

Title: Spin Glasses and Computational Complexity

Date: Oct 20, 2010 02:00 PM

URL: <http://pirsa.org/10100053>

Abstract: A system of spins with complicated interactions between them can have many possible configurations. Many configurations will be local minima of the energy, and to get from one local minimum to another requires changing the state of very many spins. A system like this is called a spin glass, and at low temperatures tends to get caught for very long times at a local minimum of energy, rather than reaching its true ground state. Indeed, in many cases, finding the ground state energy of a spin glass is a computationally hard problem, too hard to be solved on a classical computer or even a quantum computer in any reasonable amount of time. Which types of interactions give us computationally hard problems and spin glasses? I will survey what is known as we close in on finding the simplest complex spin systems.

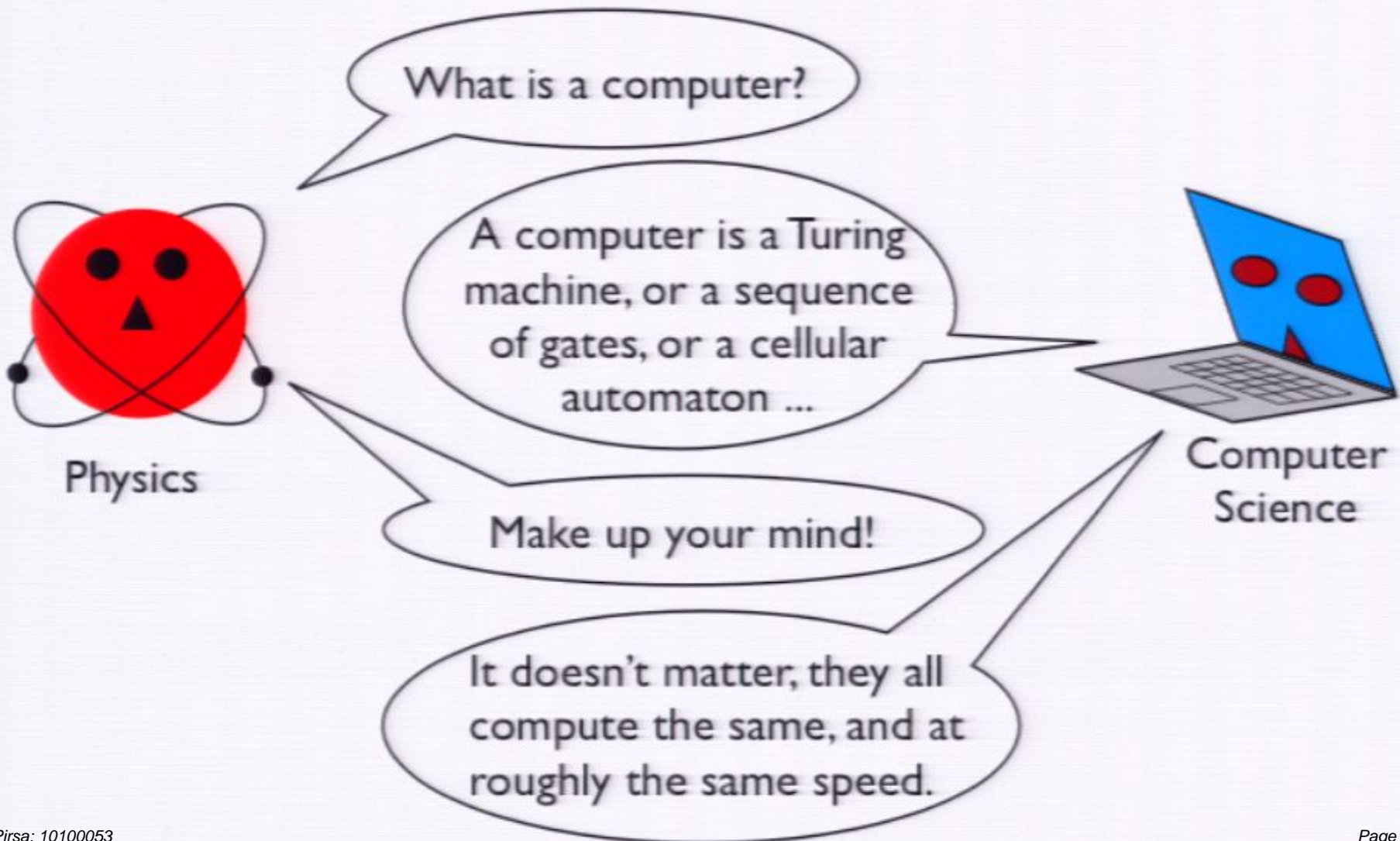


Spin Glasses and Computational Complexity

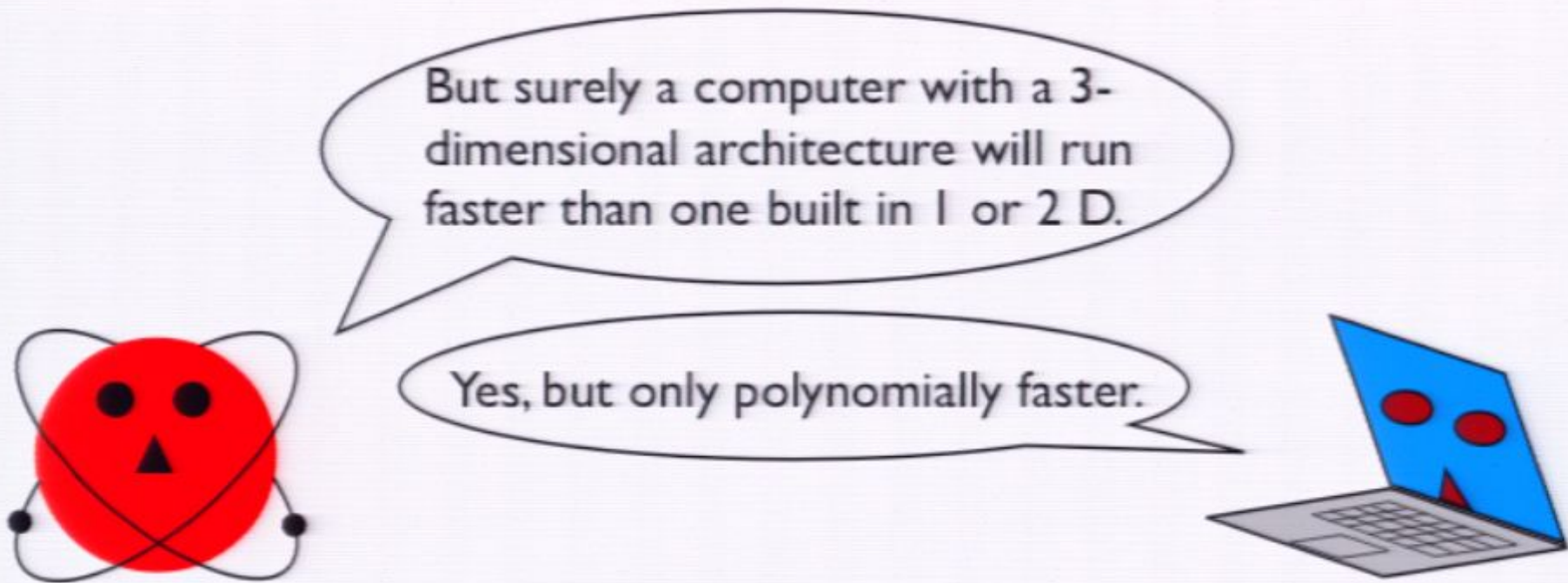
Daniel Gottesman
Perimeter Institute



The Church-Turing Thesis



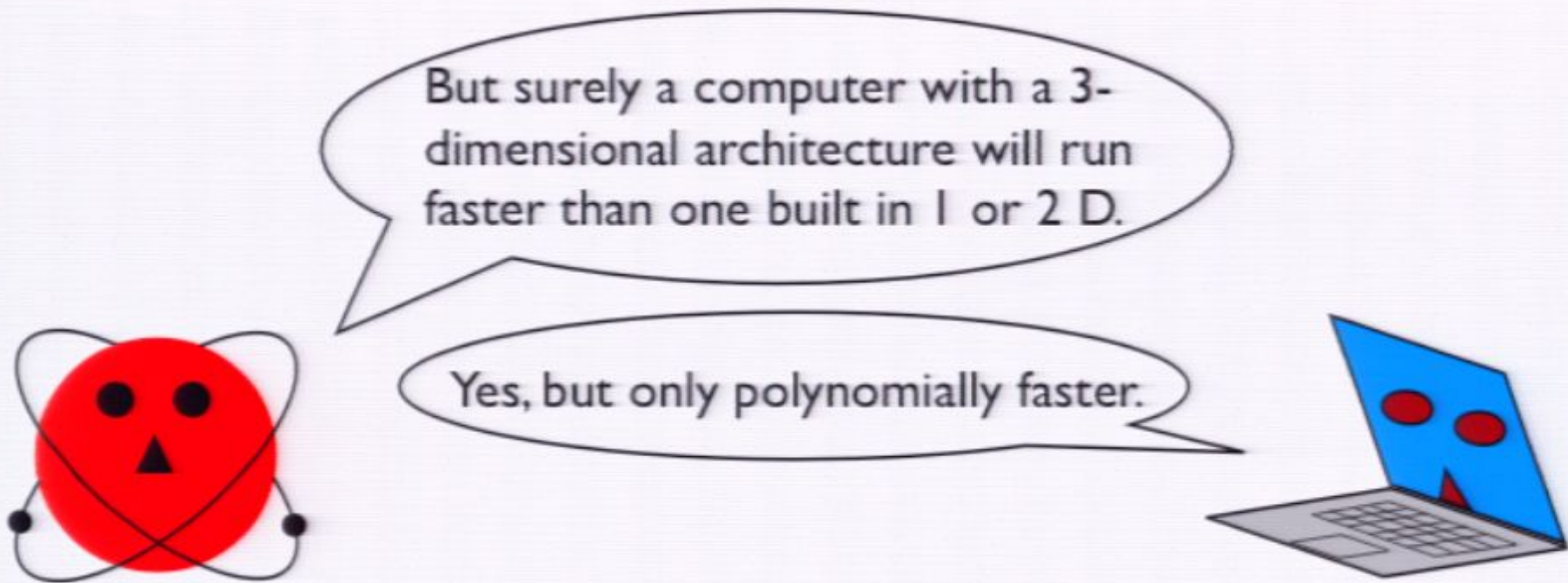
Polynomial Time



We can measure complexity by asking how long it takes to solve a problem as a function of the size of the input. A problem is “easy” if it can be solved in a time polynomial in the number of bits in the input -- it is in the **complexity class P**.

Strong Church-Turing Thesis: Any physically reasonable design of a computer will differ in complexity only by polynomial functions.

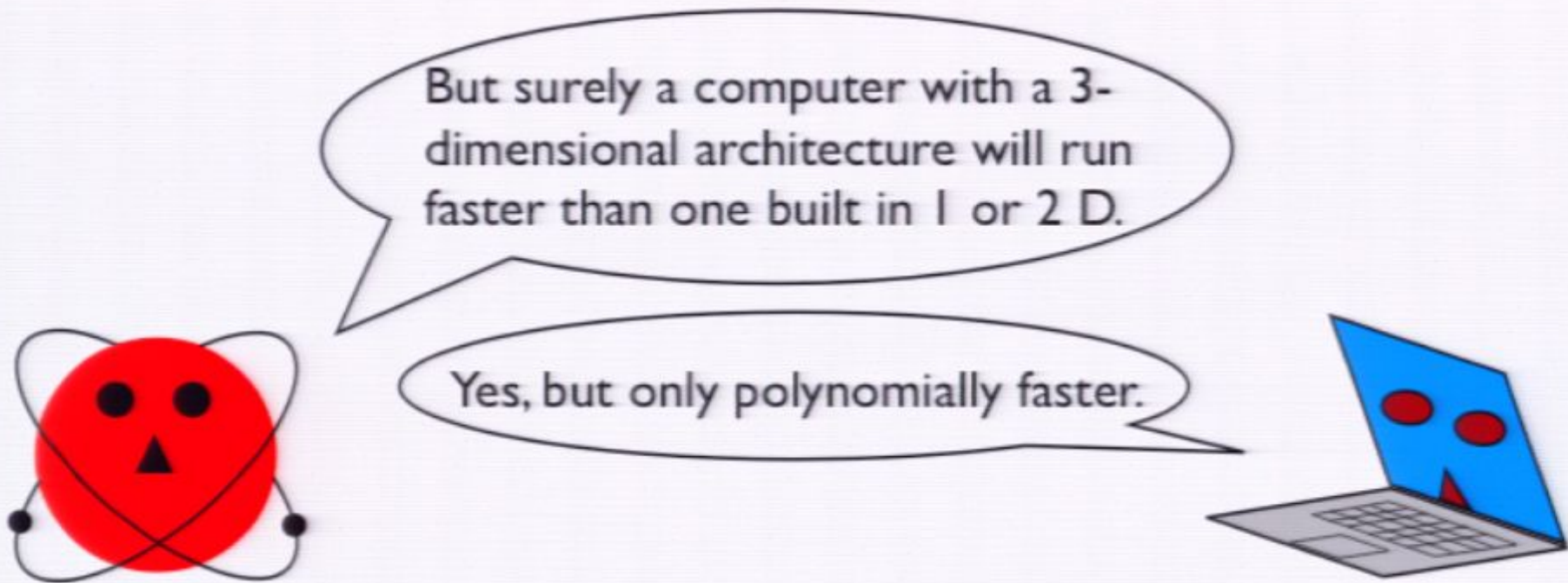
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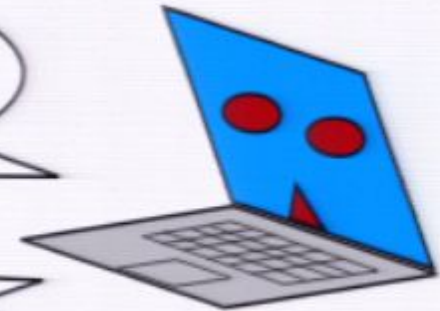


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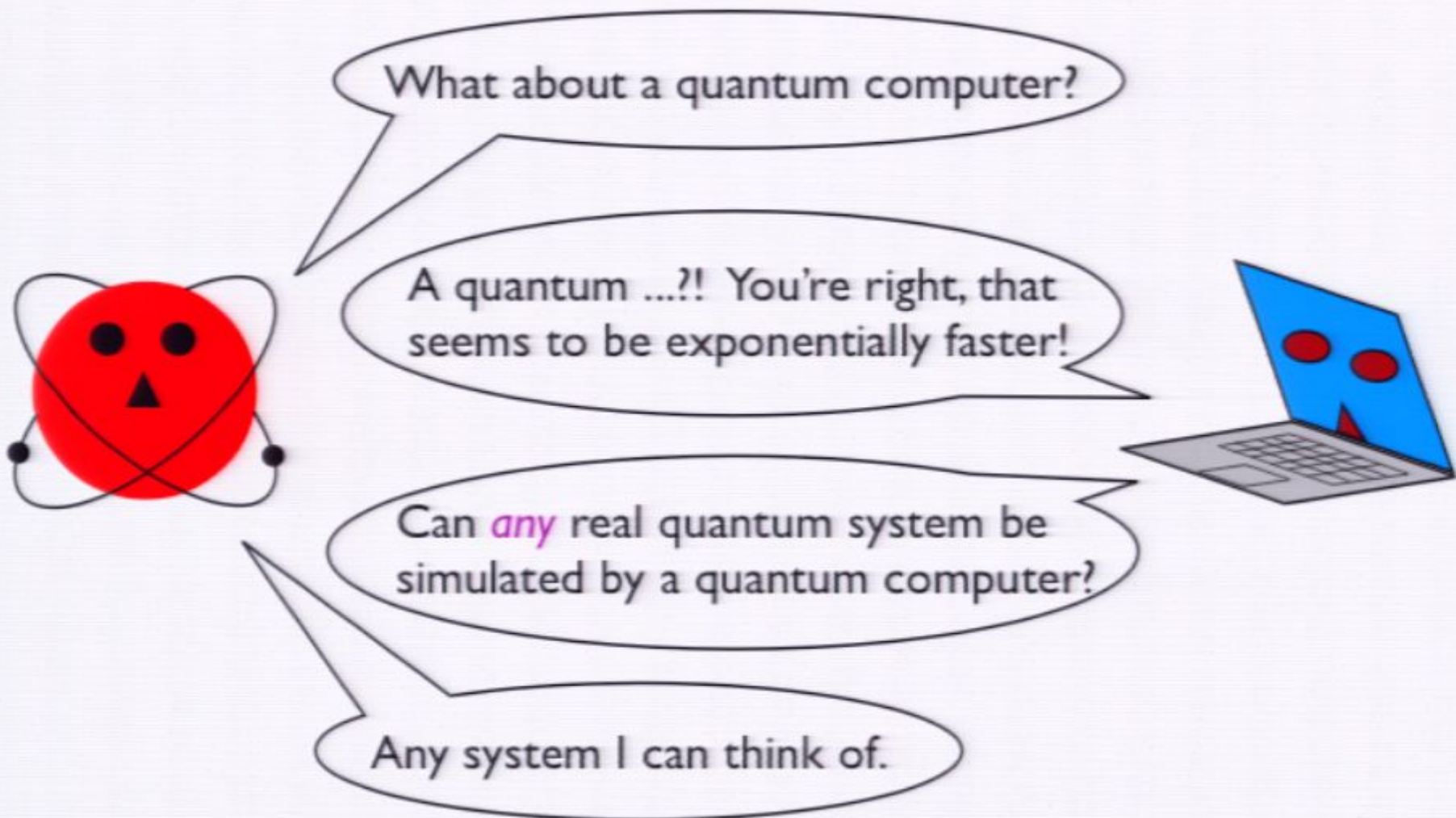
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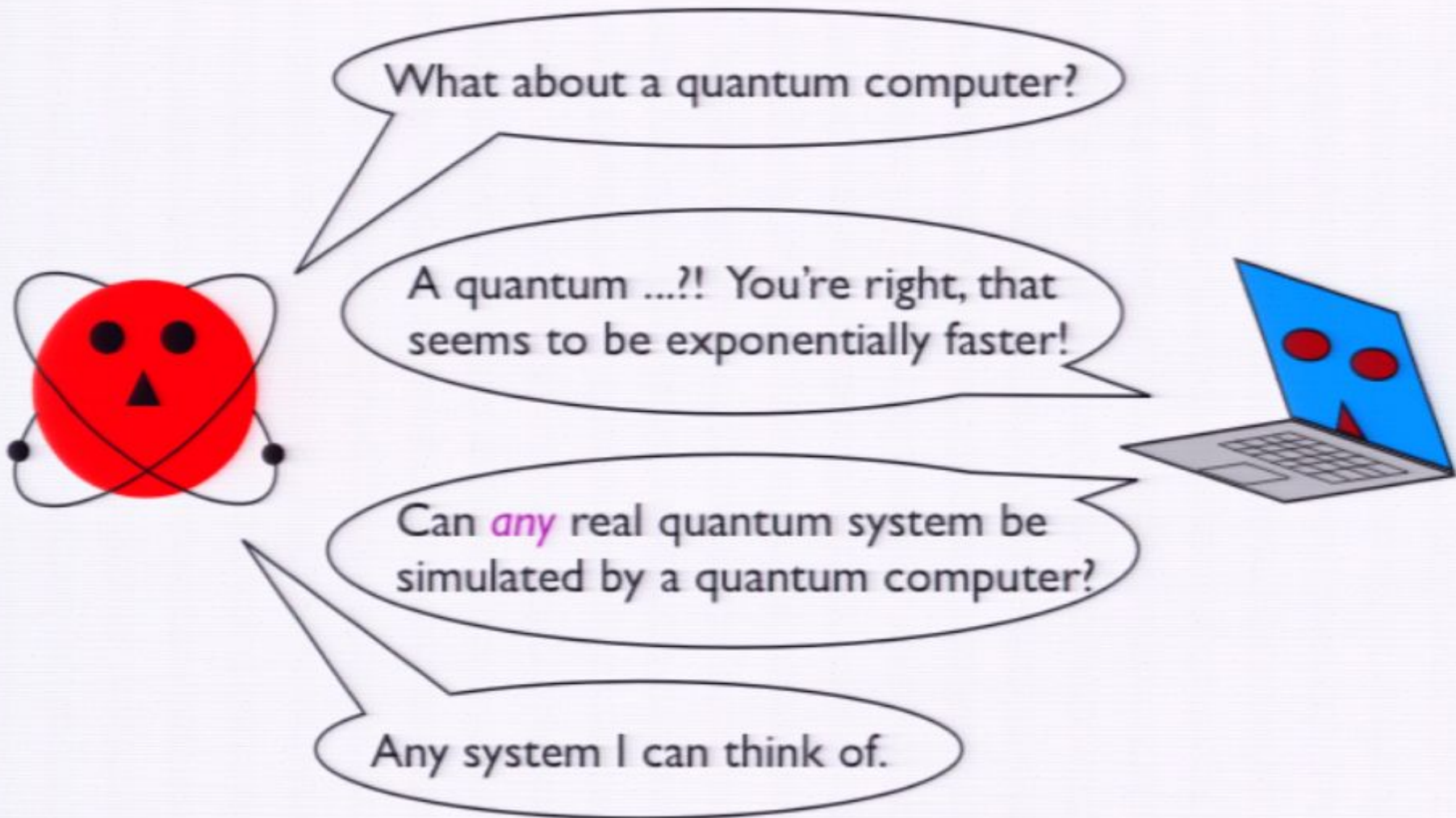
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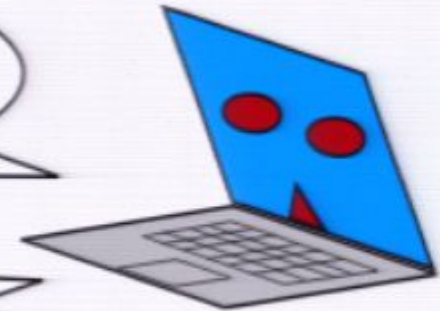


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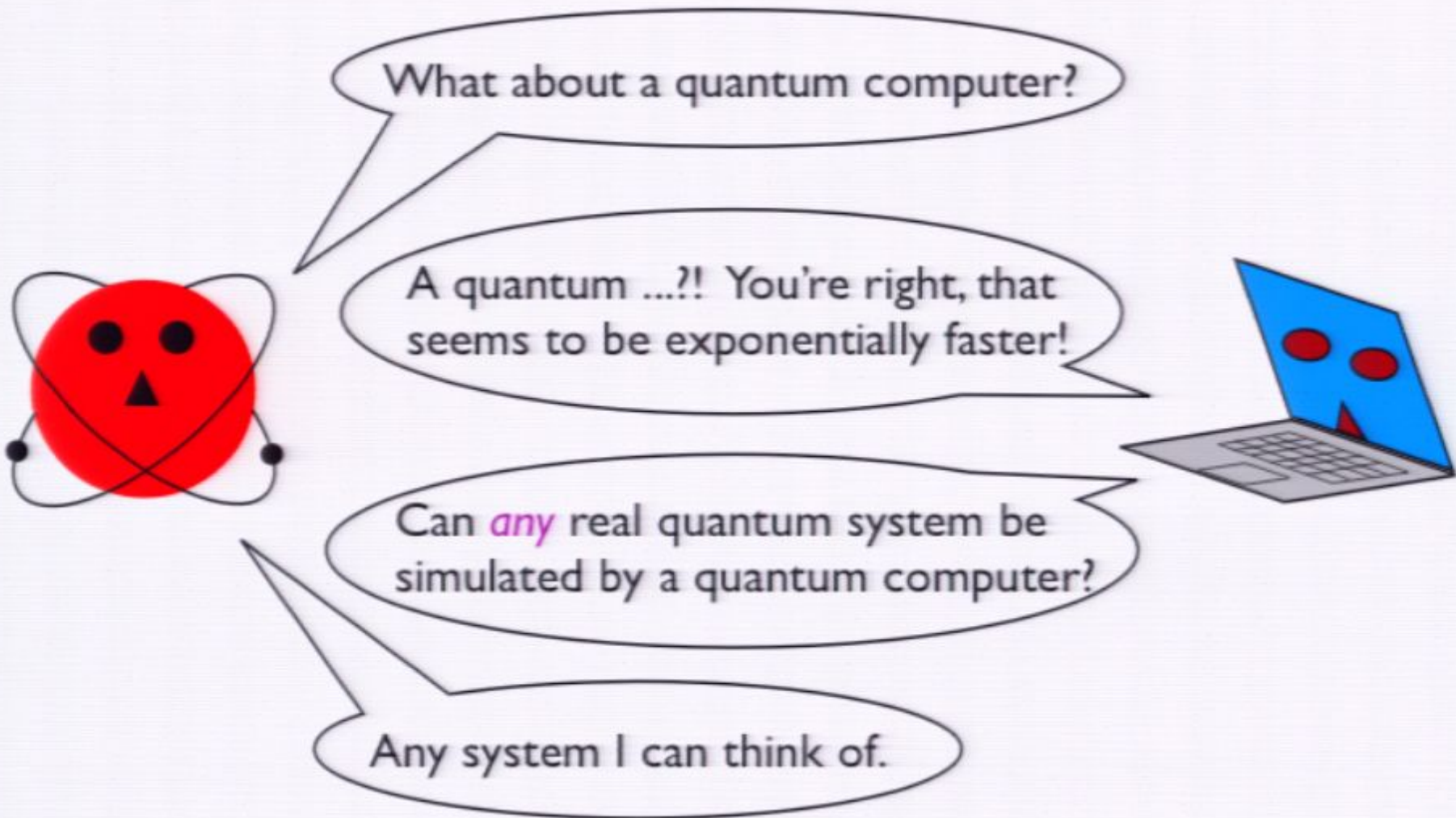
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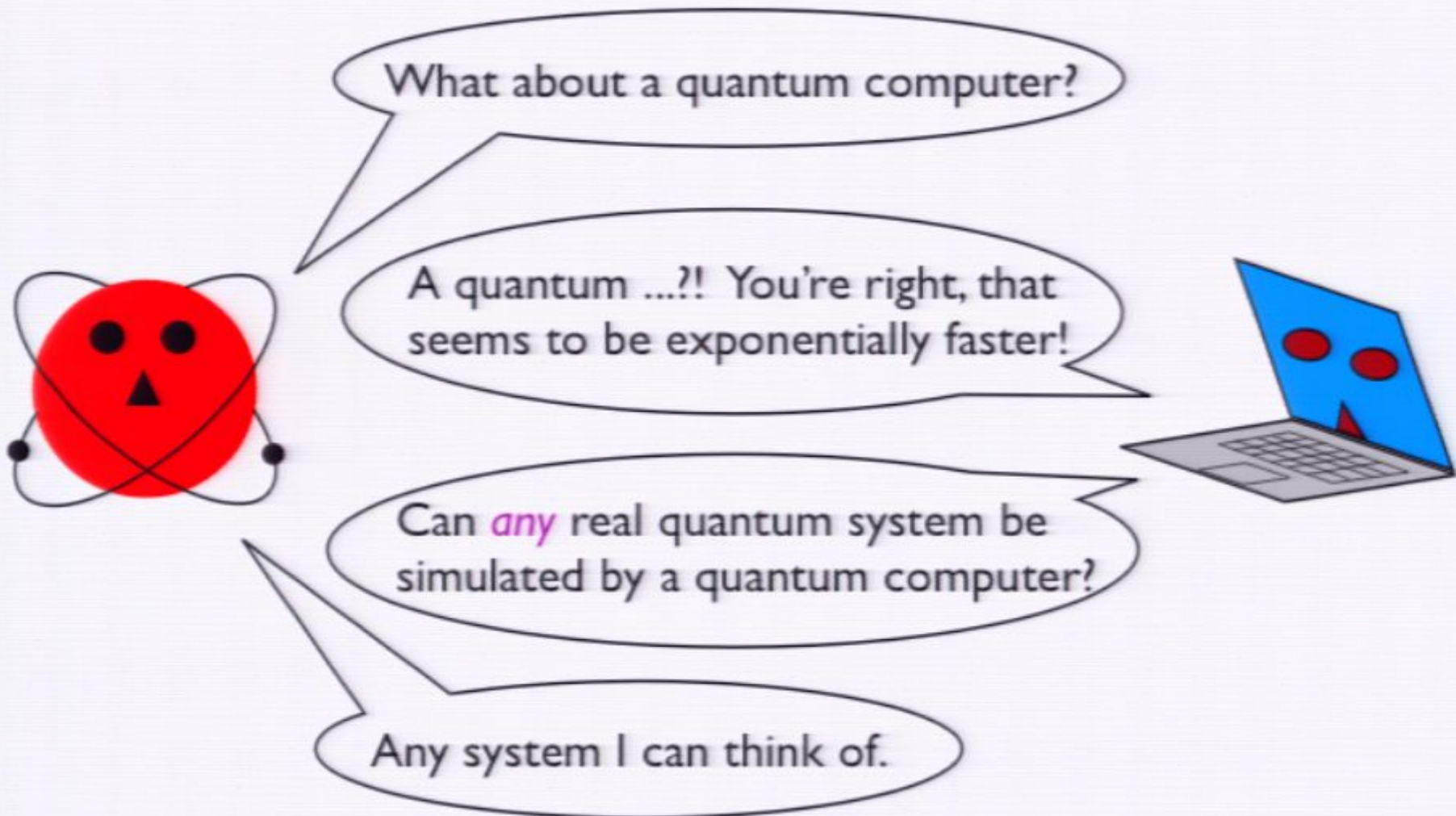
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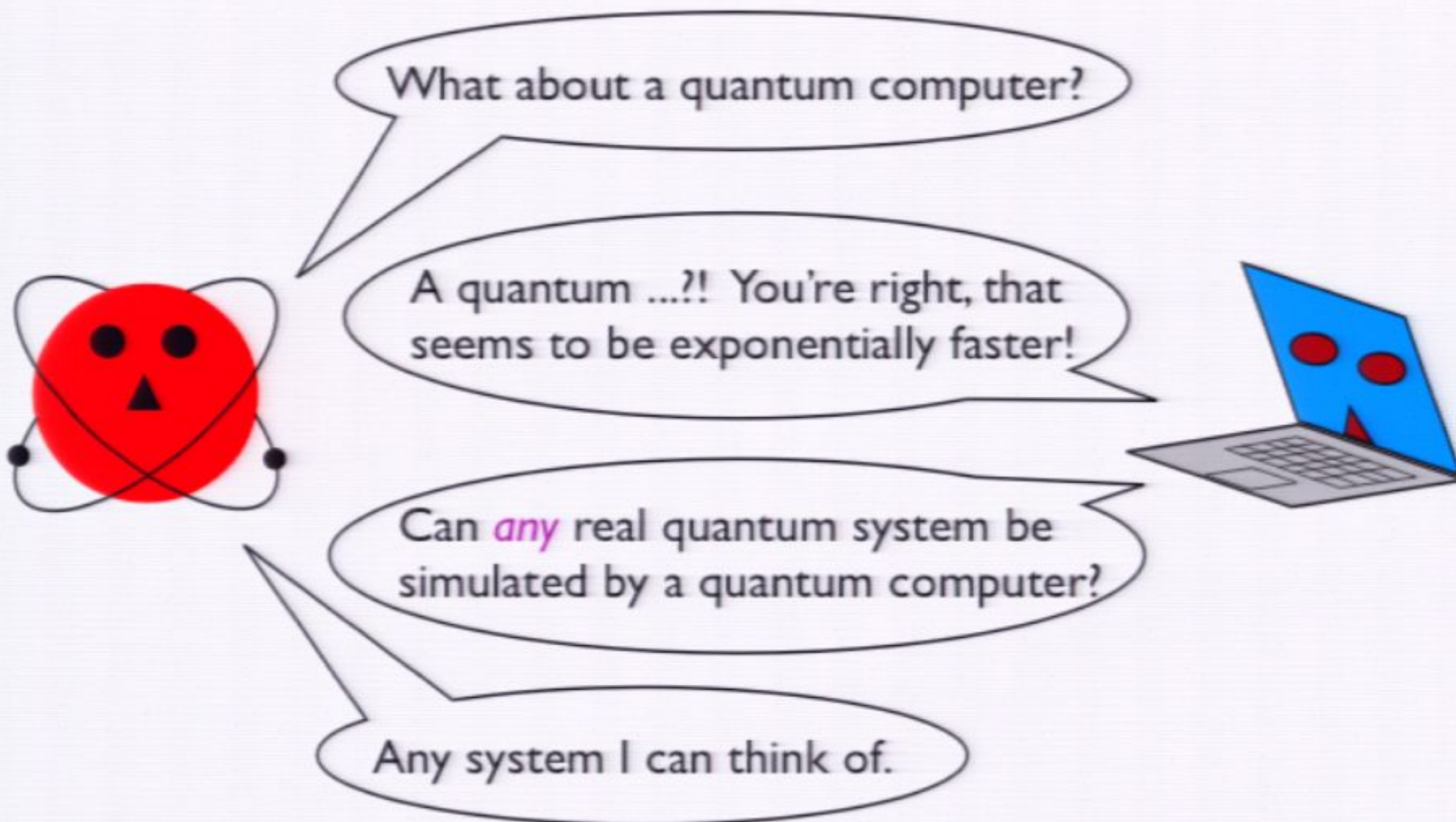
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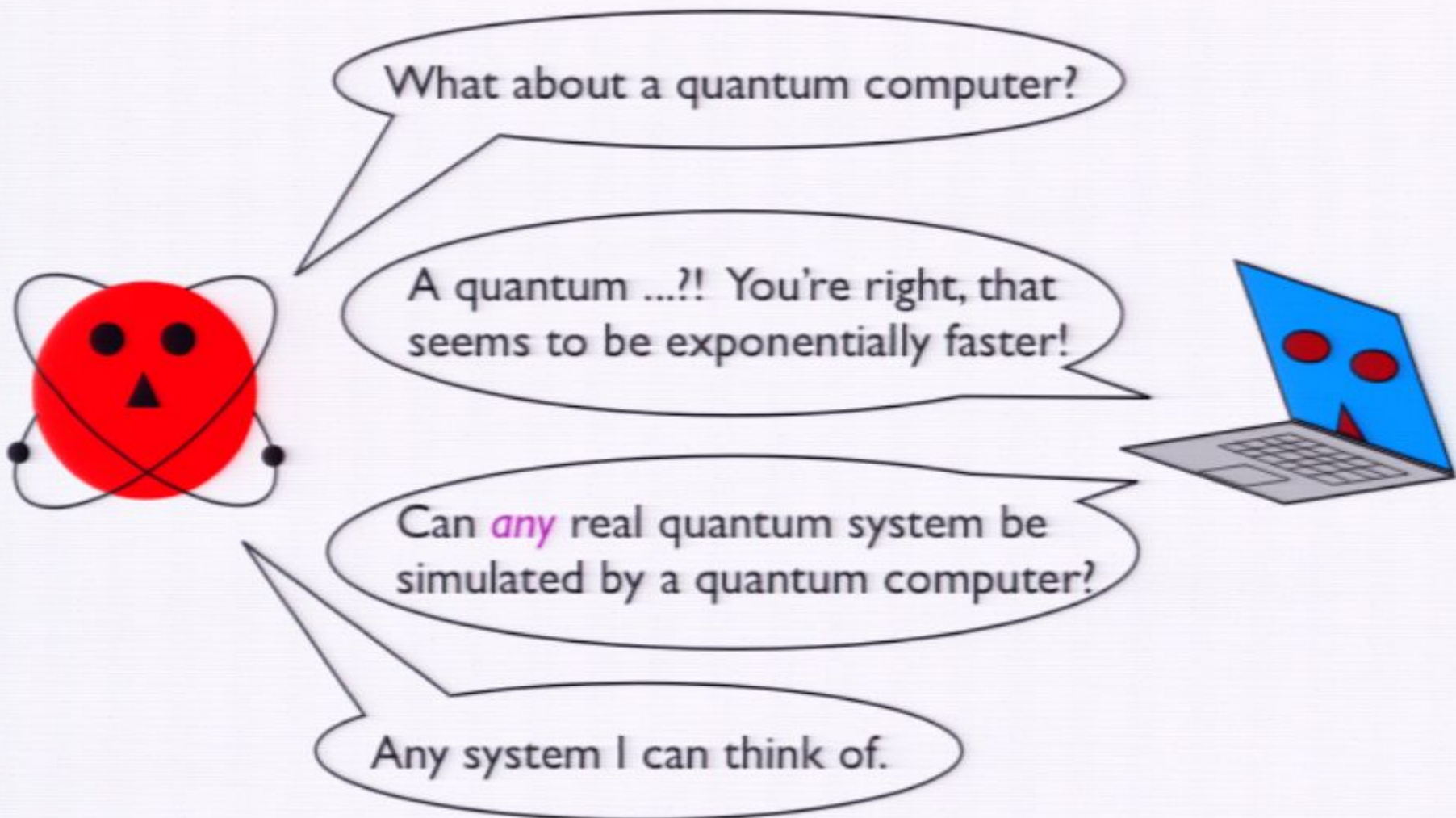
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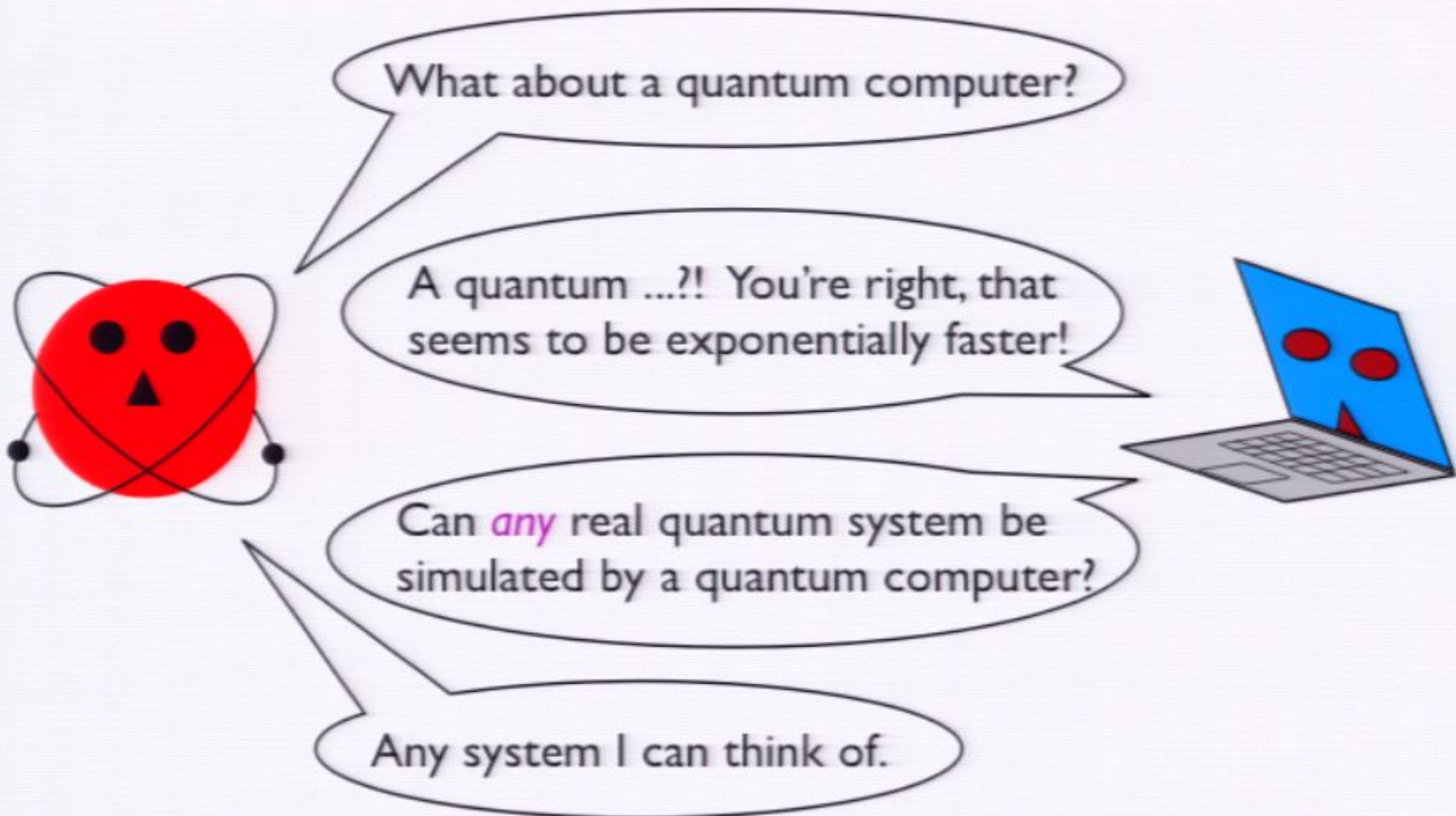
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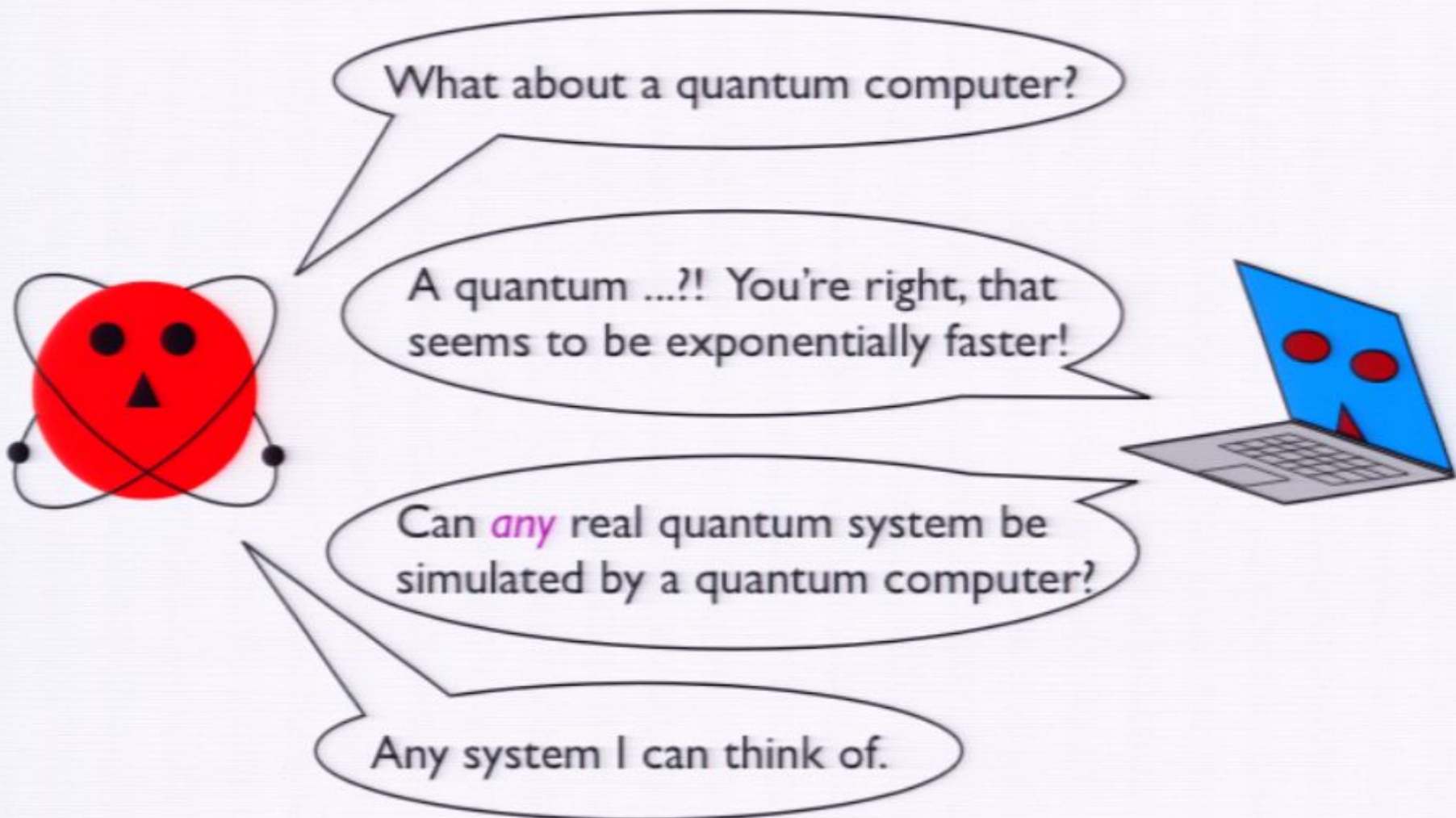
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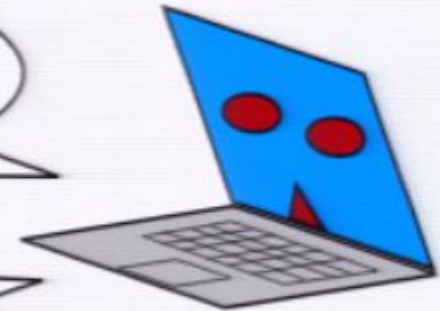


