\text{limit}} \text{ before cancellation or price move}).$$

Fill probability drives execution quality, slippage, liquidity modelling, market-making, and risk-aware routing. Even small improvements reduce implementation shortfall:

$$\text{IS} = (P_{\text{exec}} - P_{\text{decision}}) \times Q$$

Scalable Quantum Simulation of Molecular Energies

This paper is a landmark in early quantum computing. It shows, for the first time, that a real quantum processor can calculate the energy curve of a real molecule (hydrogen) in a way that is *scalable*. This means that the method could, in principle, work for much larger molecules that classical computers struggle with.

This paper steps into the realms of chemistry, because chemistry is governed by quantum mechanics. But calculating the exact energy of even small molecules becomes exponentially difficult for classical computers, something that quantum computers should be able to do this naturally, the reason being that molecules *are* quantum systems.

The hardware used used a small superconducting quantum processor, the ancestor of today's Google Sycamore-class devices. It had only two qubits for the molecule plus an ancilla qubit for one of the algorithms. But the important part is not the size. Rather, it's that the representation and algorithms were scalable, not toy models. This paper was groundbreaking in its time because it was the first time anyone used:

- real qubits
- real gate sequences
- real chemistry mappings (Bravyi–Kitaev, Jordan–Wigner)
- no precomputed classical shortcuts

to compute a molecular energy.

The researchers tested two quantum algorithms to compute the energy of molecular hydrogen across different bond lengths. The Variational Quantum Eigensolver (VQE) used a hybrid quantum–classical loop: the quantum processor prepared a trial state while a classical optimiser adjusted parameters to minimise energy. Its short circuits made it resilient to noise, and it achieved chemical accuracy (better than 1 kcal/mol). The Phase Estimation Algorithm (PEA), the traditional approach, required long, coherent, Trotterised circuits and was far more sensitive to noise, making it less successful on today's hardware.

Relationship to the HSBC Experiment

1. **It shows how to use noisy quantum hardware productively and is the intellectual ancestor of HSBC's approach.**

   Variational, hybrid quantum–classical algorithms can extract useful results from noisy hardware long before full error correction exists. This is exactly the philosophy behind HSBC's experiment. HSBC used a hybrid quantum–classical model where the quantum computer generates features and the classical model learns from them. This is conceptually the same as VQE:

   - short circuits
   - noise-tolerant
   - hybrid optimisation
   - real hardware, not simulators
   - performance emerges from sampling a quantum system

2. **It proves that "noise-aware" variational methods can outperform textbook algorithms.**

   It is the first experimental evidence that variational, noise-tolerant quantum methods are the right path for near-term quantum advantage — including in finance – which the HSBC experiment subsequently found that quantum noise became a feature, rather a bug:

   - VQE (variational) works well on noisy hardware
   - PEA (textbook, long circuits) fails on noisy hardware
   - Variational methods *adapt* to hardware imperfections
   - Noise can be tolerated — even exploited.

3. **It shows how to build *scalable* quantum workflows**

   - scalable Hamiltonian mappings (Bravyi–Kitaev)
   - real gate-model compilation
   - no exponential classical preprocessing
   - hybrid optimisation loops

Though HSBC's model is not chemistry, but the *architecture* (principles behind HSBC's quantum ML pipeline) is the same and has scalable circuits, hybrid training, no classical shortcuts and real hardware sampling.

4. **It provides the conceptual justification for using real hardware instead of simulators**

   It is the earliest demonstration of why real hardware sampling matters because a simulator cannot reproduce the behaviour of a quantum computer that produces high-dimensional, noisy samples. HSBC's experiment relies on the same idea:
   - simulators give perfect, noise-free outputs
   - real hardware gives noisy samples
   - variational algorithms need the real samples
   - the noise itself can guide optimisation

In summary, this paper teaches how to use noisy quantum hardware effectively; HSBC applies the method to finance.

Using Scalable Quantum Simulations to Evolve the HSBC Experiment

The technology described in the paper fundamentally shifts expectations for what near-term quantum devices can achieve. By demonstrating that hybrid, noise-tolerant algorithms such as VQE can extract meaningful structure from imperfect hardware, the paper reframes quantum progress not as a distant, post–error-correction dream but as a continuum in which useful results emerge long before perfection.

This is precisely the lesson that underpins the HSBC experiment: noisy quantum samples can enrich classical models in ways simulators cannot. This paper shows *why* - because short-depth circuits, variational optimisation and hardware-aware design allow quantum systems to contribute signal even when coherence is limited.

To develop the HSBC experiment further, I would apply these principles explicitly: design hardware-efficient ansätze tailored to financial feature spaces, use adaptive circuit structures that learn from market data and incorporate error-aware training loops that treat noise as part of the model rather than a defect.

In other words, I would evolve the HSBC pipeline into a fully variational quantum–classical architecture, where the quantum processor becomes not a curiosity but an active generator of high-dimensional structure - exactly the future the authors of this paper anticipated.

Pros and Cons

The technology in discussed here changes expectations because it proves that useful quantum output does not require perfect qubits or fully error-corrected machines. Hybrid, noise-aware methods such as VQE show that quantum processors can already contribute structure that classical systems struggle to generate. This is the upside: a pathway to value NOW, not in a distant fault-tolerant future.

For an investor, that matters. It suggests that quantum computing may follow the trajectory of early GPUs - initially imperfect, but already capable of producing signals that reshape entire industries. The challenge, however, is equally clear. Hardware remains fragile, scaling is slow and today's algorithms demand deep expertise to extract meaningful advantage, and I might add, suitable for someone like me who used to build classical algorithms for electronic trading. The field is promising but uneven, with breakthroughs arriving unpredictably.

Would I personally invest in this modality? I would see quantum as a strategic option rather than a near-term revenue engine: a small, deliberate allocation to gain exposure to a technology that could redefine optimisation, simulation and cryptography. Is it the most promising? Yes. It is one of the few technologies with genuinely transformative potential - but its timeline is uncertain and disciplined expectations are essential. Quantum rewards vision, but it punishes impatience.

NINE ESSENTIALS LESSONS IN QUANTUM by Jacqueline Koay

As part of my second PhD journey, I will publish a book later this year tracing both my relearning and my new insights into quantum physics. Although I was originally trained in particle physics, some quantum concepts remain profoundly counterintuitive. To make them accessible, I deconstructed the hardest ideas using music and croissants. This is the croissant treatment of VQE:

Think of VQE as a baker trying to create the perfect croissant, but the oven is unreliable and the kitchen is noisy. Instead of attempting one long, flawless bake, which would of course fail, the baker uses a clever hybrid method. The quantum oven prepares a trial croissant, shaping layers of dough and butter in a way no classical kitchen can. Then a classical chef tastes it, adjusts the recipe, and sends new instructions back to the oven. This loop repeats: quantum prepares, classical corrects, each cycle nudging the pastry closer to perfection. Because every bake is short, the noise never has time to ruin it. Slowly, through this dance of trial and refinement, the croissant converges on the lowest-energy, most delicious form. That is VQE, a quantum-classical duet that finds the best answer not by brute force, but by shaping and improving the wavefunction one fold at a time.

Reference papers:

Observation of a Many-Body Dynamical Phase Transition with a 53-qubit Quantum Simulator. *Nature*, volume 551, pages 601–604 (30 November 2017)
Scalable Quantum Simulation of Molecular Energies. *Physical Review X*, vol. 6 (2016), pp. 031007.
Hardware-efficient Variational Quantum Eigensolver for Small Molecules and Quantum Magnets. *Nature*, volume 549, pages 242–246 (14 September 2017)