How to Control the Electronic States of Quantum Dots

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Aims

This project was designed to explore the idea of understanding how quantum dots affect their environment and how this can be controlled, focussing specifically on the TEMPO method developed by Strathearn et al (2018, Nat. Com.). We delve into the background of quantum dots and their importance, linking them to quantum computers and other areas of solid-state research. The methods and theorems used to develop TEMPO are touched upon, as well as some aspects of the code needed to model this sort of complex system.

Quantum Dot

An artificial structure that limits electronic states to nanometre length scales across all three dimensions. Essentially, it is a two-level energy system of a ground state and an excited state, as seen in Figure 1, also known as a **qubit**.

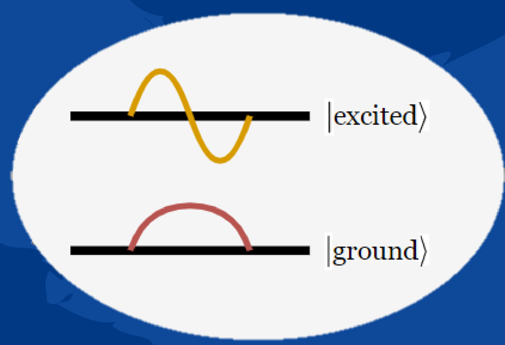

Figure 1: An energy level diagram of the ground state and the excited state, showing example waves of n=1 and n=2 for ground state energy and excited energy, respectively.

TEMPO

The structure in question is an open quantum system, which is where we have a something small enough to experience quantum effects, but it also allows environmental effects to influence it. When the coupling between the quantum system and its environment is strong, the usual approximations, used to derive the master equation for describing all motion, break down. These are called Non-Markovian systems, and they are a challenge to simulate because you must factor in the memory of the system.

The simplified example we use to test our simulations is a quantum dot lying in a bath of bosons, as depicted in Figure 3. The dot acts as our quantum system, and the bath is our environment. When the bath moves, it has a "memory" of how it moved in the past, which may change its dynamics in the present. As the memory time of the bath grows larger, the numerical methods cannot keep up and we must instead use an analytical method. The way we do this is by using matrix product states to capture the history of the system and let them have time dependence. This is the basis of TEMPO (Time Evolving Matrix Product Operator Method).

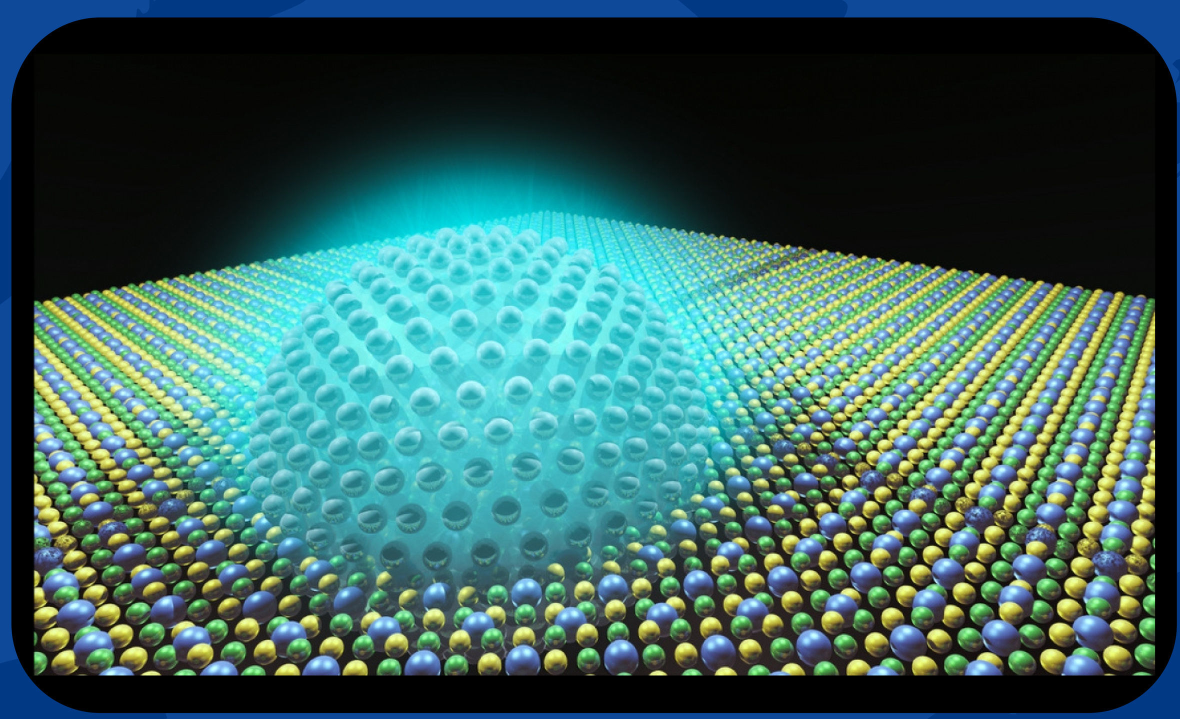

Figure 3: An artistic recreation of a quantum dot embedded in a surface, which we treat as the bosonic bath.