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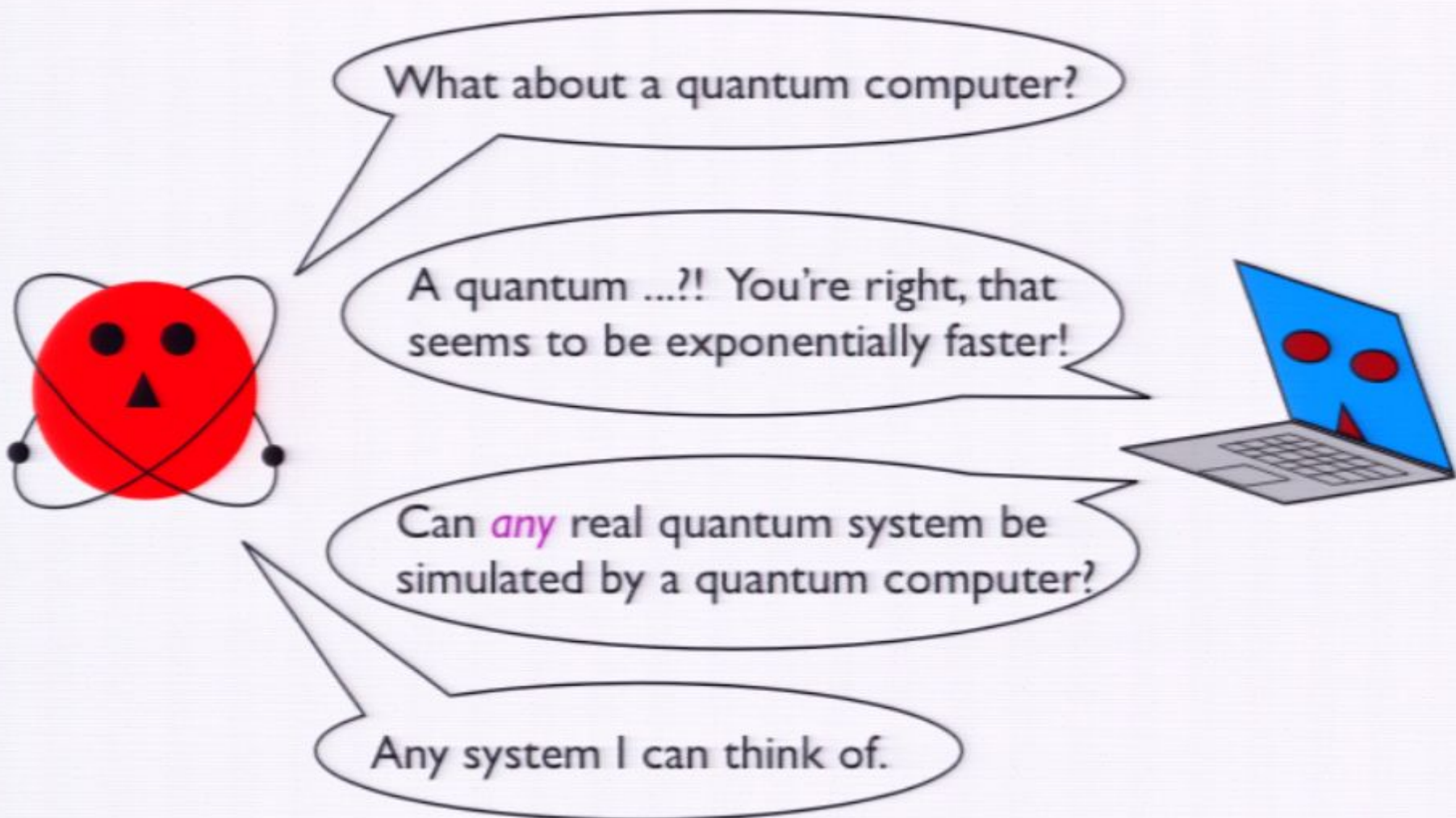
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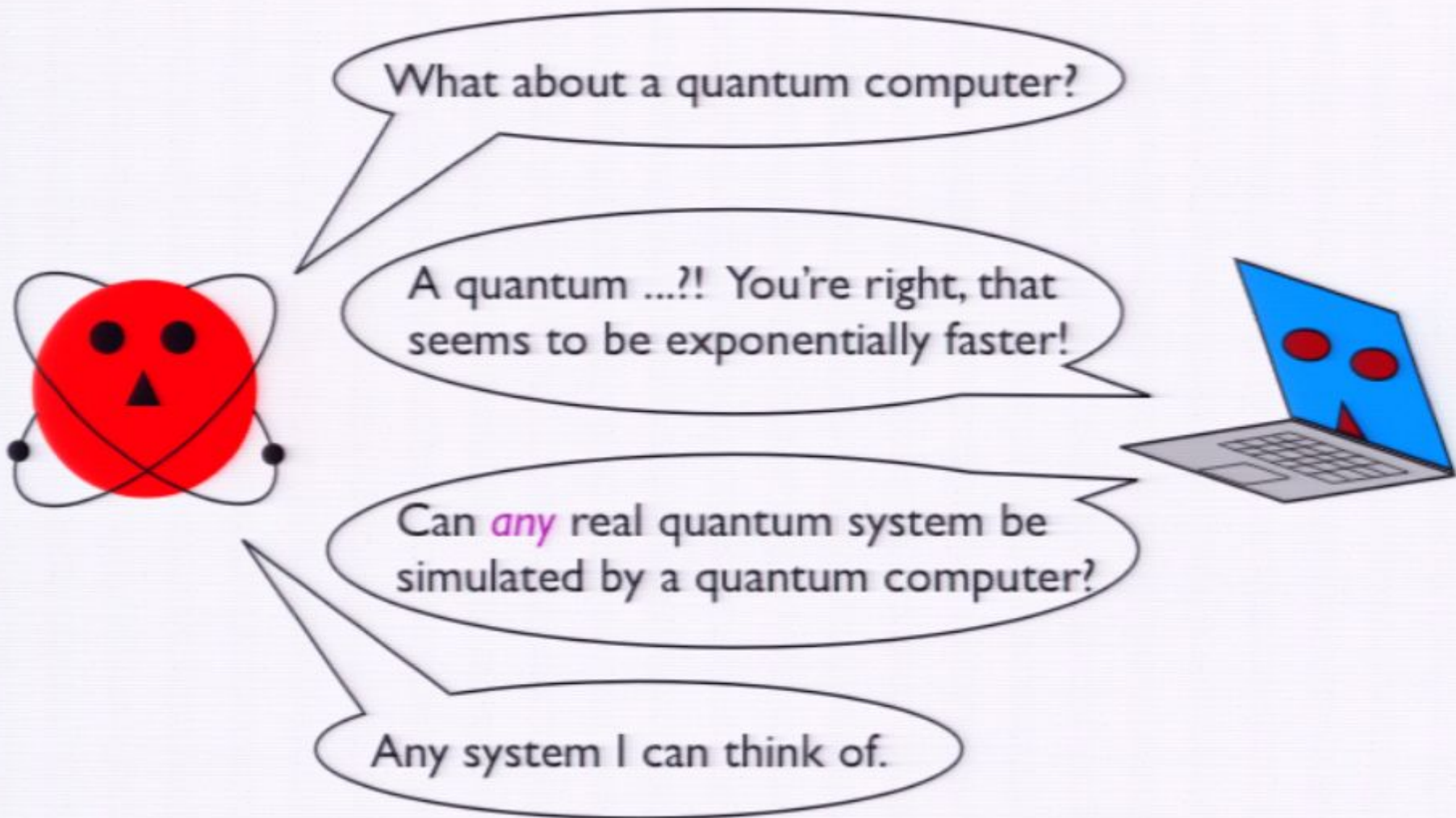
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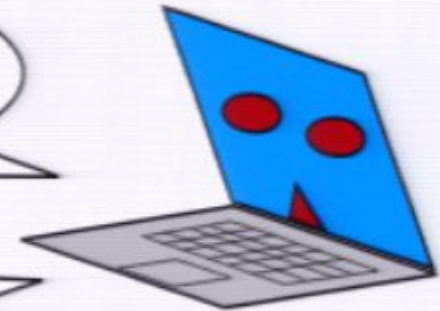


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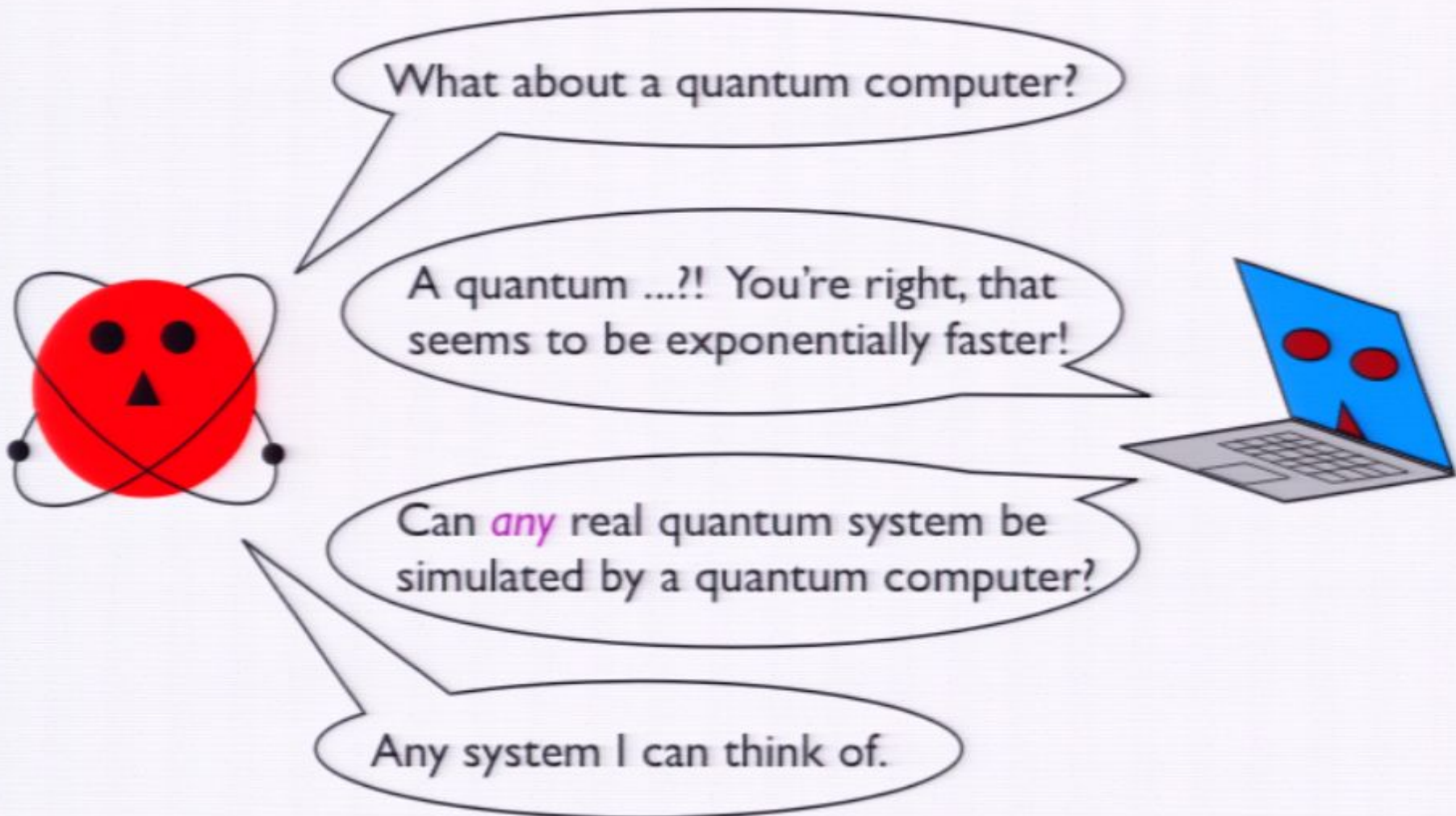
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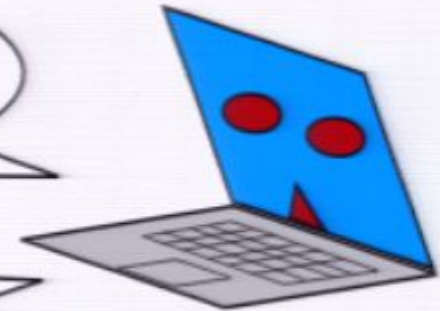


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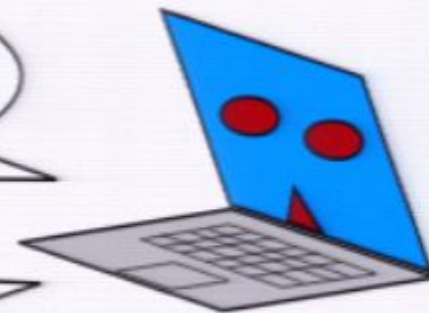


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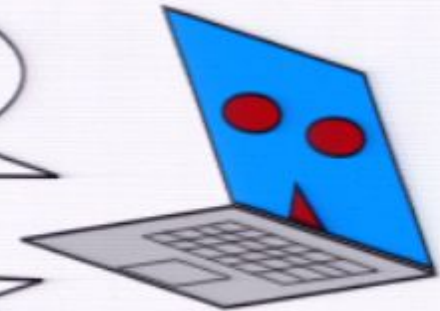


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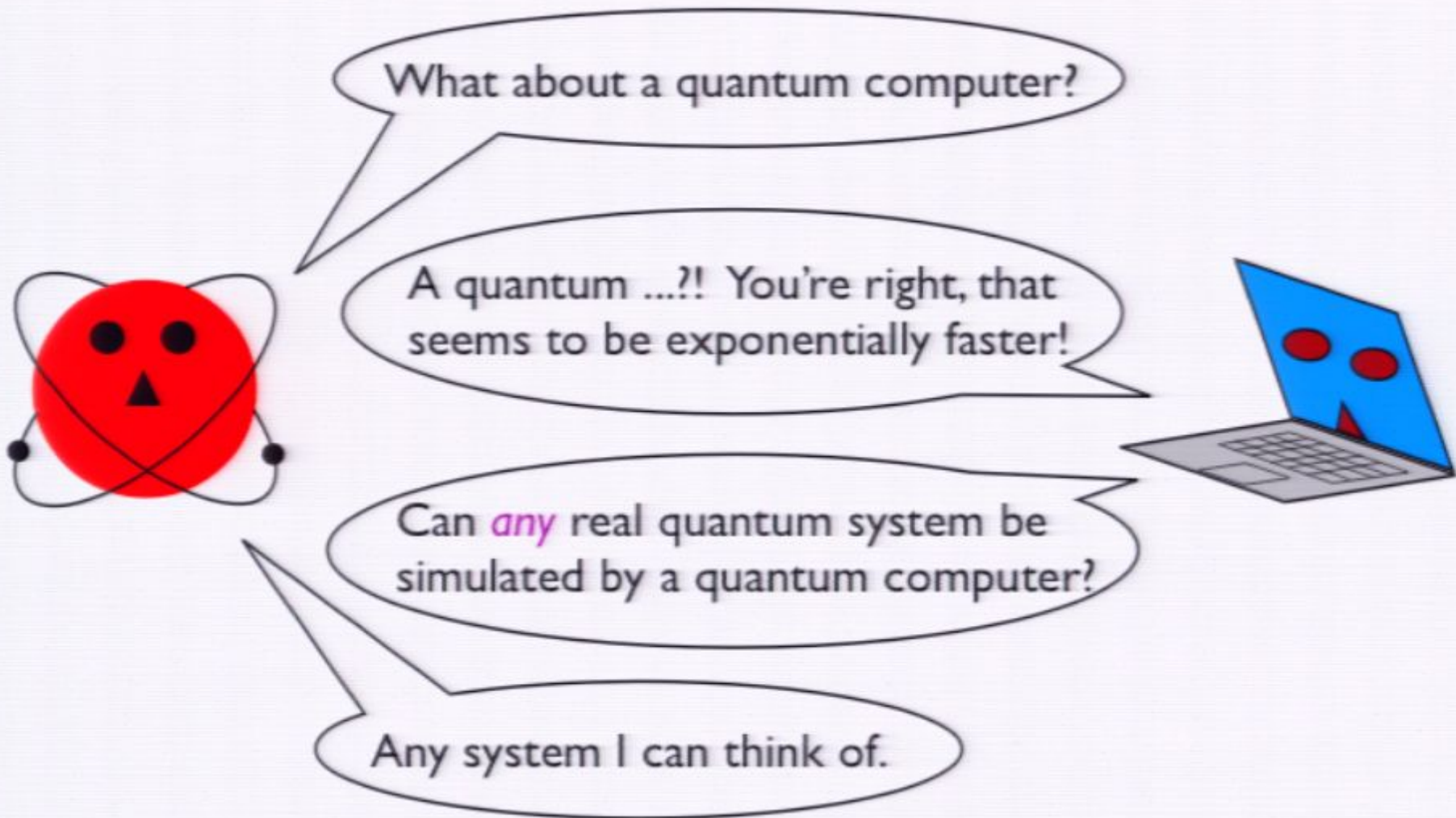
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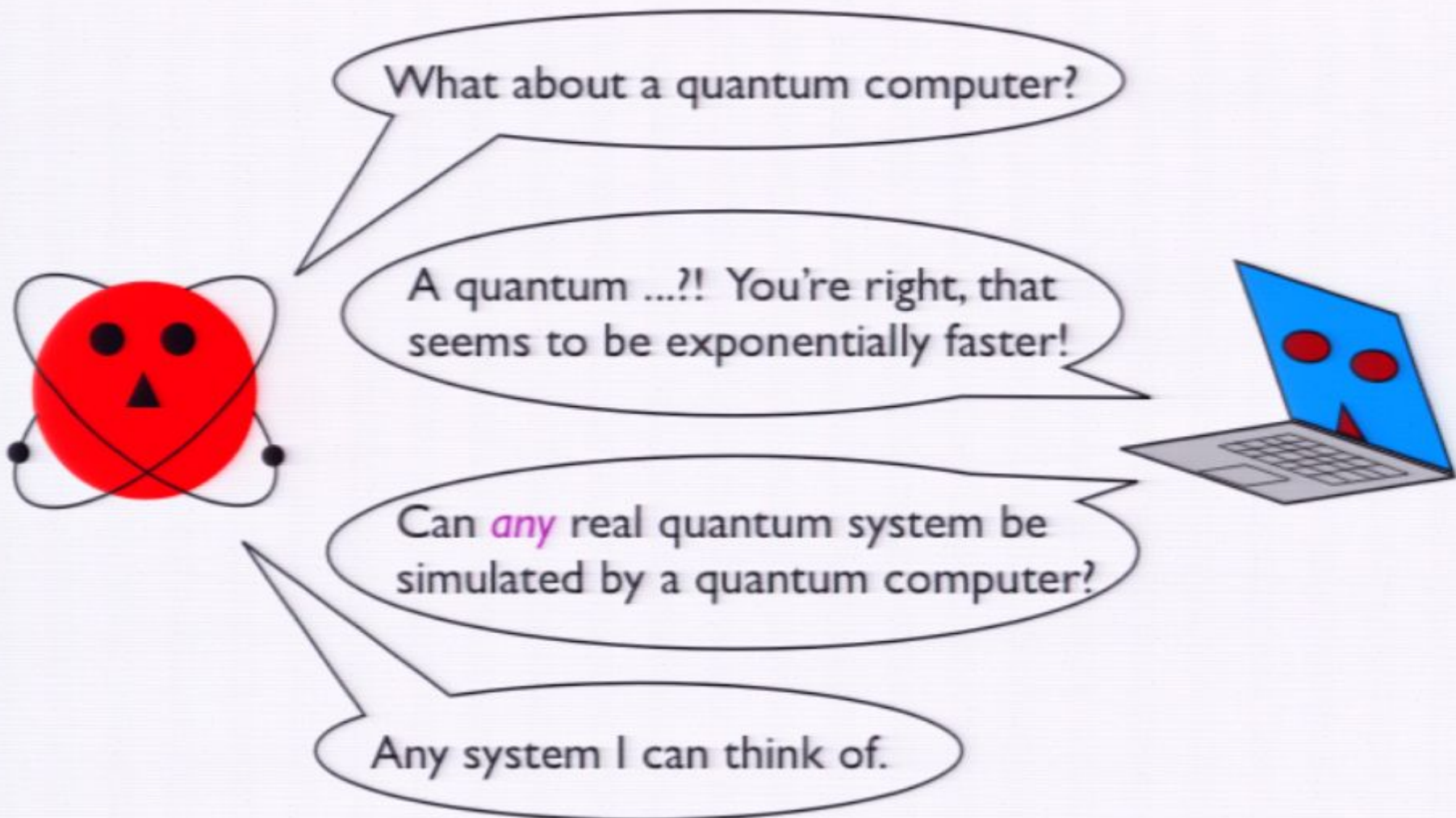
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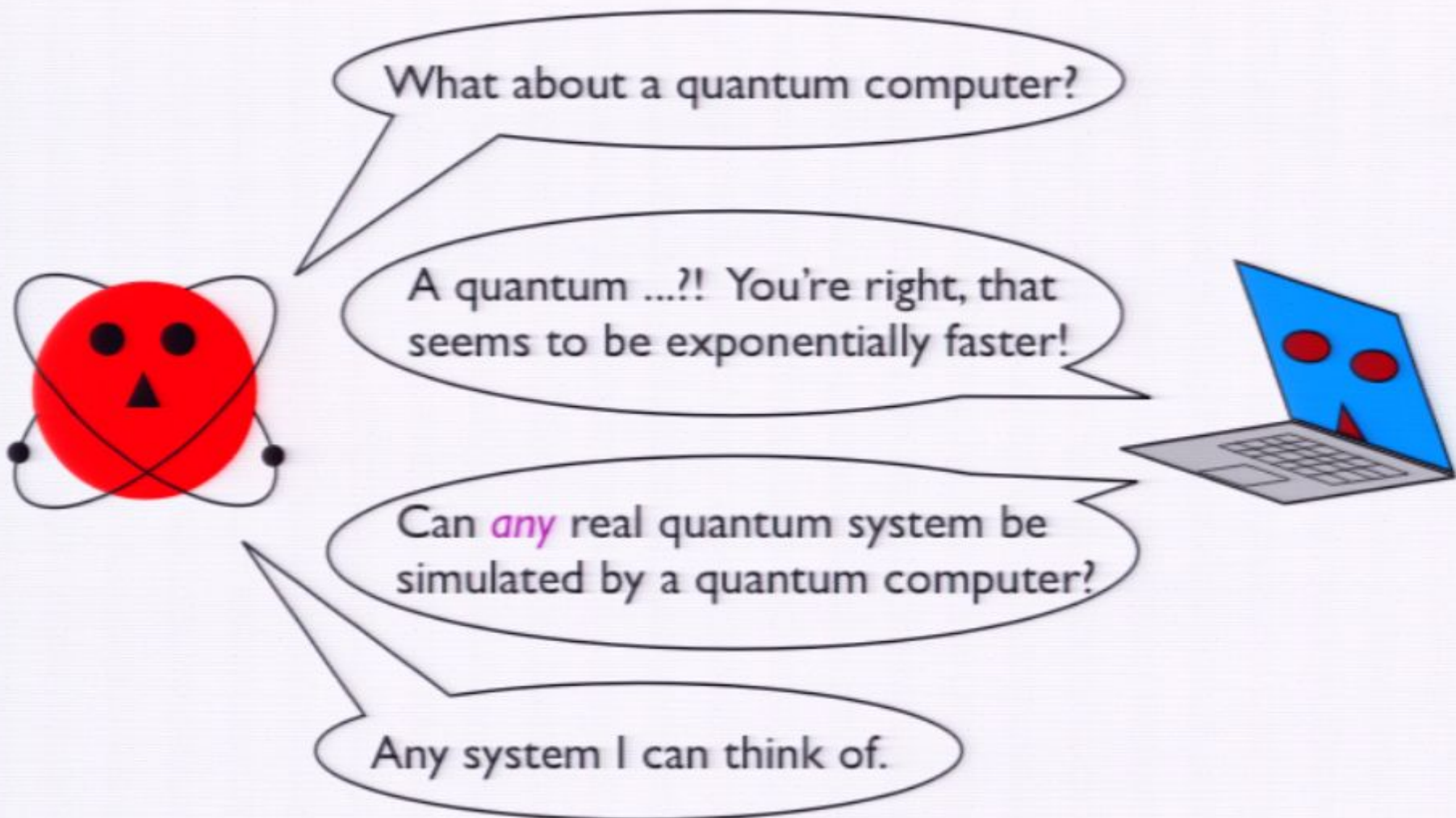
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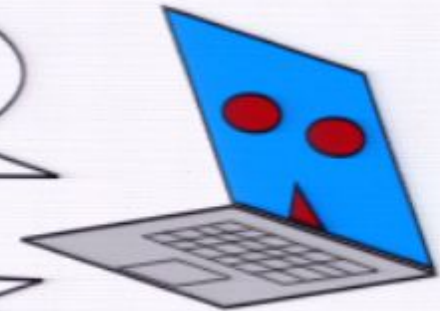


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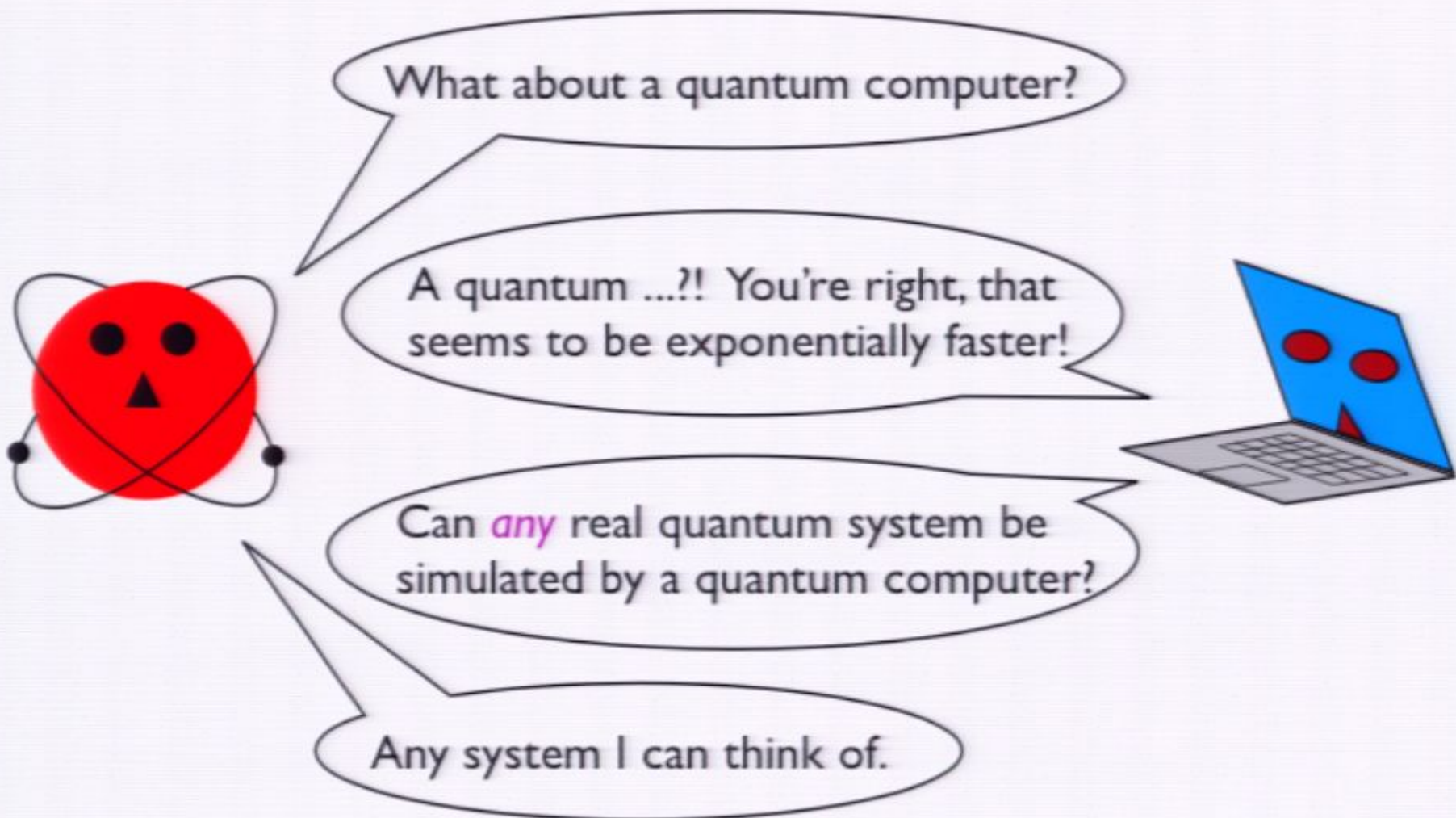
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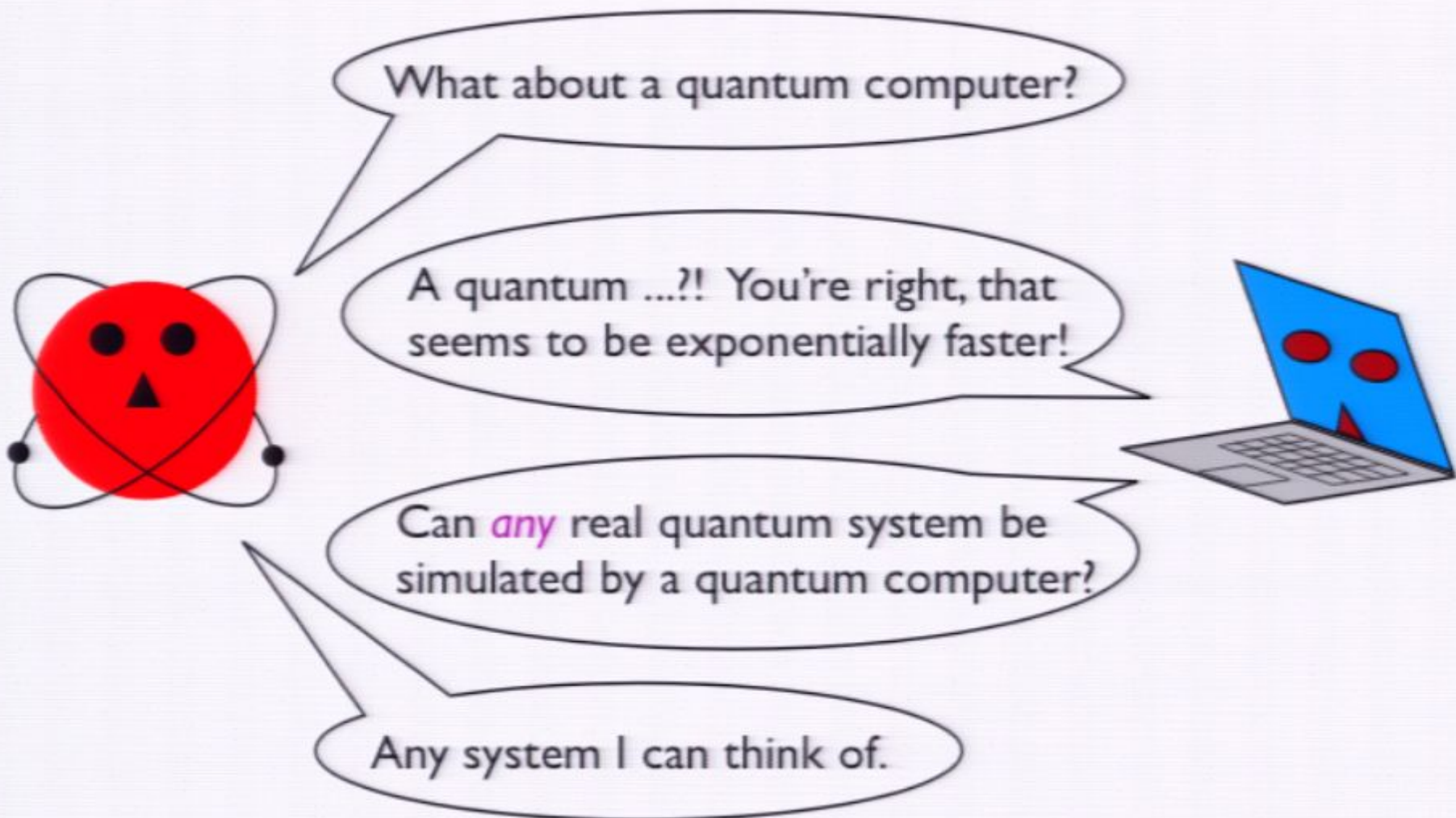
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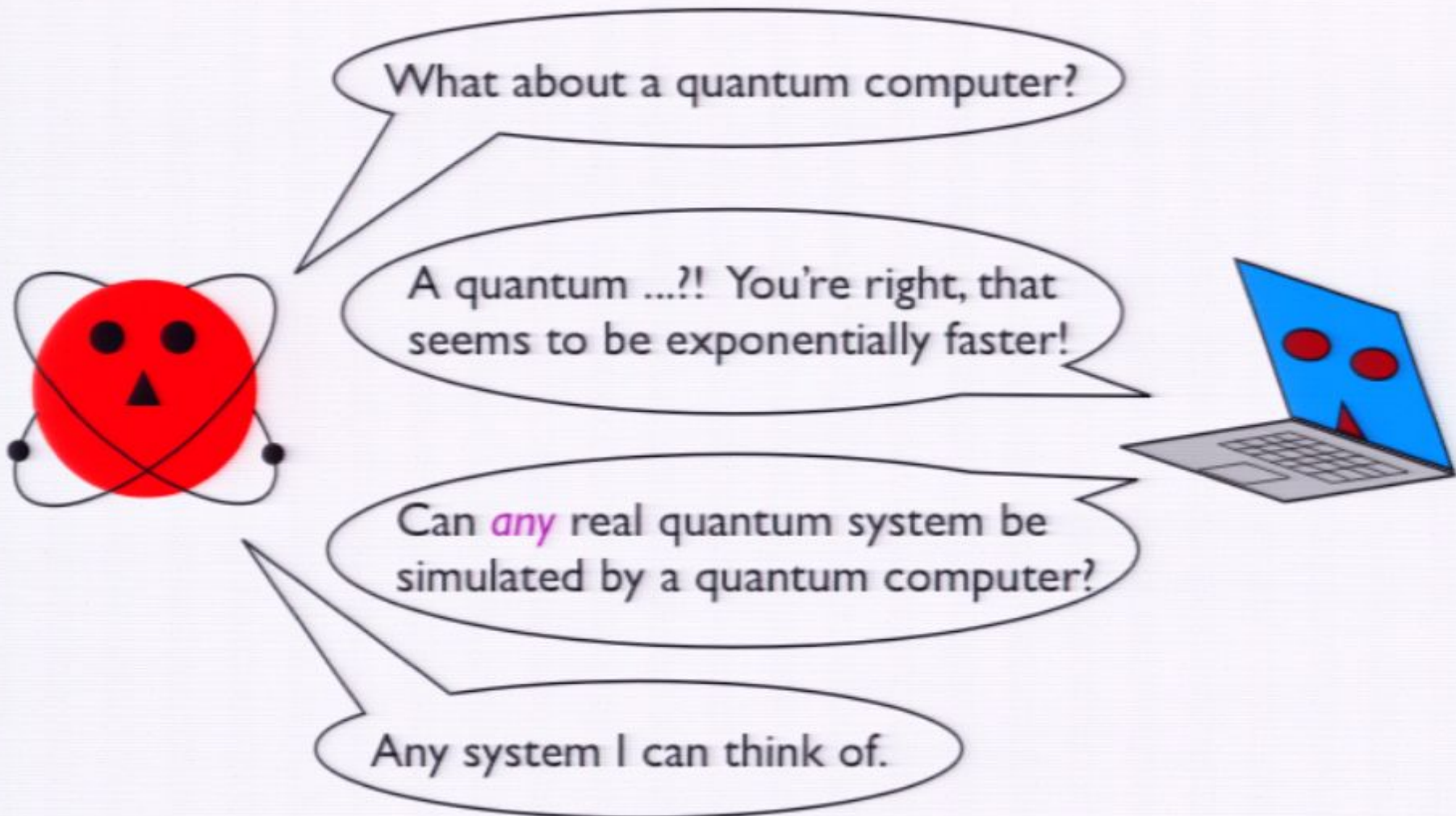
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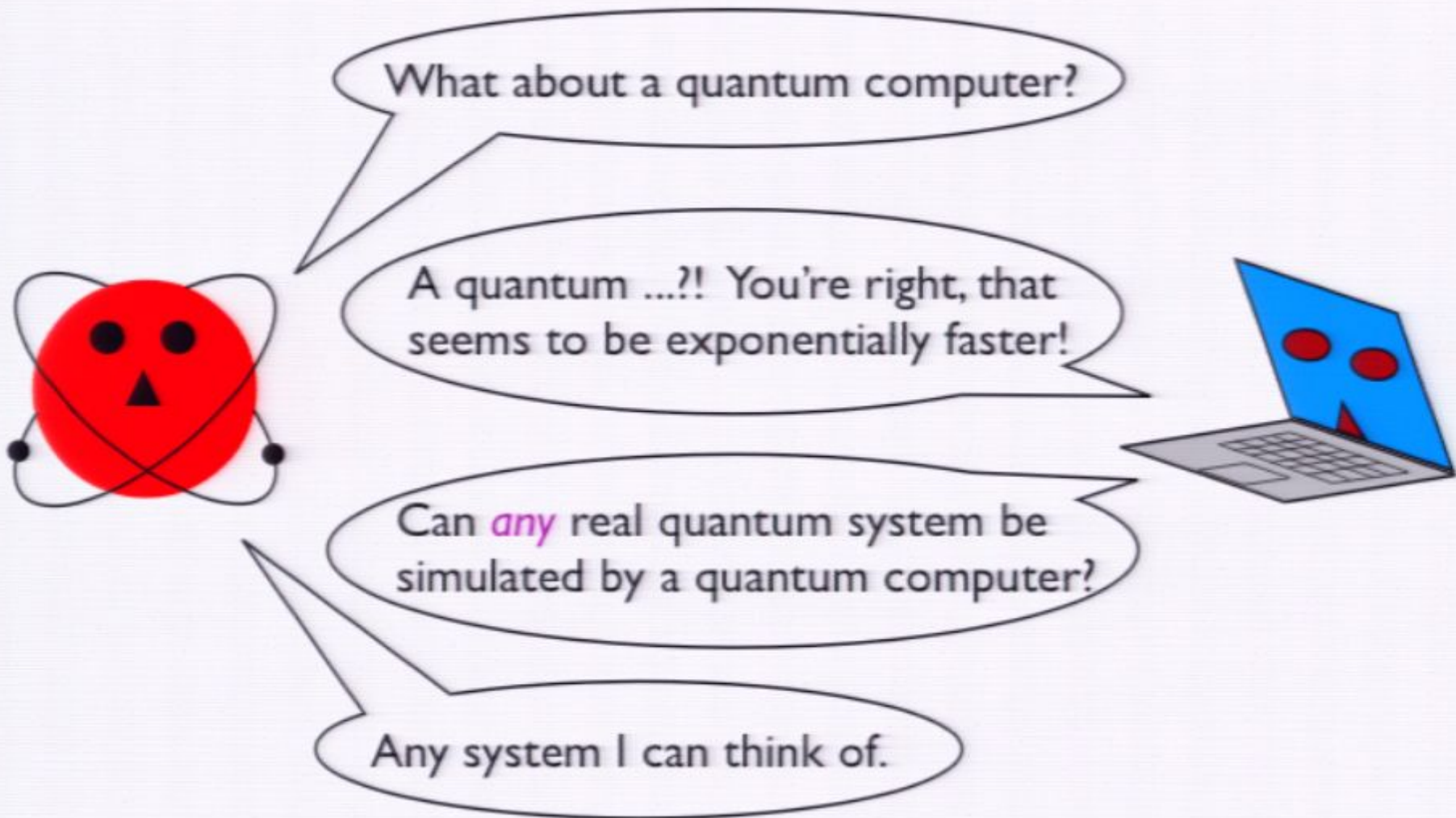
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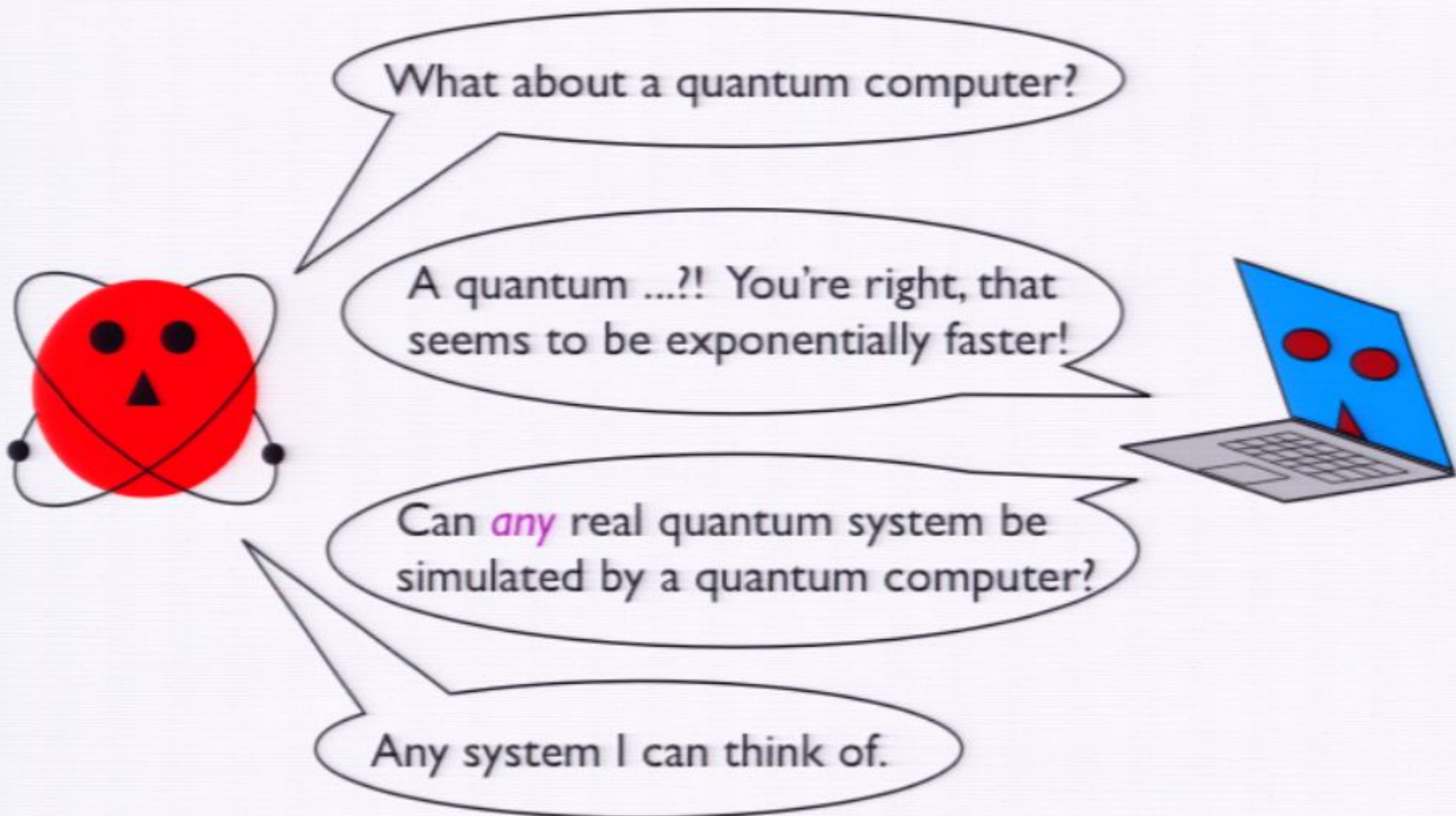
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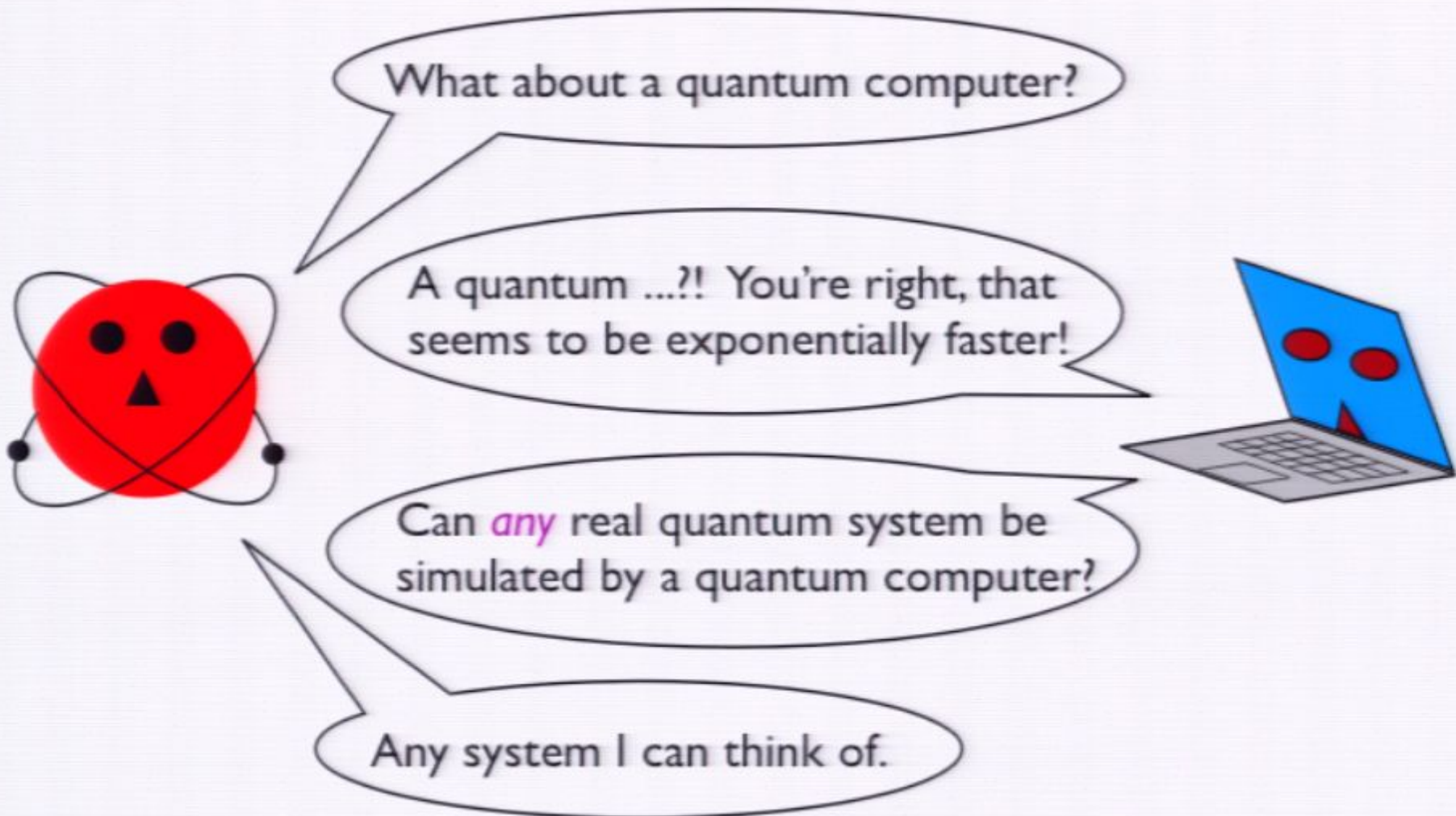
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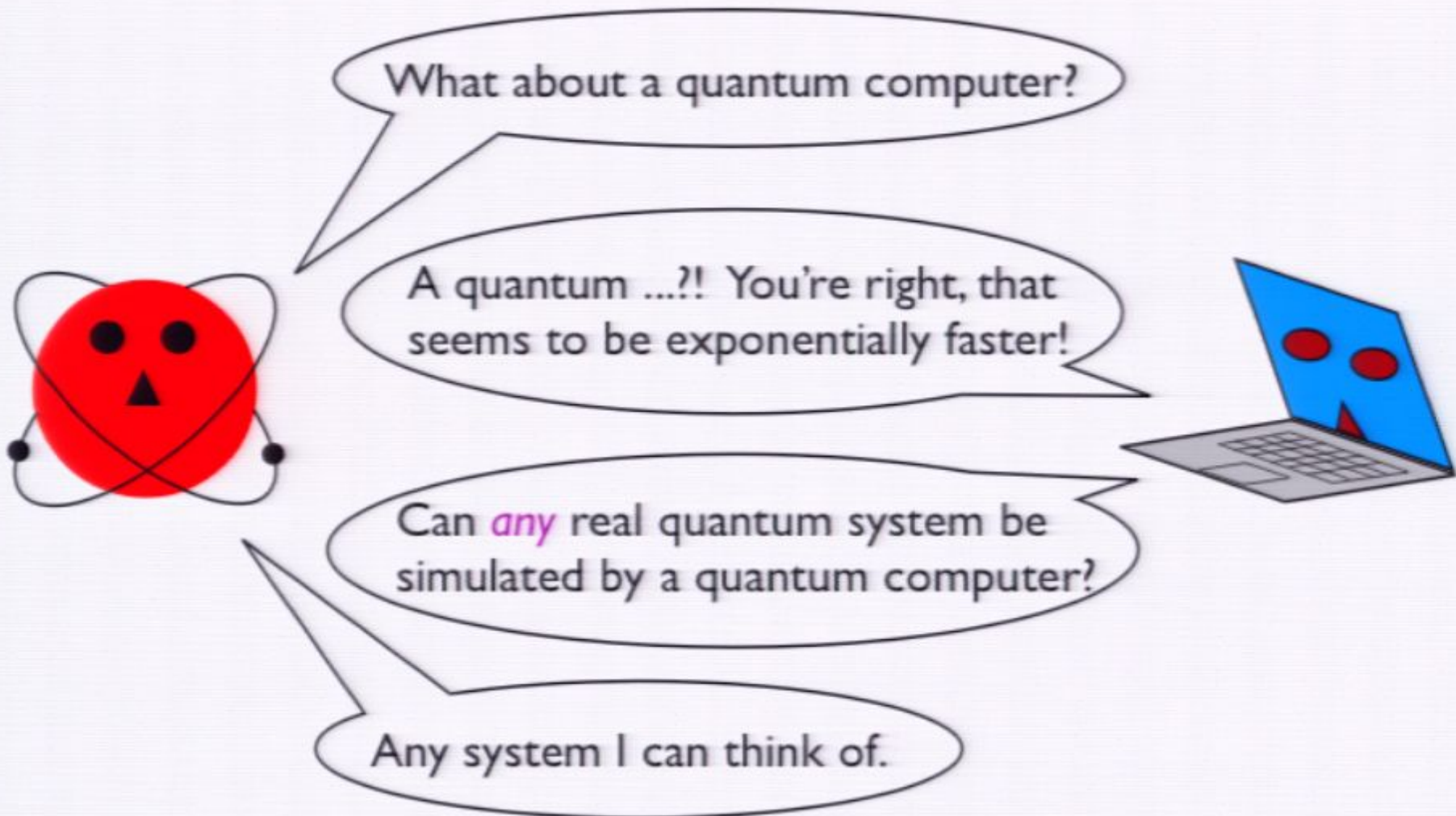
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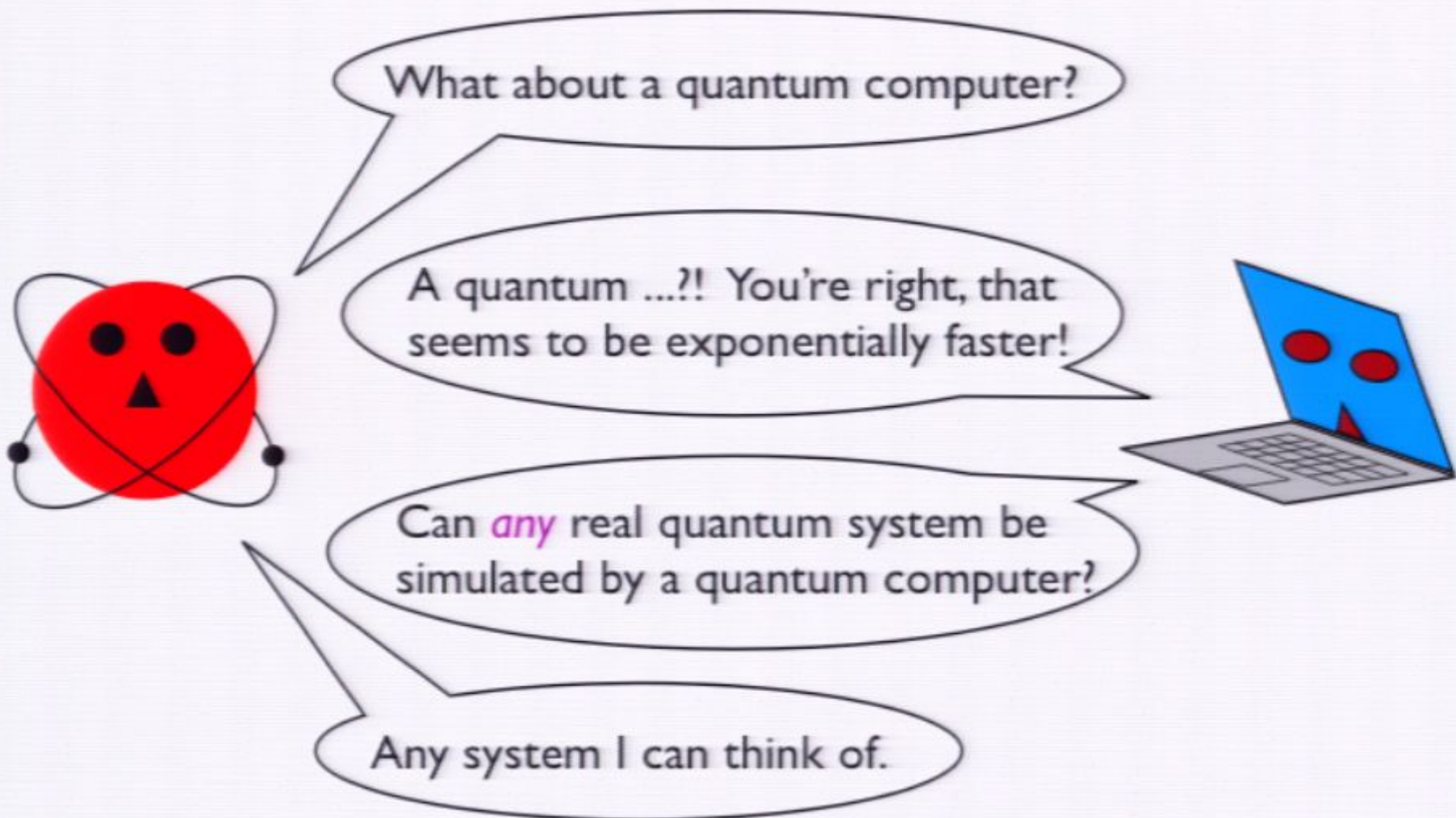
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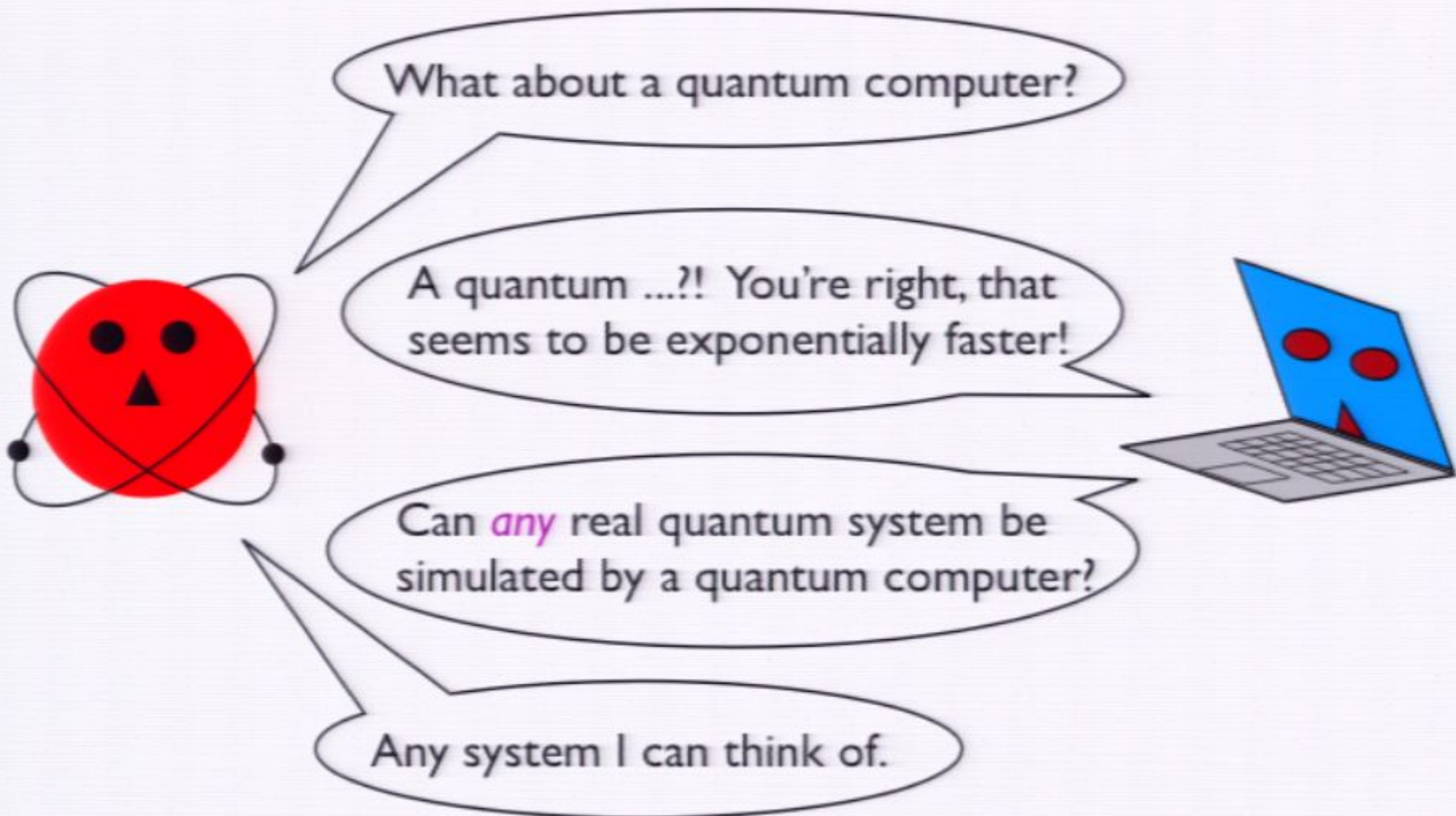
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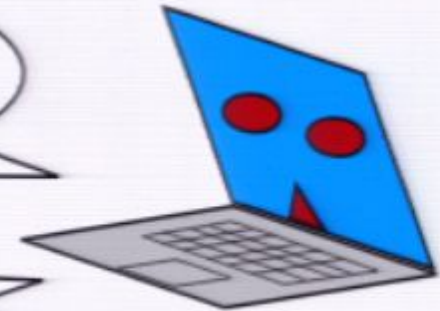


