Title: Quantum Cellular Automata Applications

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Abstract:



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# Applications of Quantum Cellular Automata

Carlos A. Pérez-Delgado

Institute for Quantum Computing
University of Waterloo
Waterloo, Ontario, Canada
Research supported in part by CIAR, ARDA, ORDCF, CFI, MITACS, and OIT.

Canadian Quantum Information Student's Conference, 2007

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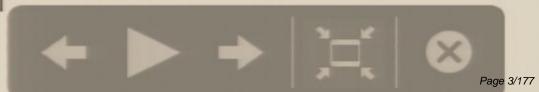
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### Applications we will discuss are...

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- Single spin Measurement (described in [P., Mosca, Cappellaro, Cory. PRL 97, 100501 (2006)]).
- Large (macroscopic) Schrödinger Cat State creation and verification (work in progress).





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In NMR, as in other settings, it would be desirable to be able to measure a single spin.





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- This would allow, among other things, NMR quantum computers that are not reliant on large ensembles.
- An NMR spectrometer can only detect the magnetic footprint of a large enough ensemble, of roughly size 10<sup>6</sup> spins.





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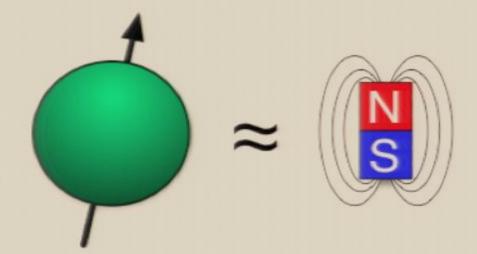
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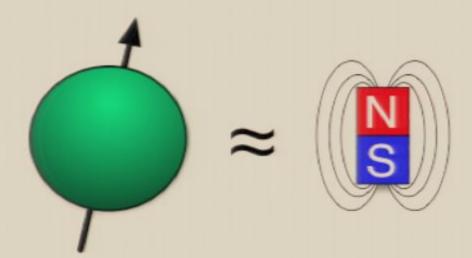
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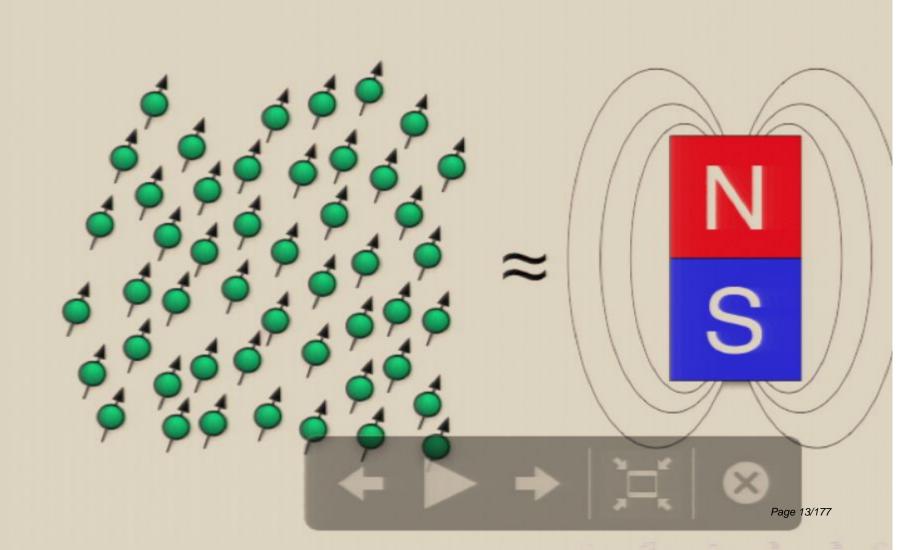