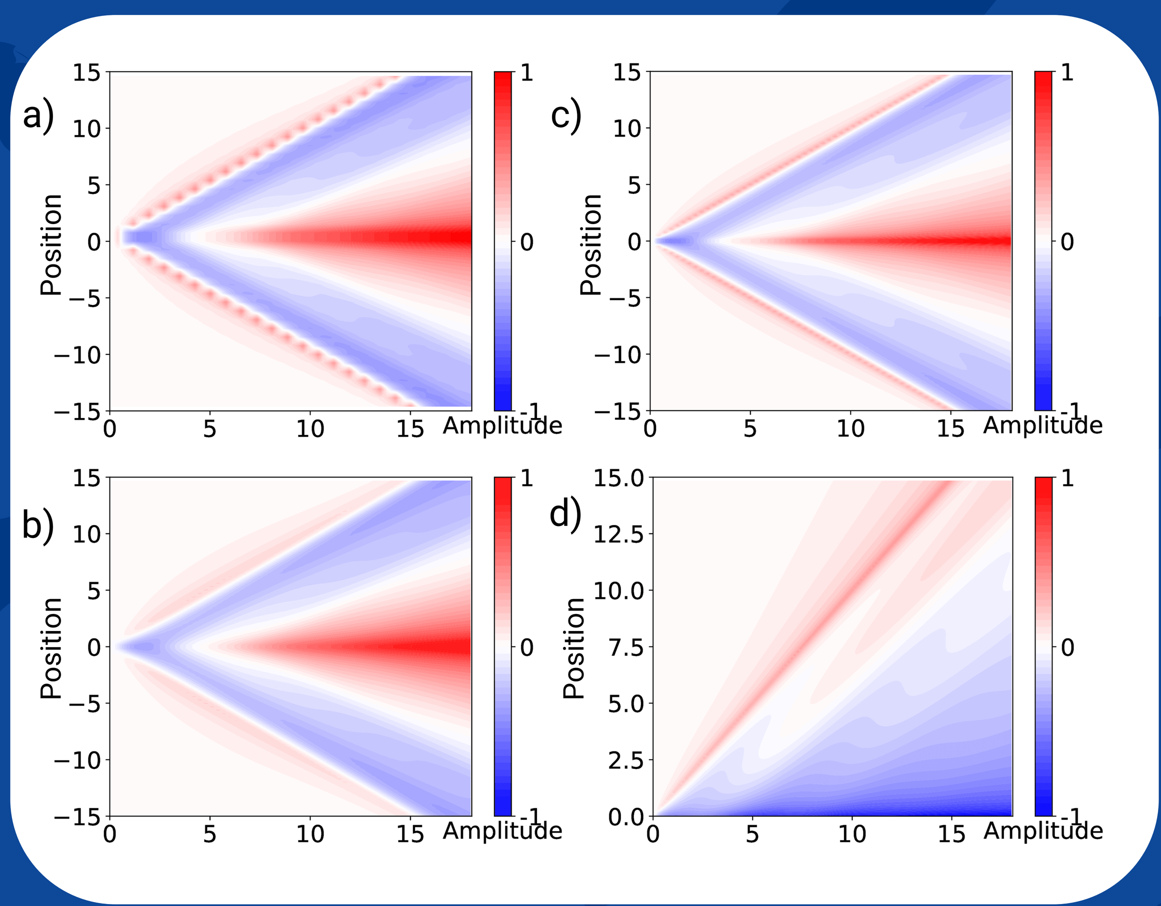

Figure 4: The graphs produced showing the displacement of a quantum dot in a bath, starting at the "zero" position. The x-axis represents time and the y-axis represents space. The red shows the bath above its equilibrium position, with the stronger red showing further displacement. The blue shows the bath under its equilibrium position. The results show a wave propergating outwards. The differences in the graphs are (a) low precision (b) high precsion (c) setting memory cutoff to wc = 1 (d) flipping the spin from spin-up to spin-down.

Quantum Computers

Quantum computers run similarly to regular computers, but instead of using bits to transfer their data, they use qubits. This way, instead of having a binary 1 or 0, they can also use the information from the characteristic of the qubit. One example of this is an electron spin qubit, where the two energy levels are either in the spin-up state or the spin-down state. These qubits will then couple to certain properties of the quantum computer, which we call the degrees-of-freedom in the solid state. These couplings will be responsible for different operations, depending on the degree-of-freedom. This can be seen in Figure 2.