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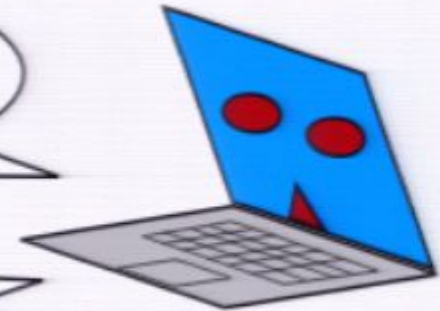


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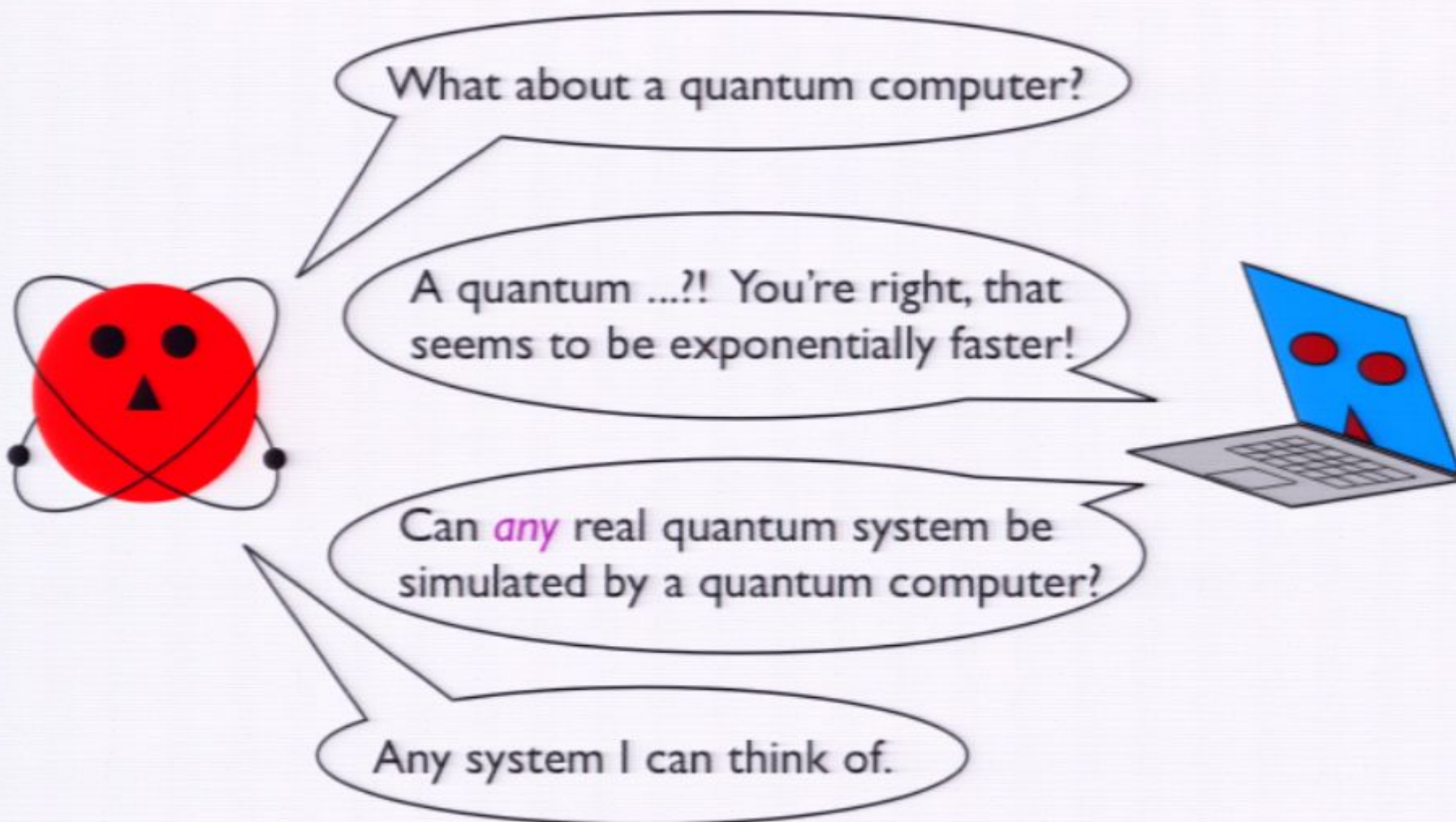
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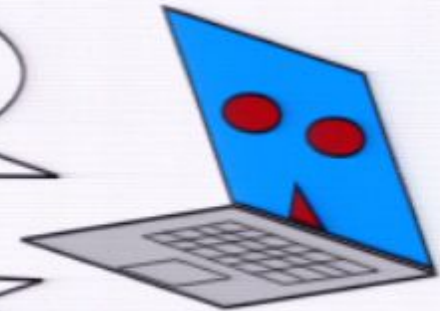


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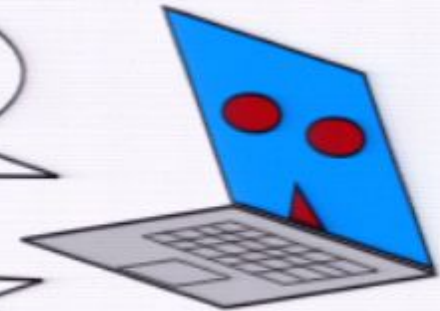


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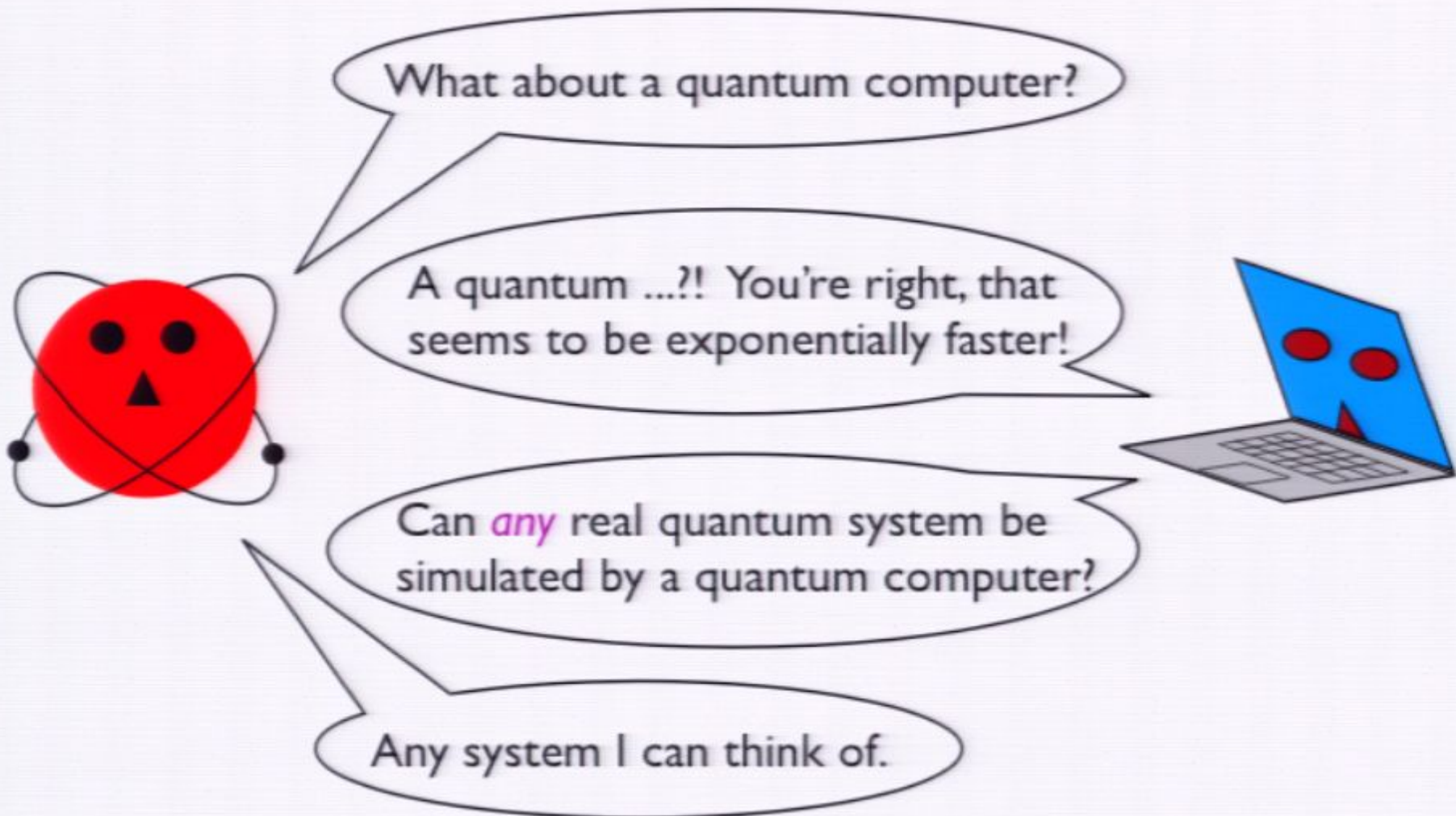
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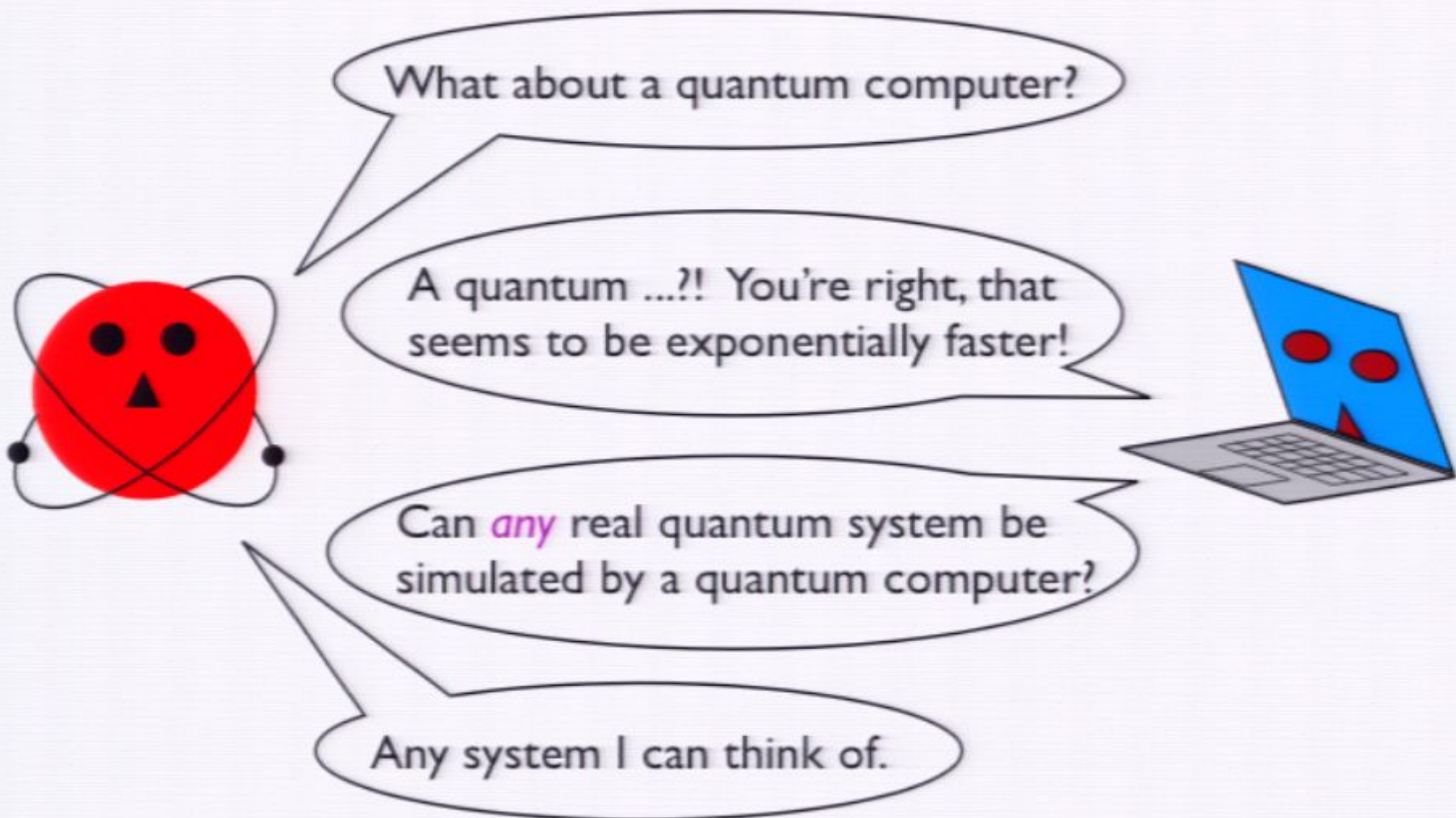
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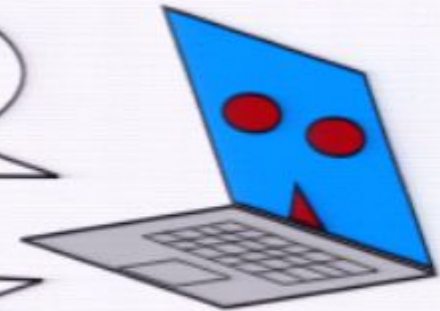


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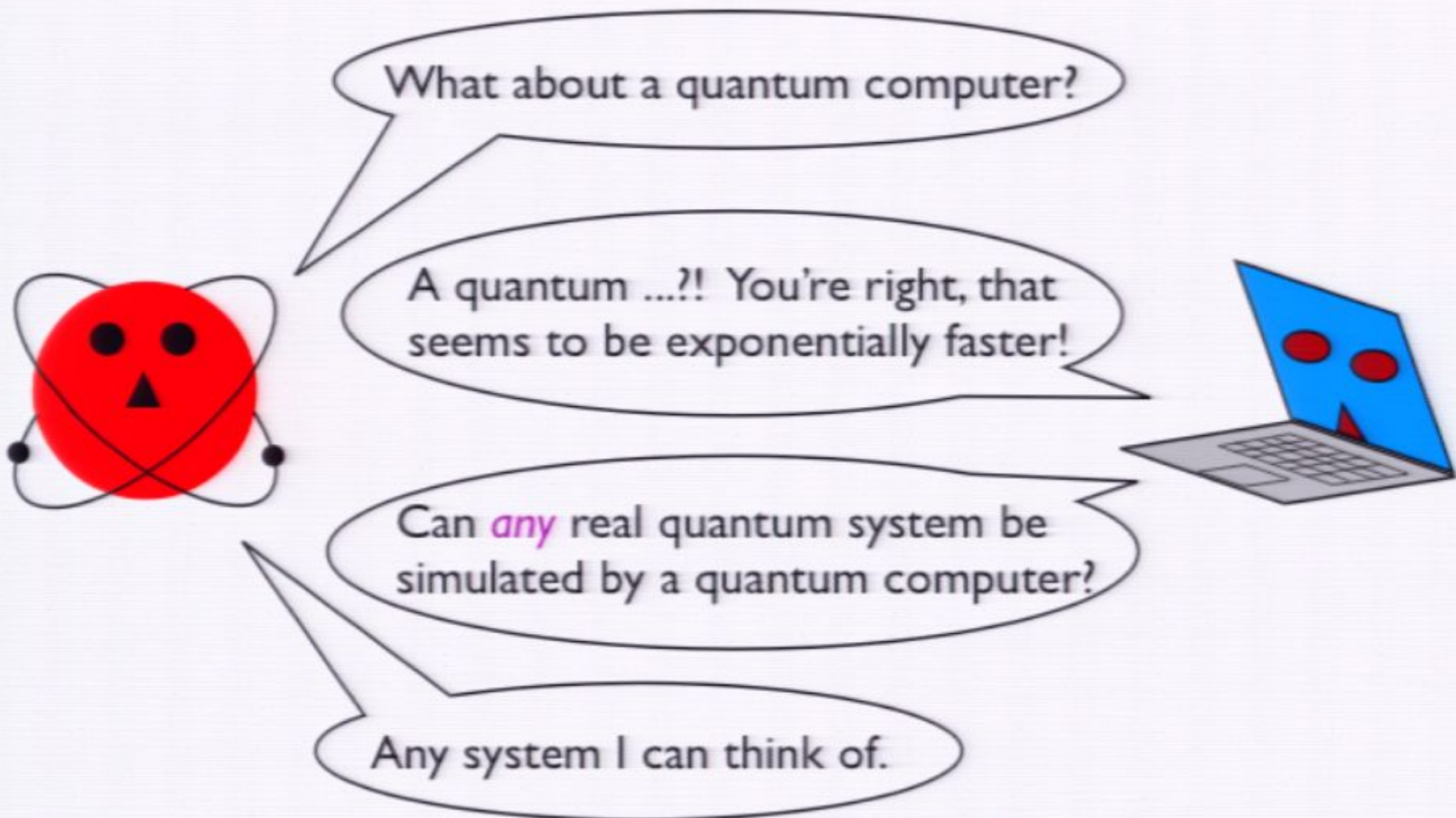
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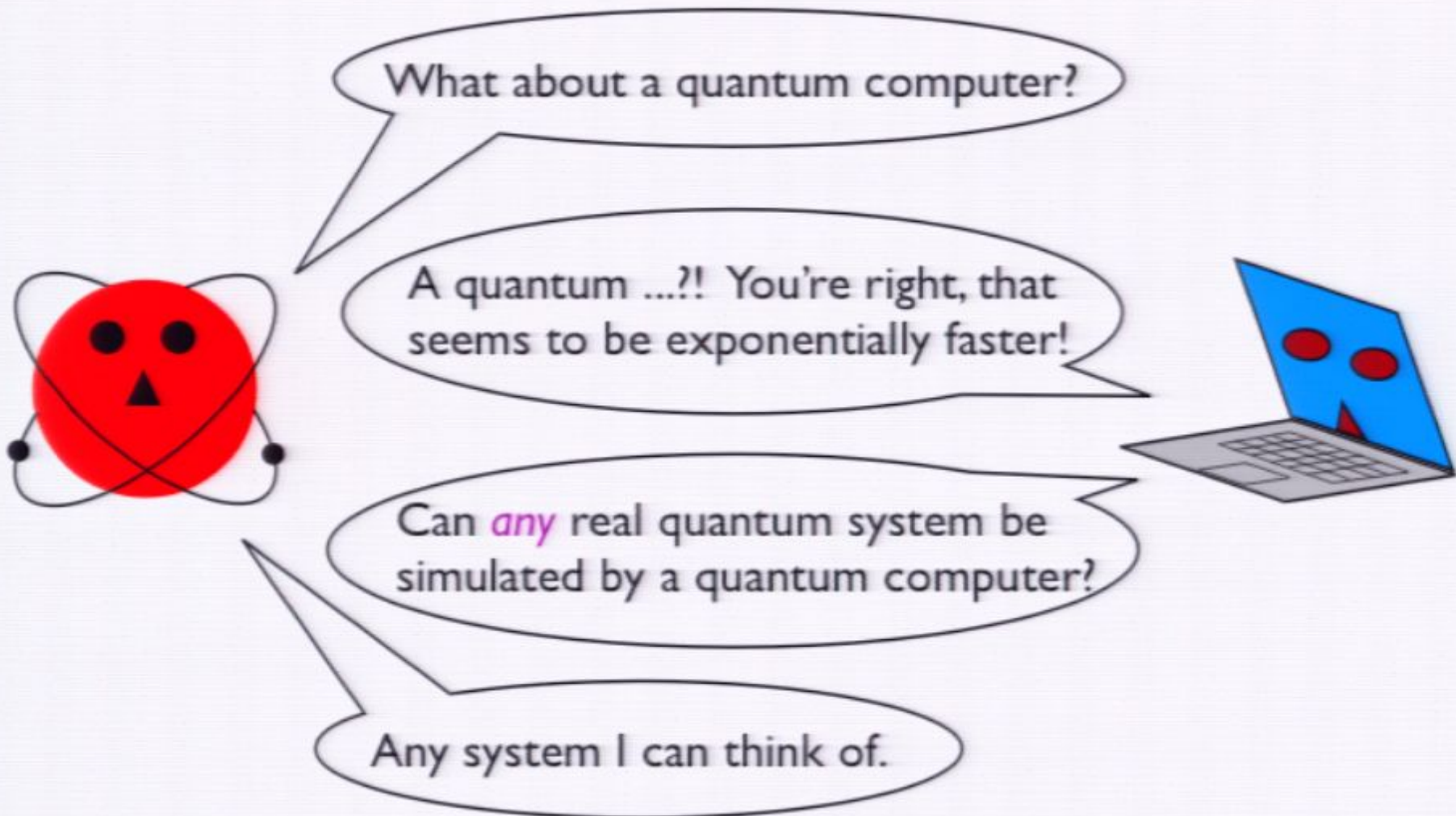
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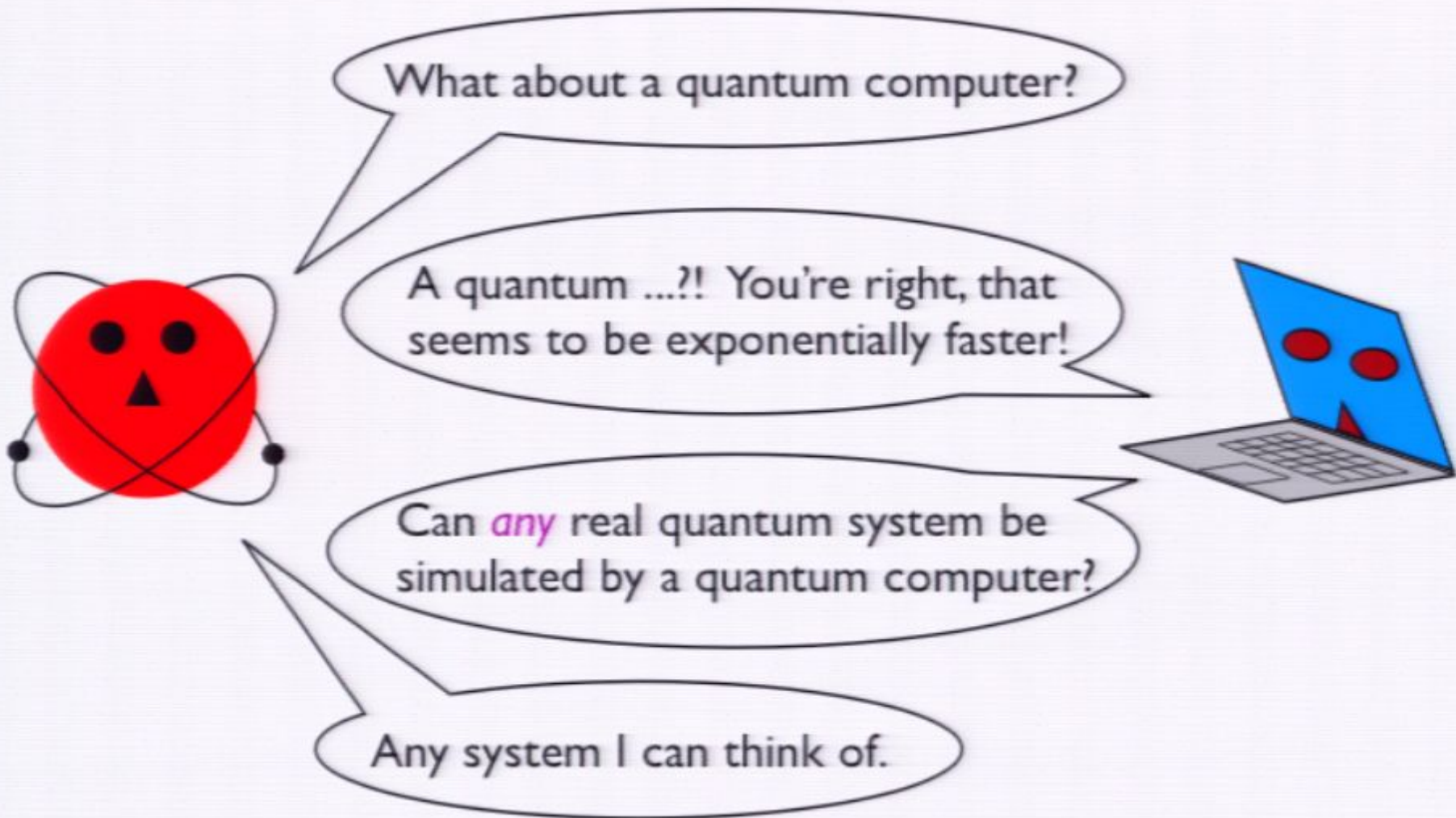
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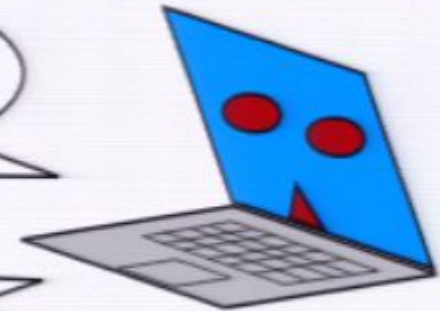