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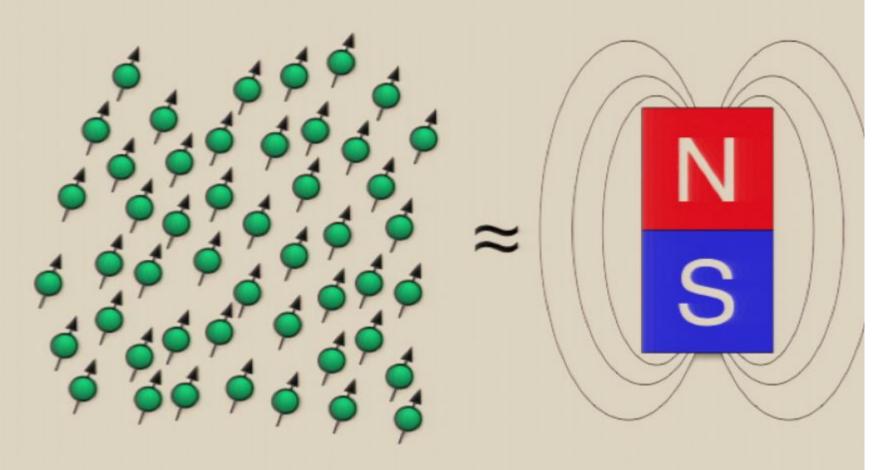
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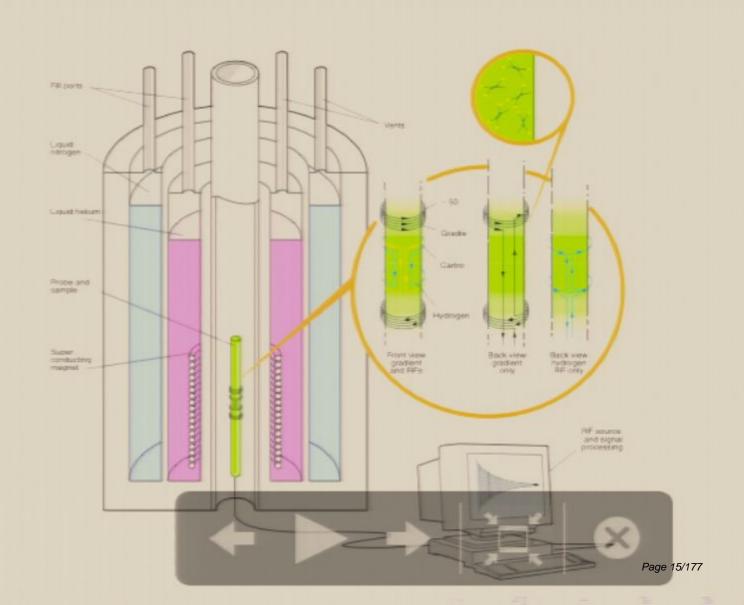
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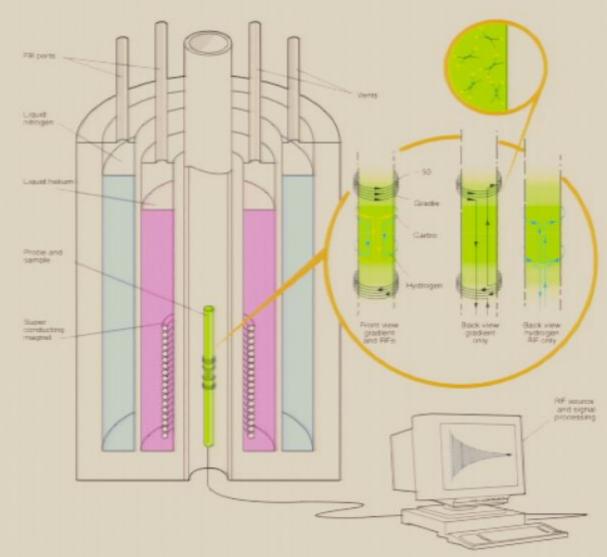
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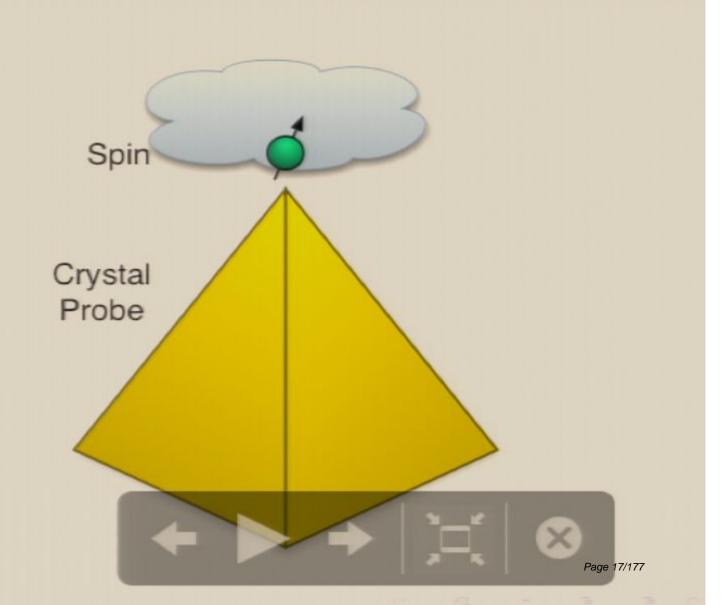
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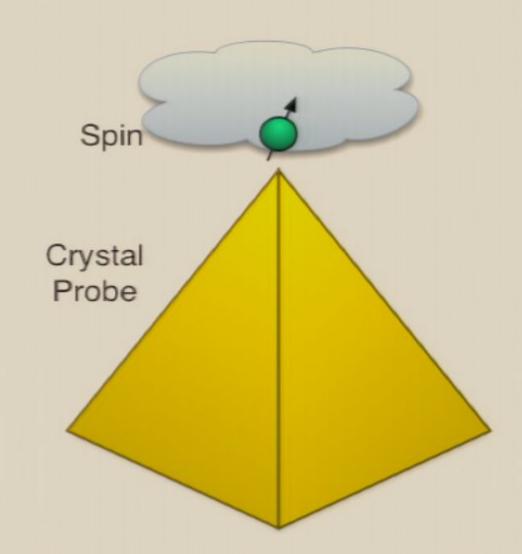
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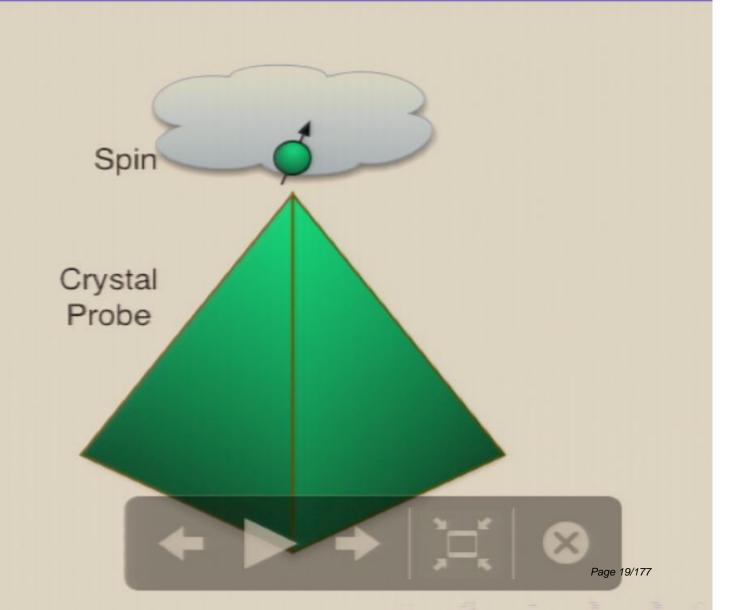
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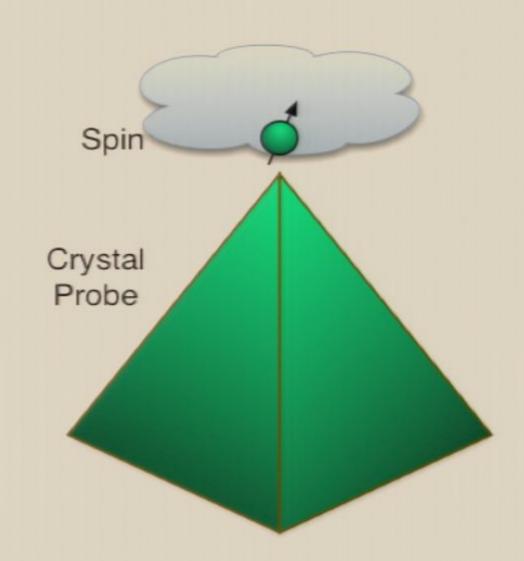
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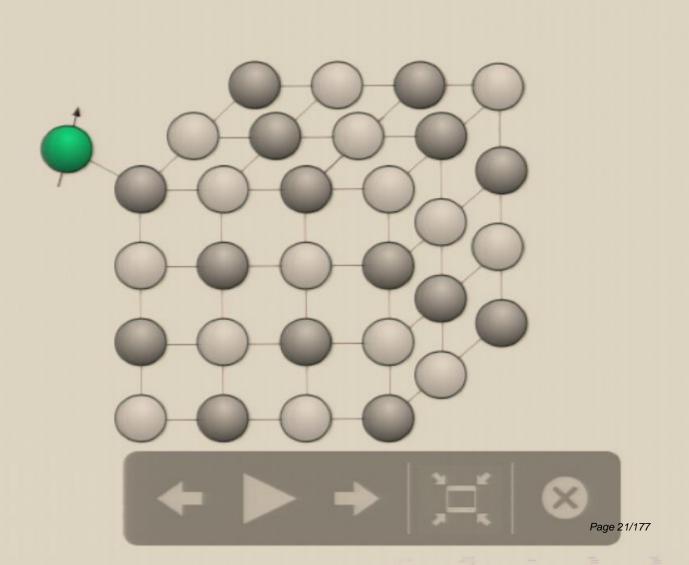
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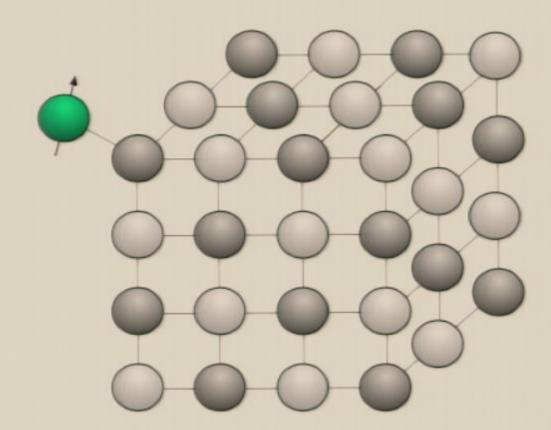
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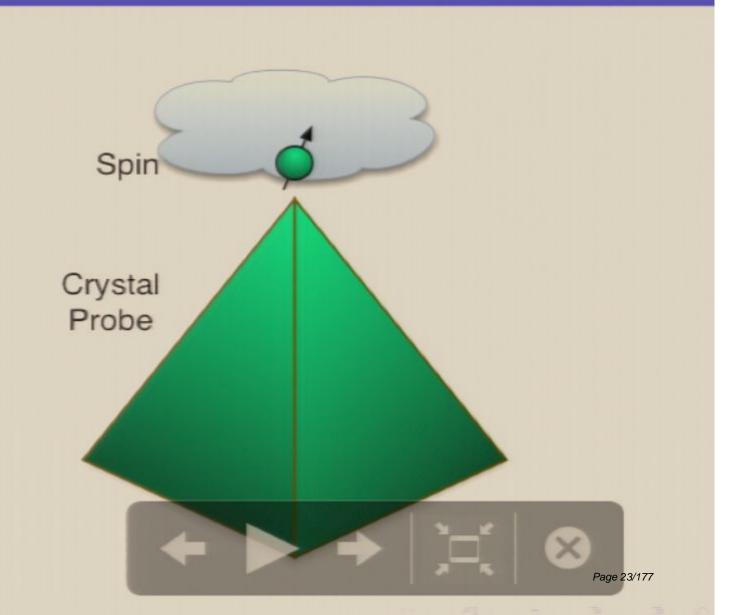
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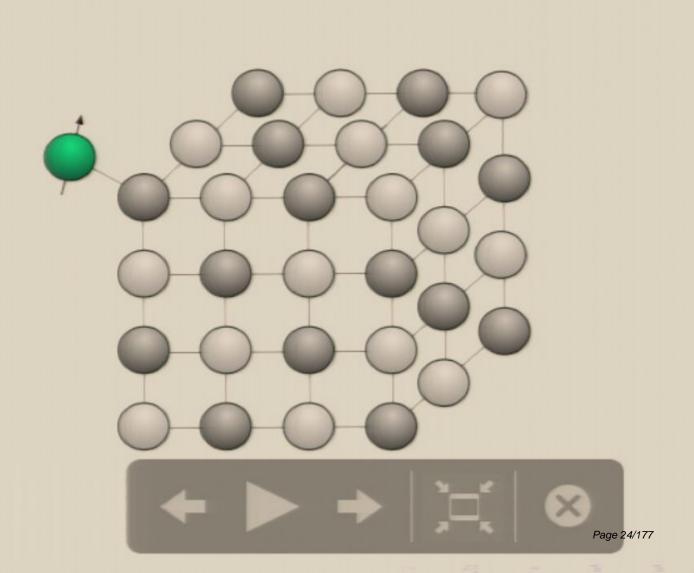
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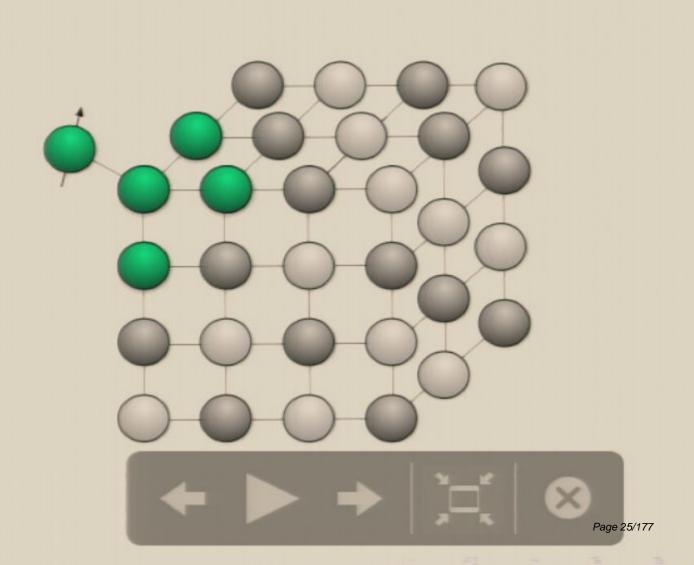
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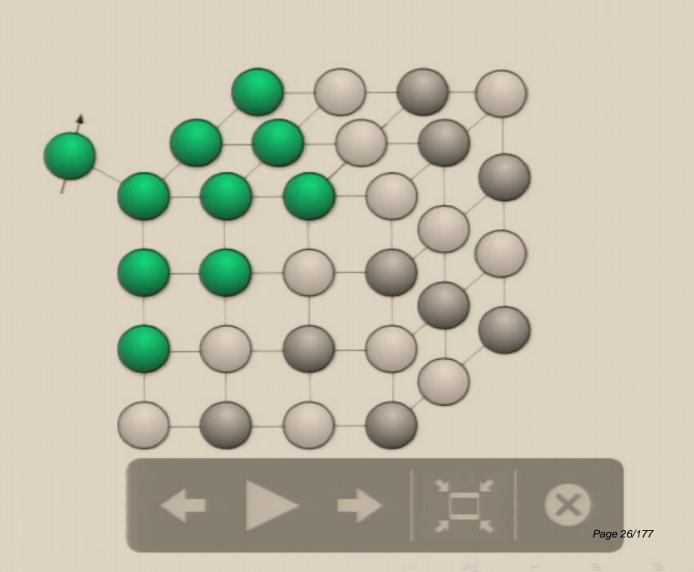
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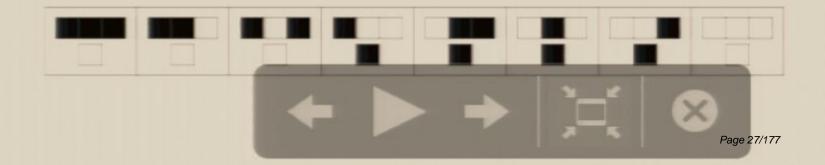
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Construction

A Cellular Automata consists of a lattice structure, where each cell is in one of a finite number of given states

For instance, Rule 30 from S. Wolfram's "A New Kind of Science" is:





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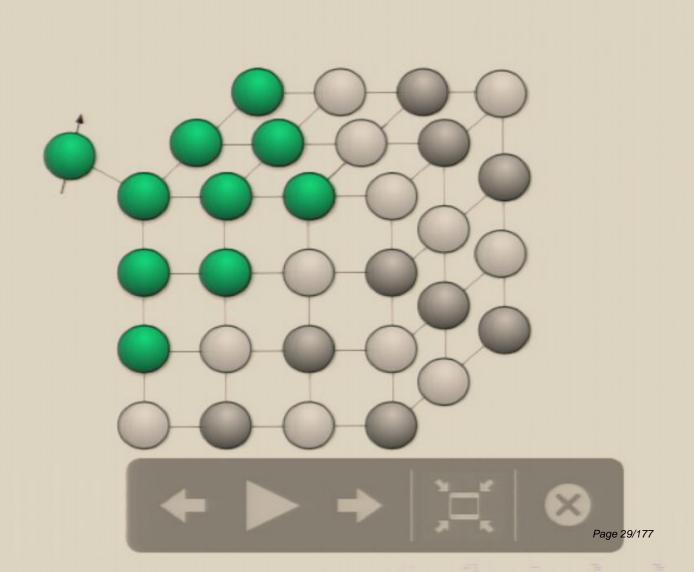
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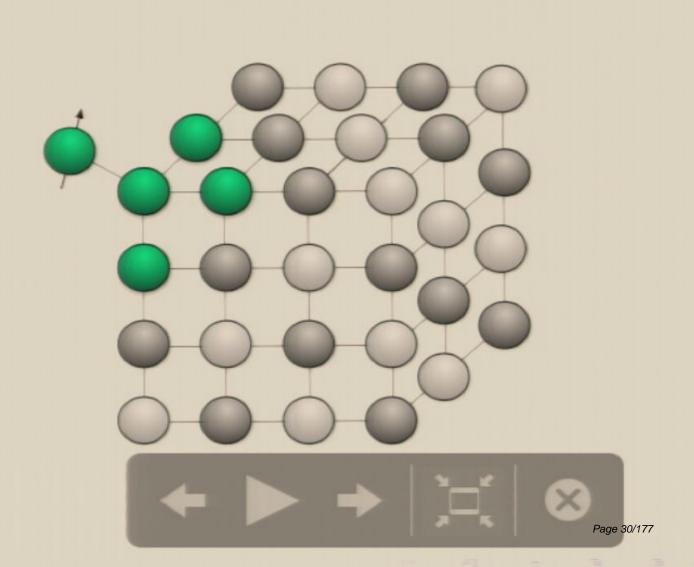
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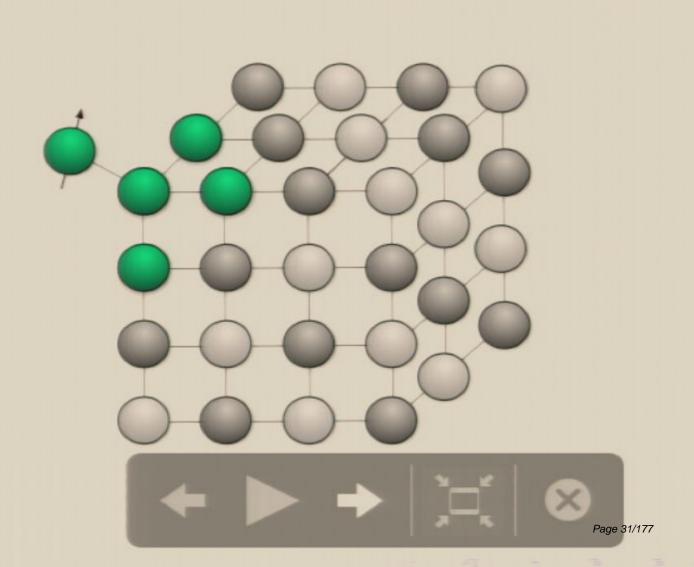
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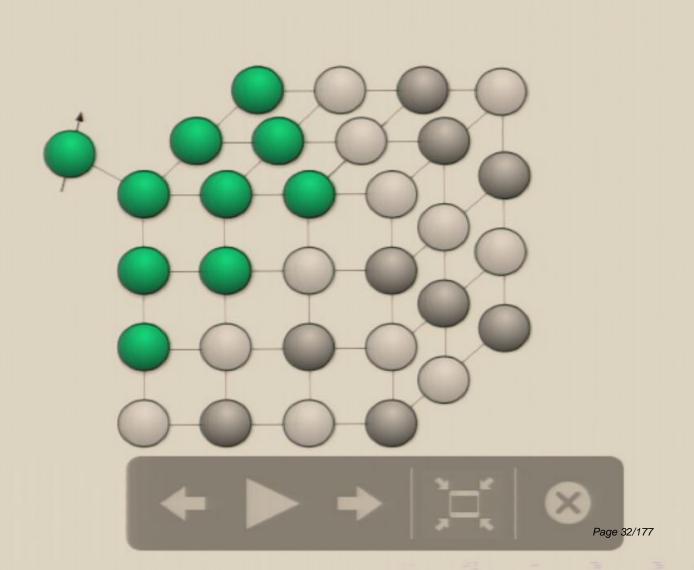
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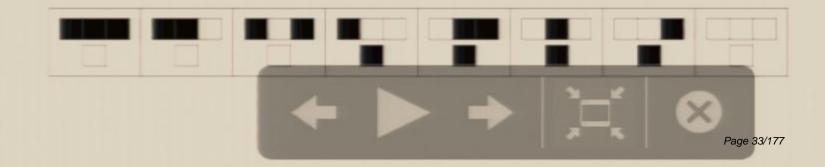
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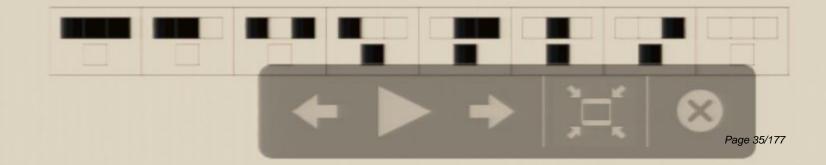
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- A Cellular Automata consists of a lattice structure, where each cell is in one of a finite number of given states
- At each discrete time-step, every cell is updated, in parallel, according to a local, spatially uniform rule.

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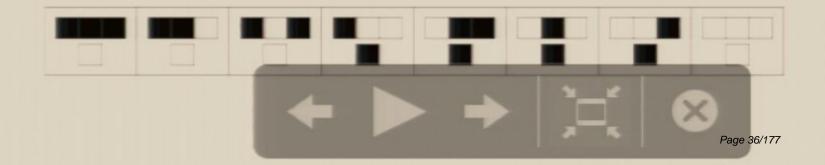
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### Interlude: Cellular Automata

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# "Rule 30" Evolution

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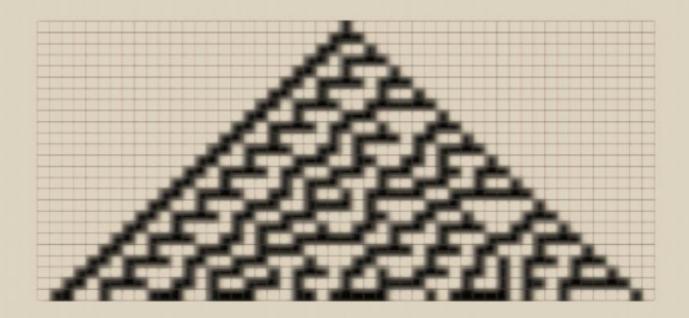
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# "Rule 30" Evolution

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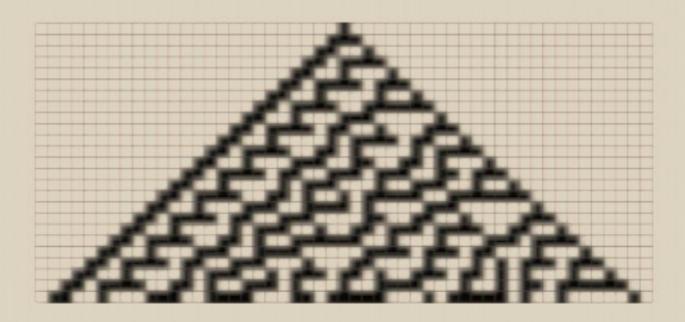
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Previous CA is not reversible.





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- Previous CA is not reversible.
- There are many ways of making a reversible classical CA, most famous is the Margolus CA.
- These can be extended to make quantum CA, or QCA
- We shall study another QCA type, the Coloured QCA, or CQCA.





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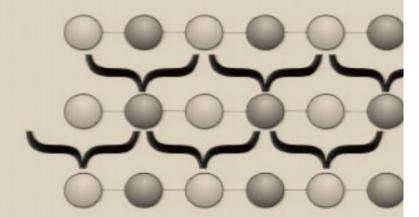
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In a CQCA each lattice is assigned a colour in a checkerboard fashion.







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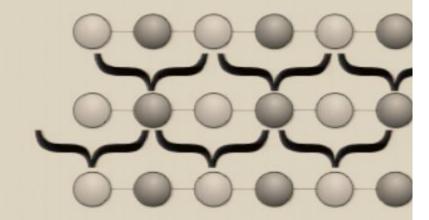
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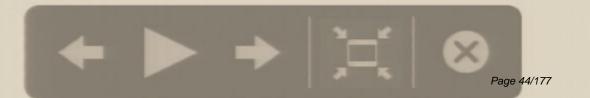
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- In a CQCA each lattice is assigned a colour in a checkerboard fashion.
- At each time step only points of a certain colour are updated with a unitary dependant on their neighbours' values.







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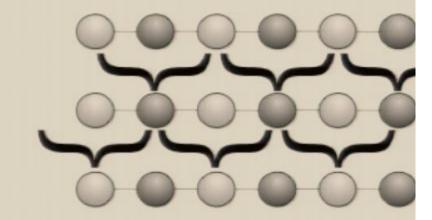
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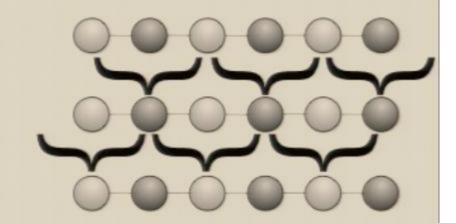
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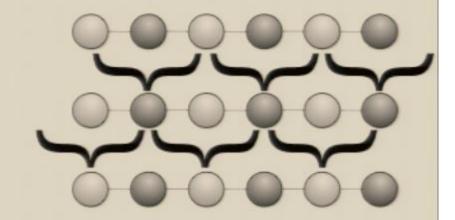
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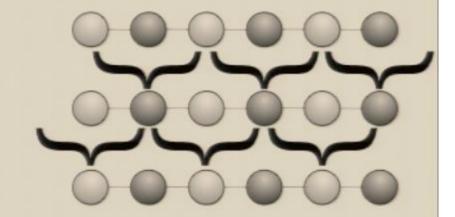
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- In a CQCA each lattice is assigned a colour in a checkerboard fashion.
- At each time step only points of a certain colour are updated with a unitary dependant on their neighbours' values.
- Neighbours which are of the same colour are not distinguishable.





