Automated Tuning of Electrostatically Defined Quantum Dots:
Navigating Through High-Dimensional Potential Energy Landscapes

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Industrial sponsor: HRL Laboratories, LLC

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Project Description:
Electrons confined in lithographically-defined semiconductor quantum dots are of great interest as qubits for use in future quantum information processing devices. These kinds of quantum dots are formed using semiconductor heterostructures (stacks of different semiconductor materials with different band offsets) together with metallic gates patterned on the semiconductor surface in close analogy to standard CMOS transistors. The heterostructure confines electrons in one spatial dimension and voltages applied to the patterned gates create a confining potential in the other two dimensions. These gates control the electrostatic potential well enough that the number of electrons in each dot can be exquisitely controlled. For use as qubits, each dot would hold a single electron, however arbitrary few-electron configurations can be created and manipulated.

The creation of arbitrary charge configurations in quantum dot devices via manipulation of electrostatic gate voltages turns out to be a challenging problem, as each gate voltage influences the entire potential energy landscape. A desirable approach would be to have a model-based algorithm in which a sequence of voltage changes would automatically manipulate the charge occupancy configuration. A relatively straightforward model was developed a number of years ago primarily to understand the so-called charge stability diagrams that are produced in experiments [1]. Electrostatics is included relatively simply in this model – the gate voltages linearly control the potential energy of each dot, which in turn controls the occupancy. Additional electrons are added to a dot once the potential energy has been lowered to a point where the Coulomb repulsion for adding another electron is overcome and it becomes energetically favorable to increase the dot occupancy by one. The crosstalk between gates and its effect on the potential energy is captured through a capacitance matrix. While the electrostatics are linear, the discrete changes in occupancy that occur when the charging energy to add the next electron is overcome makes the model highly nonlinear and high dimensional. This nonlinearity implies that no direct inversion of the model is possible in order to obtain the voltages required to achieve a given charge occupancy configuration. However this model can still be used in a feed-forward fashion to navigate through the complex potential energy / charge occupancy landscape to achieve any desired configuration. Examining approaches to achieve controlled trajectories between charge configurations is the primary objective of this project.

The model problem we have in mind is a triple quantum dot system in which the three dots lie along a line; the outer two dots connected to reservoirs that contain an

inexhaustible supply of electrons [2,3]. There is a gate above each dot that primarily controls its potential energy and four gates connect the three dots to each other and to the reservoirs. These gates couple electrostatically to the dot potentials but their voltages will be constrained to values that ensure the potential energy is not so large that electrons cannot move freely between the dots and reservoirs. A tempting scenario for finding the (1,1,1) charge occupancy state, for example, is to simply do an exhaustive search of the configuration space by varying all seven voltages in small increments until the desired configuration is found. However this is likely to be a painfully slow procedure, and not practical for real time of control of an actual experiment . Similarly, moving all the gate voltages instantaneously from zero to a set of desired, pre-computed values likely results in a configuration that is not in equilibrium, i.e., the system is trapped in a local minimum that is not the ground state energy configuration. The *path* taken through voltage space therefore matters a great deal and hence, the best approach would appear to be one in which the system is bootstrapped from one configuration to the next, on the way to the final configuration, while ensuring that unintended intermediate states are avoided. This amounts to navigating through a high-dimensional potential energy landscape with constraints, as reflected in the project title. Approaches for successfully achieving this navigation in a triple dot system is the main goal of this project. An equally interesting aspect to this project will be the development of visualization tools for aiding in the understanding of these high-dimensional charge configuration landscapes. These should be developed for both debugging purposes and to help gain a more intuitive understanding of the highly-complex configuration space and trajectories through it.

Special requirements:
No external software packages are required, although Matlab might be a useful development environment. That would be at the discretion of the academic mentor and the team. Certainly everything could be done in C++ or any other common language. Parameters for the initial model will be provided by HRL so it produces results that are close to those observed in experiments.

Expectations:
The last few sentences of the project description capture the expectations reasonably well. Further refinement of the project goals can be done in consultation with the academic mentor and the team members in the early stages of the project.

References:
[1] van der Wiel, W., De Franceschi, S., Elzerman, J., Fujisawa, T., Tarucha, S., and Kouwenhoven, L., “Electron transport through double quantum dots”, Reviews of Modern Physics, **75**, 1–22 (2003).

[2] Borselli, M. G., Eng, K., Ross, R. S., Hazard, T. M., Holabird, K. S., Huang, B., et al., “Undoped accumulation-mode Si/SiGe quantum dots”, Nanotechnology, **26**, 1–5 (2015).

[3] Reed, M. D., Maune, B. M., Andrews, R. W., Borselli, M. G., Eng, K., Jura, M. P., et al., “Reduced Sensitivity to Charge Noise in Semiconductor Spin Qubits via Symmetric Operation”, Physical Review Letters **116**, 110402–6 (2016).