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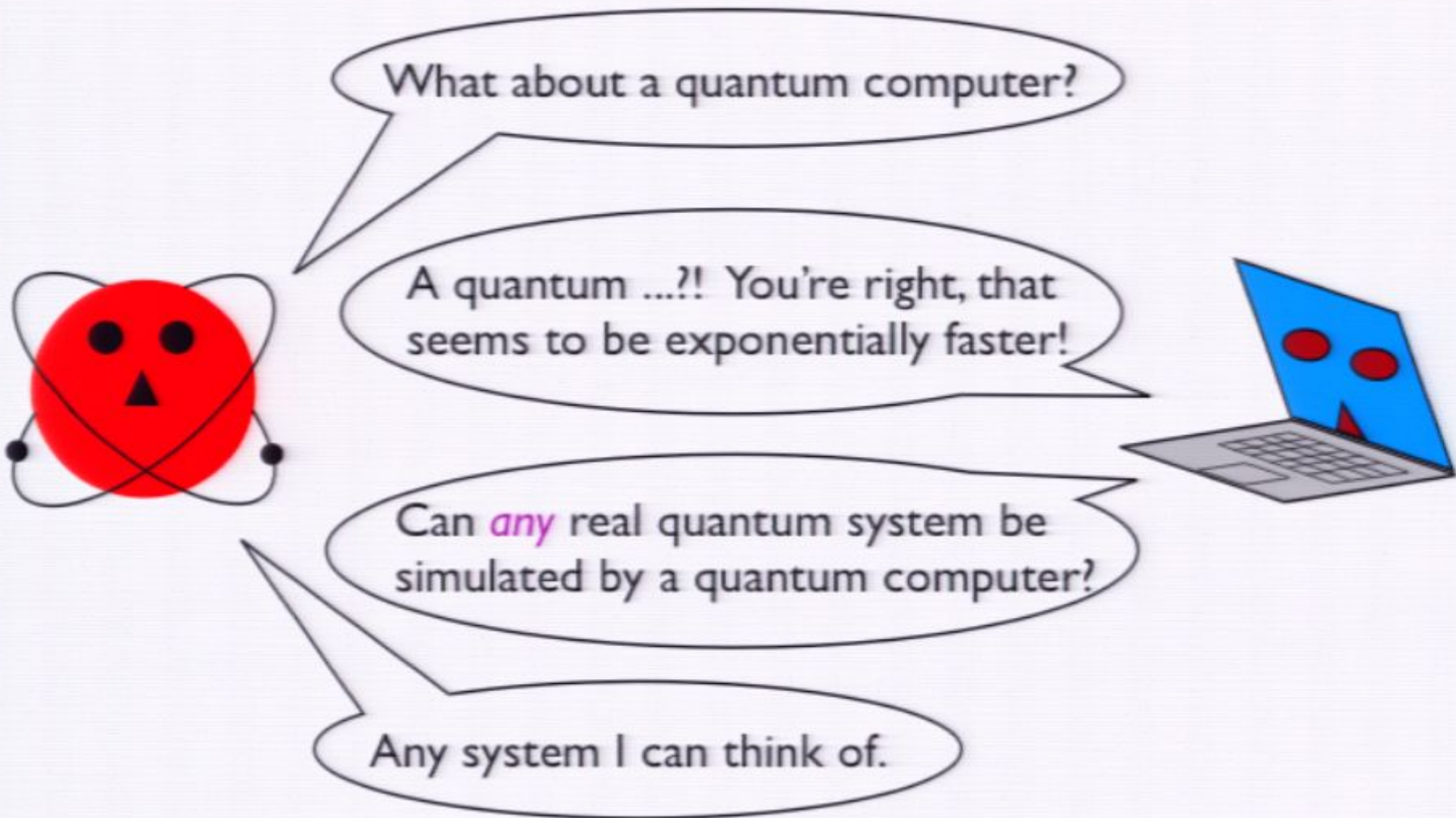
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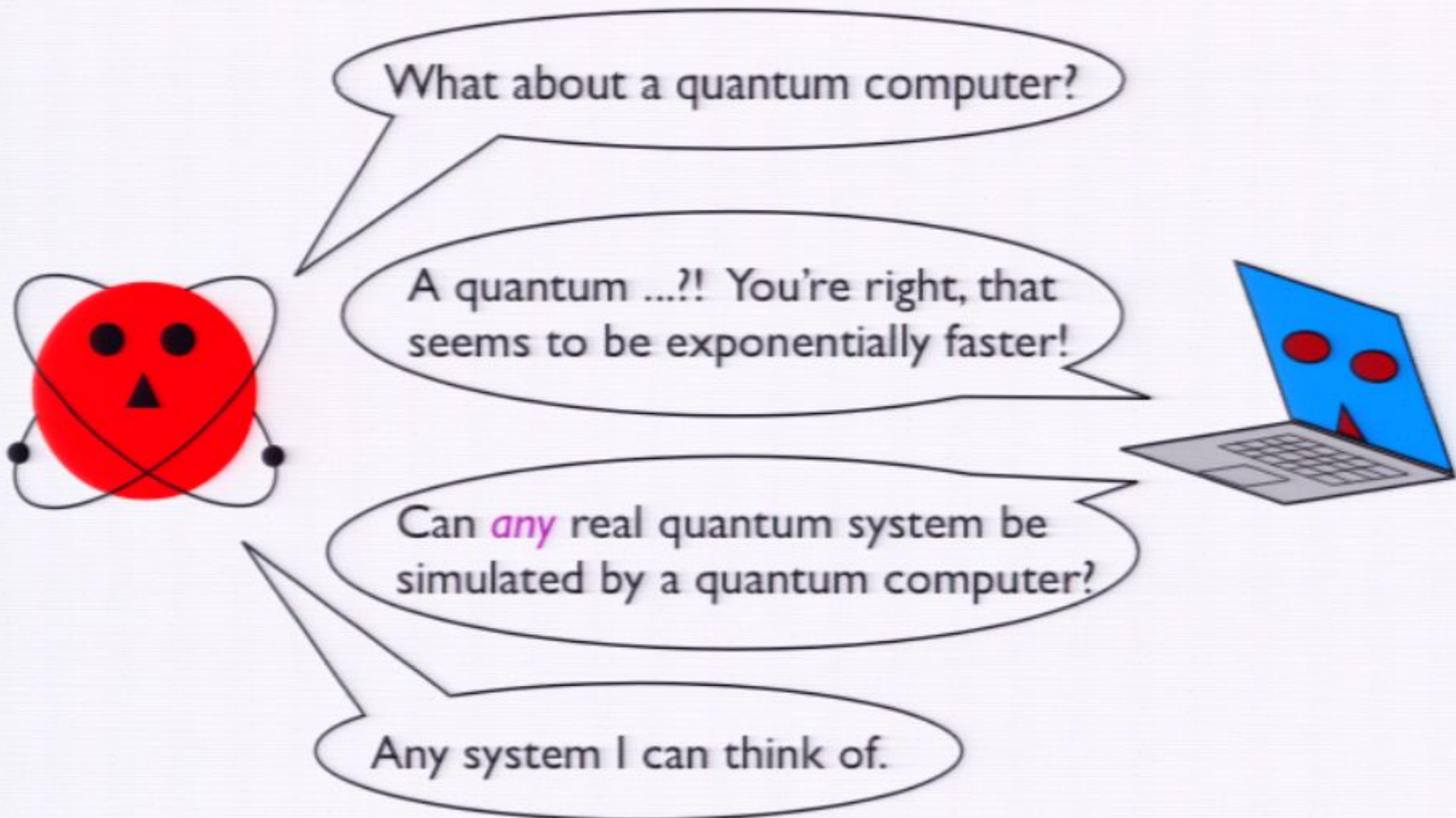
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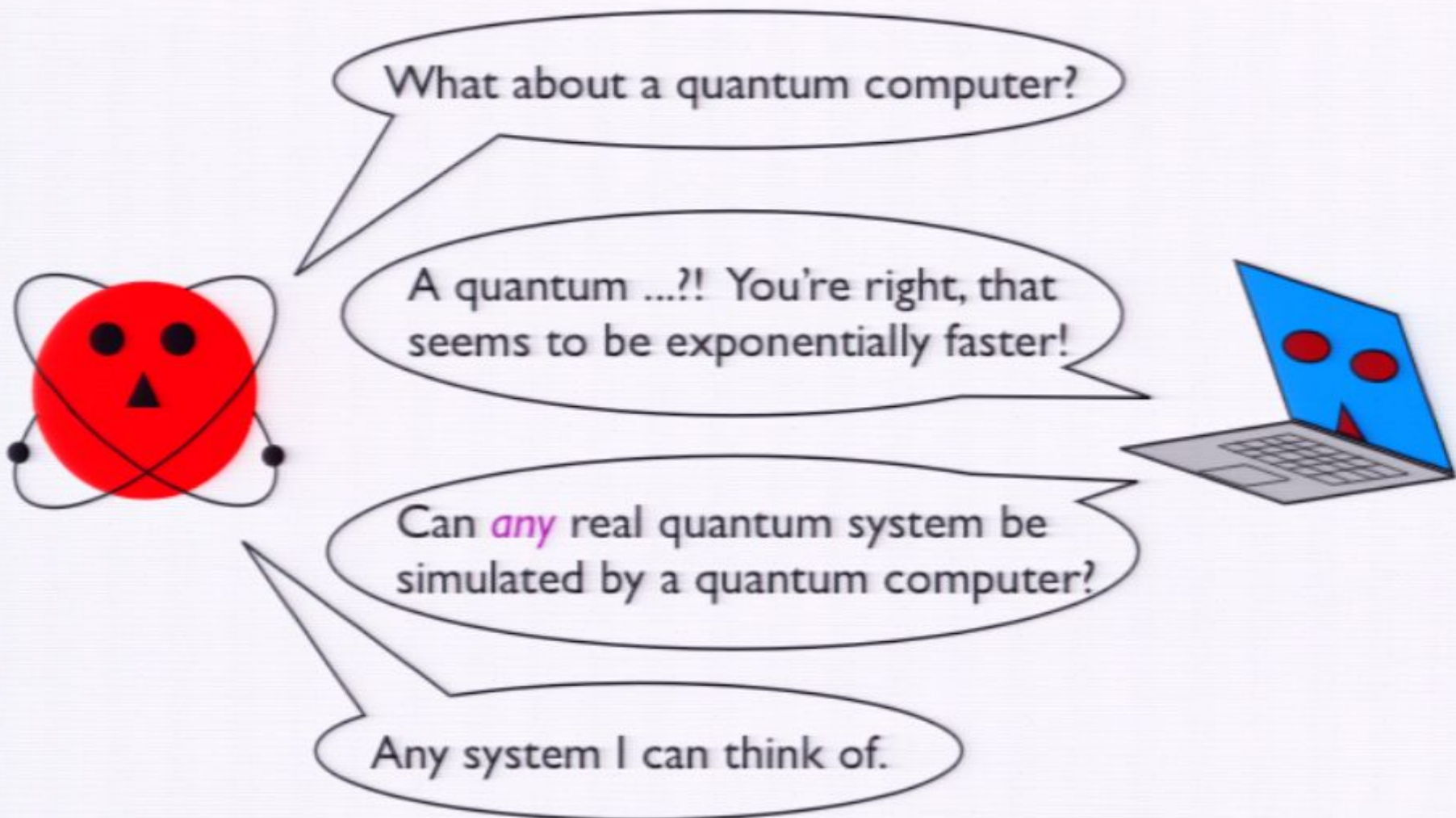
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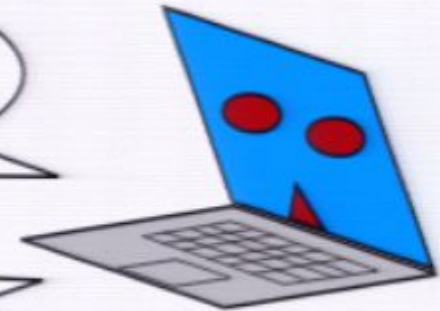


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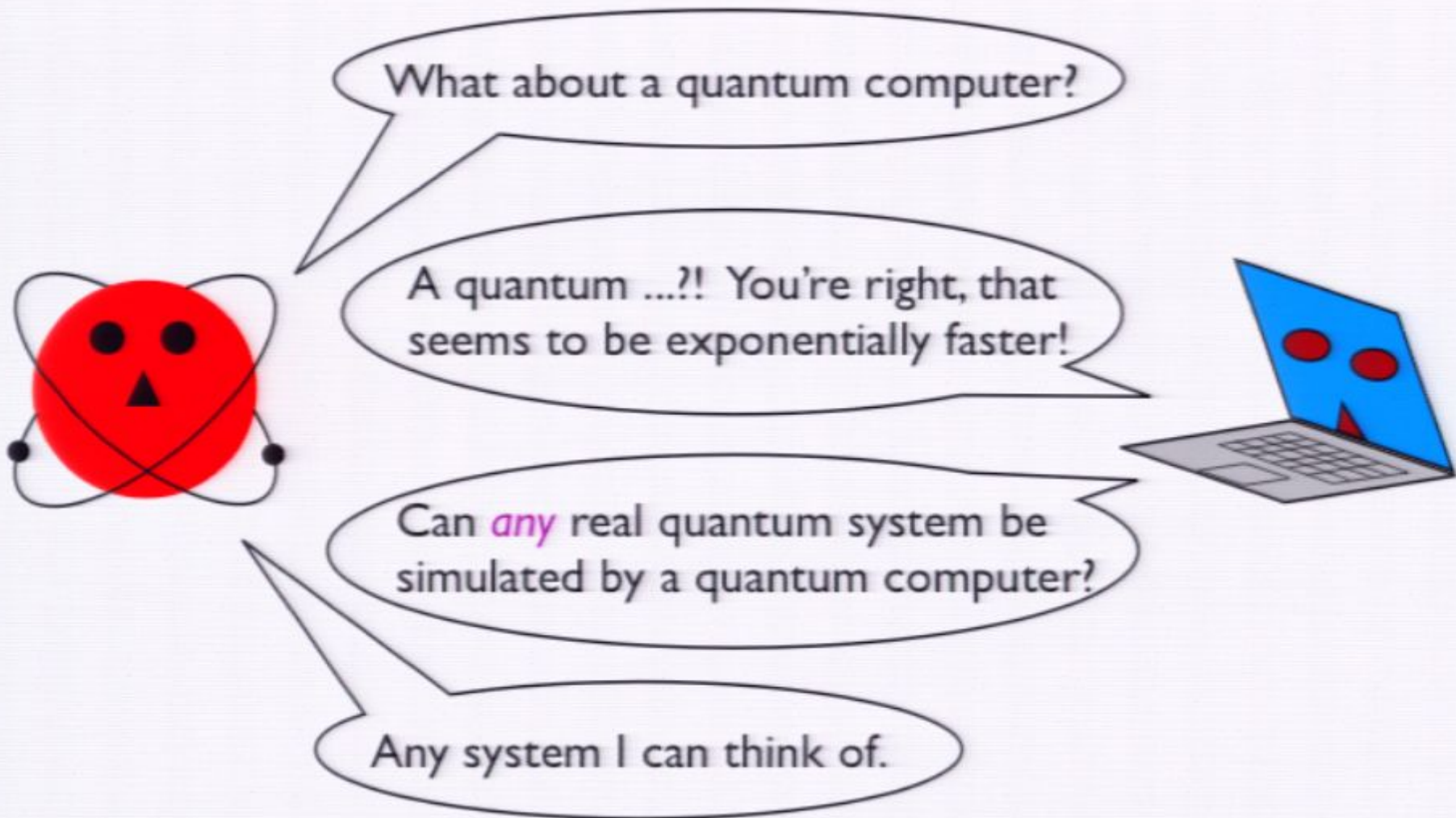
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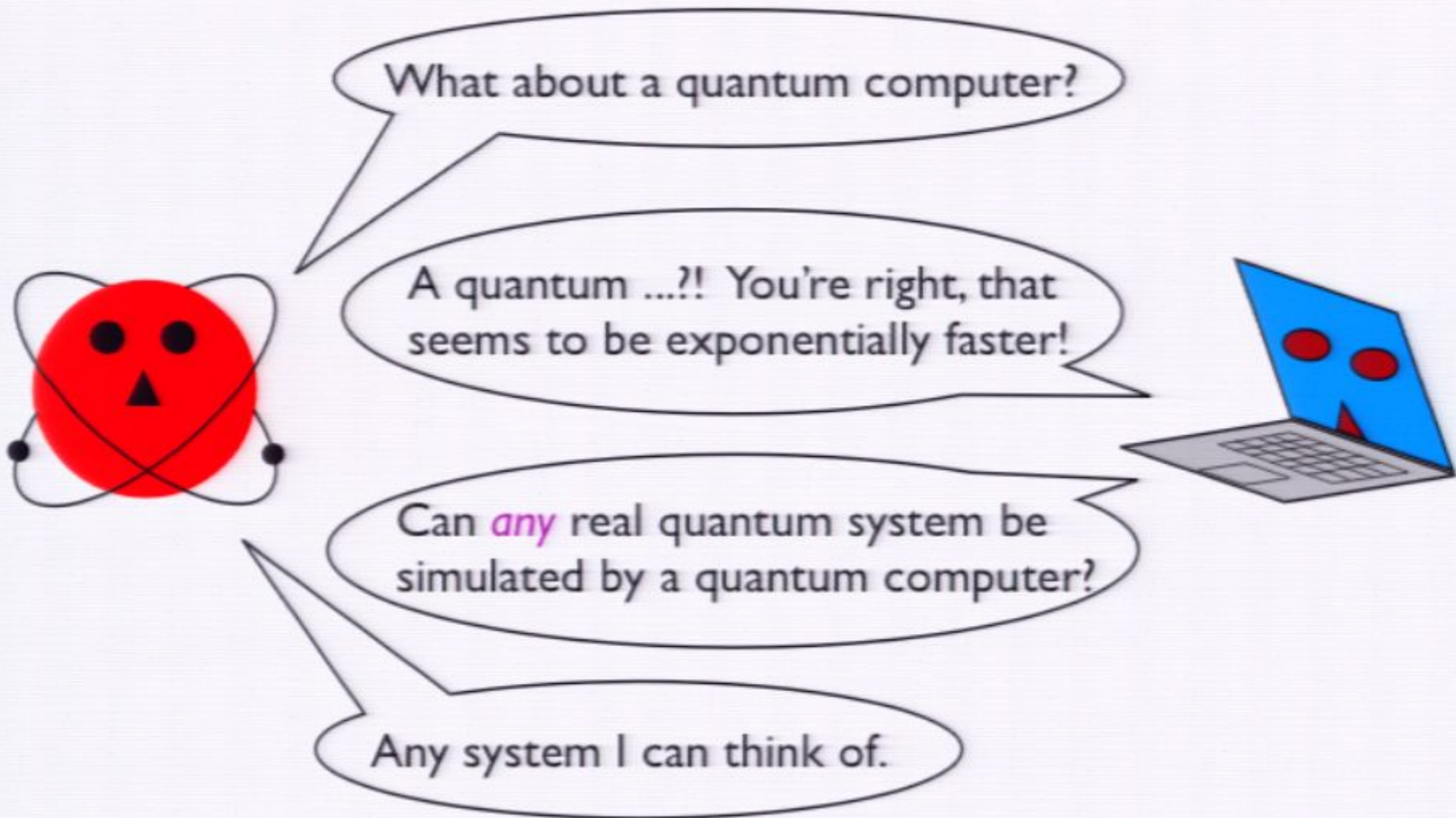
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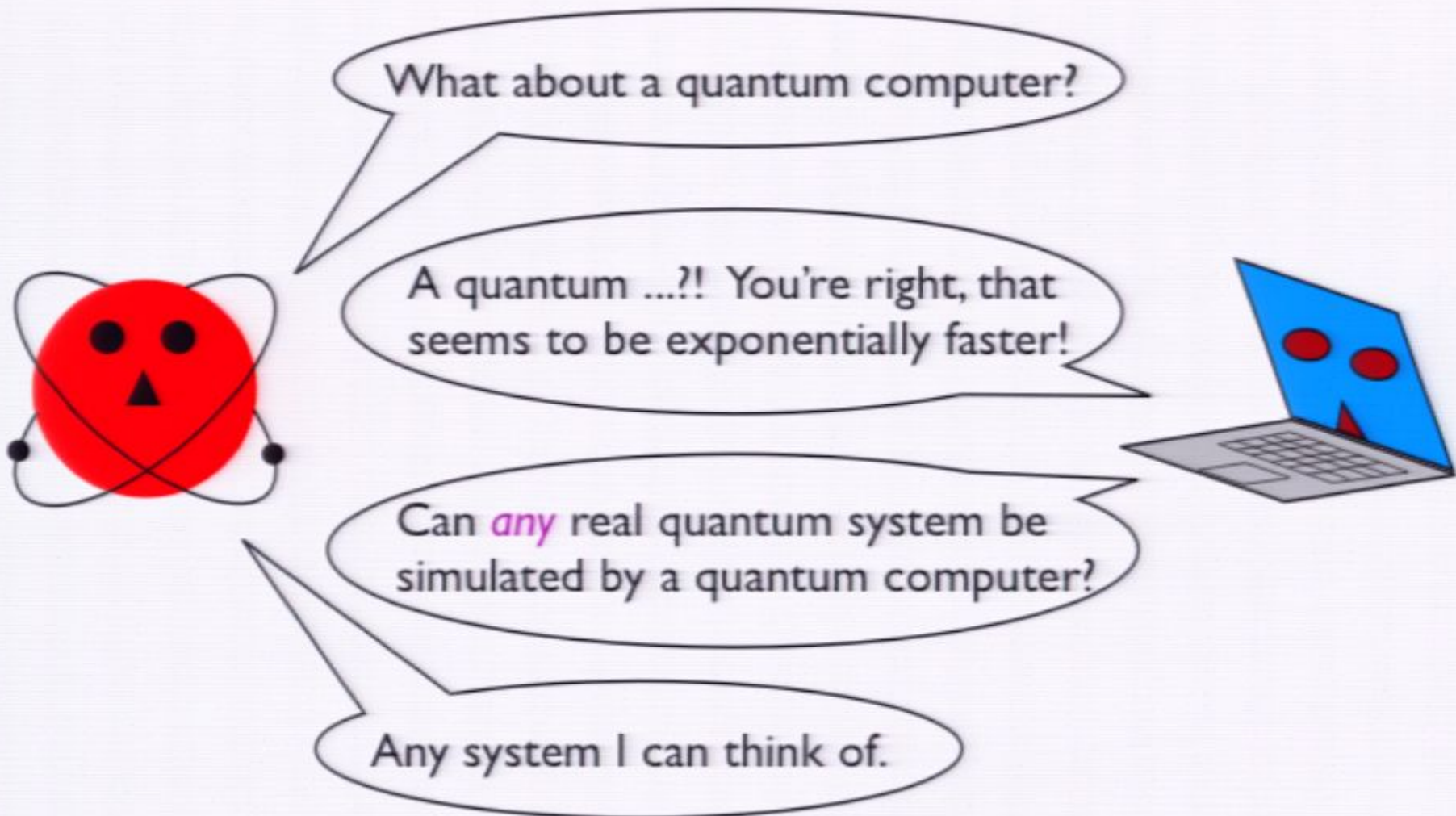
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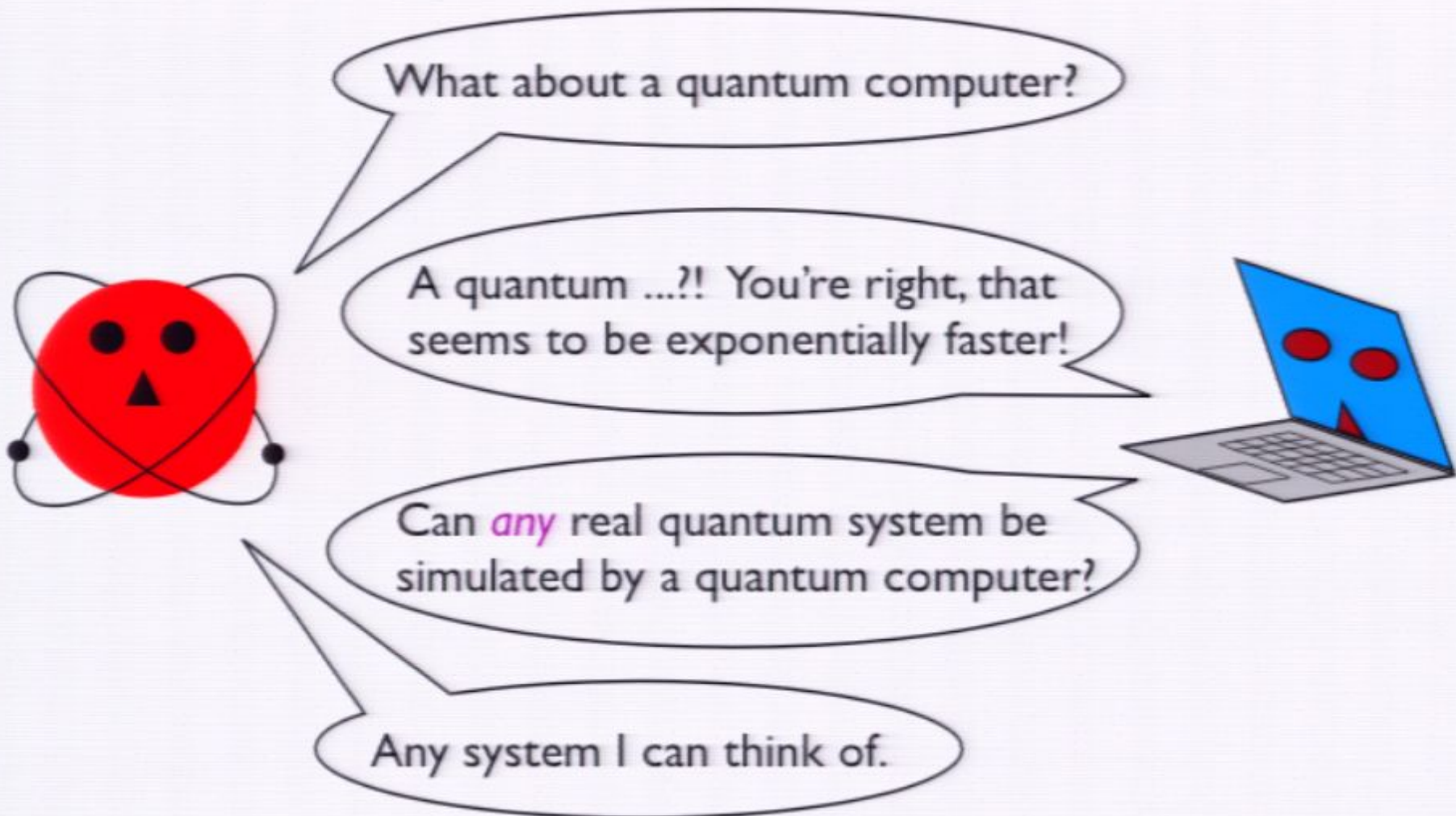
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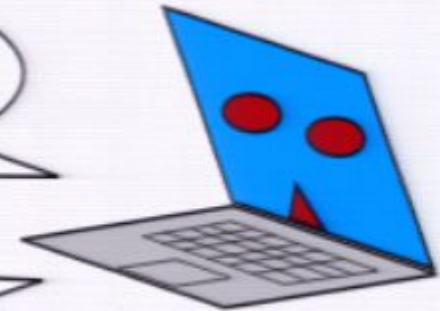


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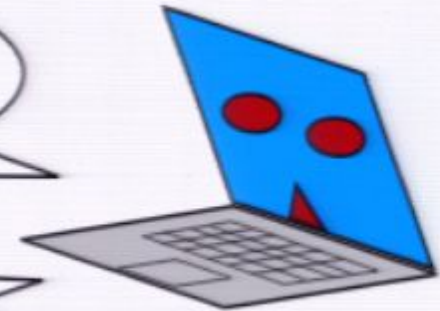


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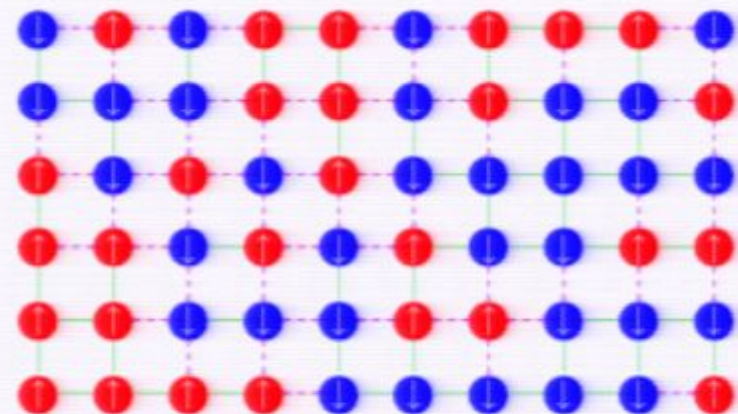
Spin Glasses

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Like ground states. But wait, there are some systems that can't find their own ground state.