## CQCA

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- These were first introduced by S. Lloyd (Science 261, 1993), it has since been further developed by S. Benjamin, and others.





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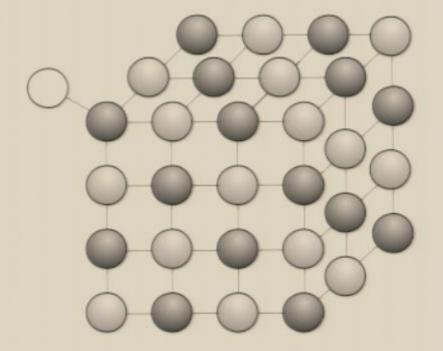
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Suppose we have a three dimensional 2 colour finite QCA.







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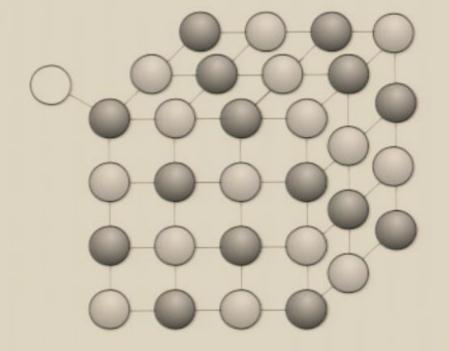
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- Each cell is a spin 1/2 particle, initially pointing down, except for the top-front-left corner which is initialized to the value we wish to 'amplify'.



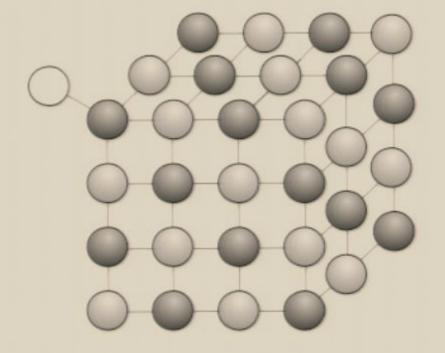




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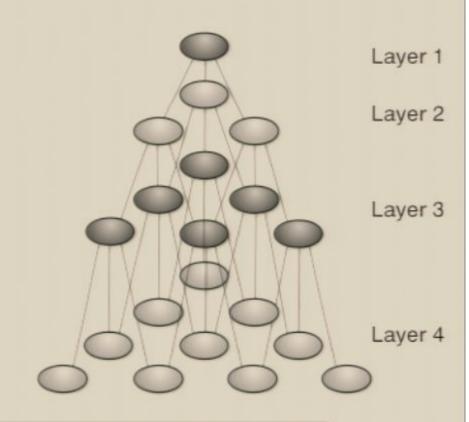
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Top-front half of the cube can be visualized as a pyramid. We will only concern ourselves with this half of the cube lattice.







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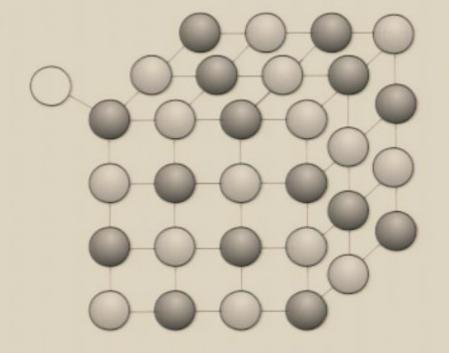
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- Each cell is a spin 1/2 particle, initially pointing down, except for the top-front-left corner which is initialized to the value we wish to 'amplify'.







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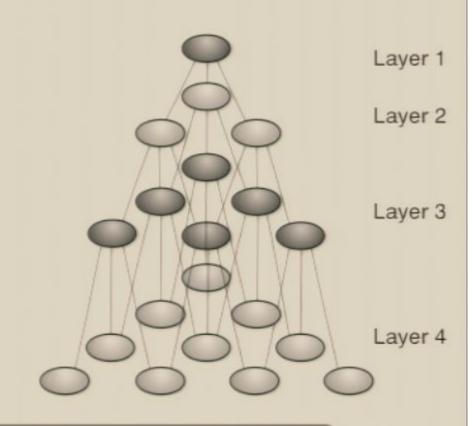
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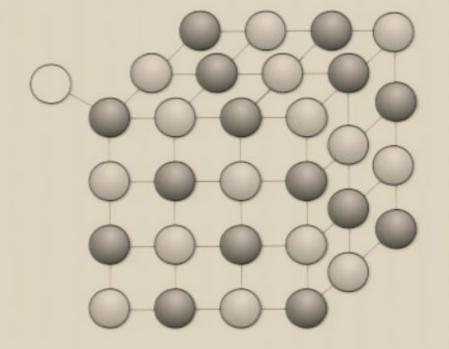
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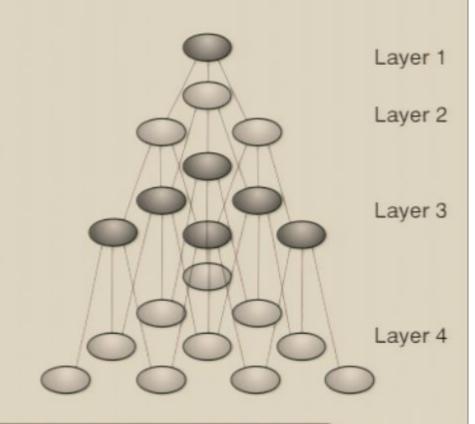
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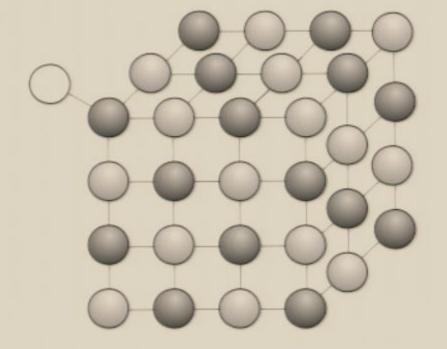
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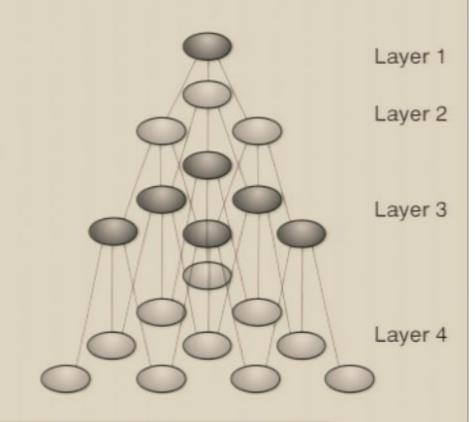
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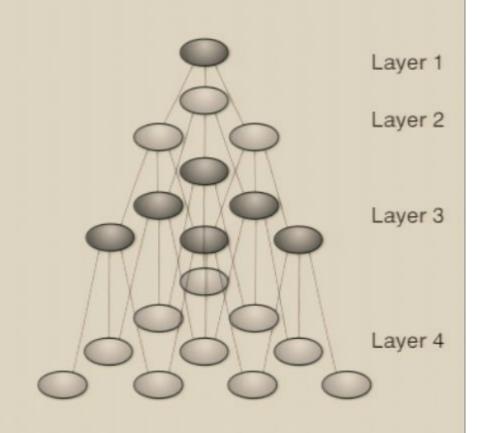
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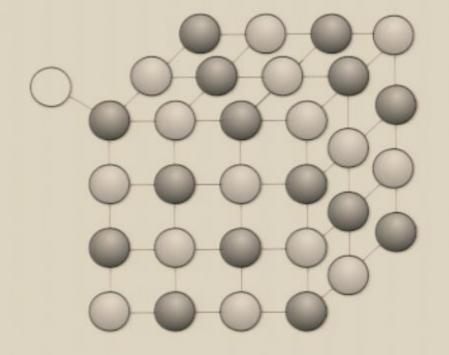
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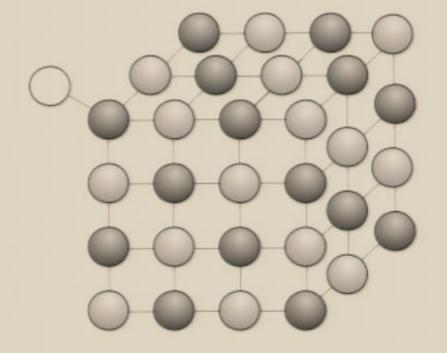
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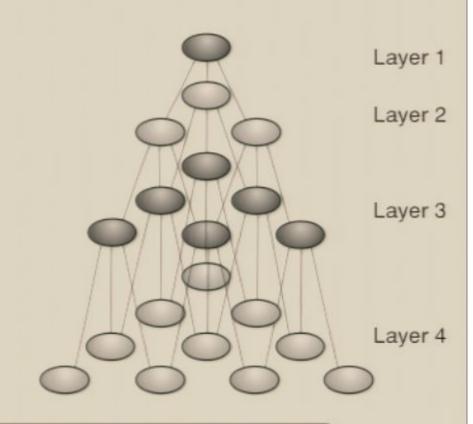
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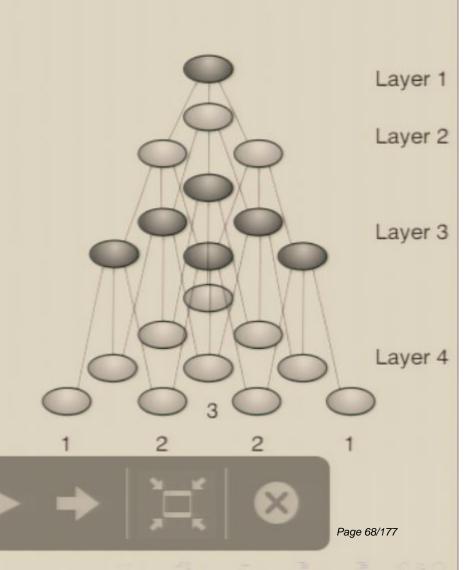
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Each spin has anywhere from four to six neighbours,