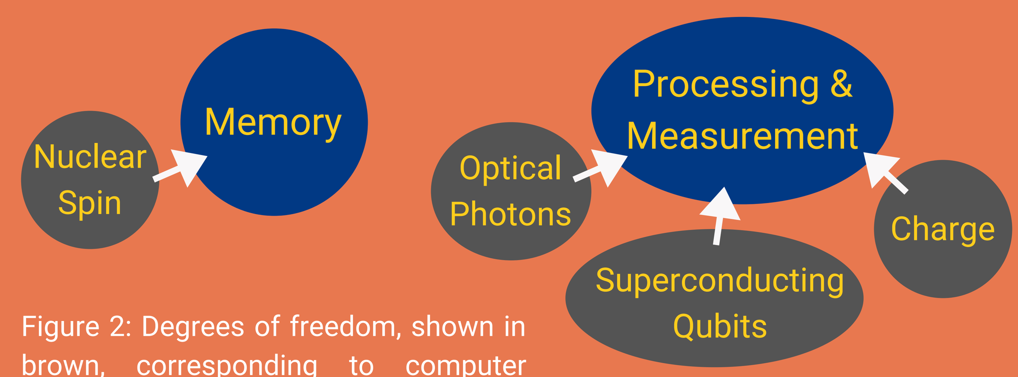

Figure 2: Degrees of freedom, shown in brown, corresponding to computer operations, shown in blue.

There are two ways the qubit can couple:

Weak Interaction	Can transfer a small amount of classical information, like a small change in conductivity.
Strong Interaction	Can coherently transfer a quantum state, with the two degrees-of-freedom being similar enough to allow storage of information and entangling operations.

To get closer to building an efficient and complete quantum computer, we must know these properties and be able to optically control quantum dots. This is where the TEMPO system becomes useful.

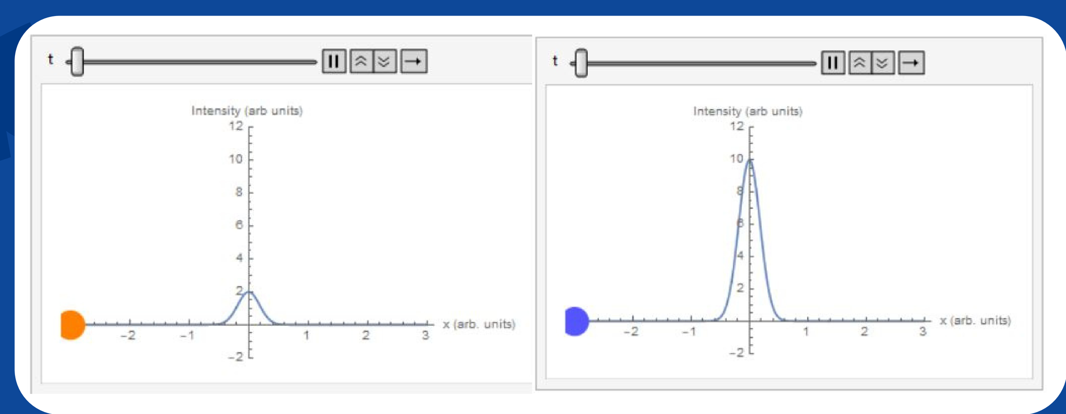

Figure 5: A still from an animation showing a side view of the bath dynamics, where the differing pulse intensity results in differing wave amplitudes.

Code and Conclusions

The dynamics was shown using the code by producing a heat map diagram, as seen in Figure 4. This worked on the principles of red being a positive displacement from the equilibrium position and blue being a negative displacement. The deeper the colour, the greater magnitude of displacement measured. After giving the system an initial input pulse, which could be a single pulse of specified frequency or a ramped pulse that change magnitude as time goes on, we want to look at how the bath moves and how that changes when we vary the parameters of the system. The system shown in Figure 4 and 5 are both of a single quantum dot given a single driving pulse. We were shown that we could expect a series of waves propagating outwards from the position of the quantum dot. If we increased the amplitude of the pulse, the amplitude of displacement also increased, as can be seen in Figure 5. We found we could also vary how quickly the waves dispersed by altering the frequency of the driving pulse, changing it from being on-resonance with the systems intrinsic characteristic frequency to off-resonance.

There were many ideas on how to extend this simulation that were unable to be achieved due to time and resource restrictions during quarantine. Despite this, the results proved to be of interest and the full scope of how useful the TEMPO method of analysis is yet to be fully explored.

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