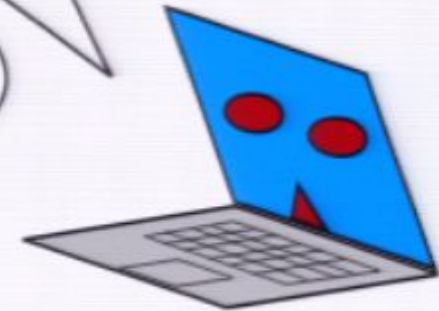
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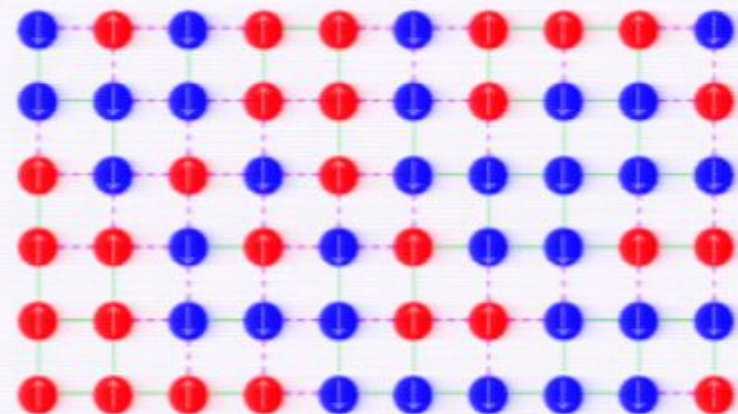
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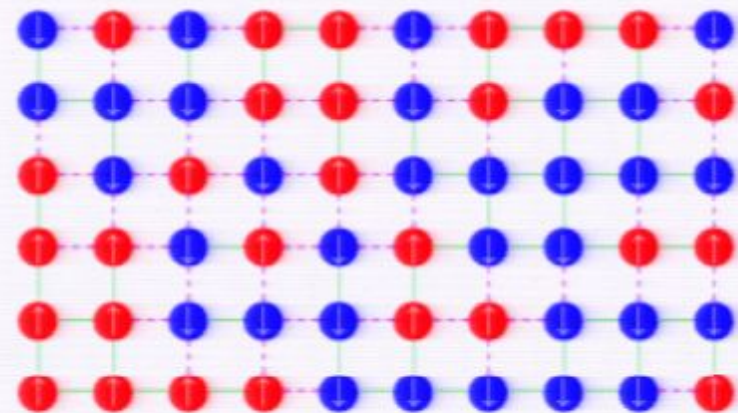
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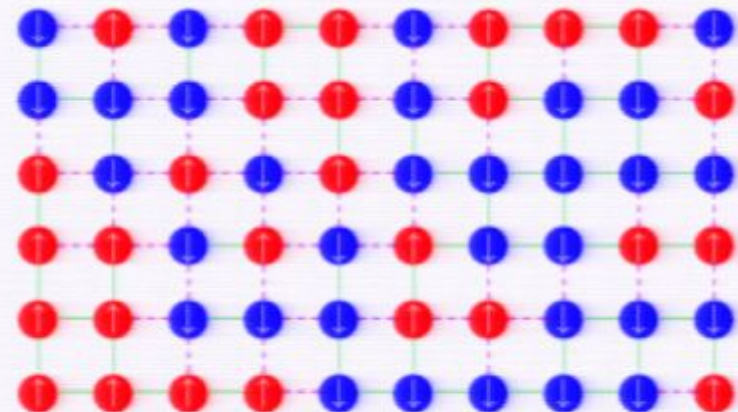
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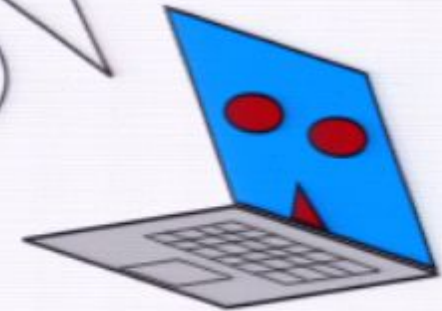
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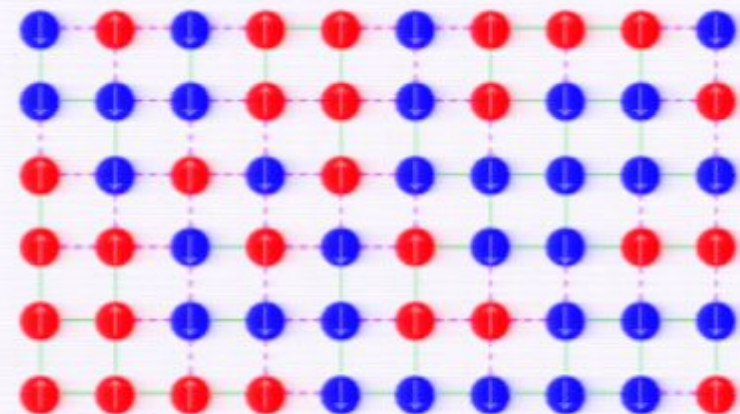
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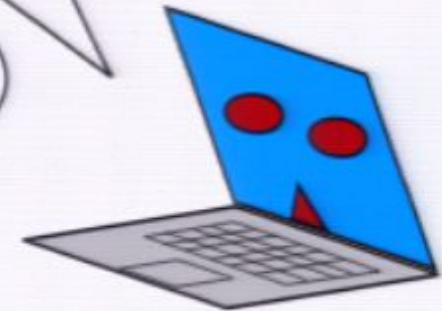
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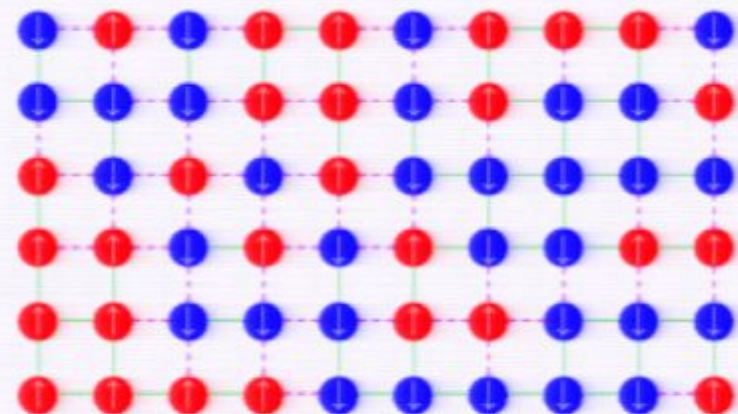
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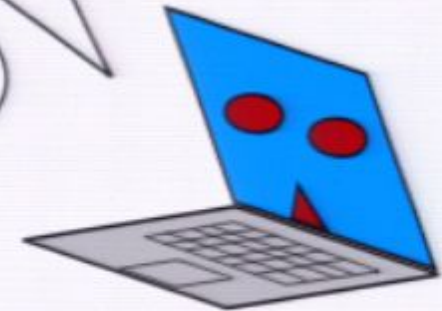
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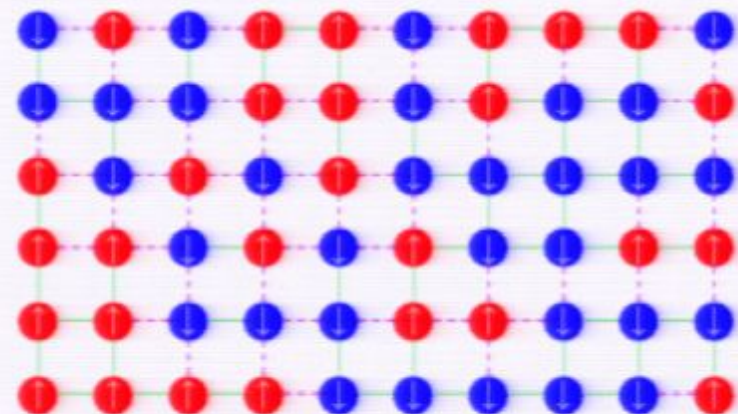
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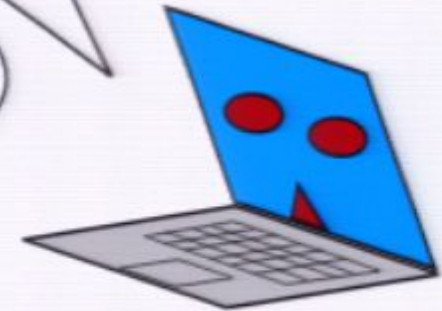
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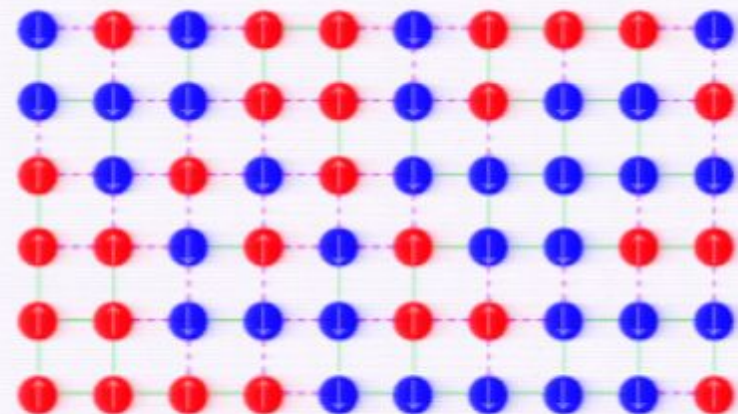
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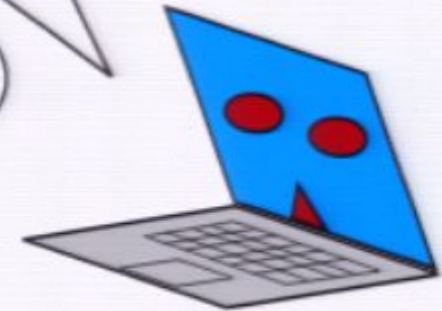
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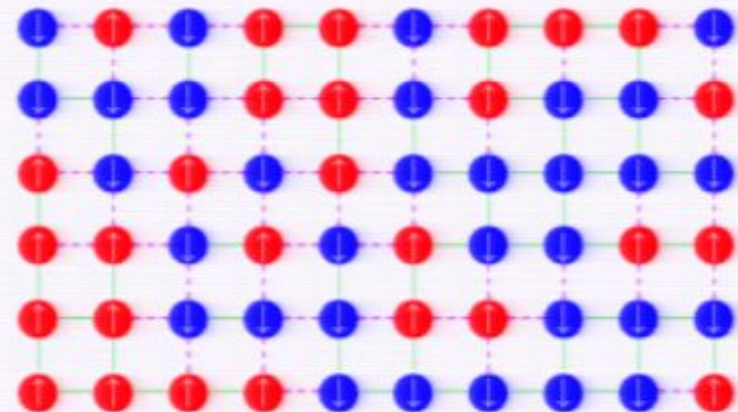
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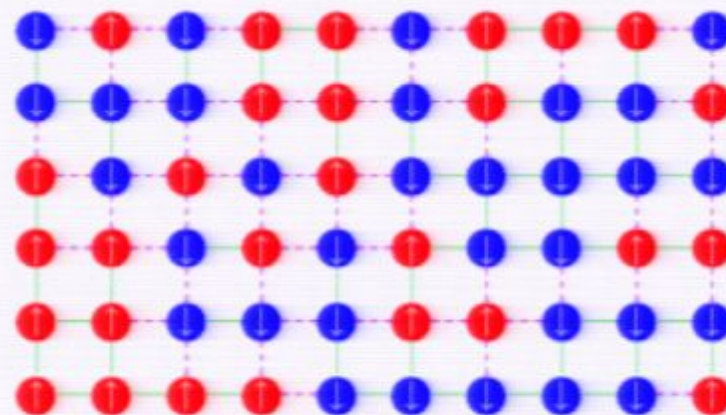
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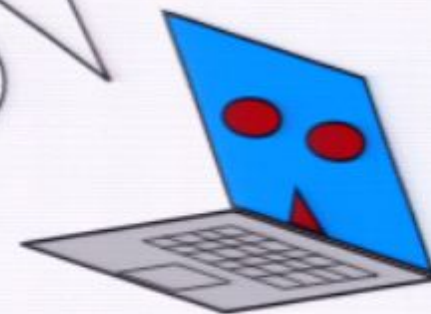
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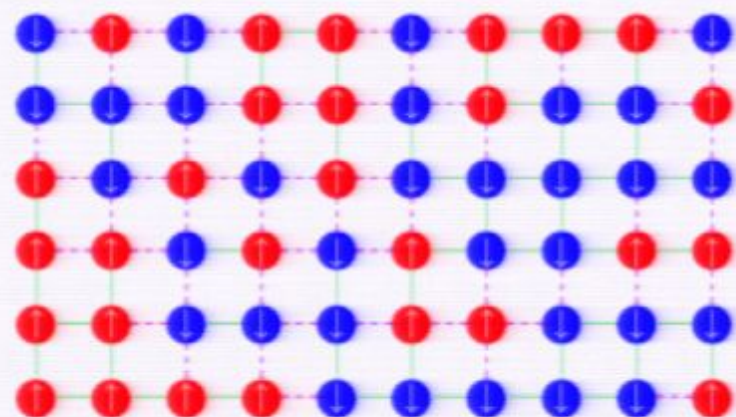
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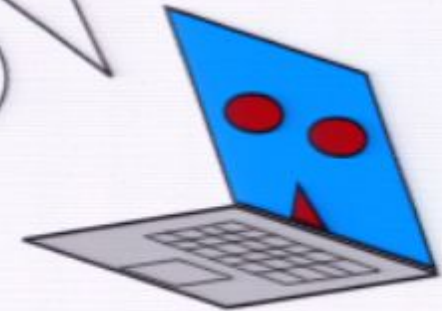
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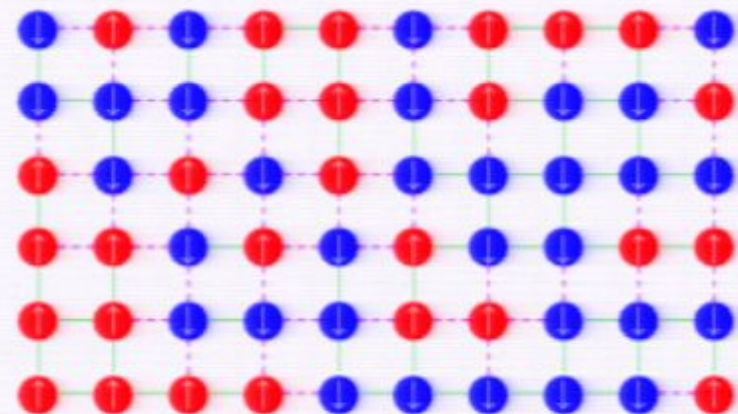
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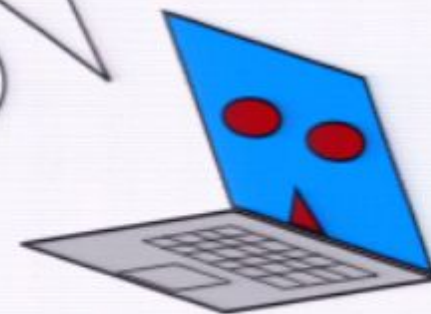
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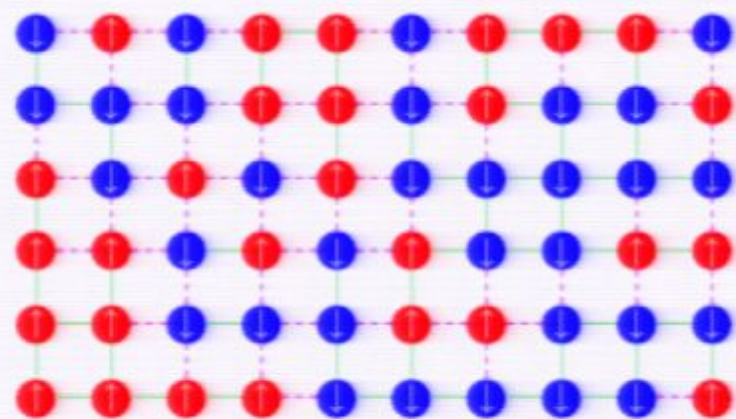
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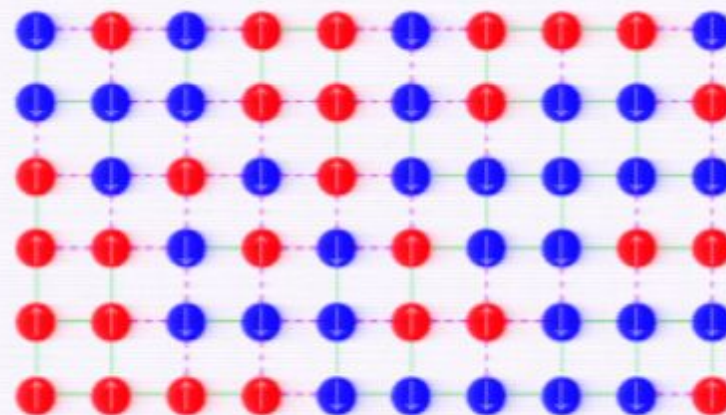
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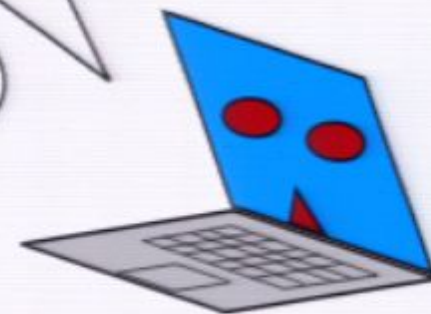
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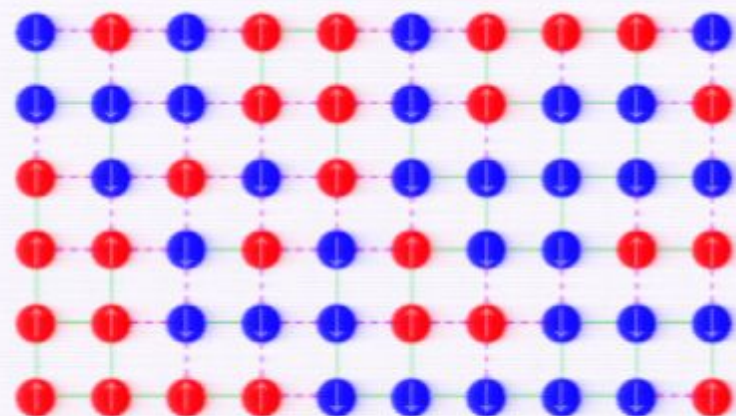
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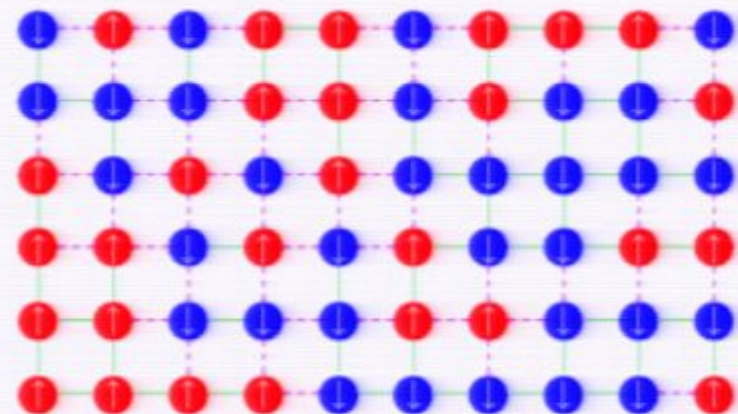
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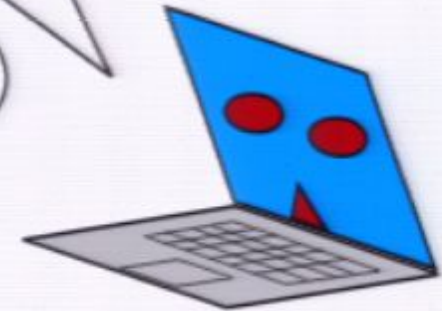
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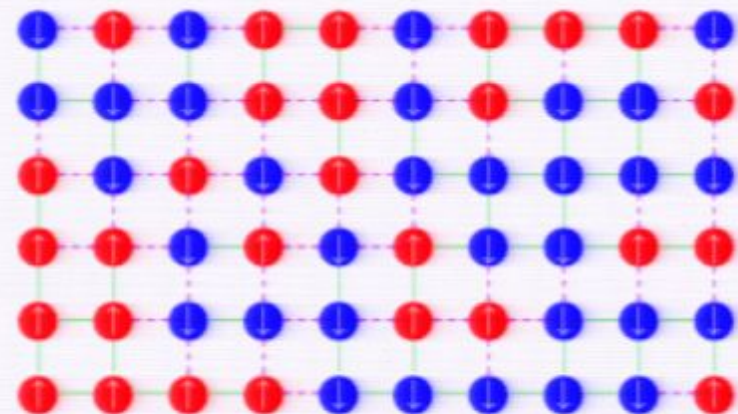
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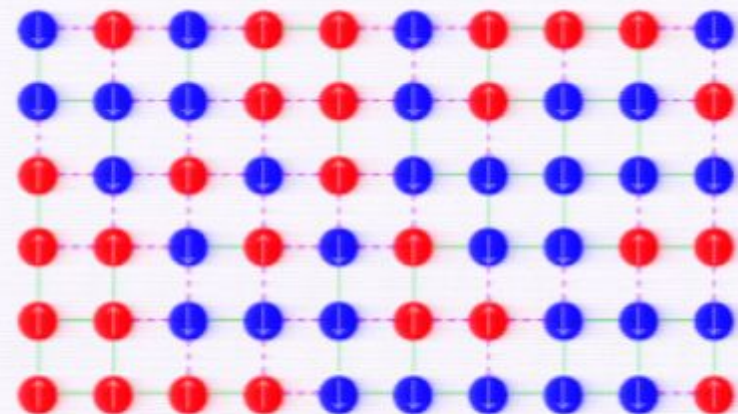
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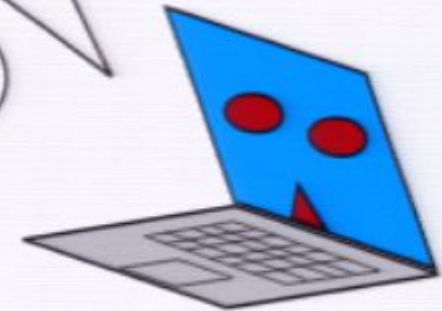
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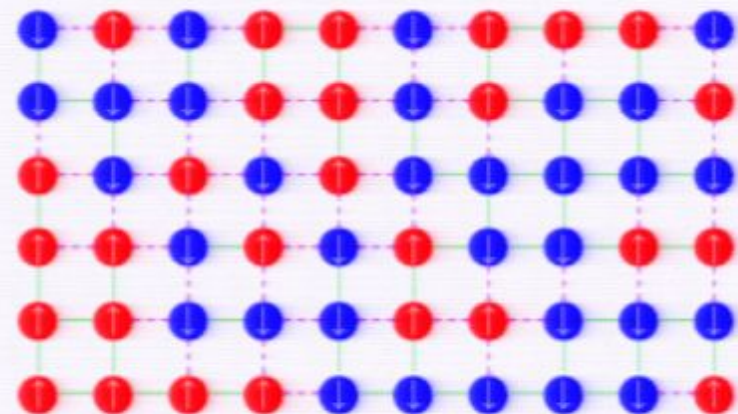
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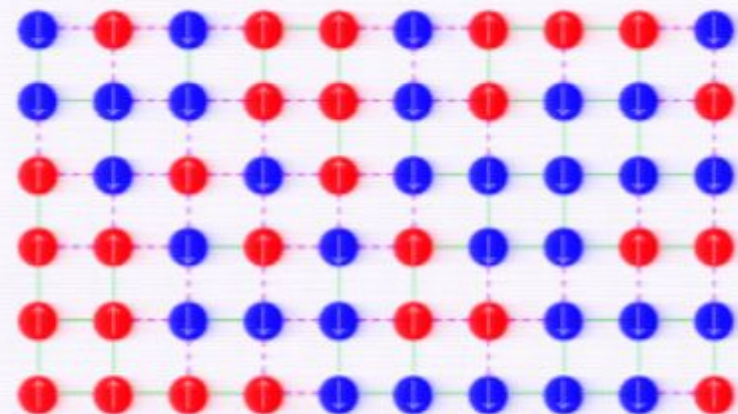
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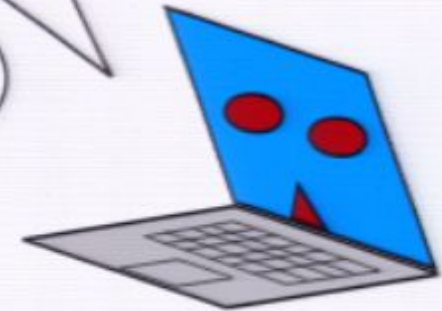
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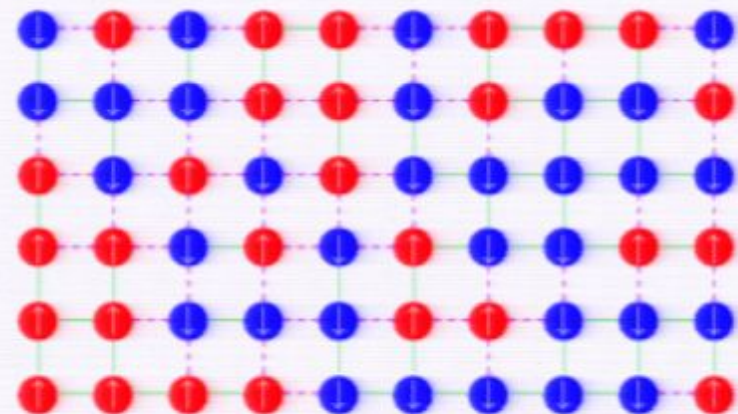
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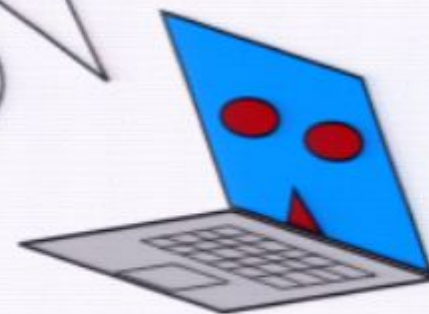
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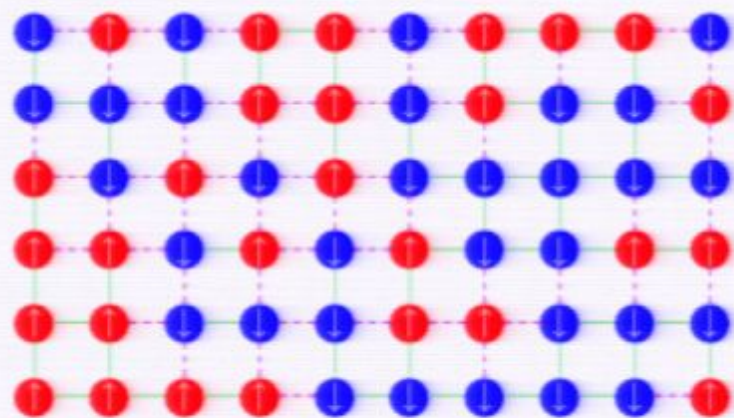
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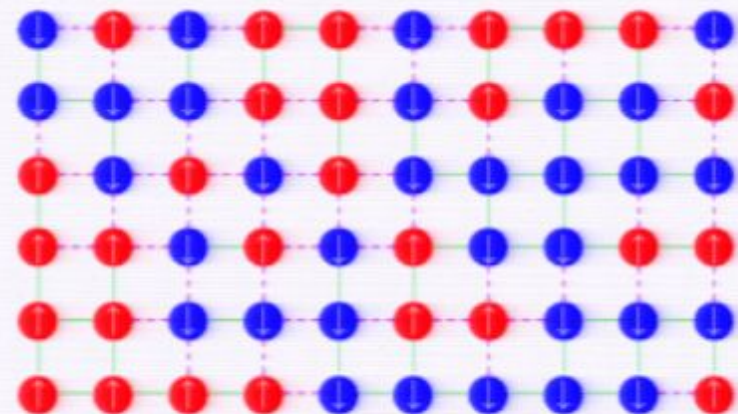
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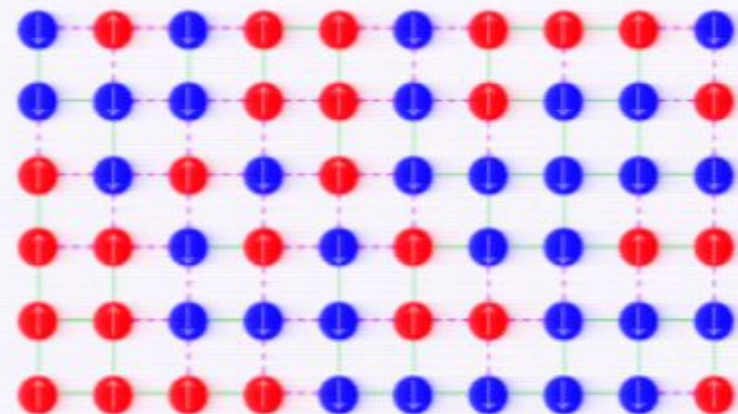
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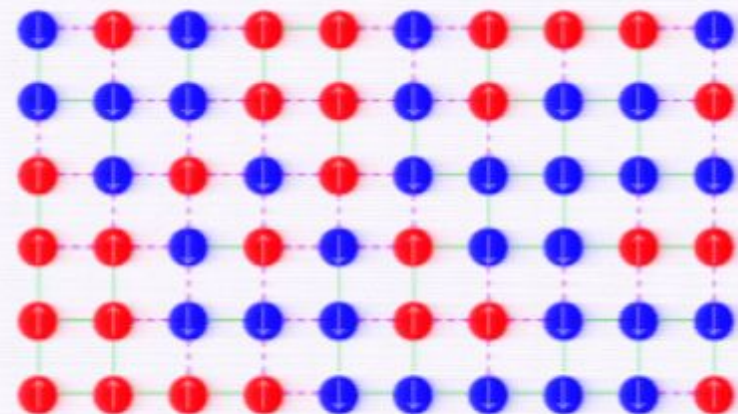
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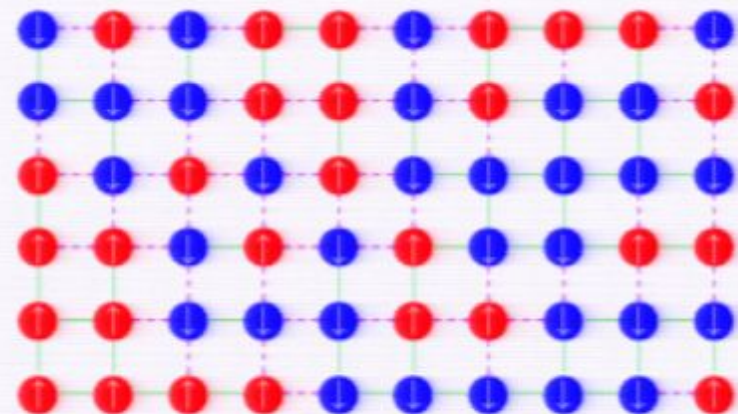
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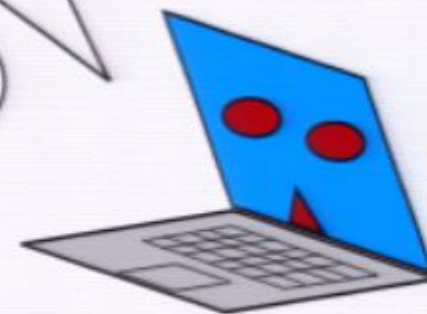
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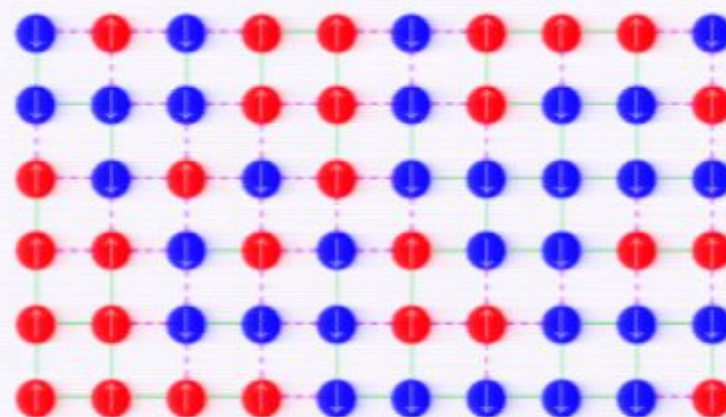
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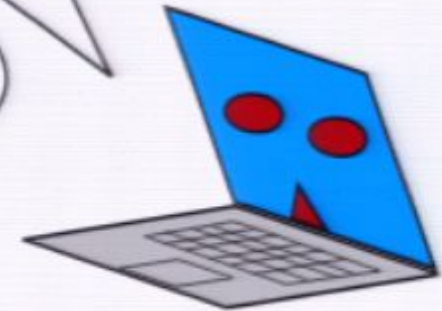
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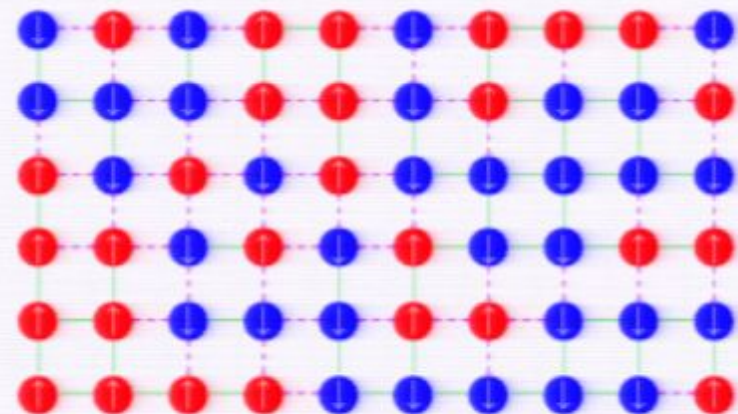
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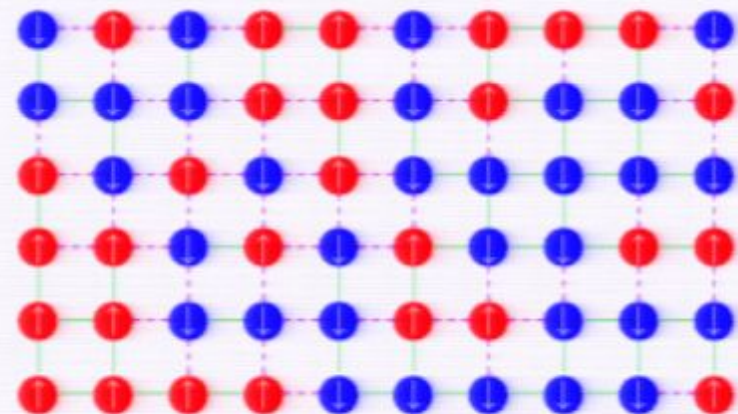
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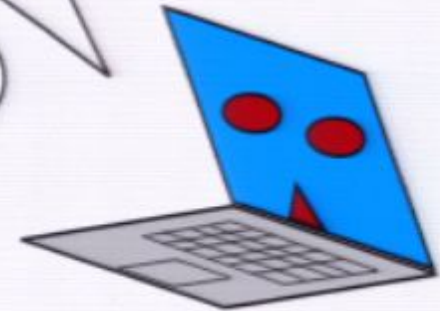
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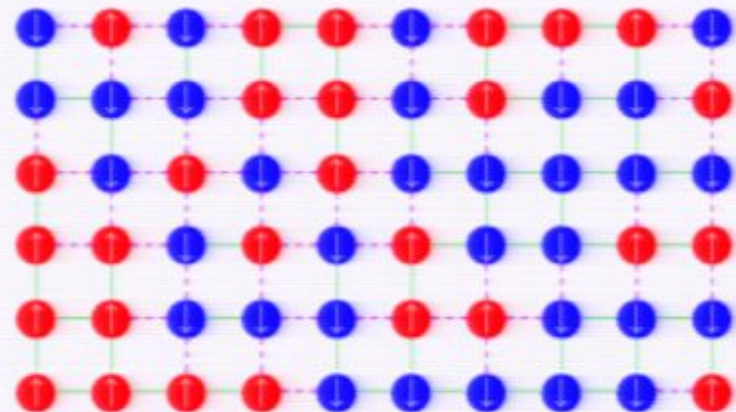
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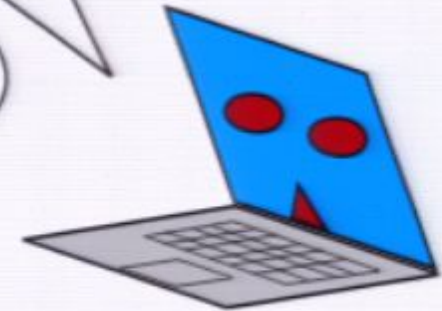
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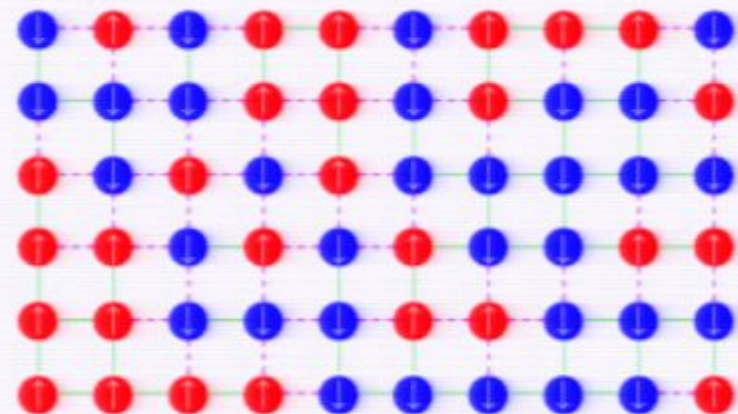
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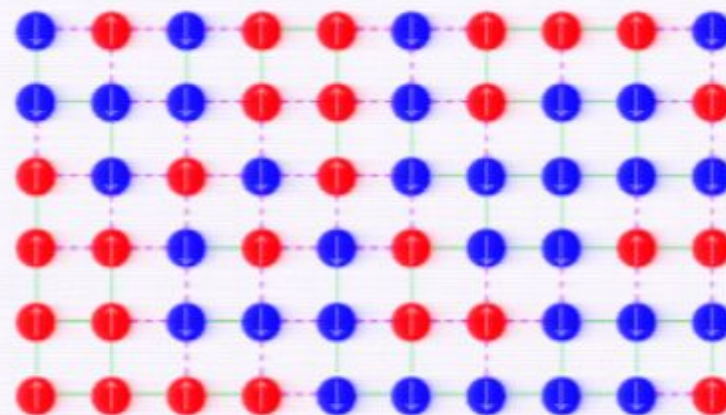
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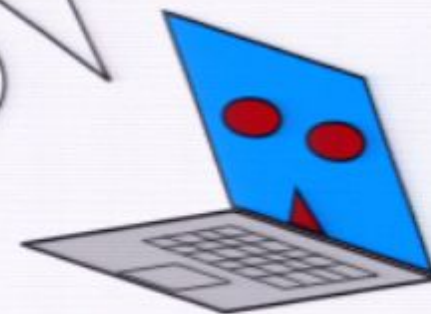
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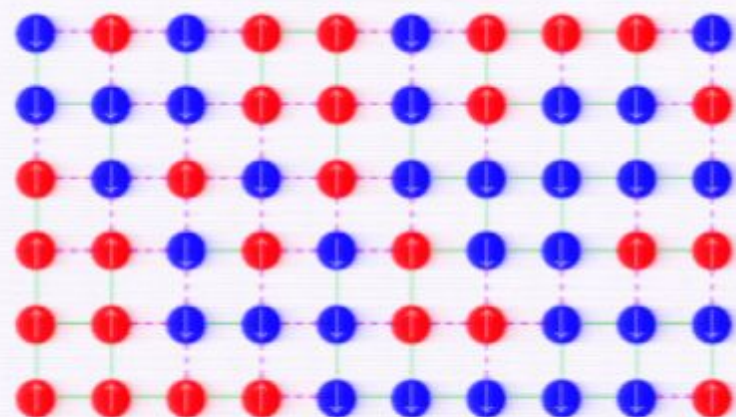
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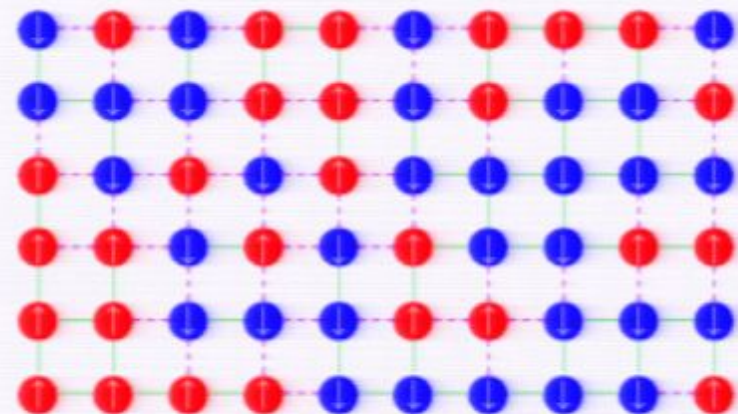
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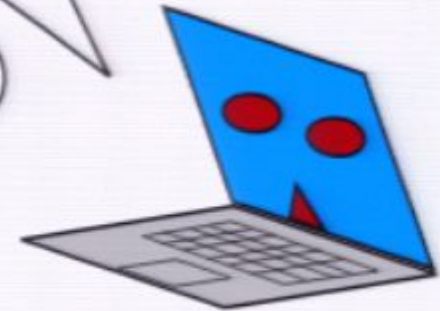
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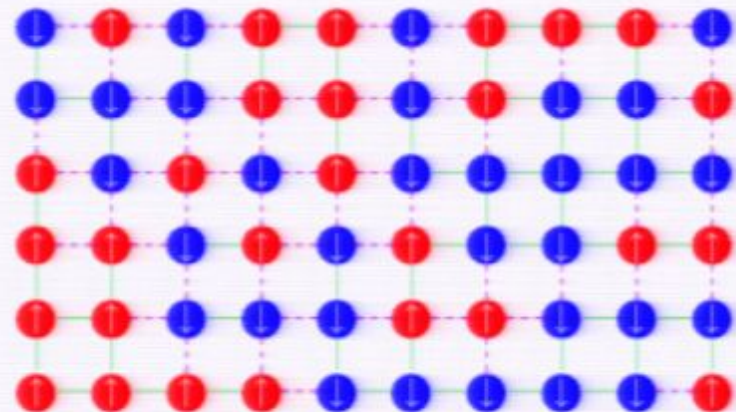
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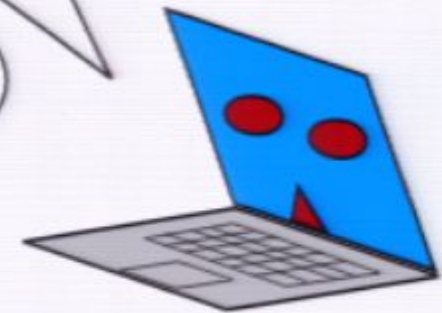
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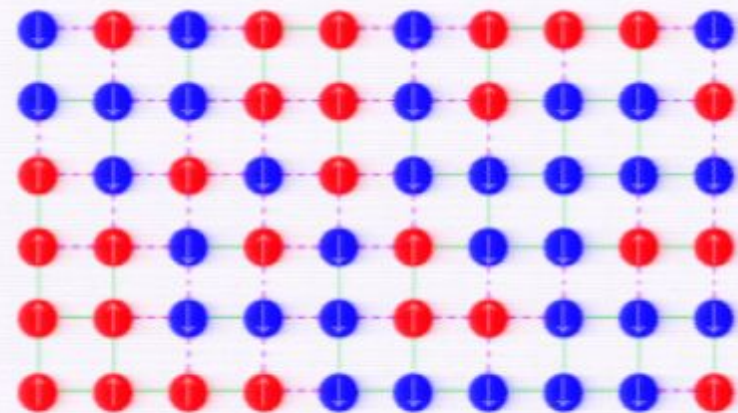
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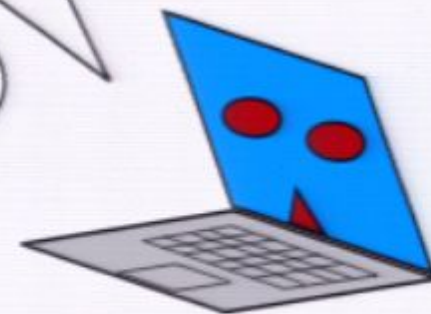
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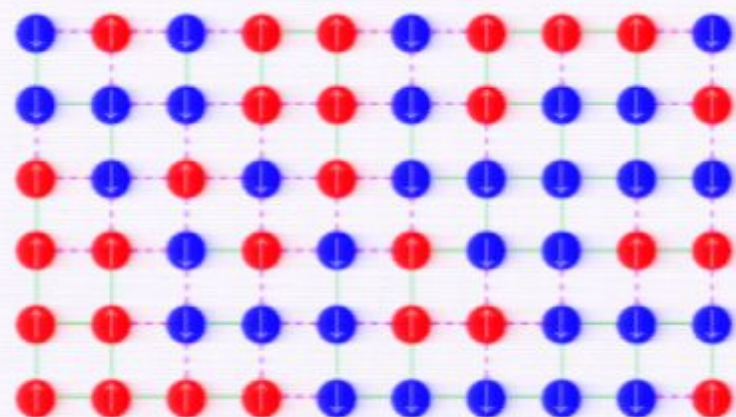
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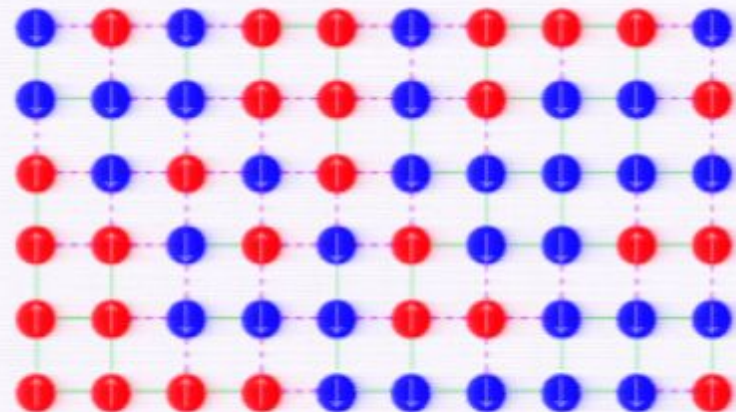
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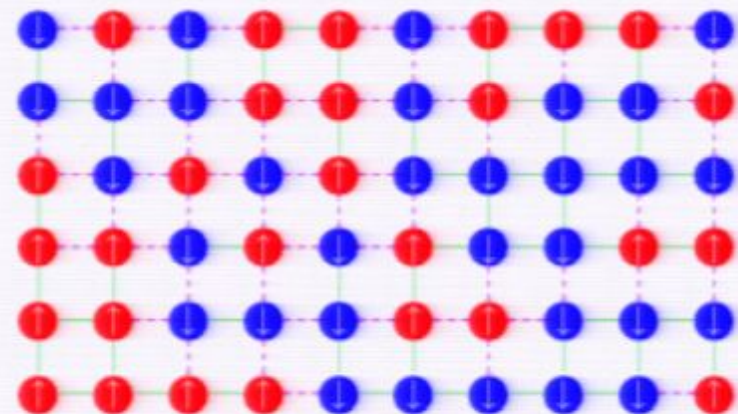
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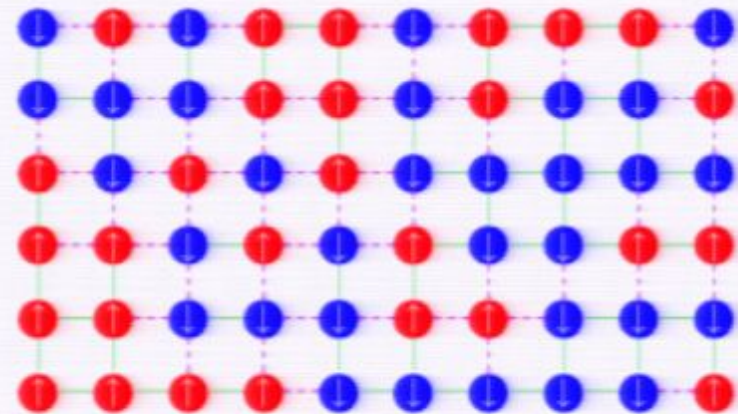
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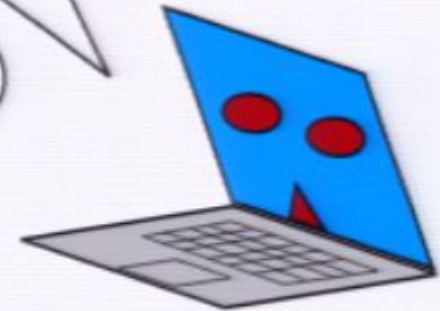
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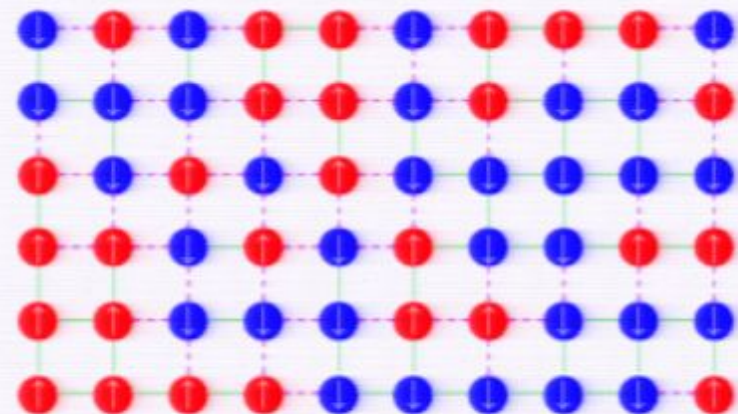
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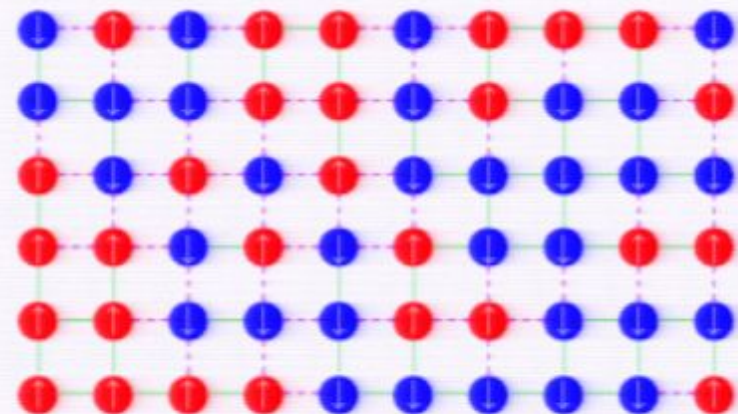
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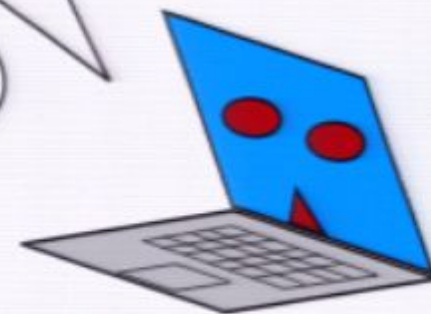
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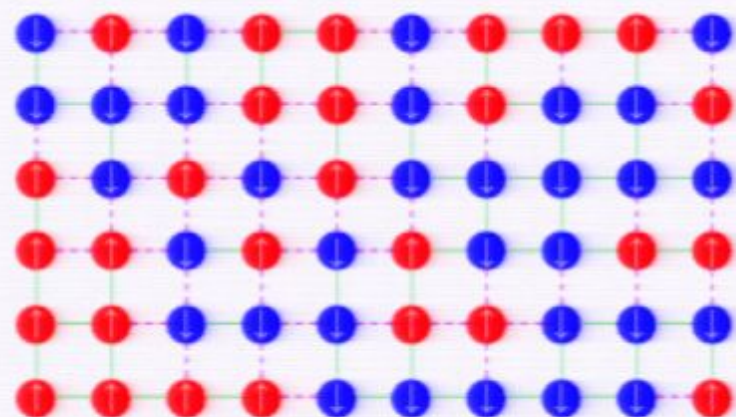
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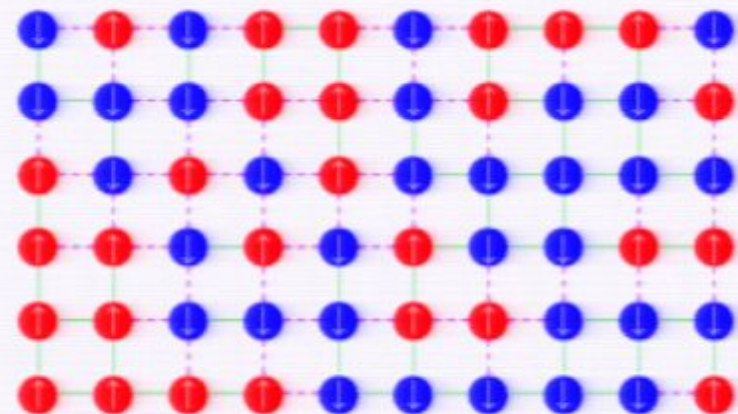
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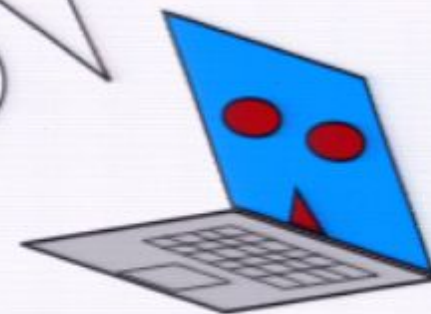
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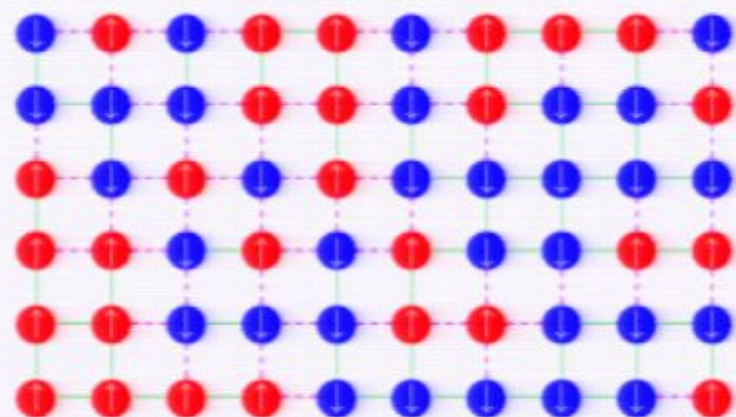
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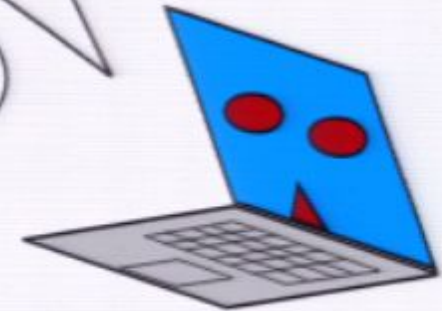
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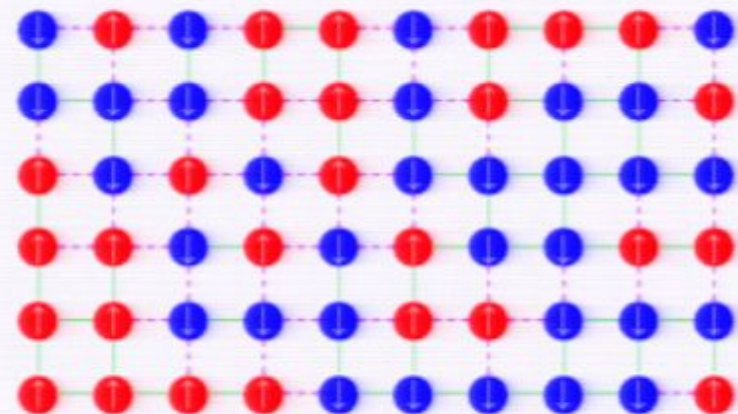
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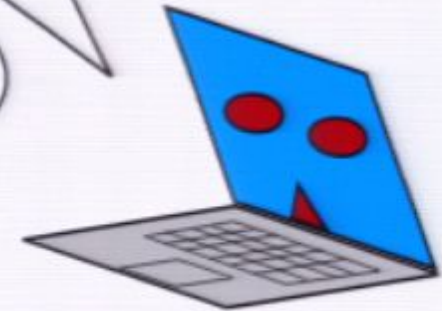
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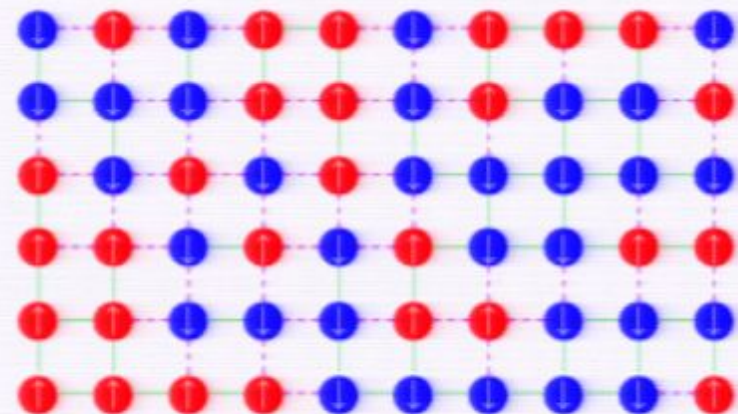
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Like ground states. But wait, there are some systems that can't find their own ground state.



A **spin glass** is a spin system with the property that, at low temperatures, it does not relax to its true ground state, but instead gets caught in local energy minima.