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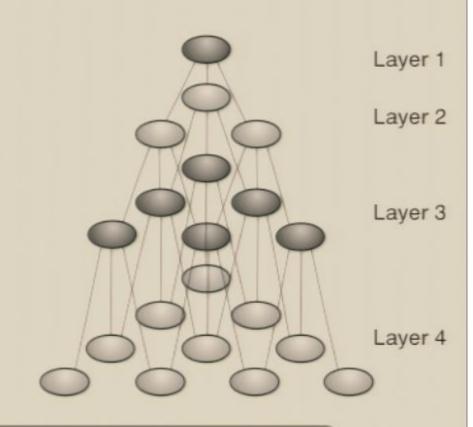
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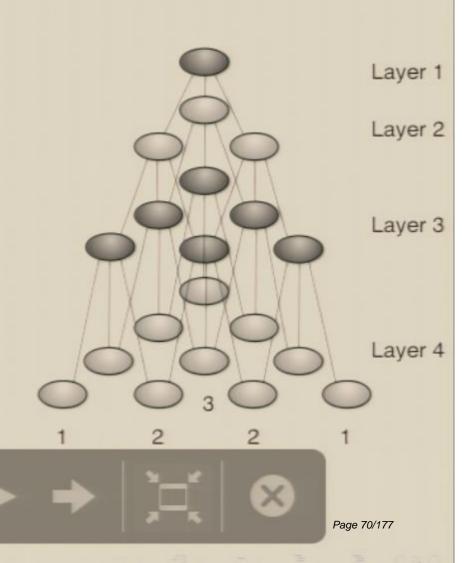
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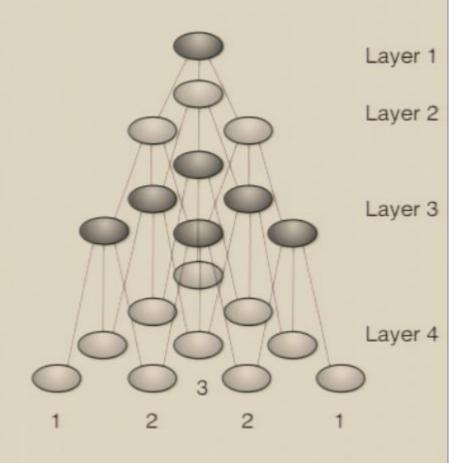
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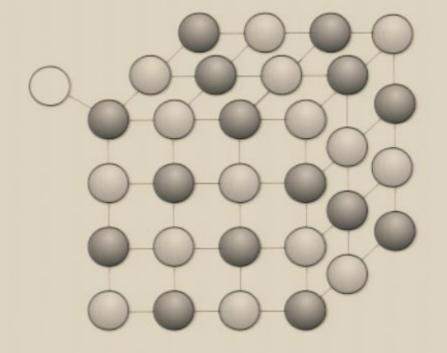
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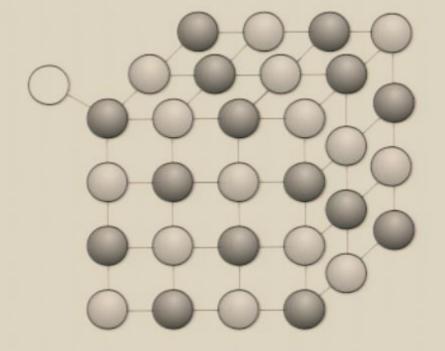
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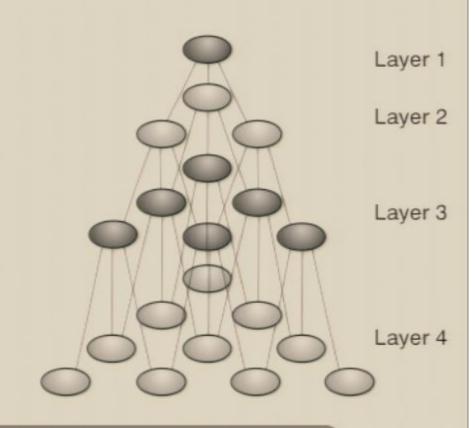
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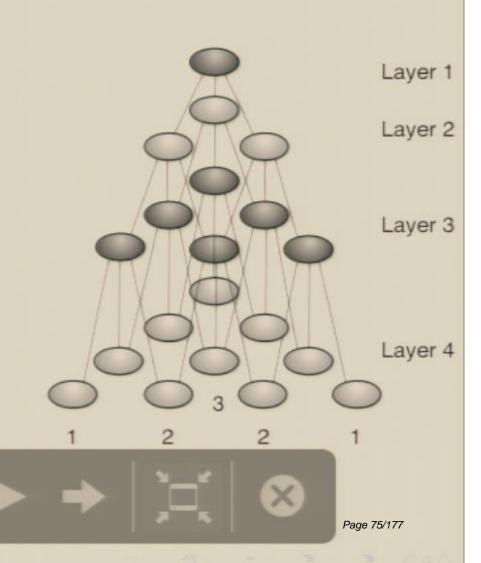
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Each spin has anywhere from four to six neighbours,

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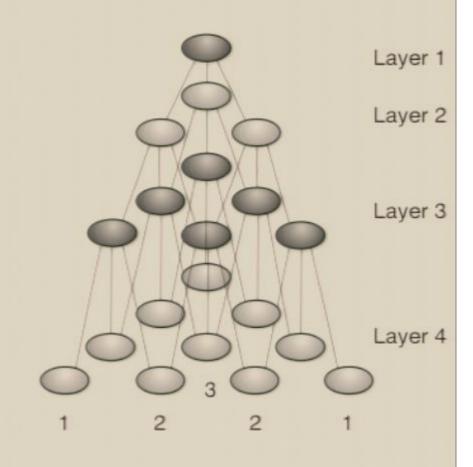
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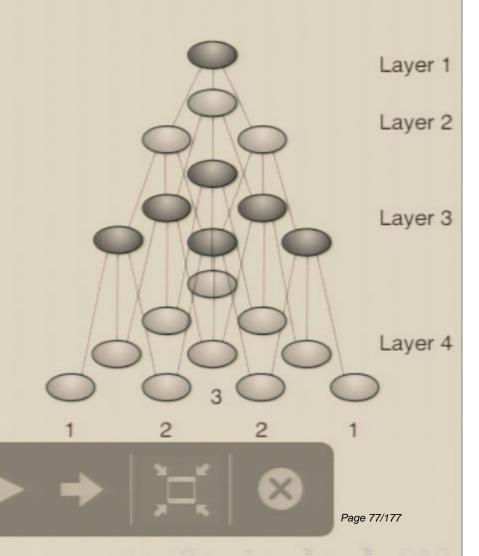
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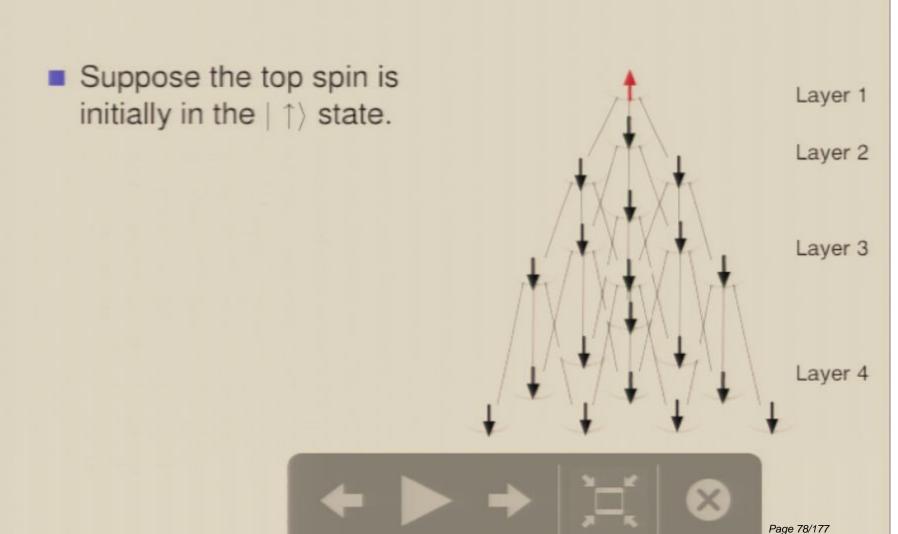
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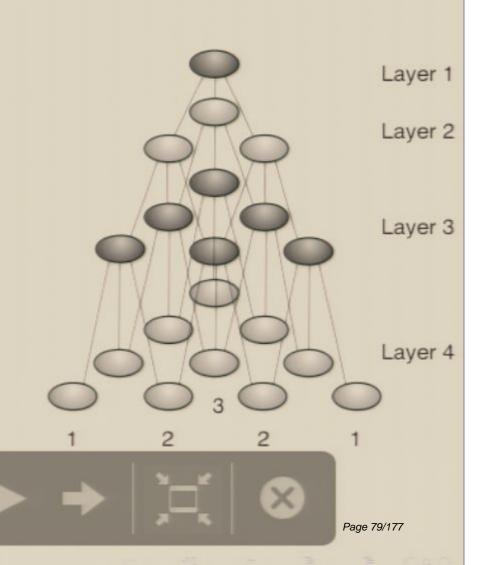
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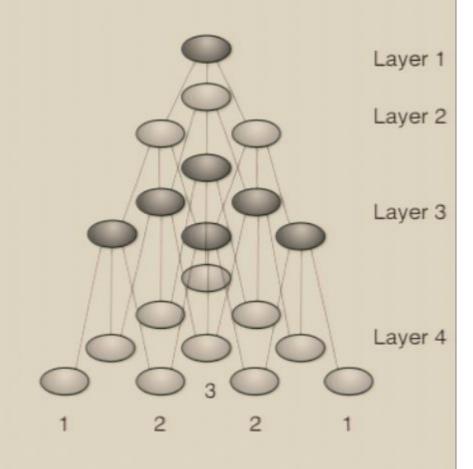
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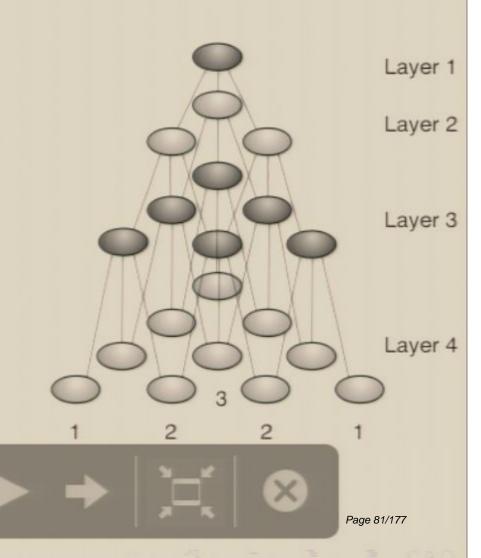
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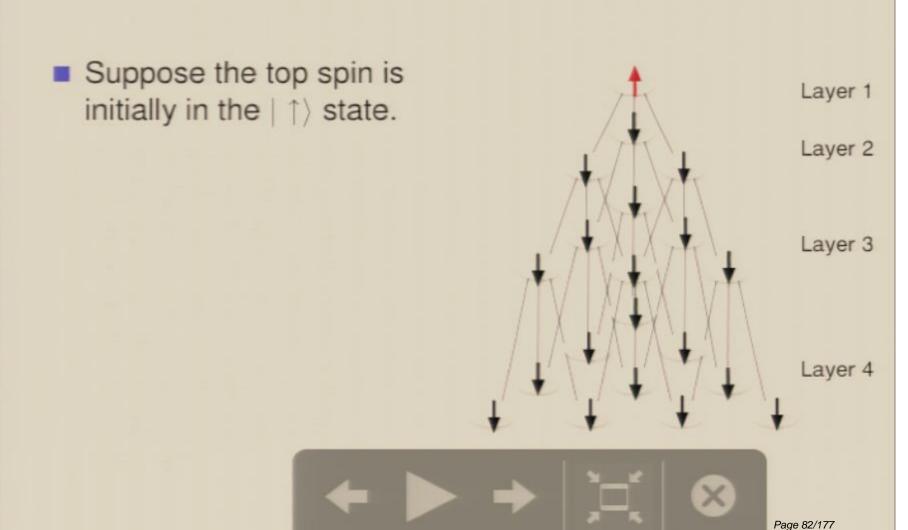
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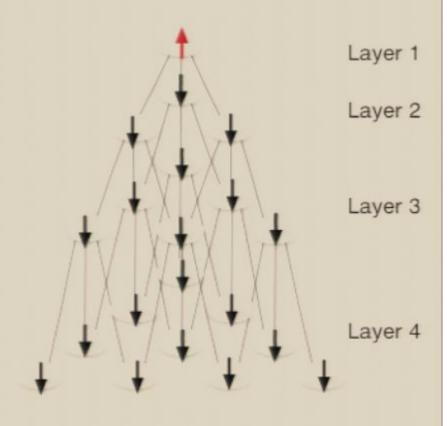
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Suppose the top spin is initially in the | ↑ > state.