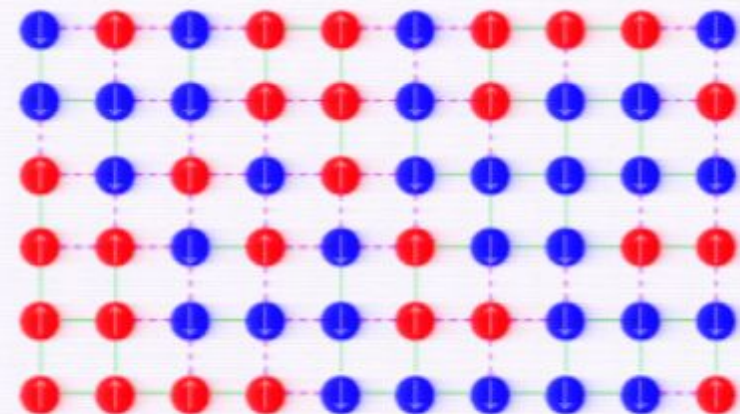
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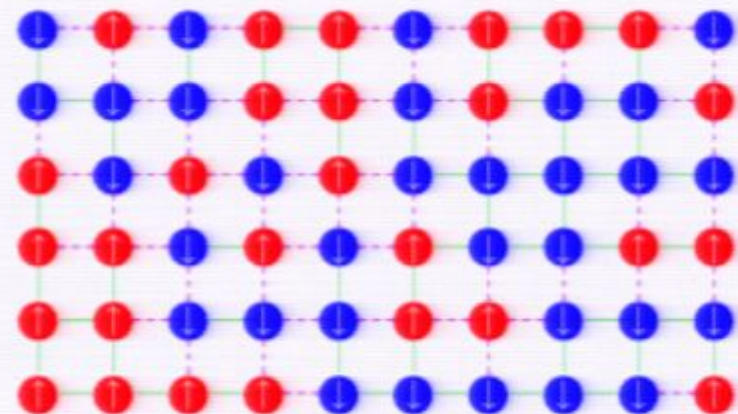
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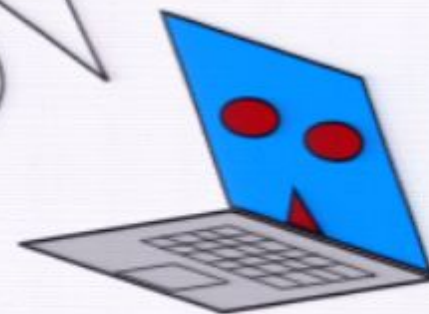
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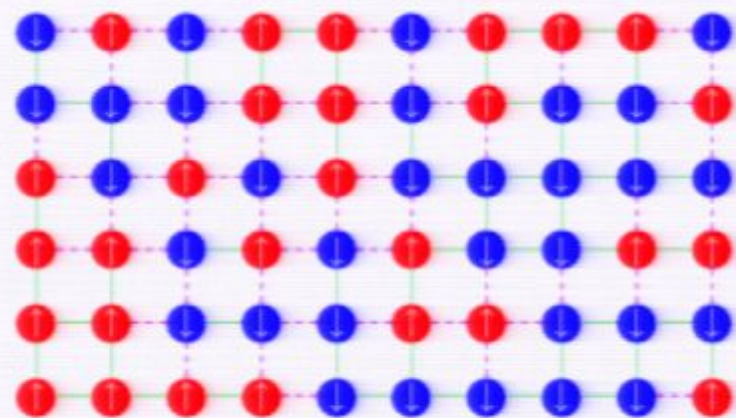
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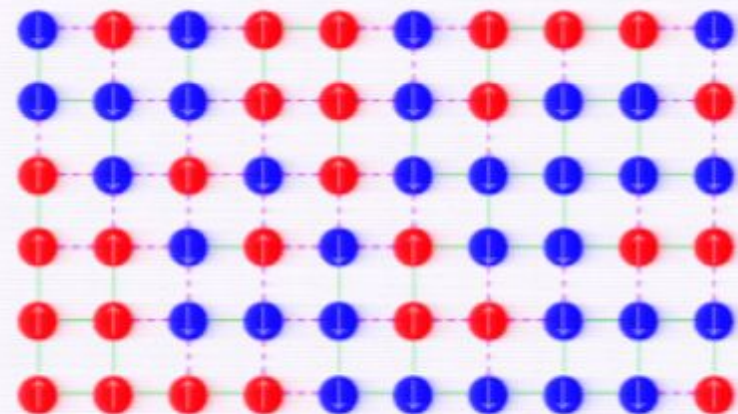
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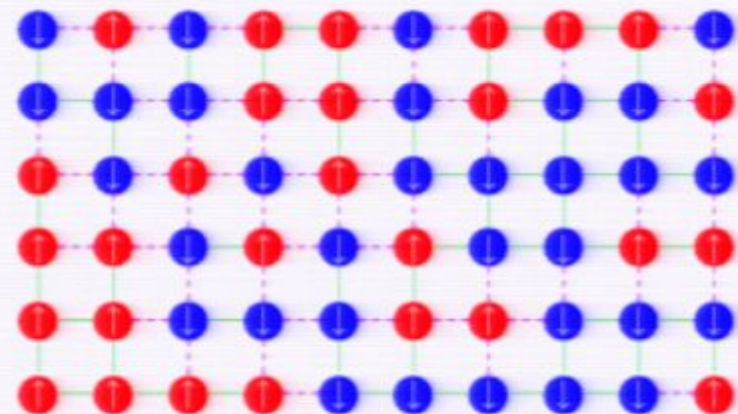
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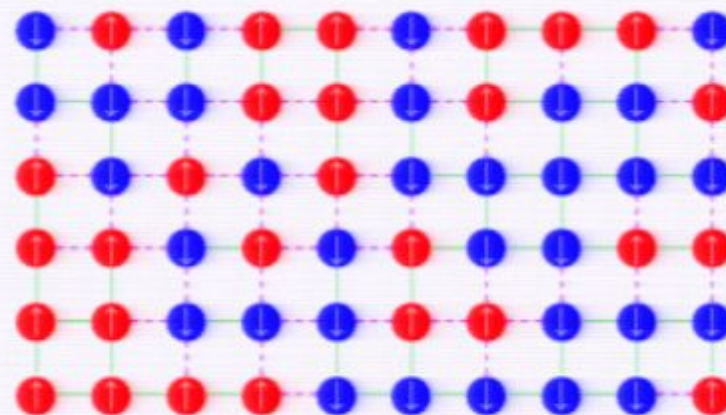
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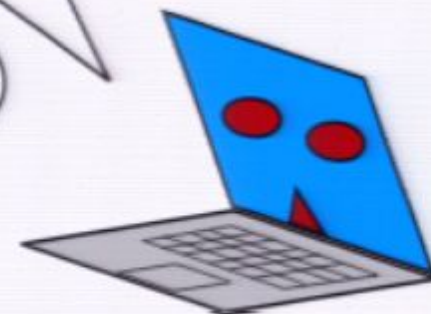
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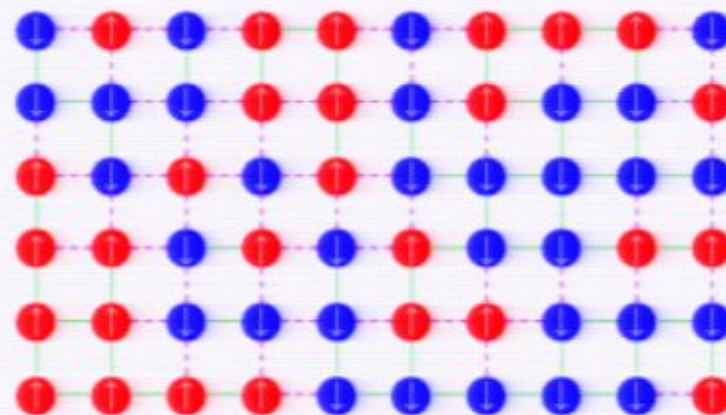
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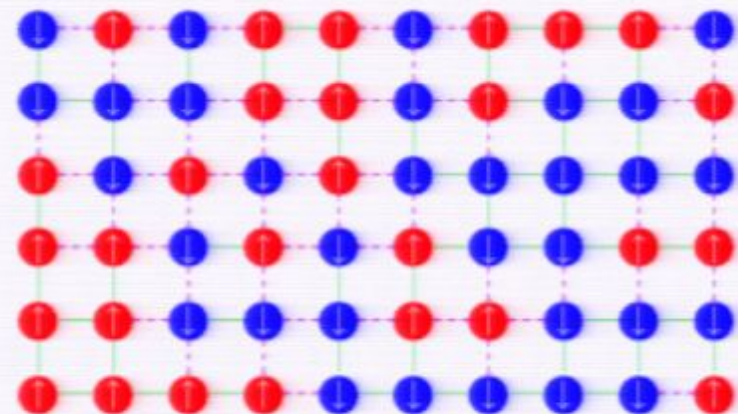
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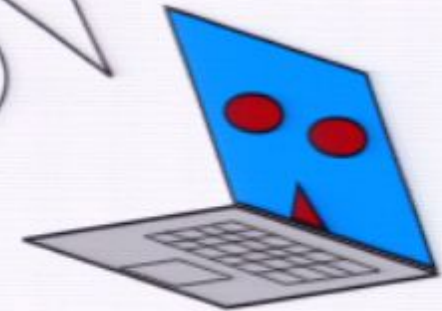
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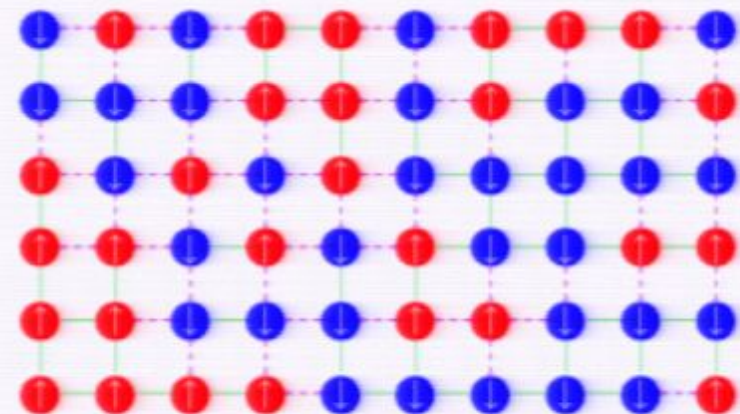
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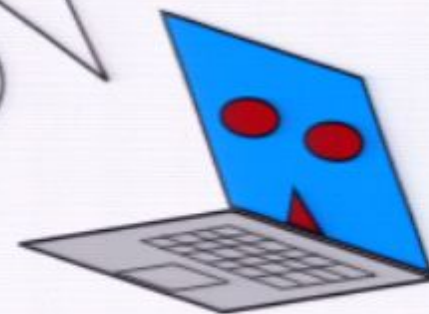
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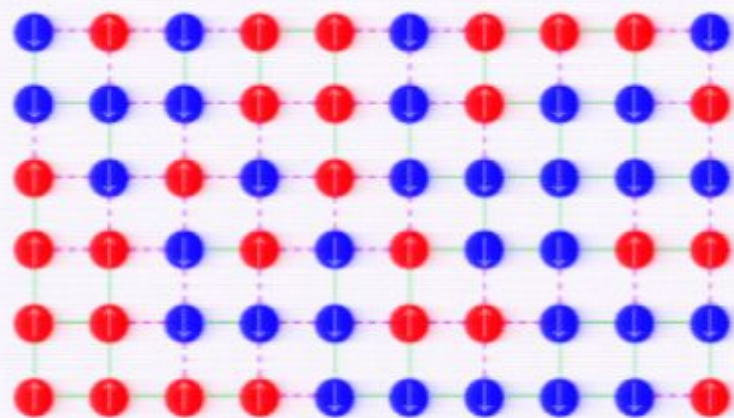
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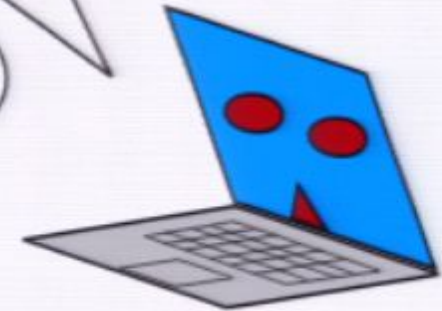
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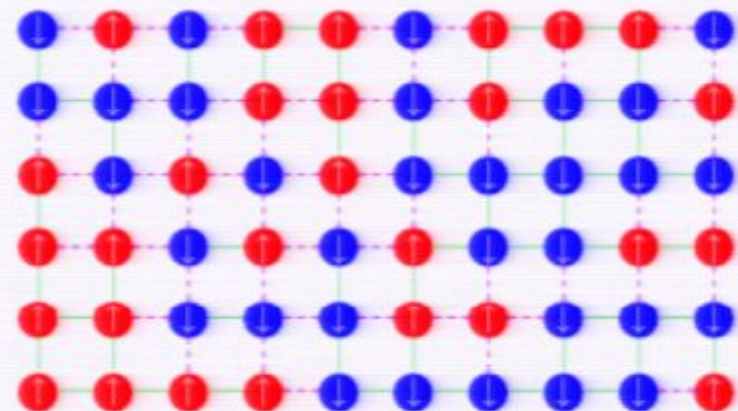
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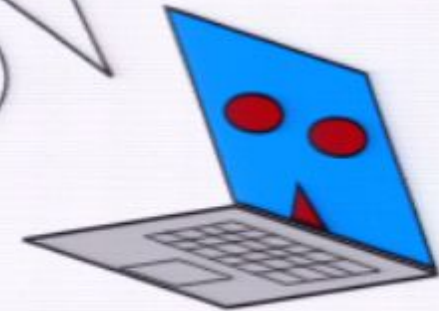
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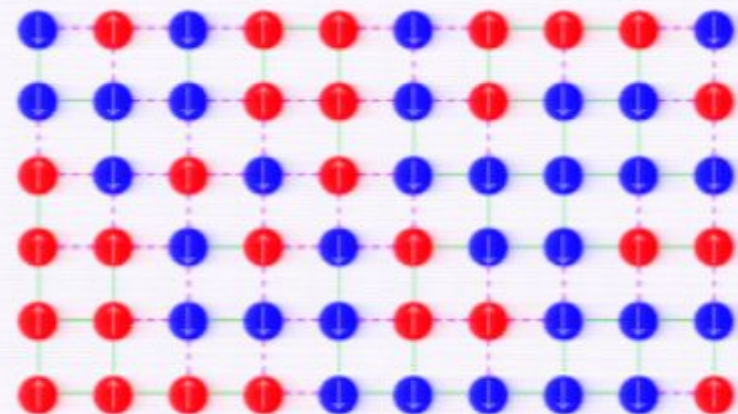
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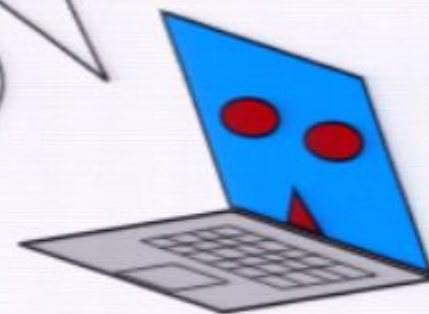
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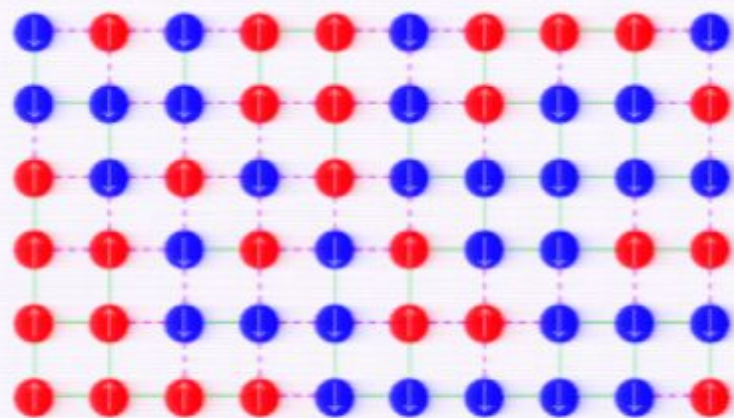
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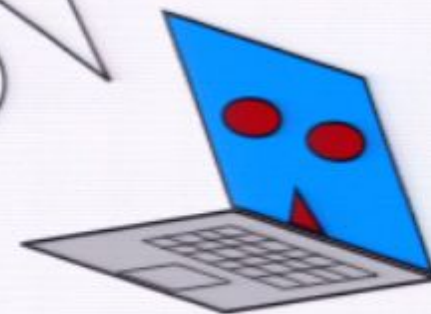
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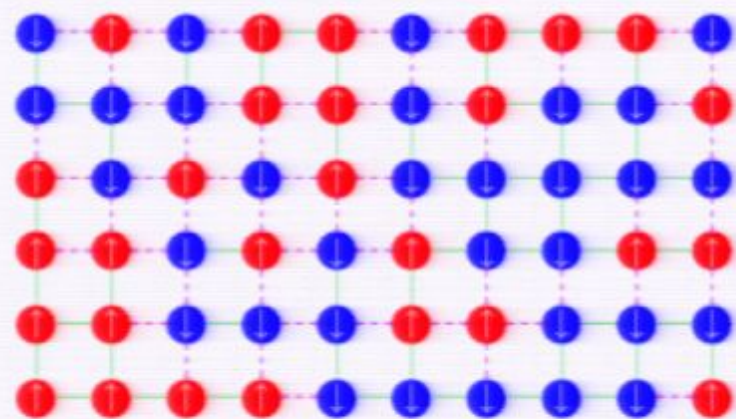
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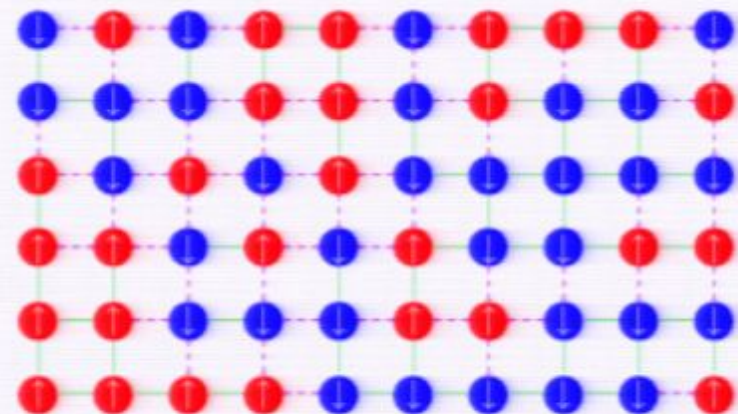
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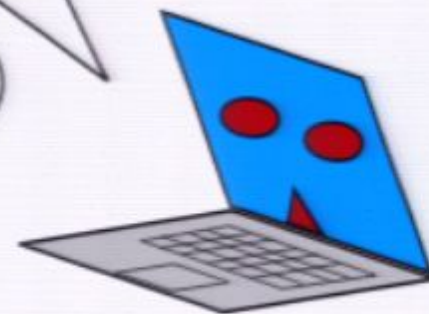
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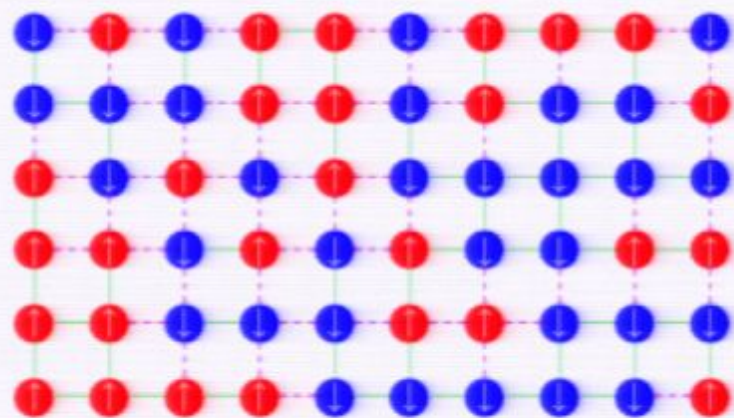
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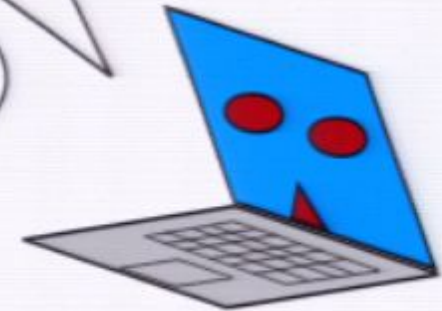
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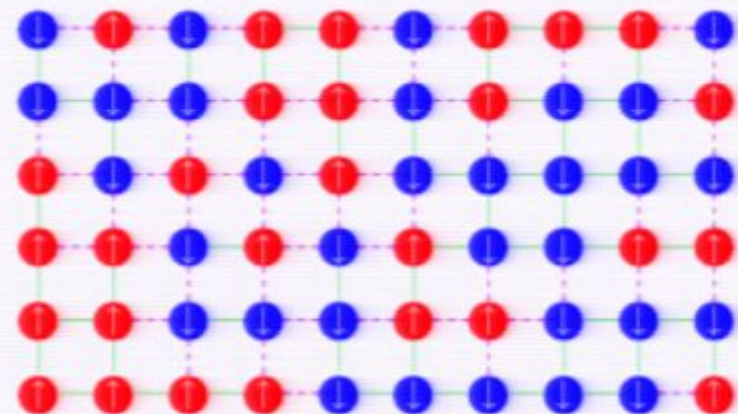
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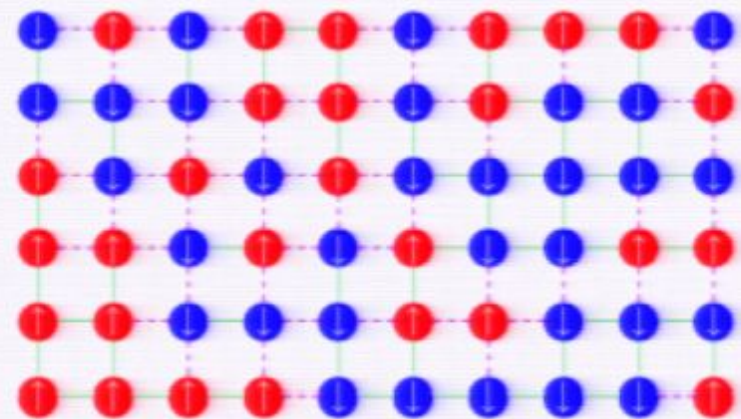
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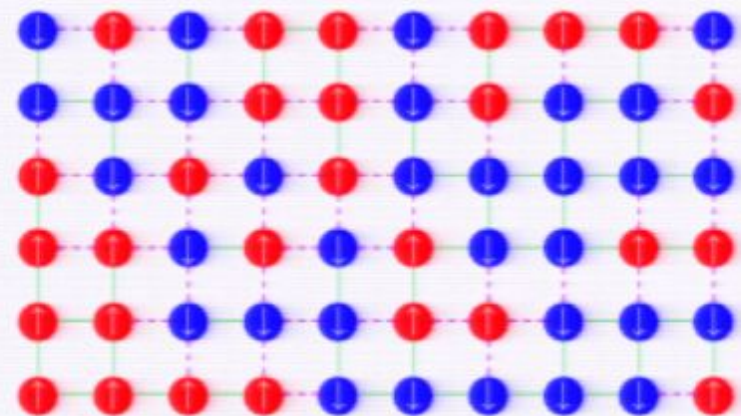
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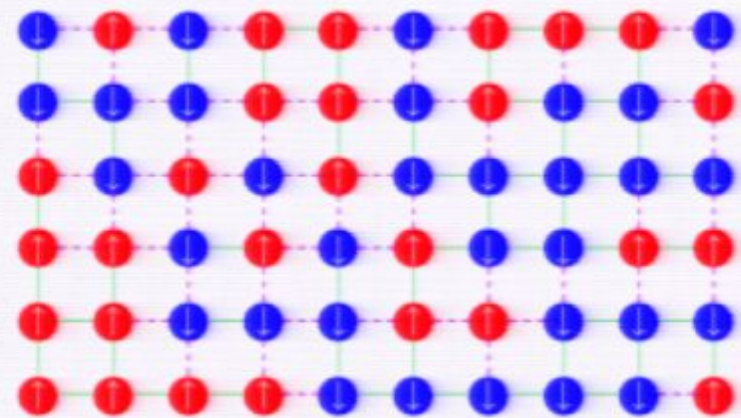
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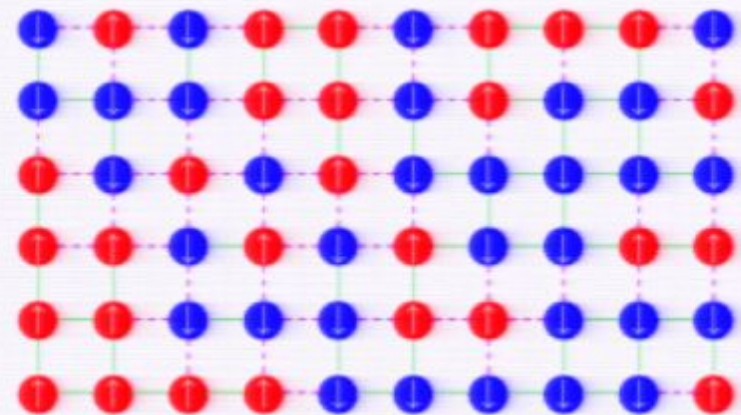
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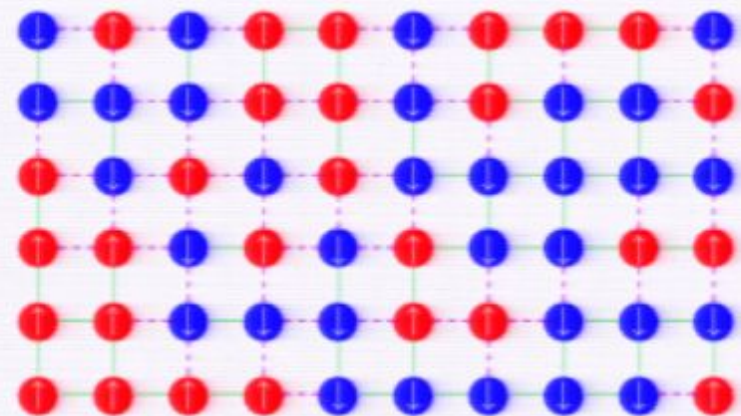
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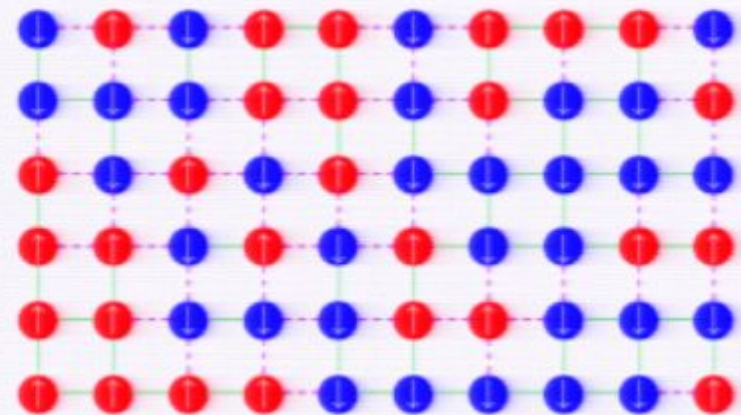
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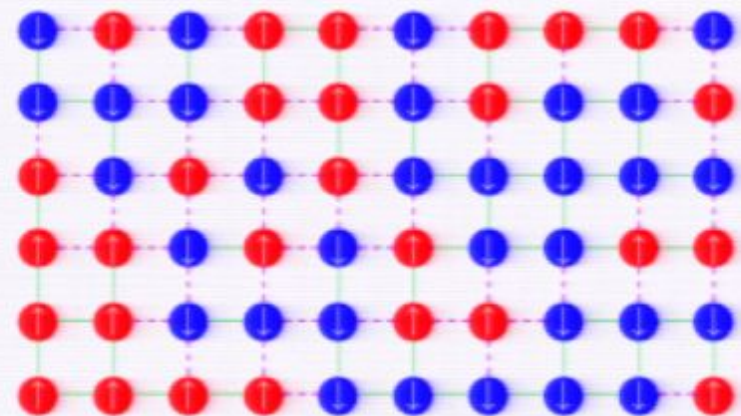
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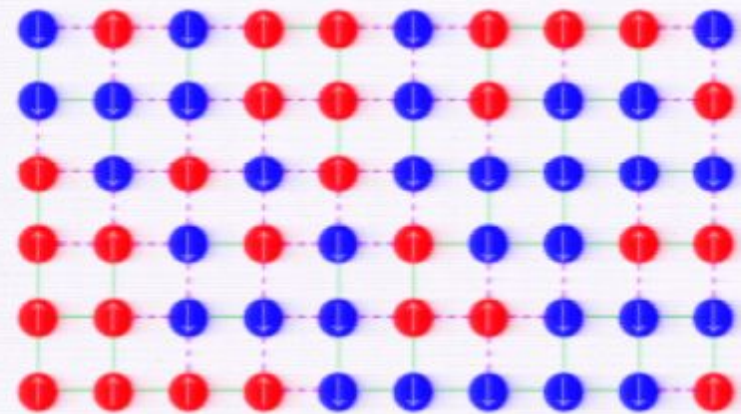
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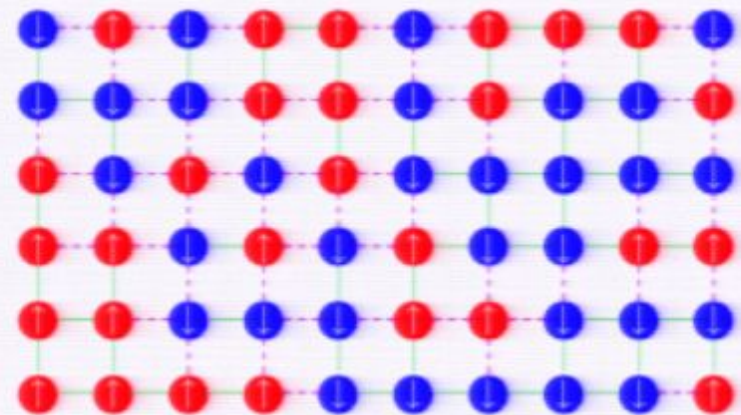
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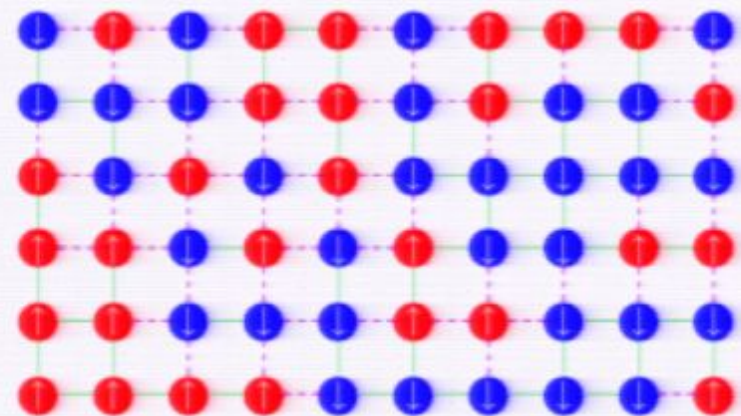
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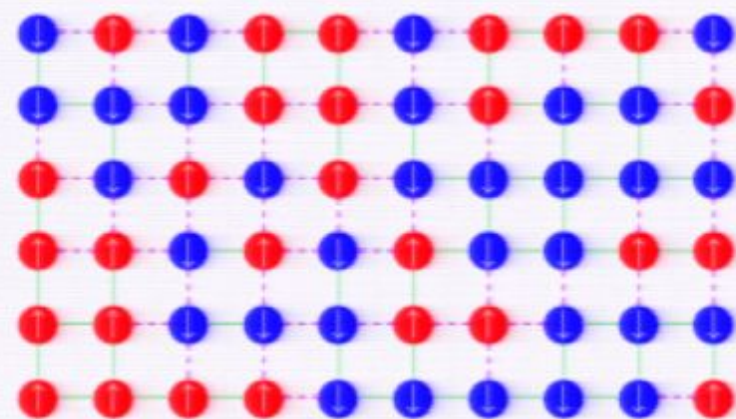
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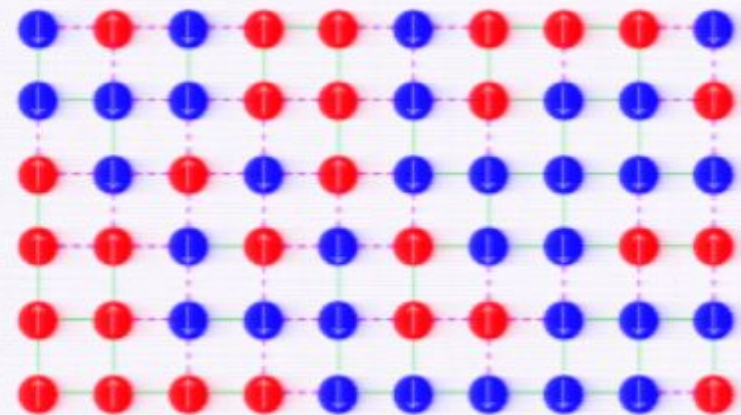
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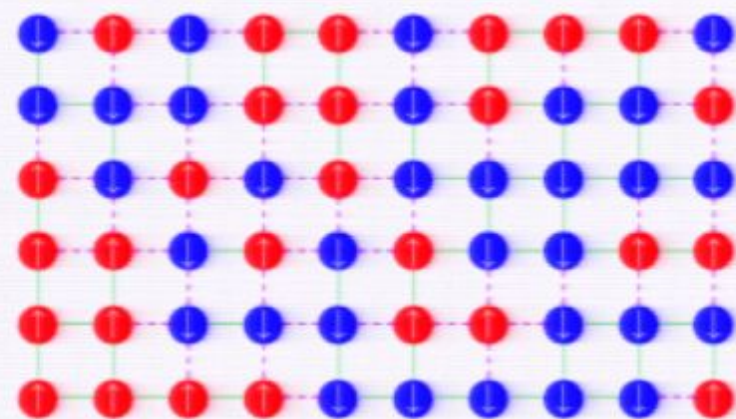
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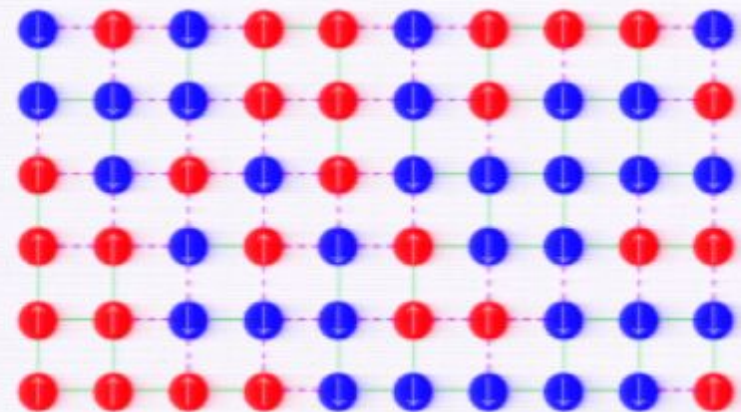
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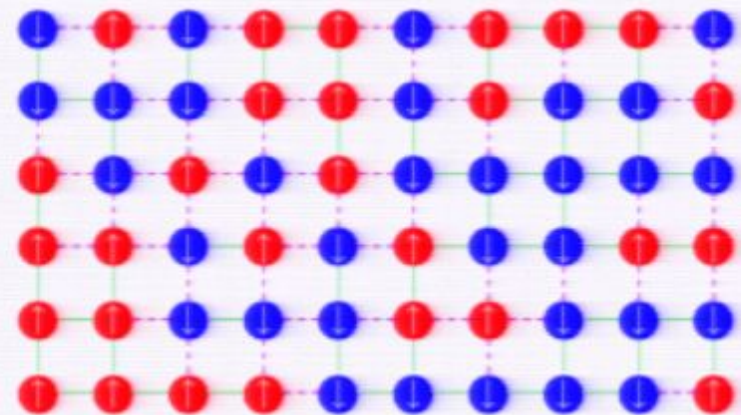
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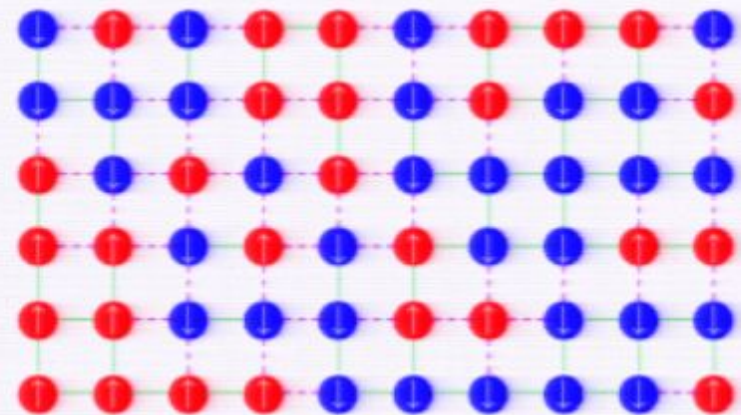
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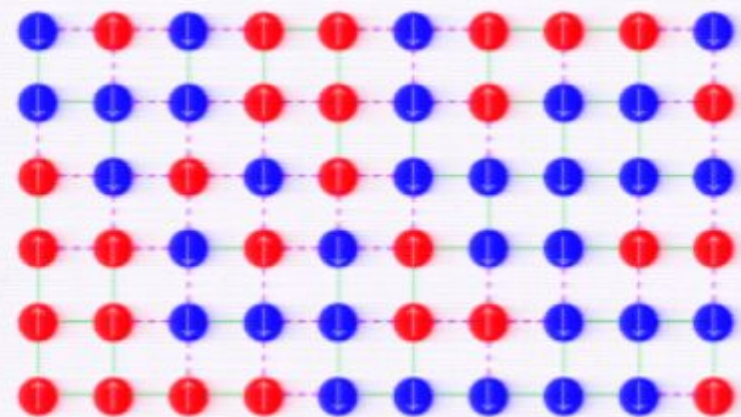
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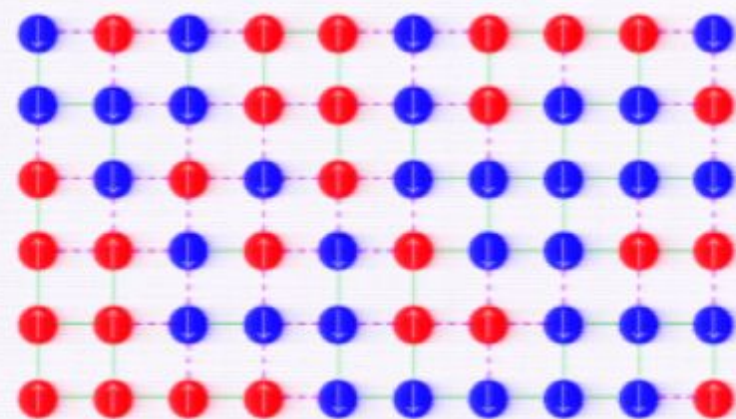
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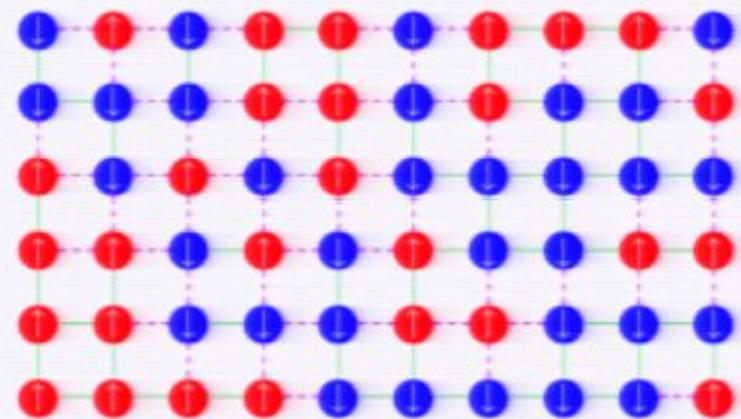
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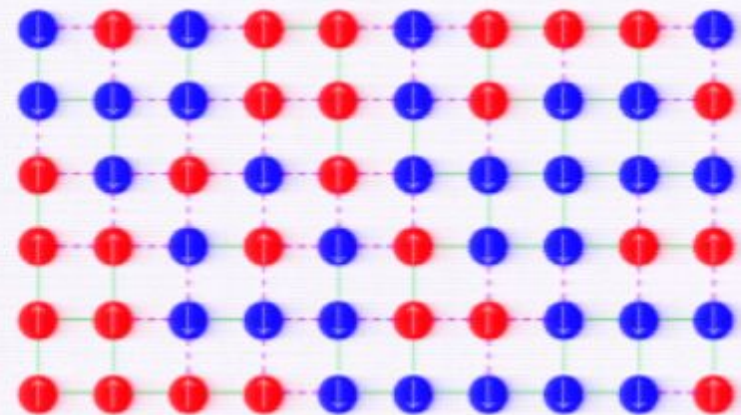
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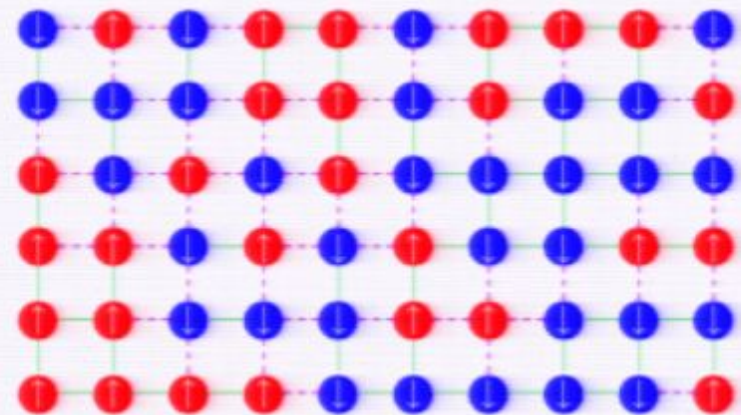
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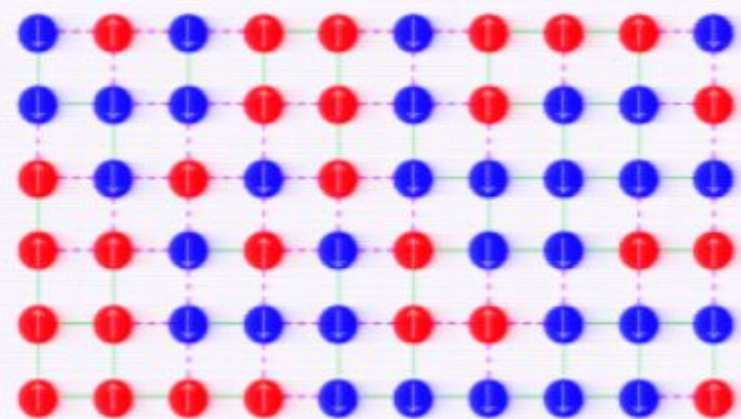
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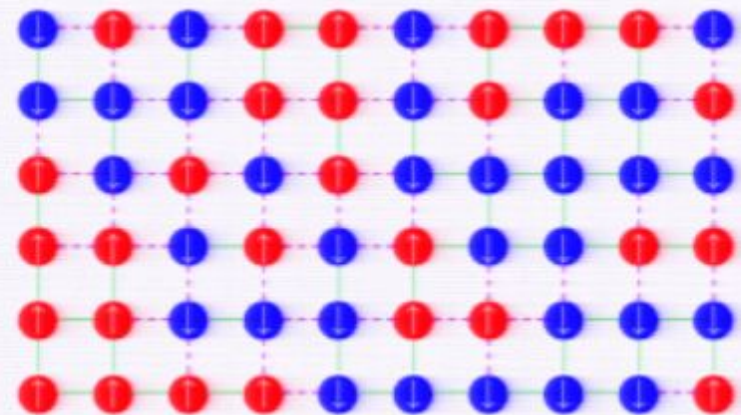
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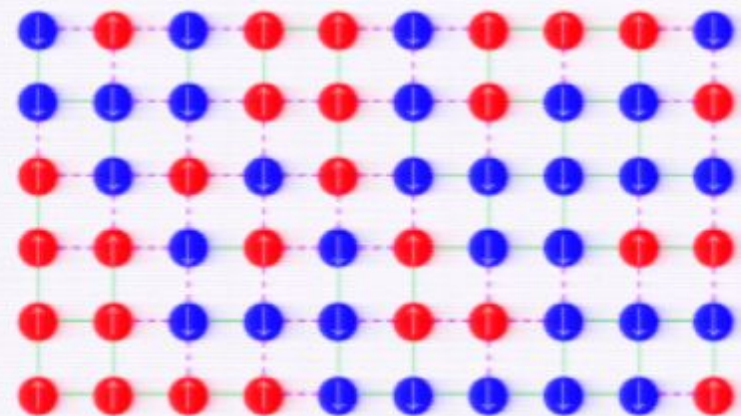
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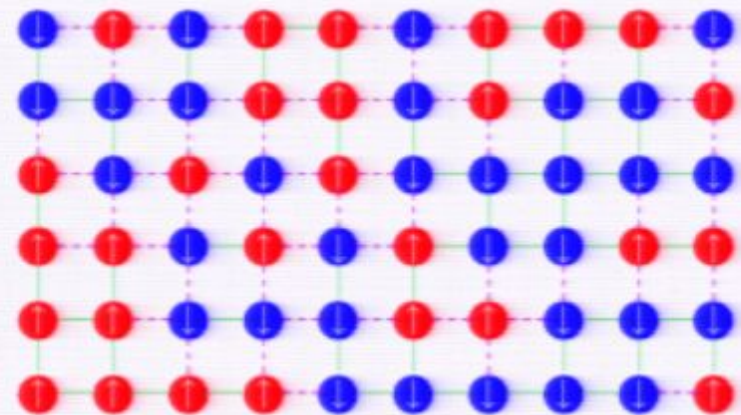
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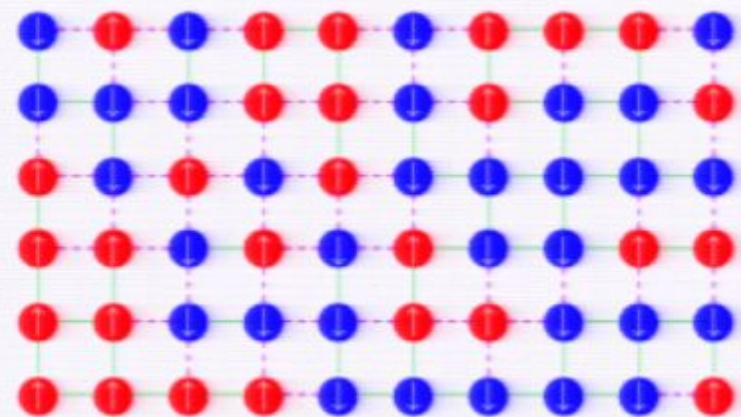
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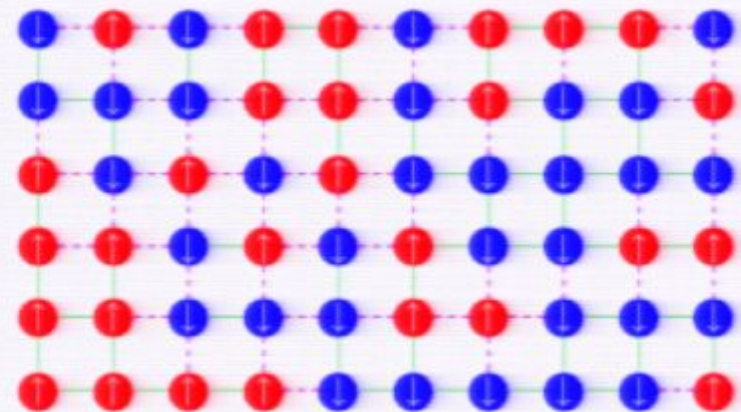
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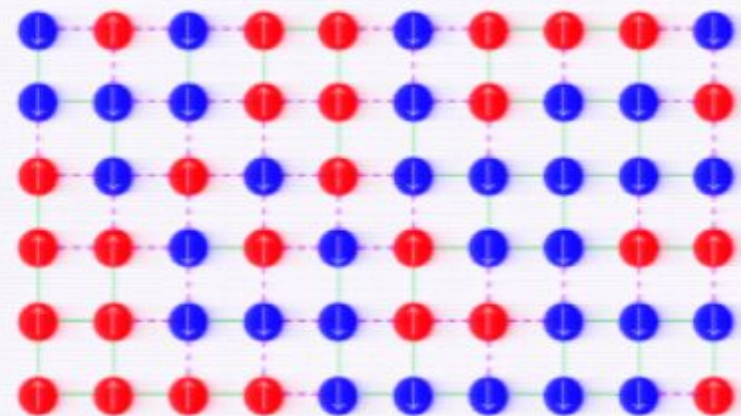
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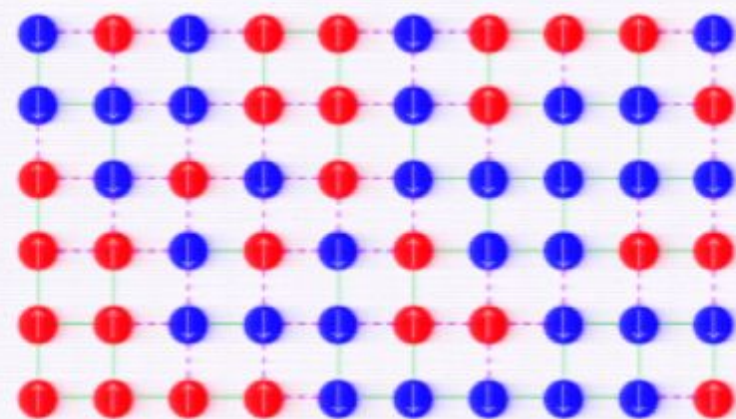
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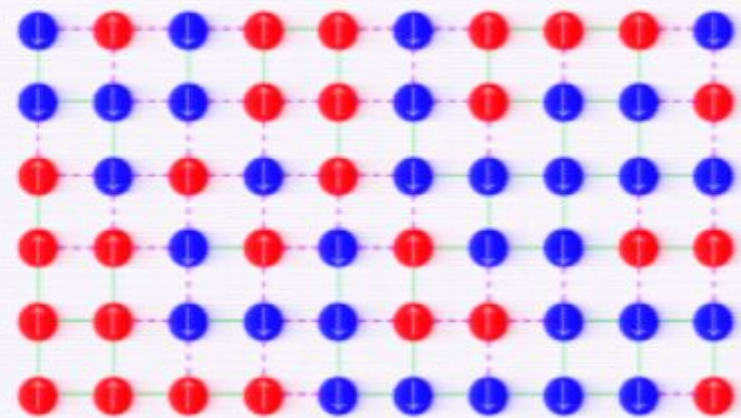
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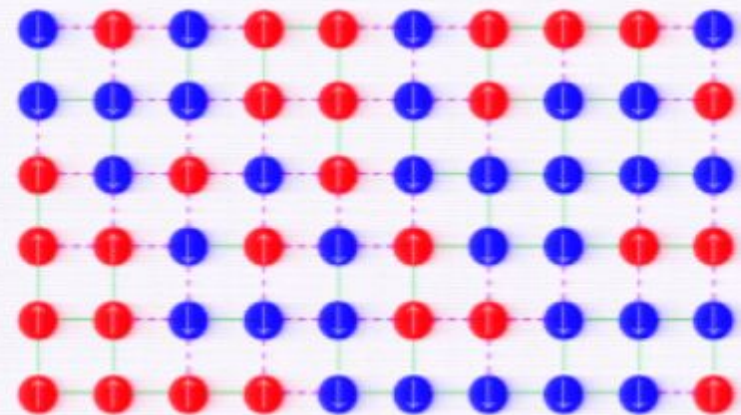
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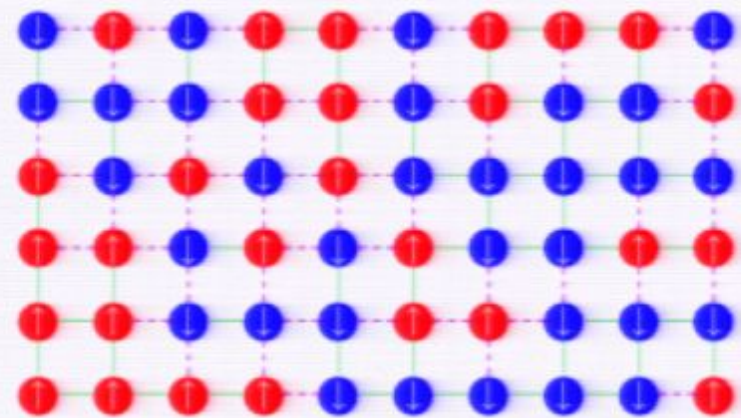
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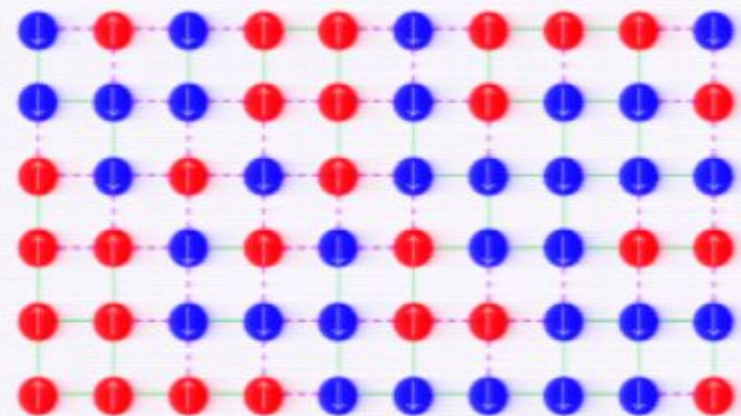
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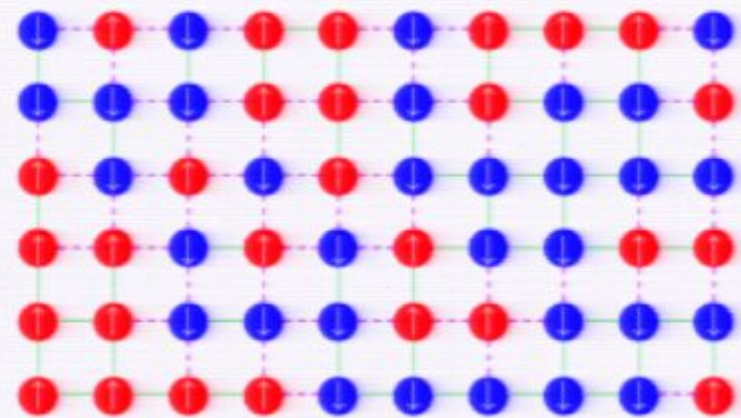
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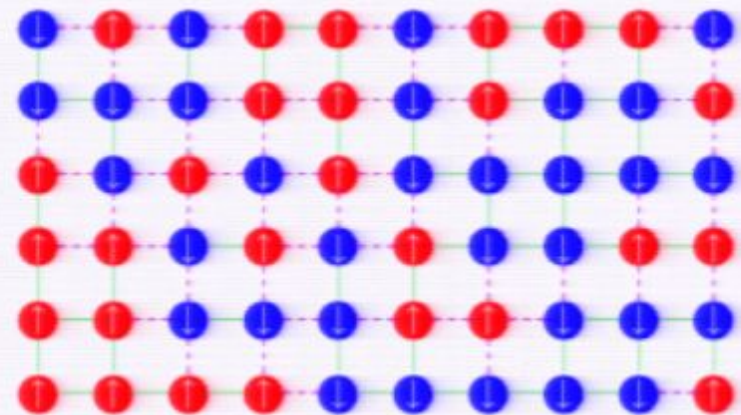
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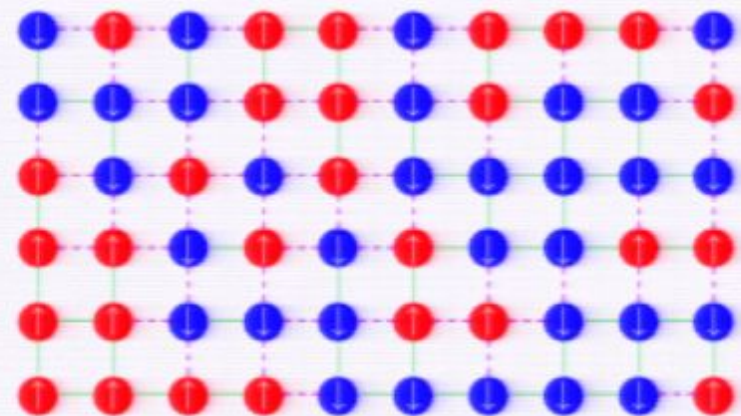
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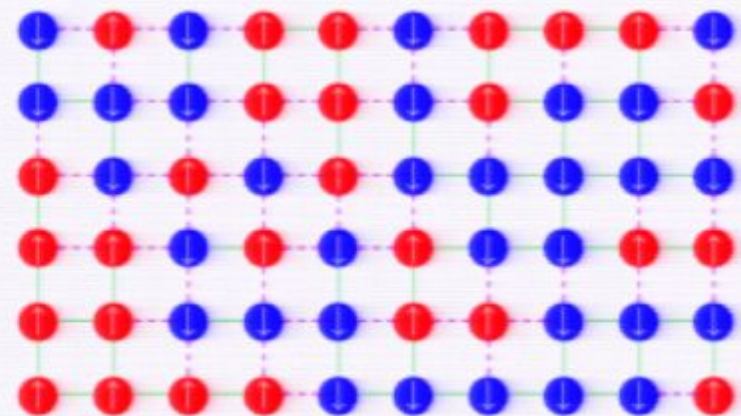
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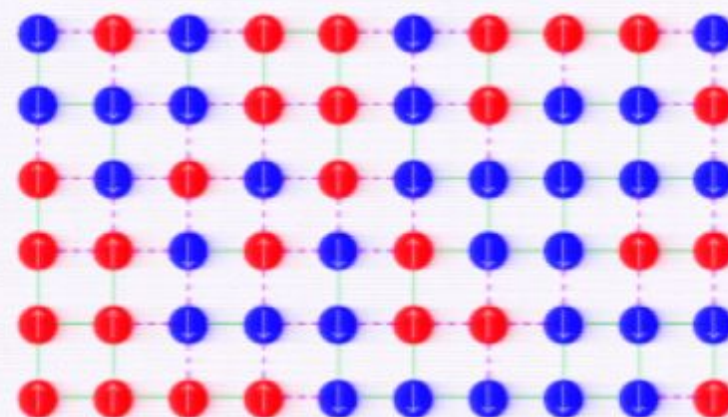
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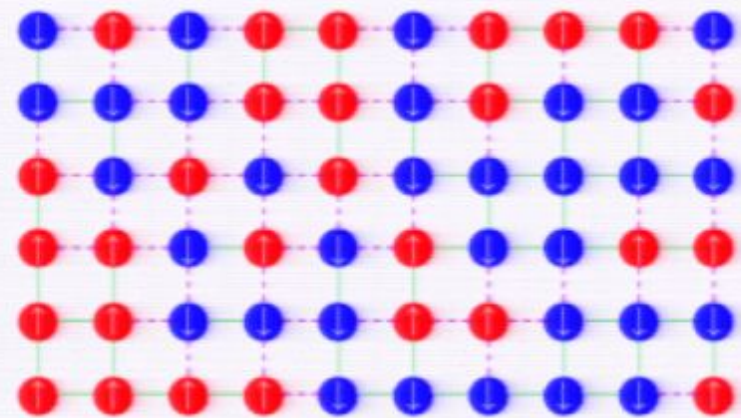
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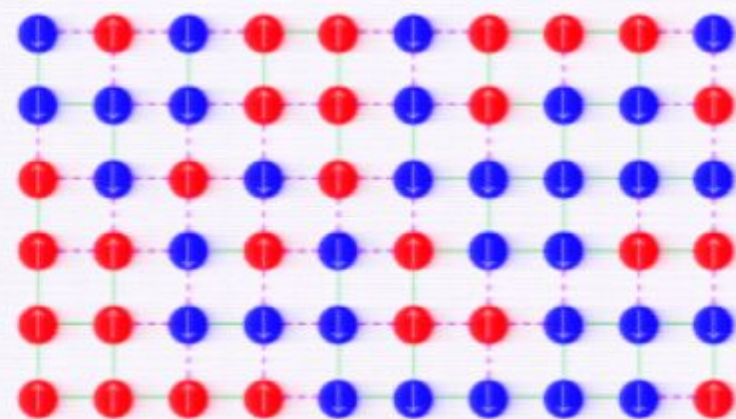
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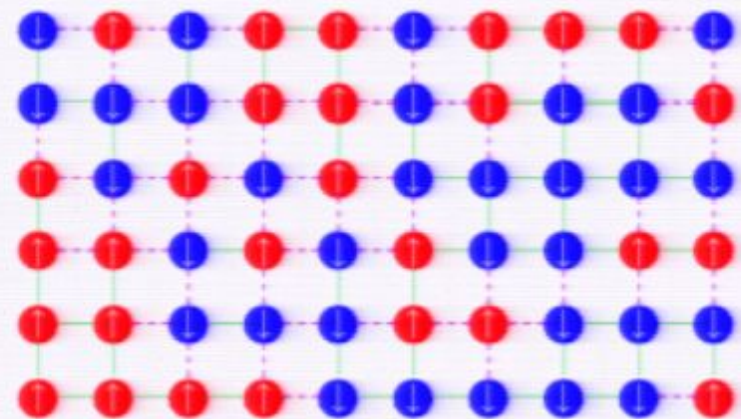
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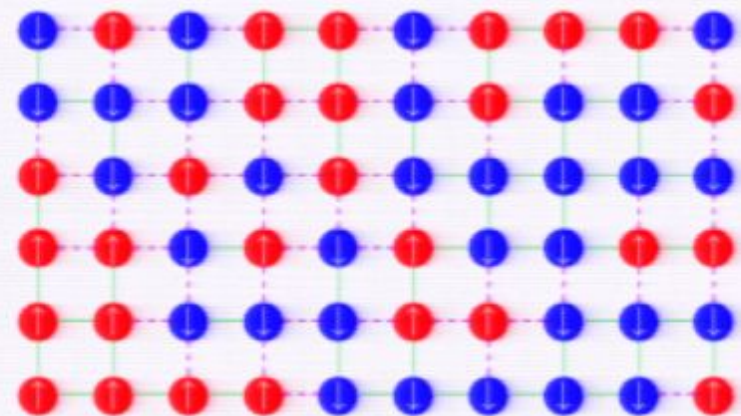
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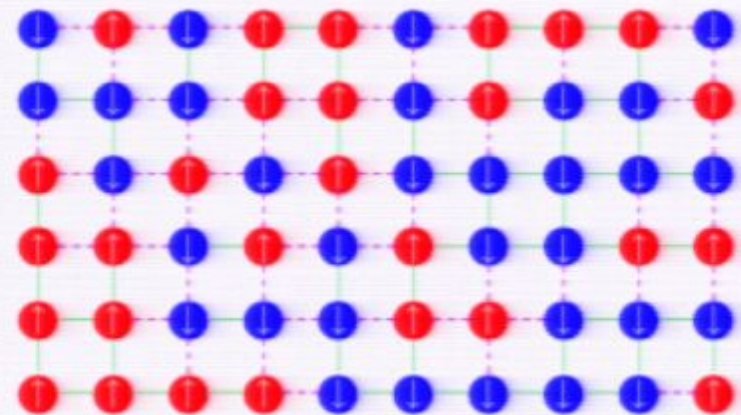
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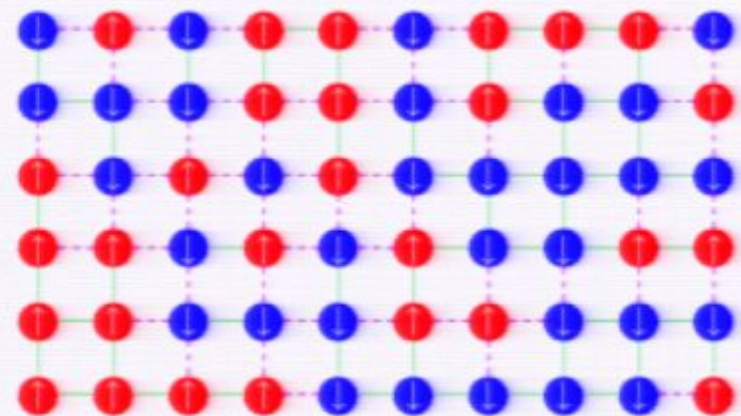
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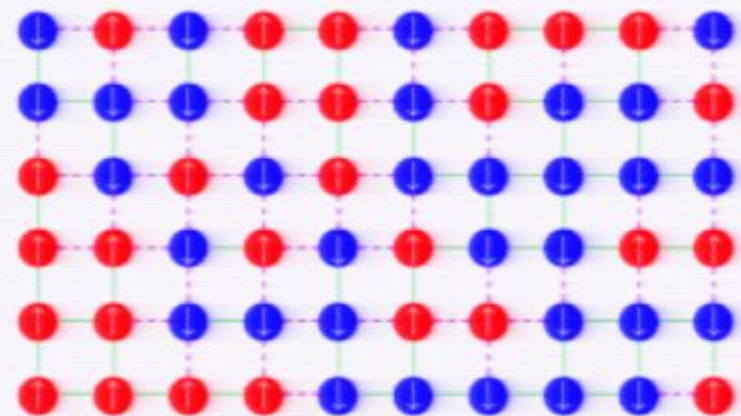
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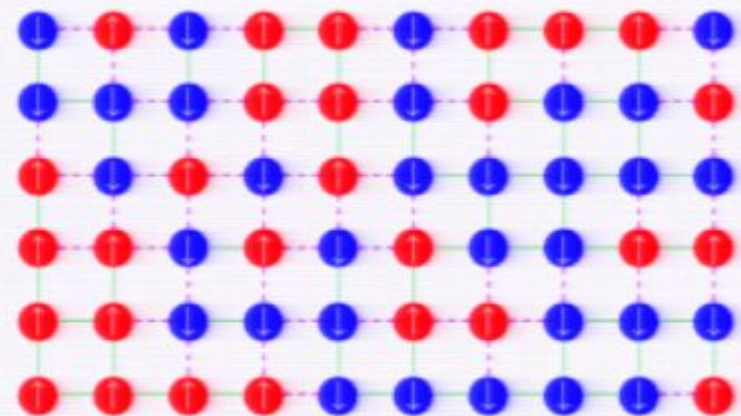
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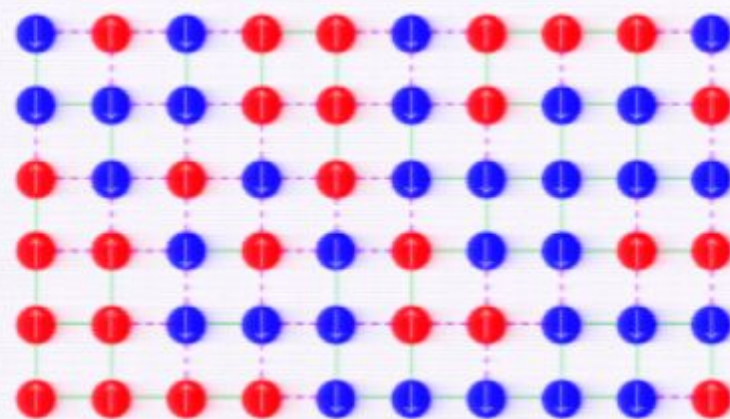
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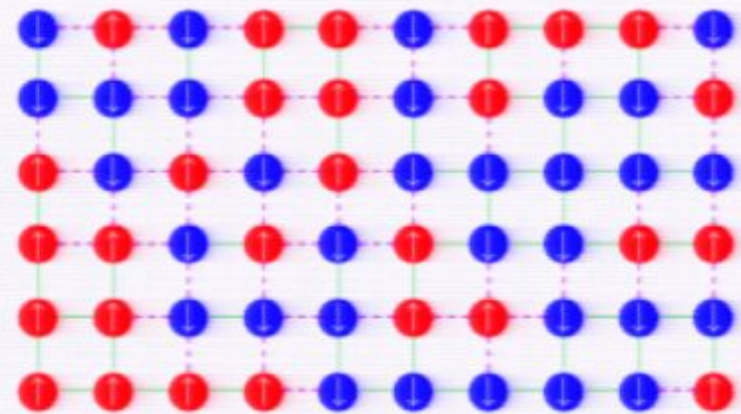
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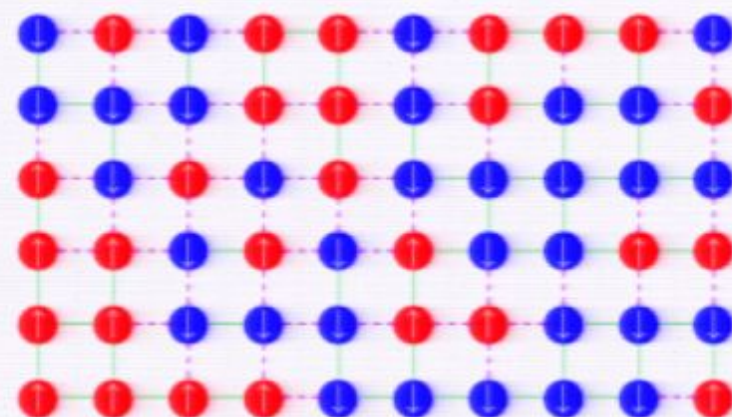
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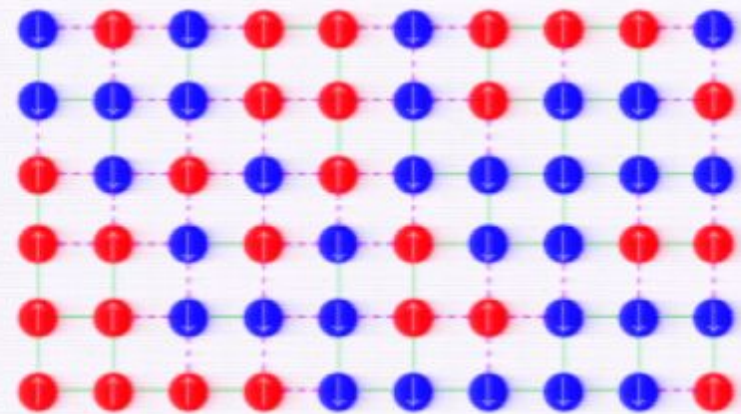
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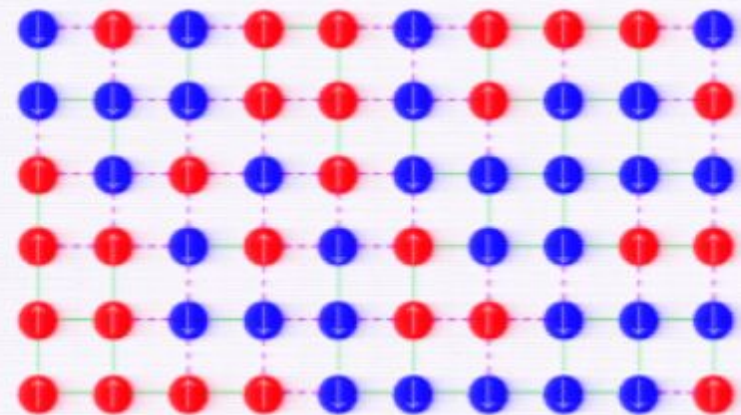
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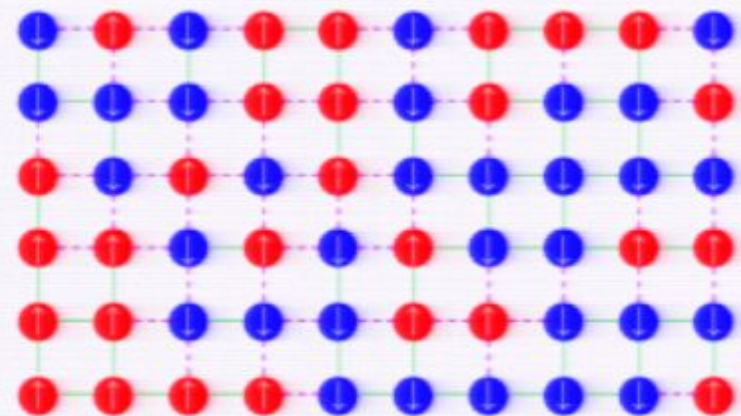
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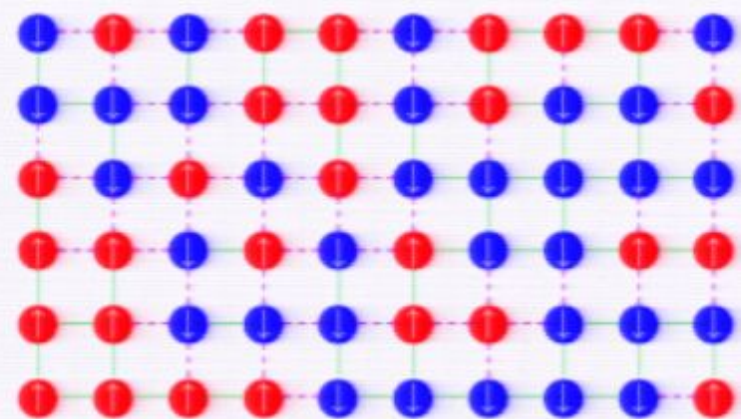
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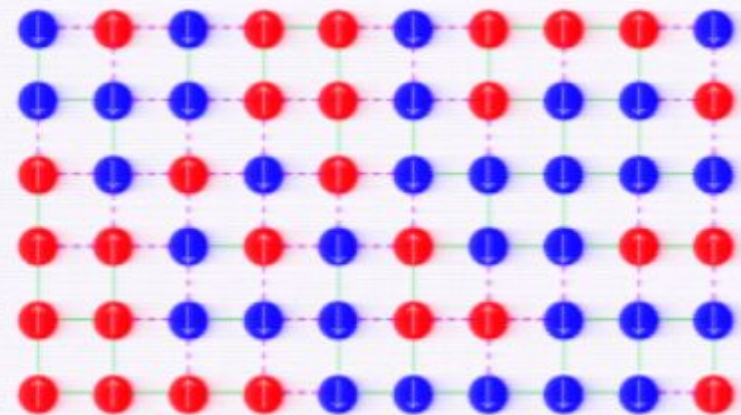
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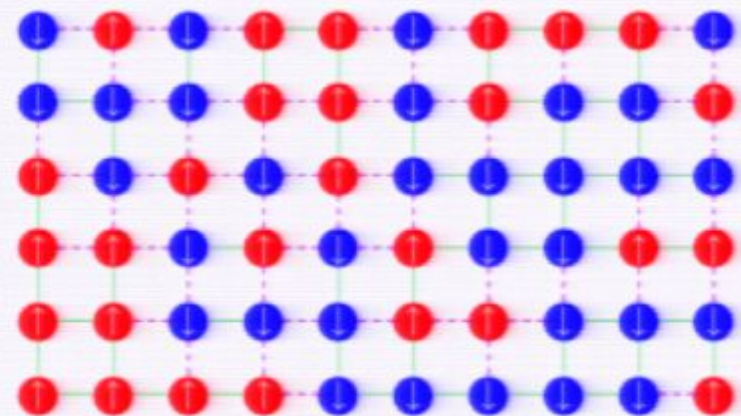
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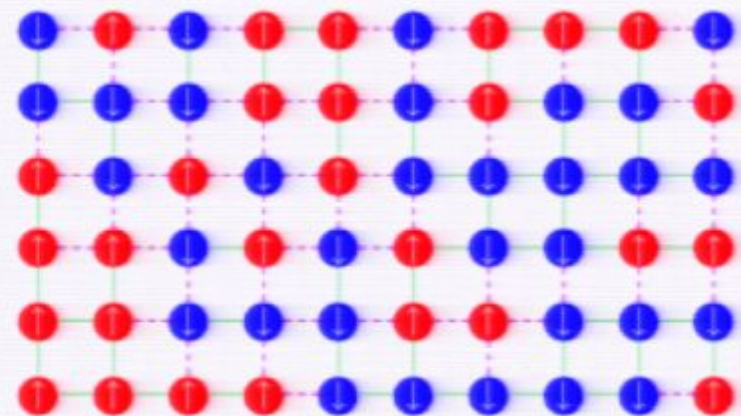
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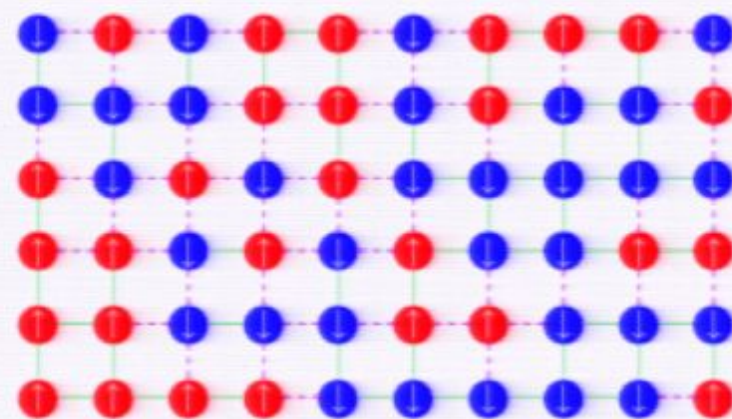
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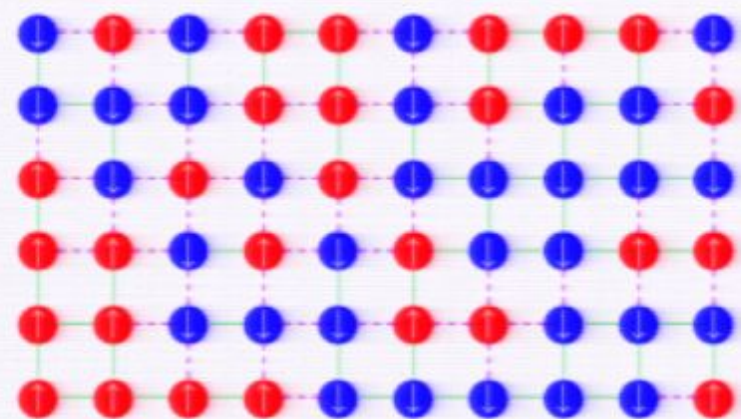
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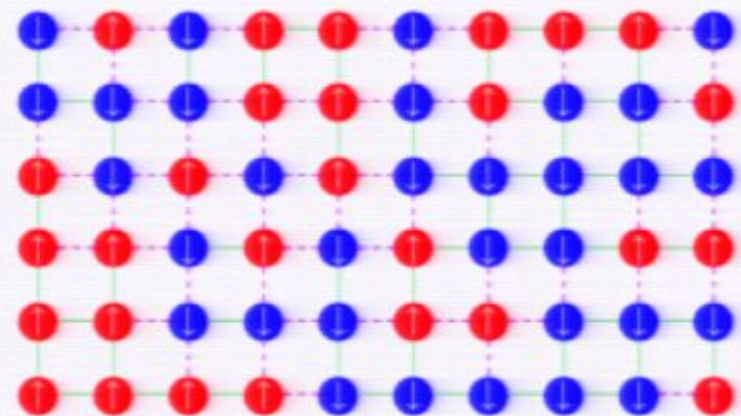
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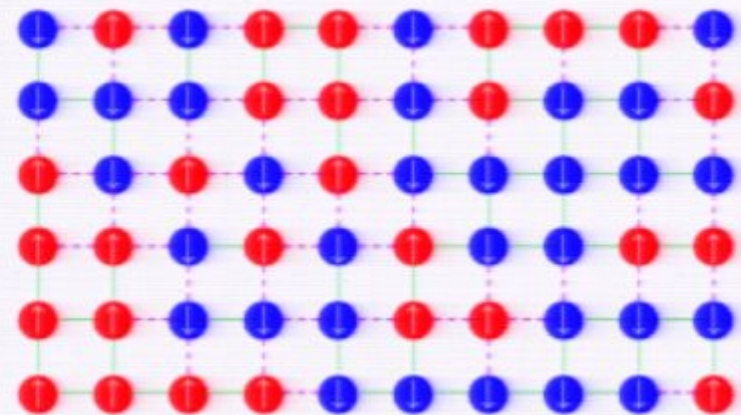
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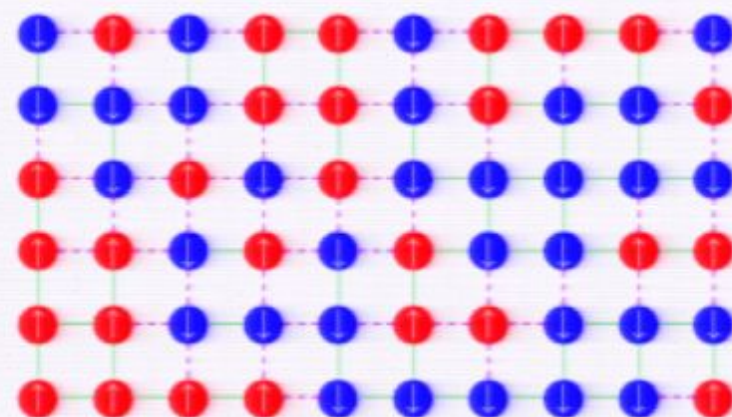
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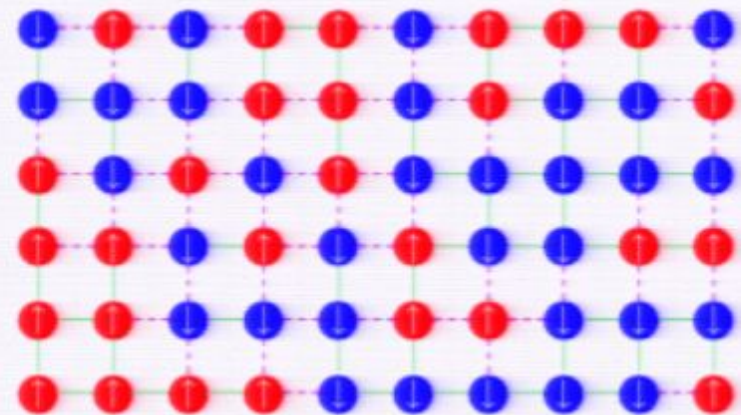
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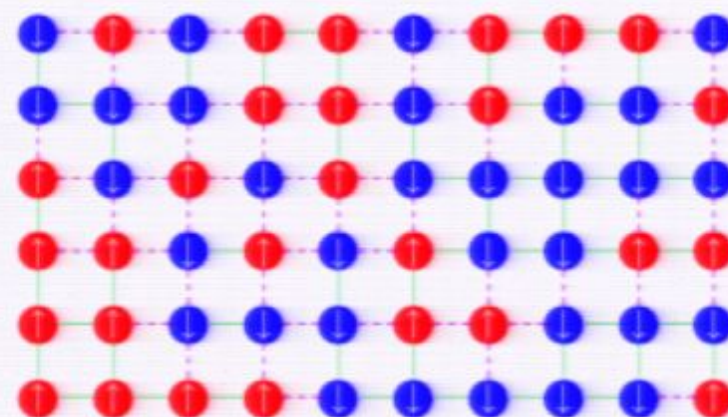
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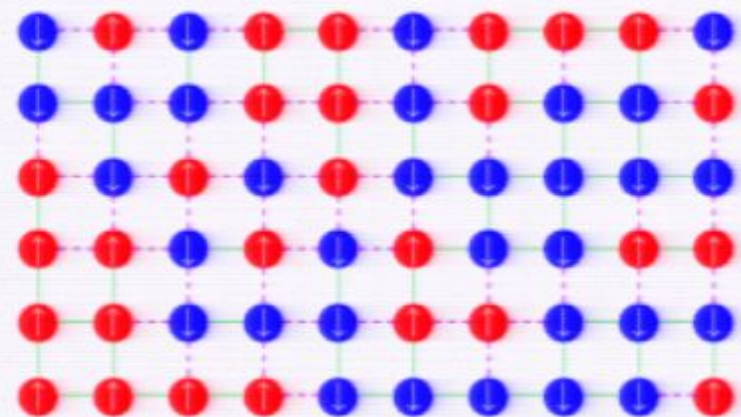
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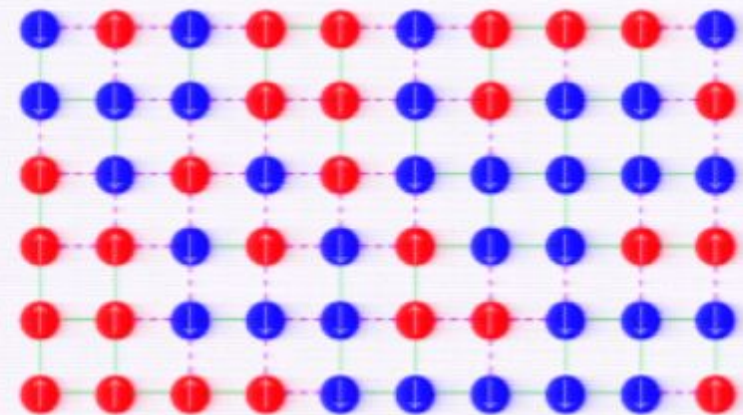
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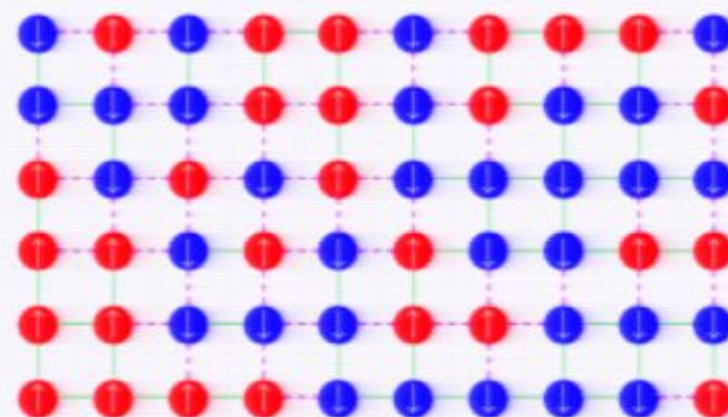
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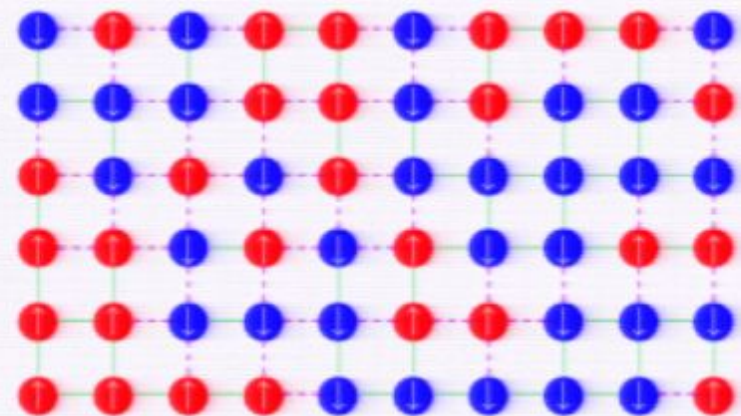
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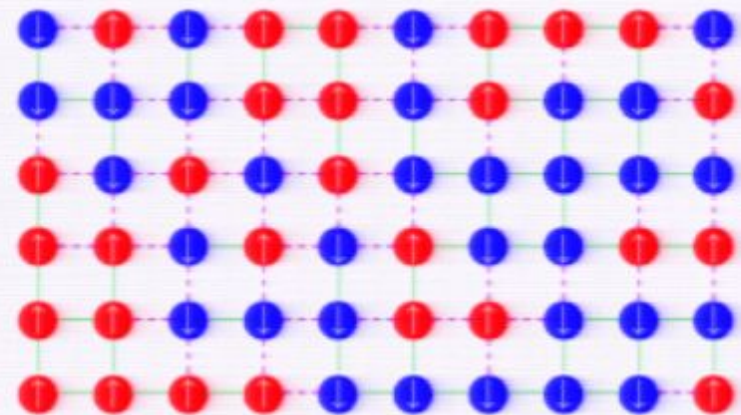
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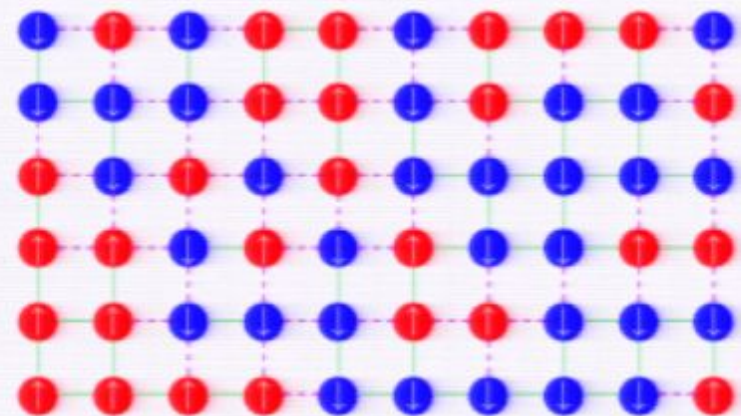
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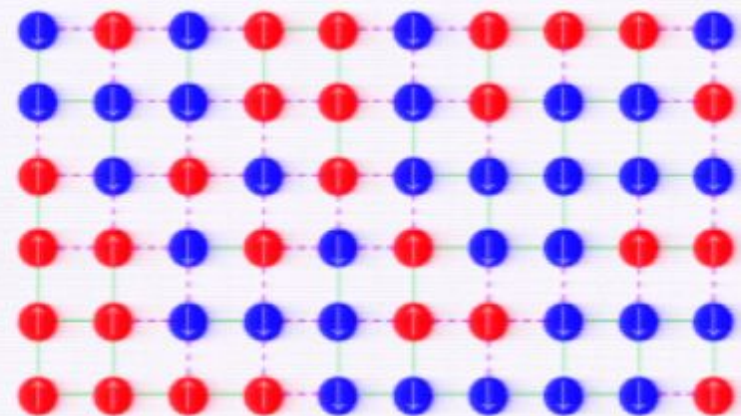
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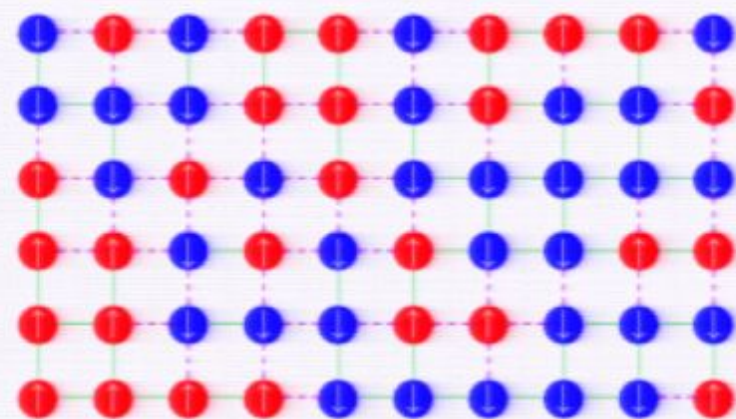
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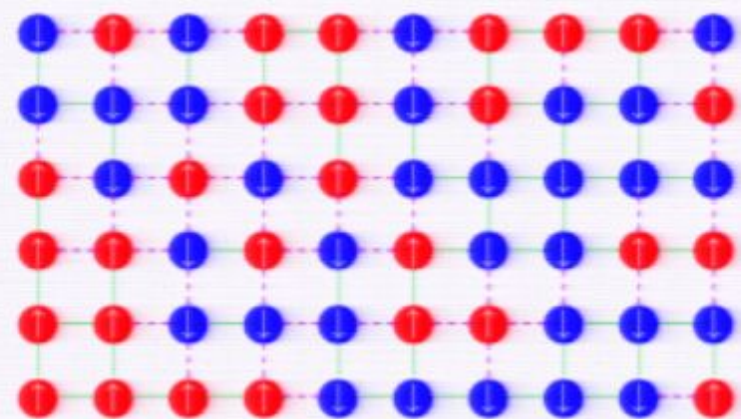
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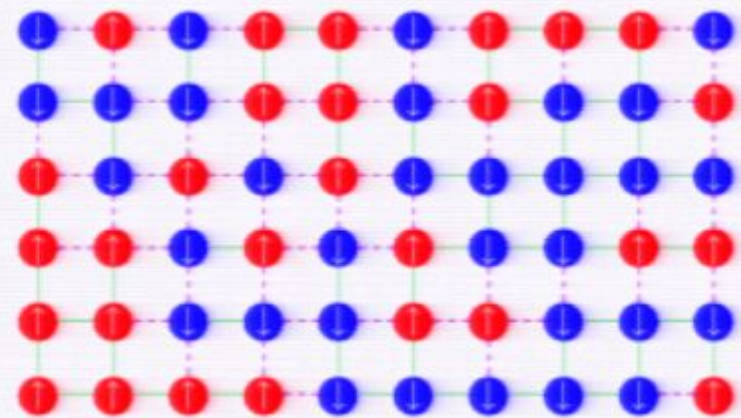
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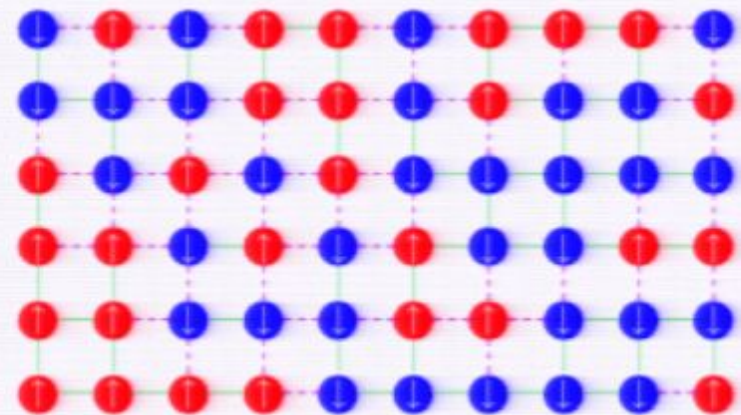
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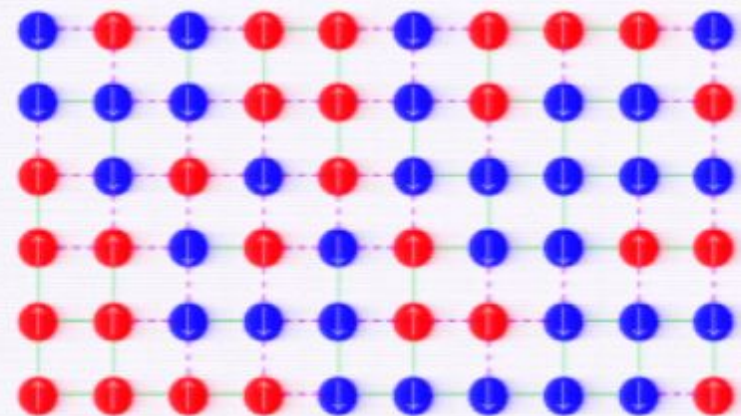
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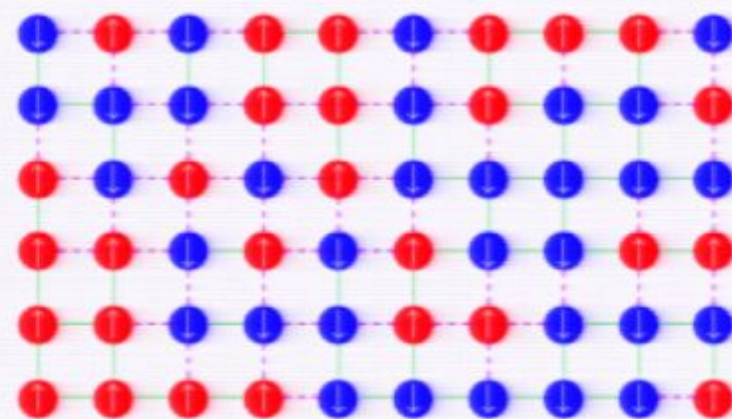
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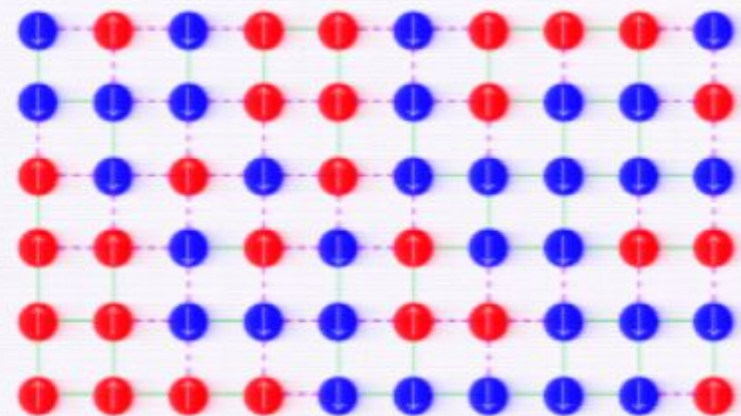
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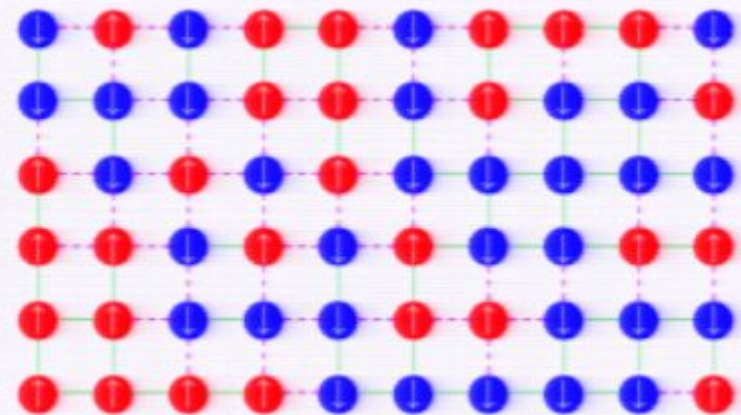
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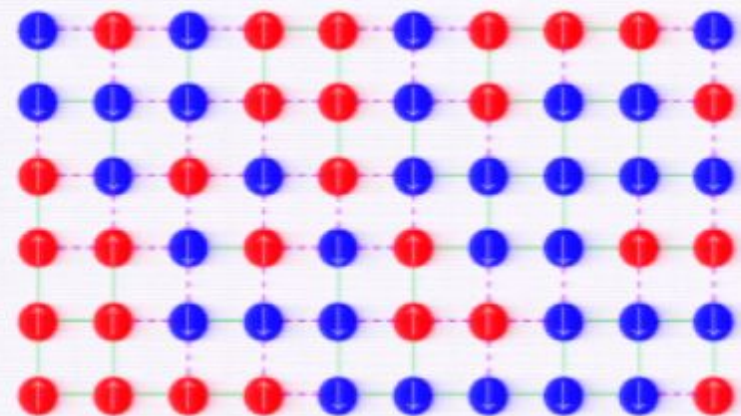
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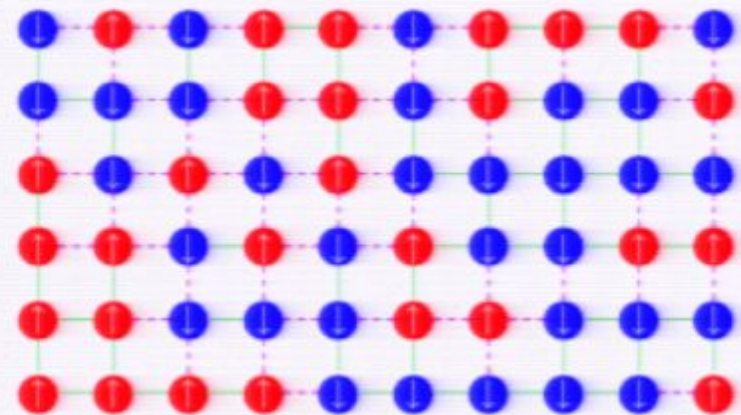
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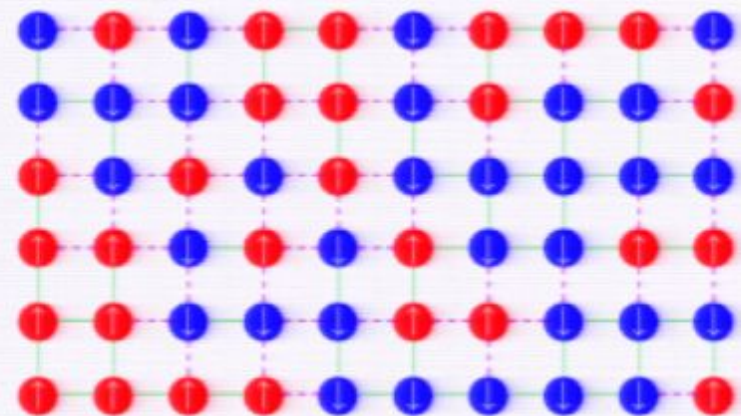
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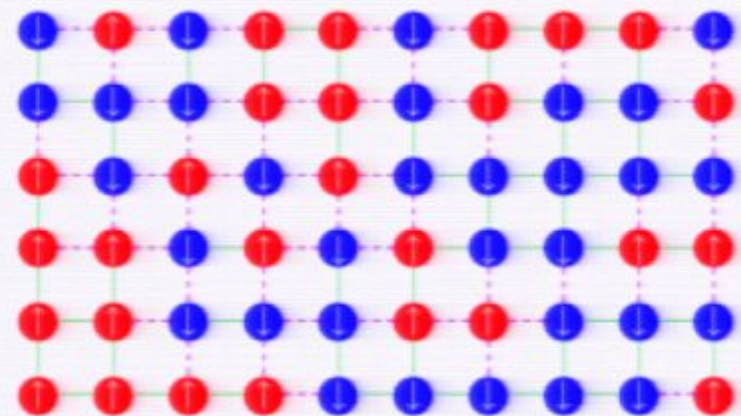
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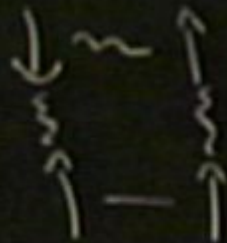