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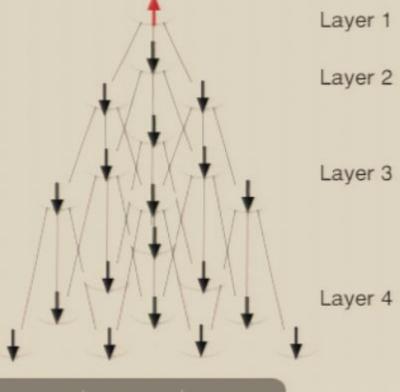
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Suppose the top spin is initially in the | ↑⟩ state.

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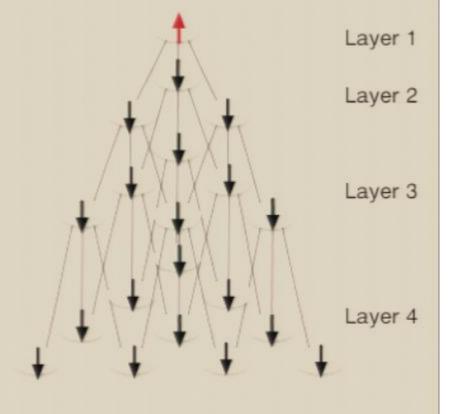
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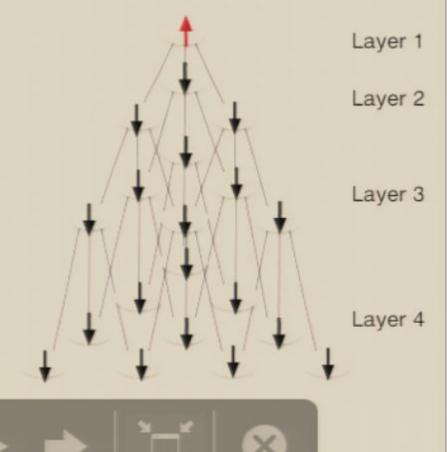
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- If we were to apply a NOT gate to B spins with neighbour field −2, all second layer spins would be flipped to the | ↑⟩ state,
- Nothing else in the pyramid would be affected.



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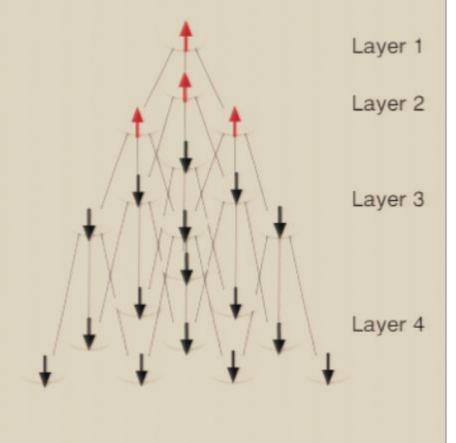
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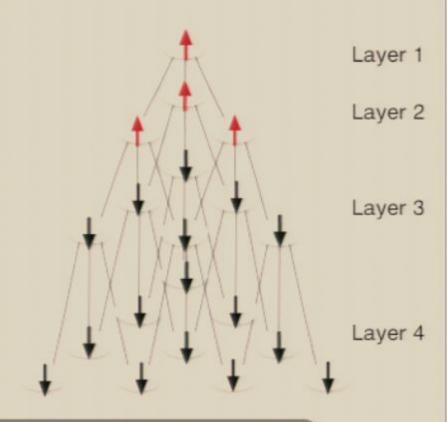
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In the next step, in order to flip all spins in the third layer we apply NOT gates to A spins with neighbour fields -2 and -1.







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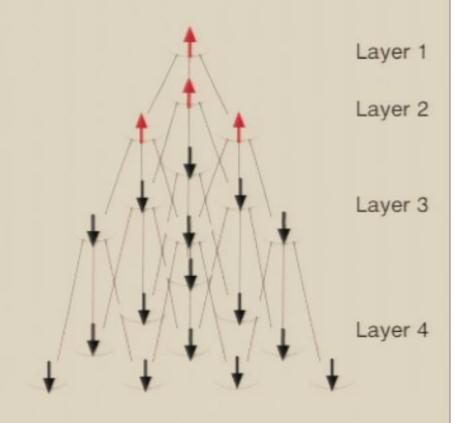
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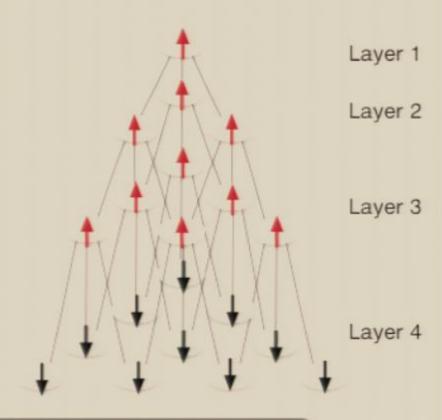
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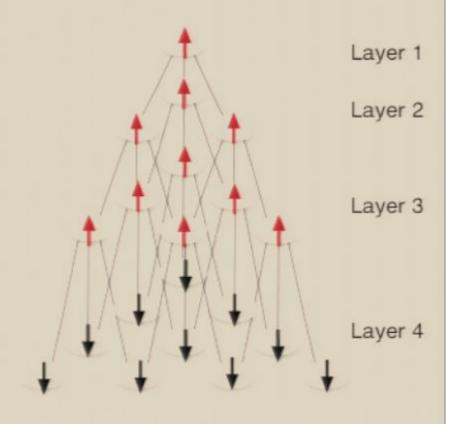
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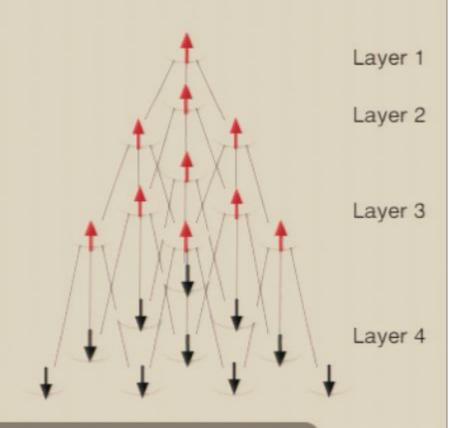
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In subsequent steps we need to apply NOT gates to spins with neighbour fields -2, -1, and 0.







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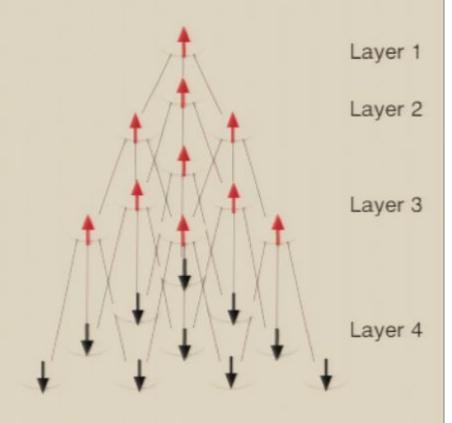
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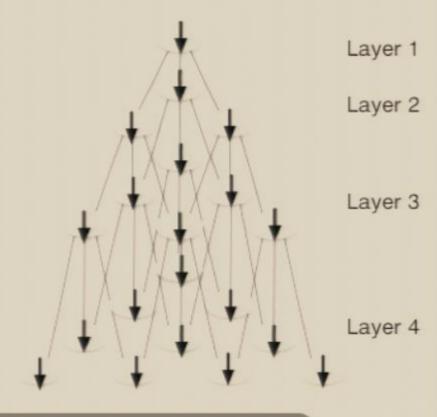
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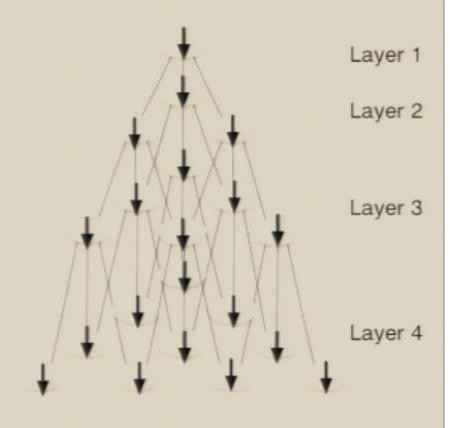
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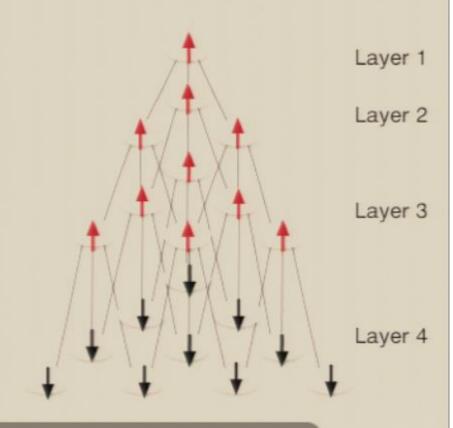
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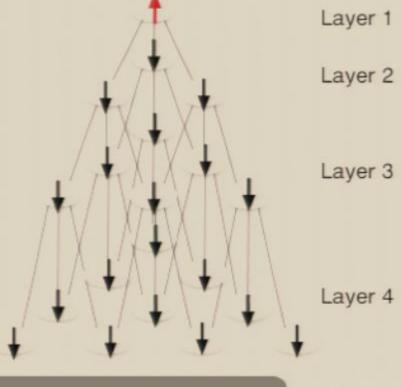
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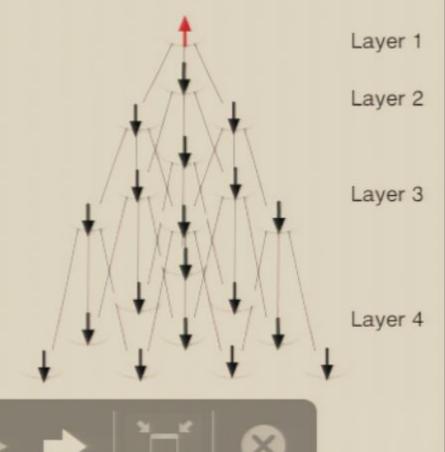
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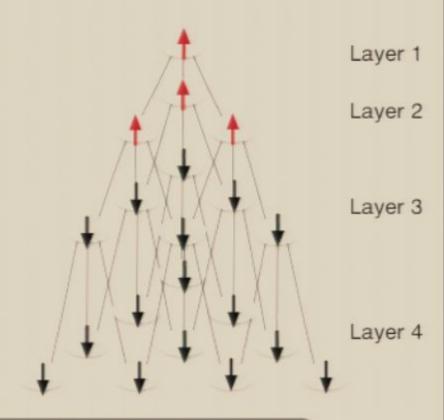
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In the next step, in order to flip all spins in the third layer we apply NOT gates to A spins with neighbour fields -2 and -1.







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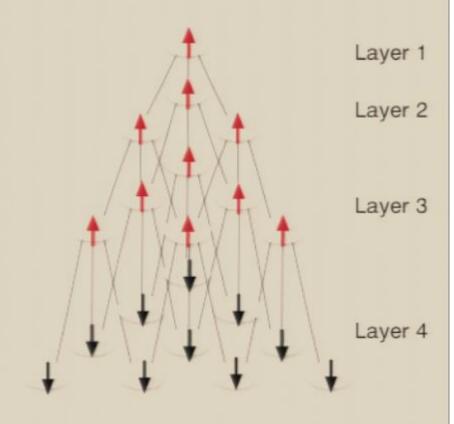
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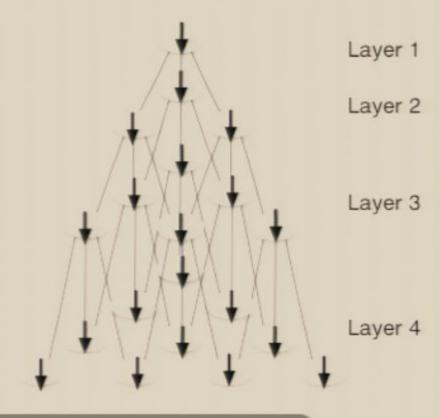
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Notice that if the top spin is initially in the state  $|\downarrow\rangle$ , then the procedure leaves the lattice invariant.







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The QCA rule can be summarized as

$$NOT(A, \{-2, -1, 0\})NOT(B, \{-2, -1, 0\})$$

The algorithm simply repeats these two steps until enough spins have been properly polarized. It take  $O(\sqrt[3]{N})$  steps to polarize N spins.





# QCA Rule / Algorithm

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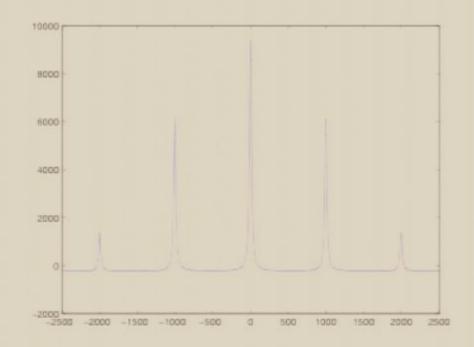
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Until now we have assumed a very simple nearest neighbour only coupling Hamiltonian.
Under this assumption the spectrum of a layer two spin would look like







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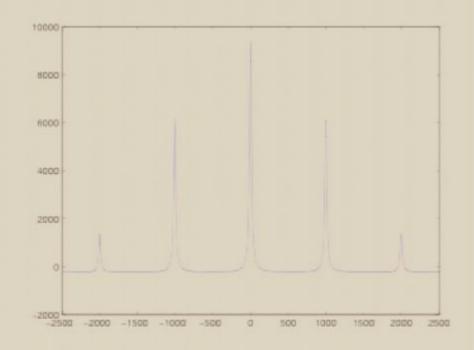
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More accurately, however, a solid crystal is governed by a direct dipole coupling Hamiltonian,

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 $\mathbf{k}_{i,j}$  equals 1 if i, j are the same species, 0 otherwise.

$$d_{i,j} = \frac{g_{i,j}}{r_{i,j}^3} \frac{1}{2} \left( 3\cos^2\Theta_{i,j} - 1 \right),$$

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The couplings depend on the angle to the Z axis of the magnetic field.





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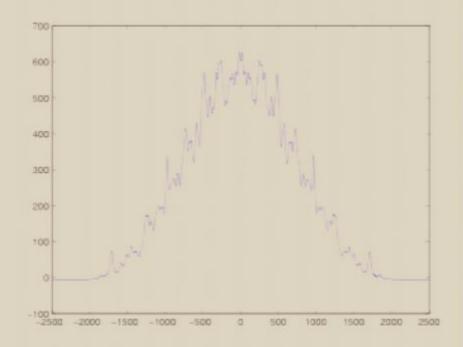
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In a rombohedral lattice, with angles between edges of 60 degrees, the spectrum of the same second layer spin under this Hamlitonian looks like







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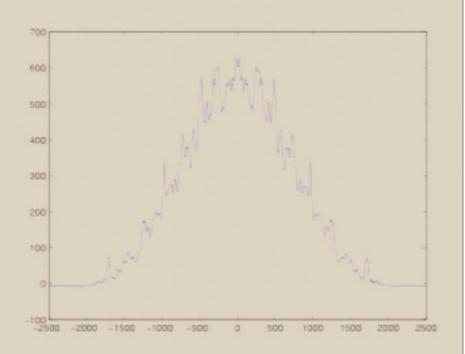
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It is obvious that the right spins cannot be addressed without affecting unwanted spins.





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- It is obvious that the right spins cannot be addressed without affecting unwanted spins.
- This situation can be corrected by suppressing the homonuclear coupling





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- This situation can be corrected by suppressing the homonuclear coupling
- Methods for doing so under several conditions in NMR have been studied (e.g. D. Cory et. al. J. Magnetic, 90, 205 - 213),





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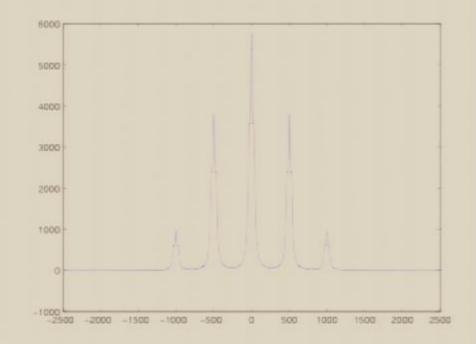
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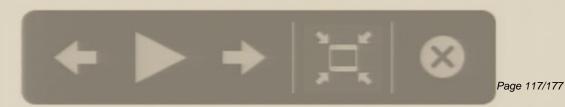
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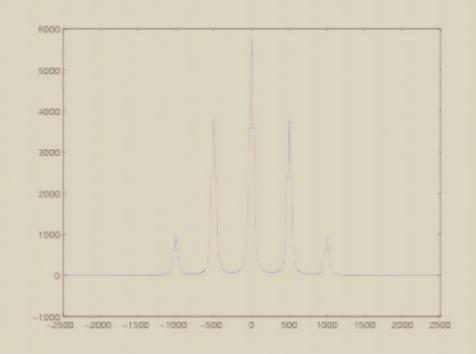
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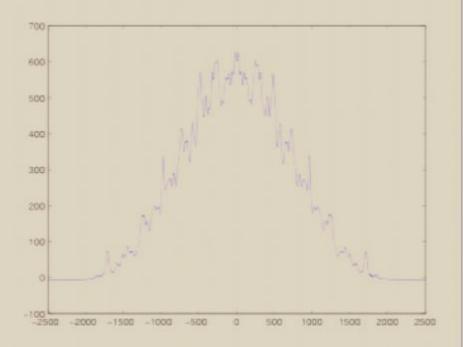
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- The couplings depend on the angle to the Z axis of the magnetic field.
- Hence, it makes sense to orient the crystal in such a way that ensures maximum symmetry.
- This, however, means that we cannot use a perfect cubic crystal.
- However, we shall see that any simple rombohedral lattice crystal will do fine.