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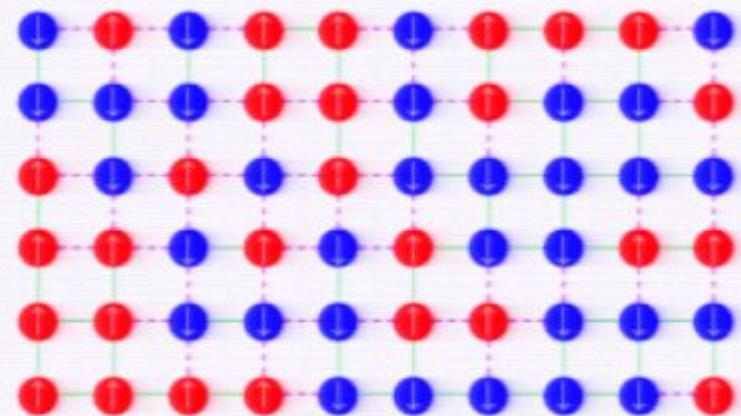
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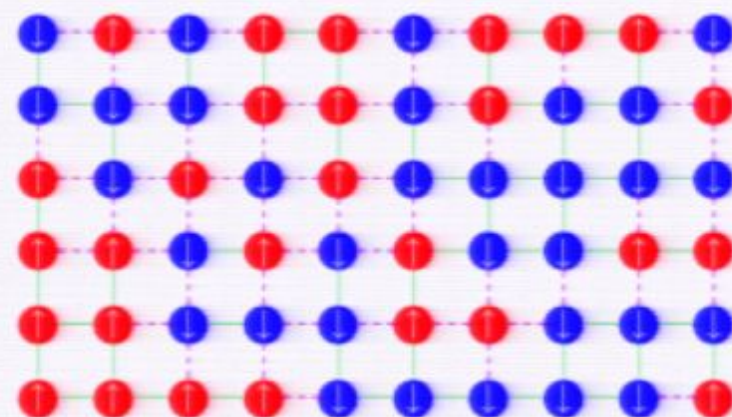
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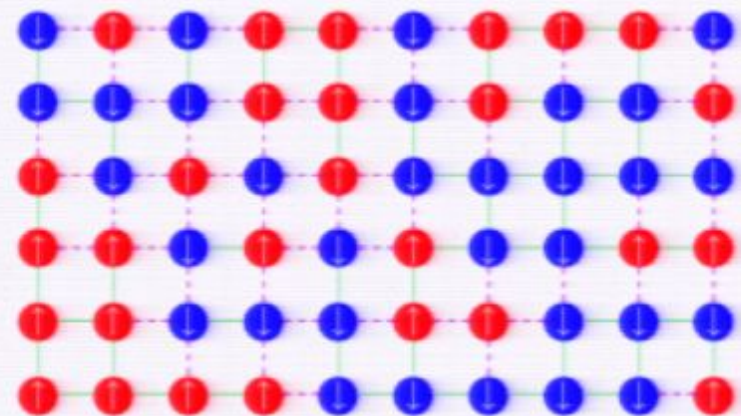
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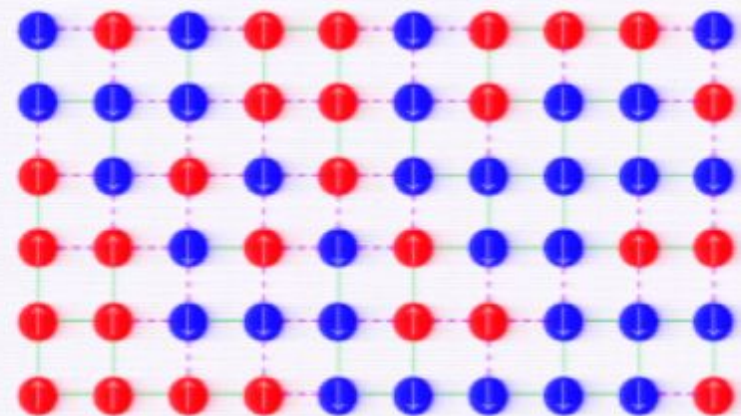
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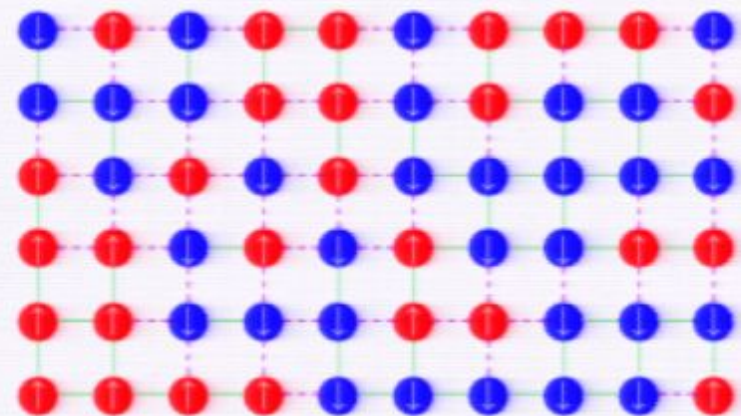
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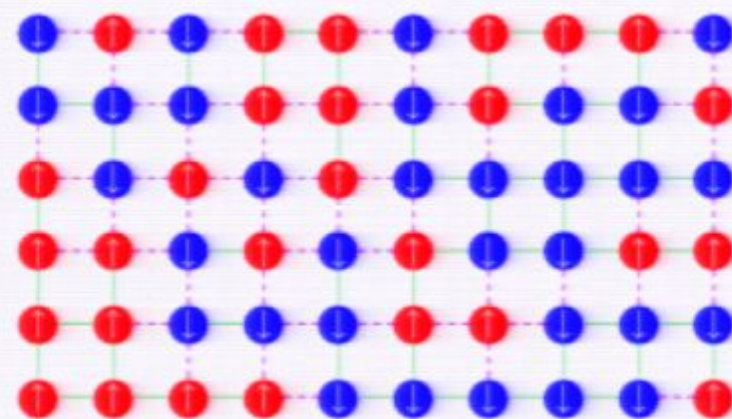
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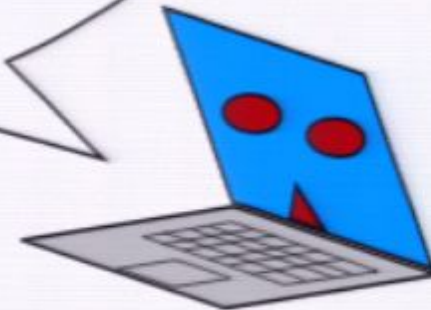
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NP is, roughly speaking, the class of problems for which it may be hard to find the answer, but it is easy to check the answer when given it.