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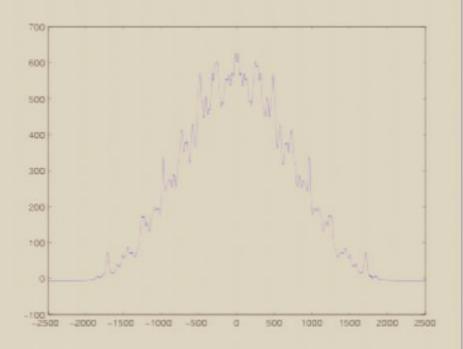
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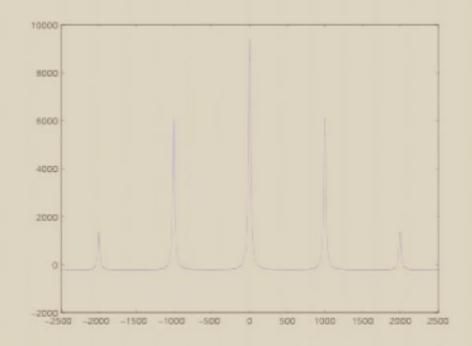
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Until now we have assumed a very simple nearest neighbour only coupling Hamiltonian.
Under this assumption the spectrum of a layer two spin would look like







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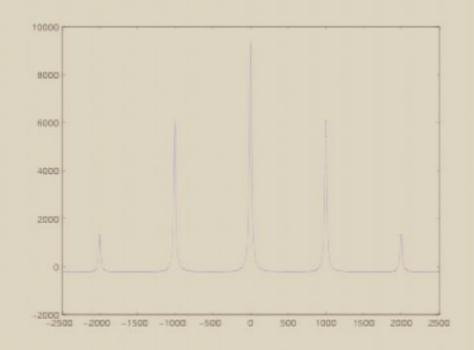
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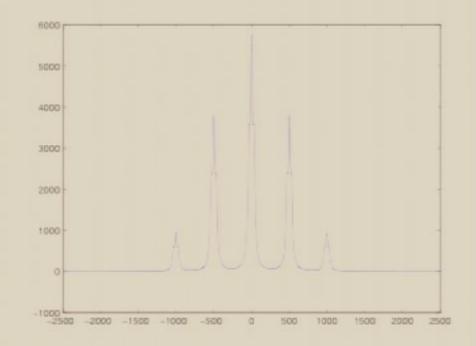
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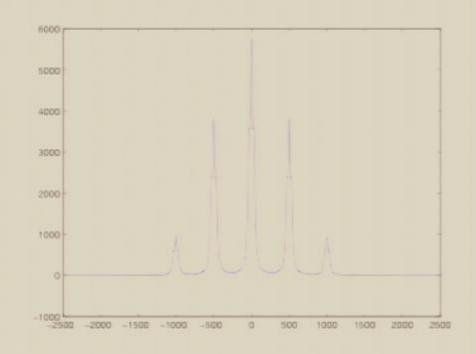
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## Schrödinger and his Cat

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- Ever since Schrödinger noted that quantum mechanics allows for superpositions of arbitrarily large, even macroscopic, systems, e.g. cats, there has been a myriad of experiments, and experiment proposals for generating ever larger 'Cat States'.
- One purpose of such experiments is to better understand decoherence, and the transition from quantum to classical.





# Schrödinger and his Cat

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#### Past Cats

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- Bucky Ball (C<sub>60</sub>) interferometer. (Arndt, Nairz, Vos-Andreae, Keller, van der Zouw, Zeilinger, 1999]
- Superposition of a mirror proposal [Marshal, Simon, Penrose, Bouwmeester, 2003]
- Many others, see for example [Legget. J. Phys, 2002]





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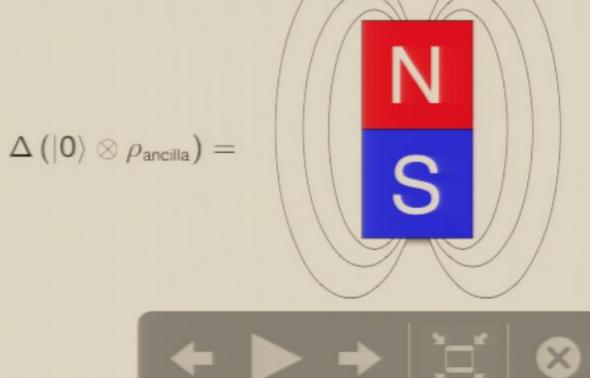
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Lets call our spin-amplification process  $\Delta$ . Then





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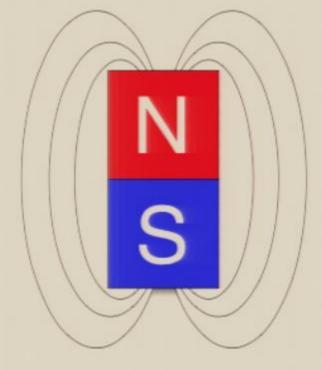
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$$\Delta \left( \ket{0} \otimes 
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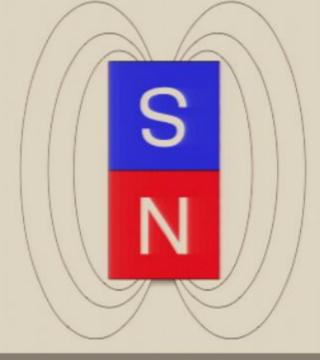
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And of course,

$$\Delta (X|0) \otimes \rho_{\text{ancilla}}) =$$







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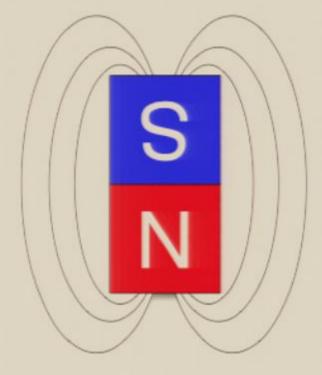
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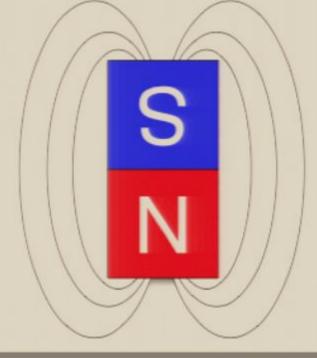
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Ergo,

$$\Delta\left(H\ket{0}\otimes
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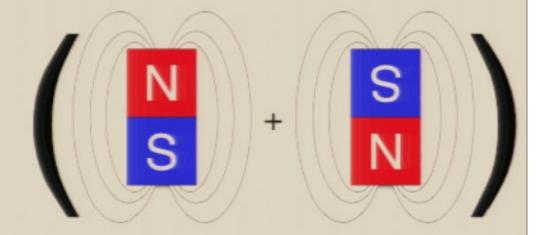
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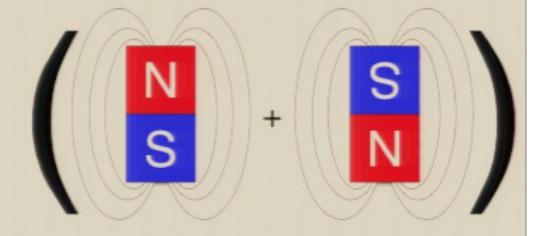
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$$H\left(\mathrm{tr}_{\mathsf{ancilla}}\left(\Delta^{\dagger}\left(\Delta\left(H|0
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Technically, in the absence of perfect polarization the state we create is not a superposition of two basis states, but rather the superposition of two mixtures of basis states  $\rho_0$  and  $\rho_1$ , *i.e.* the state can be written as  $\frac{1}{\sqrt{2}}(\rho_0 + \rho_1)$ 





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- It does create a problem in trying to quantify the size of the cat state.





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#### What's next...

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An experiment of this sort requires a high degree of quantum control in solid state NMR. It will not be implemented any time soon.





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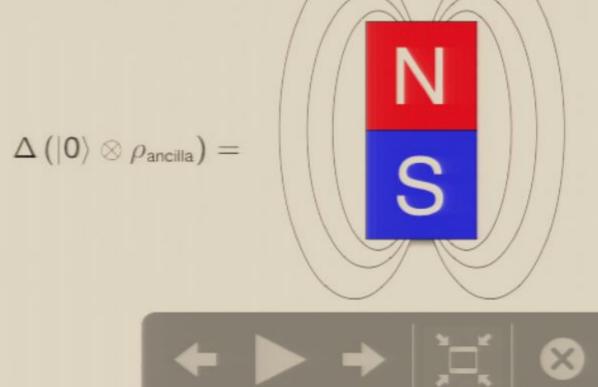
Thank you for waking up!





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Lets call our spin-amplification process  $\Delta$ . Then



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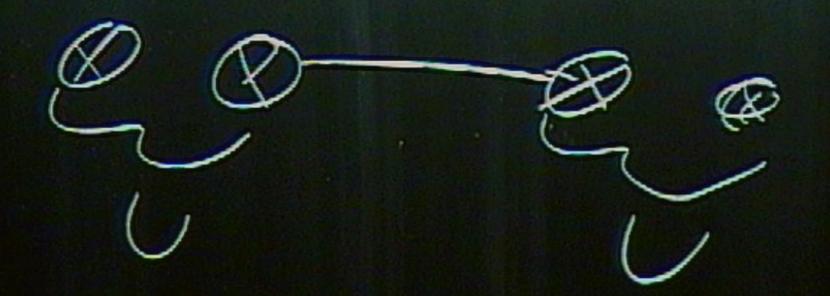
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- It is a priori unclear whether the state created is a cat state, i.e. a real superposition, or simply a classical mixture.
- In order to verify that we succeeded in creating a cat state it suffices to show that:

$$H\left(\mathrm{tr}_{\mathsf{ancilla}}\left(\Delta^{\dagger}\left(\Delta\left(H\left|0
ight)\otimes
ho_{\mathsf{ancilla}}
ight)
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ight)=\left|0
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