NP-complete problems are the most difficult problems in NP. If you can solve an NP-complete problem, you can solve all of NP.

Examples of NP-complete problems:

- Satisfiability of Boolean formulas
- Graph coloring
- Travelling Salesman



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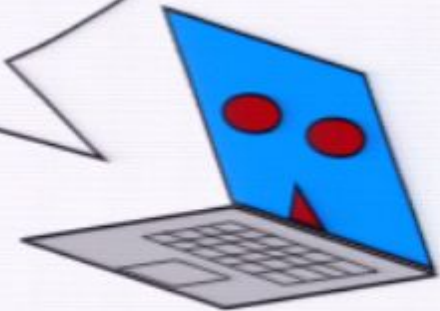
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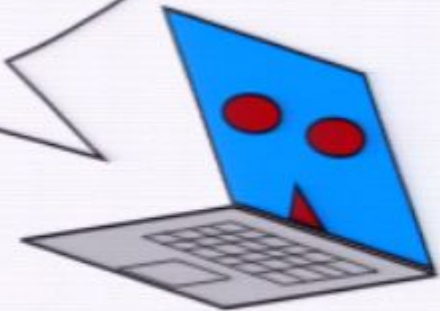
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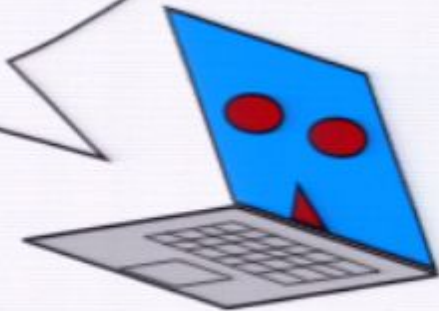
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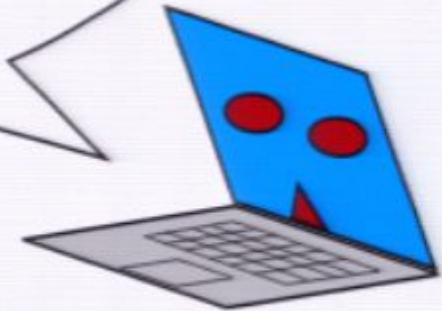
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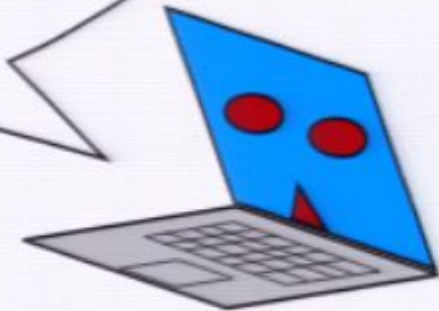
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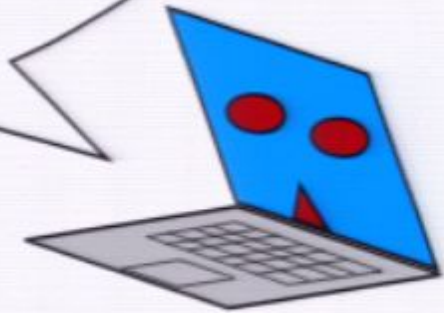
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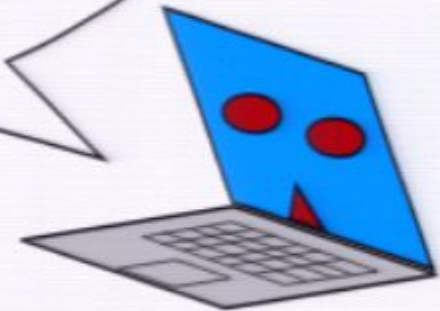
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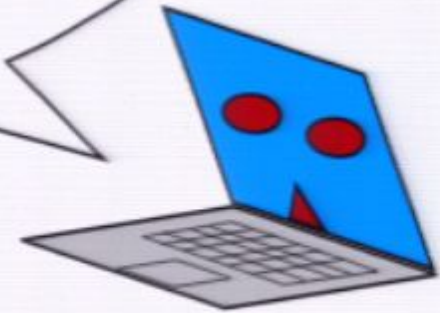
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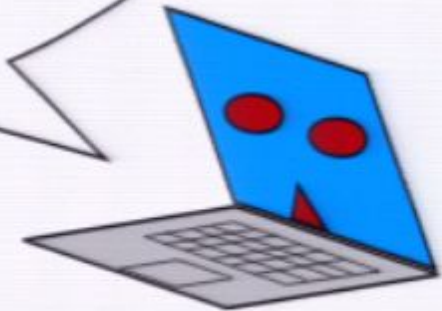
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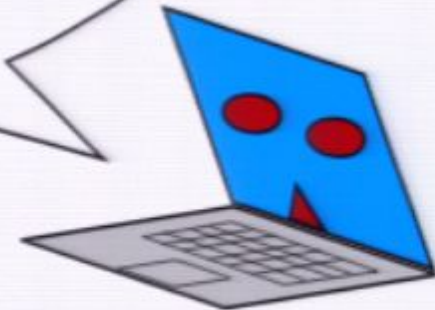
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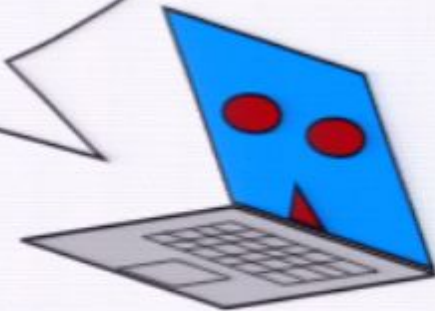
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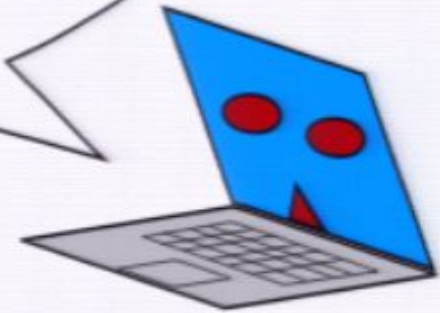
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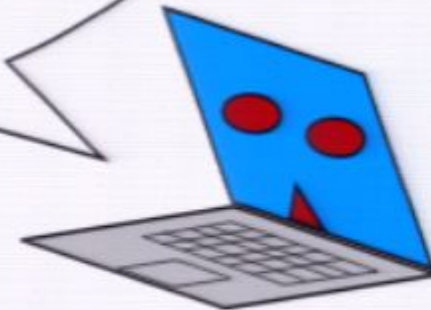
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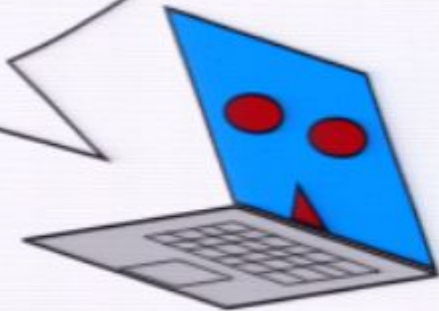
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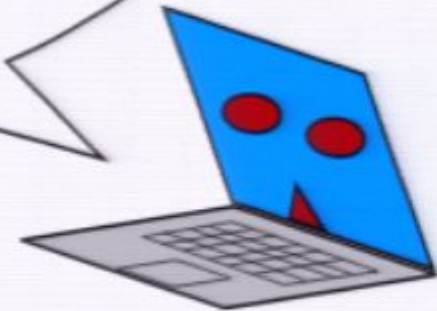
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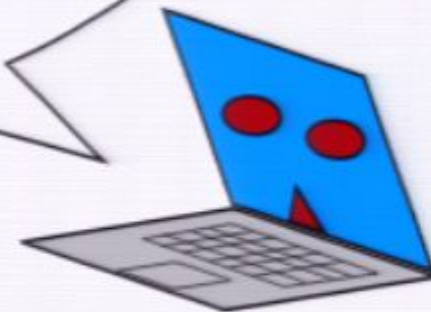
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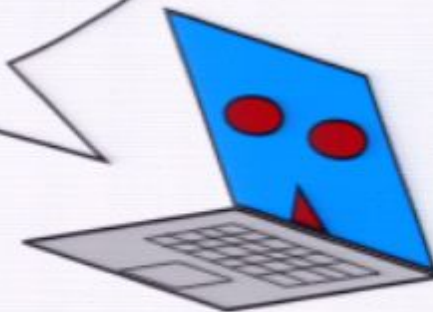
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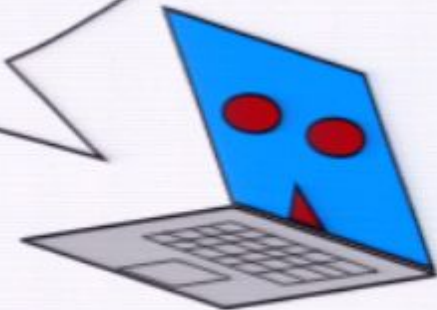
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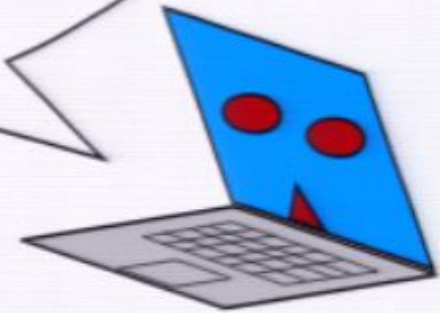
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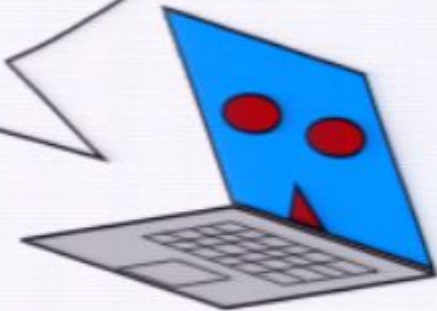
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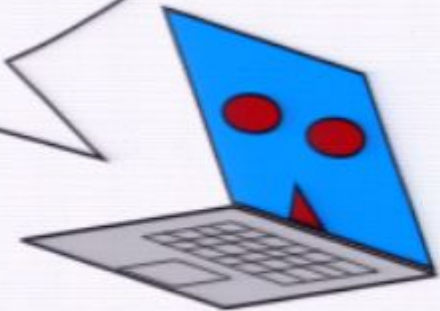
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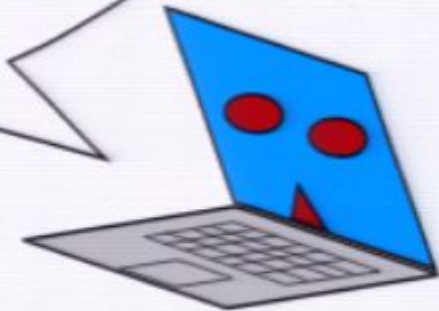
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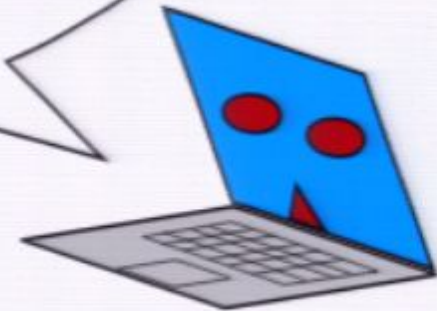
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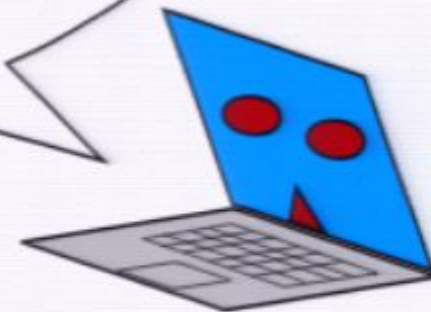
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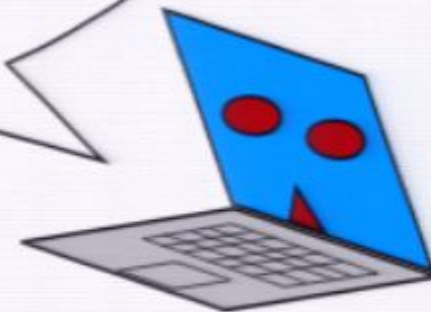
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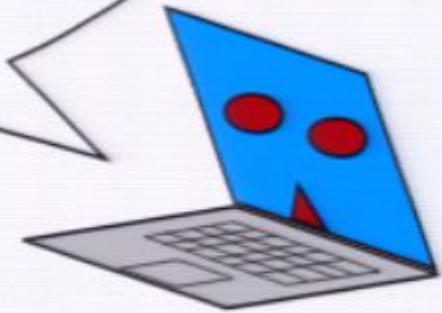
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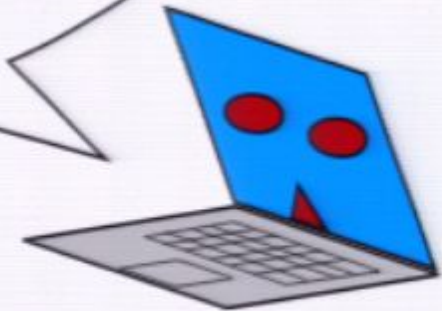
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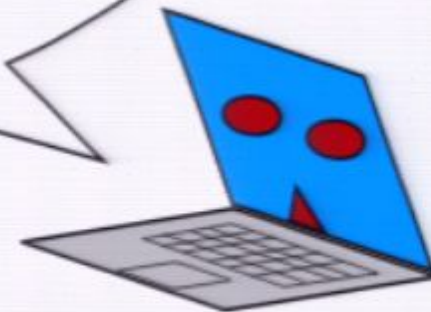
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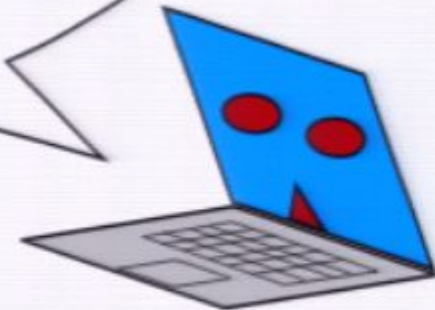
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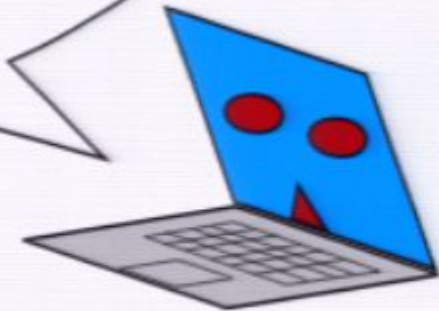
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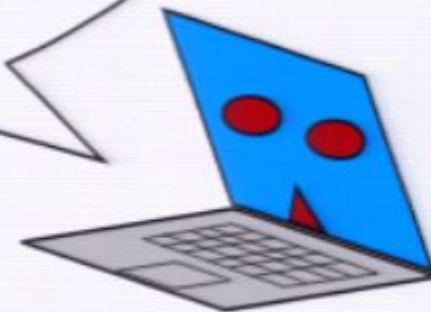
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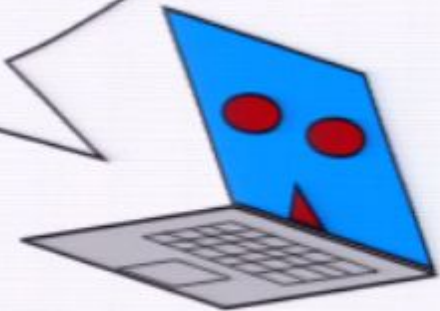
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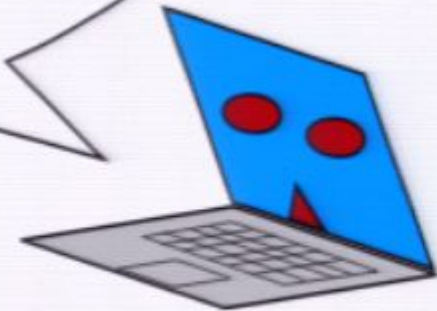
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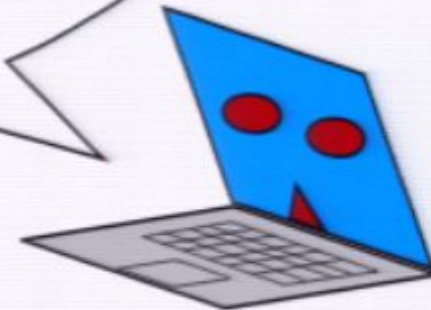
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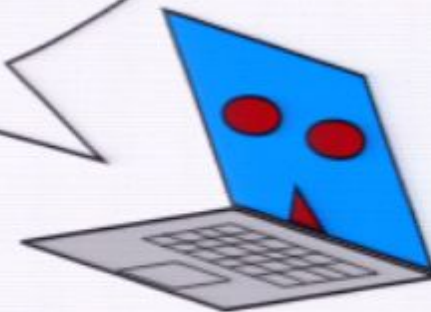
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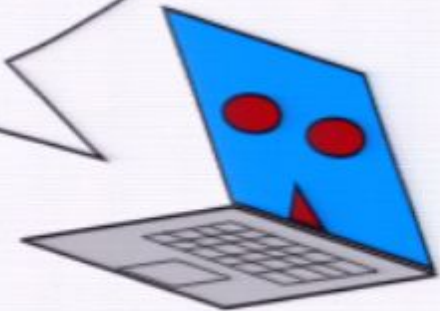
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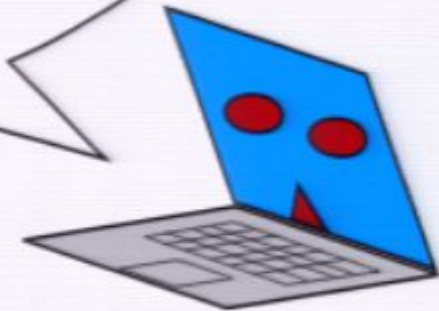
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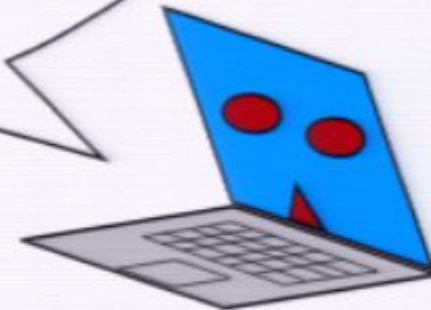
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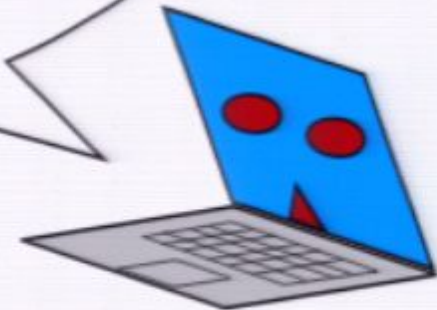
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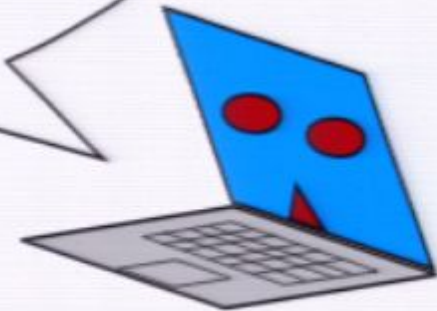
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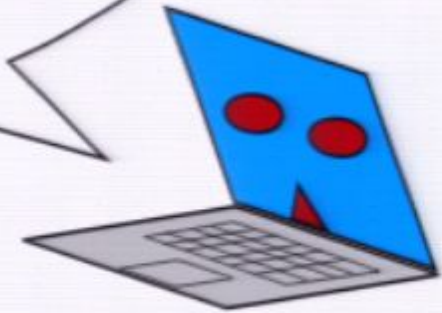
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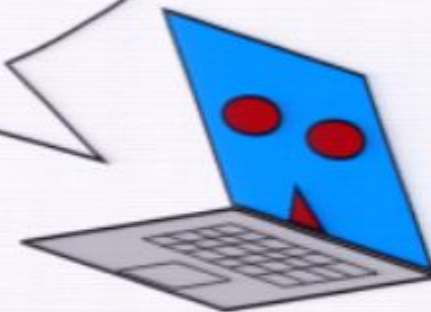
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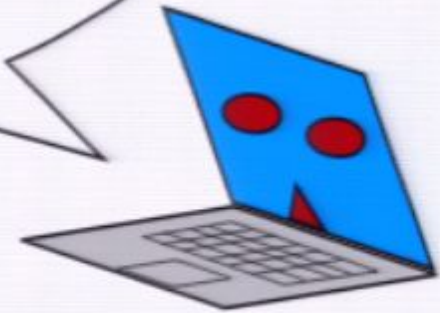
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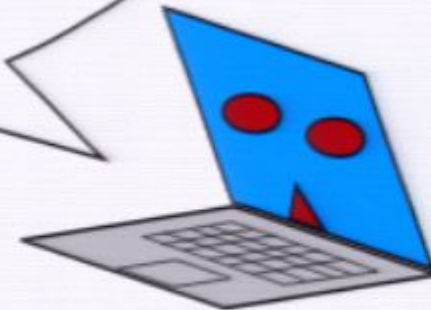
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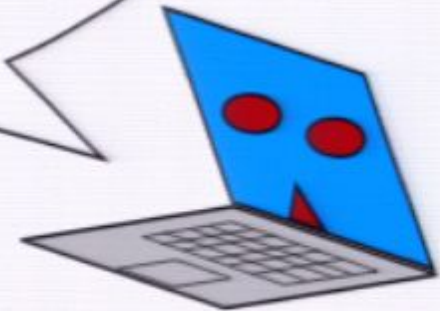
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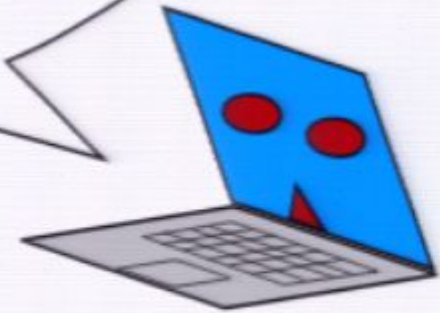
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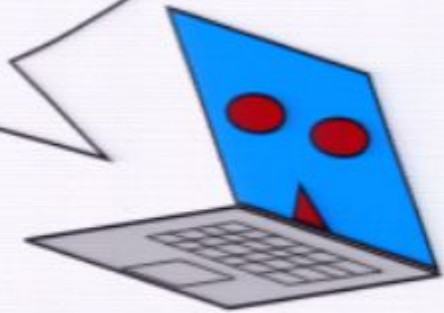
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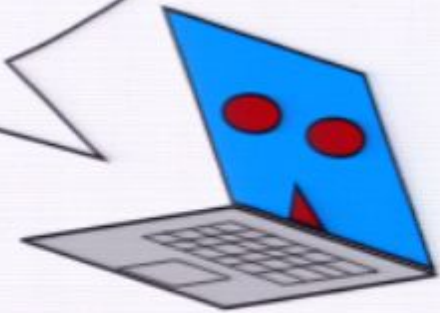
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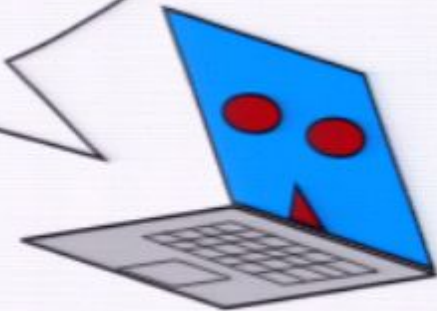
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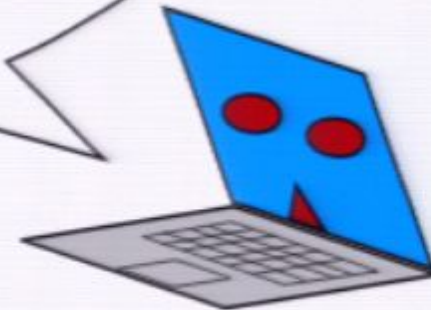
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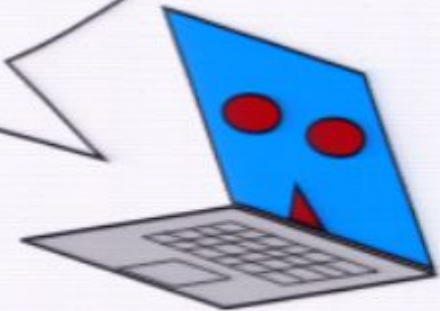
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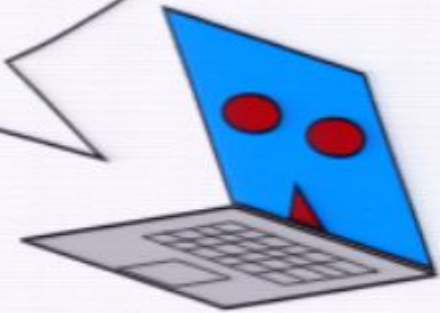
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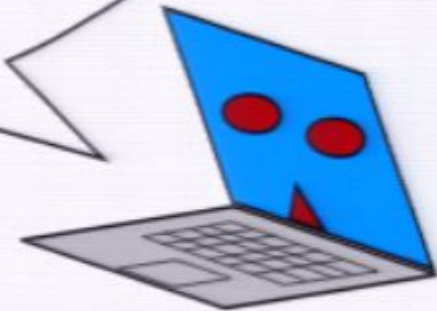
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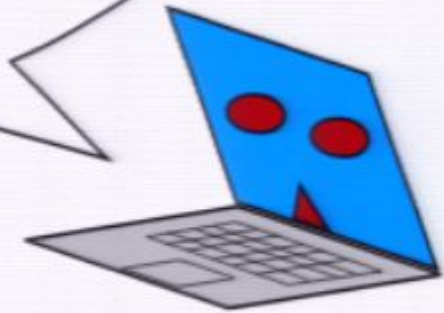
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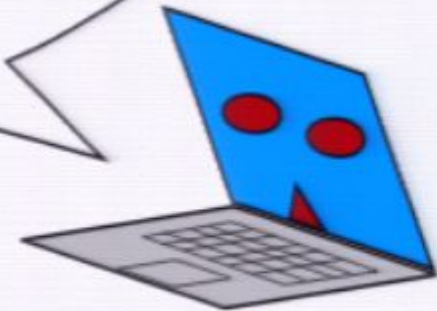
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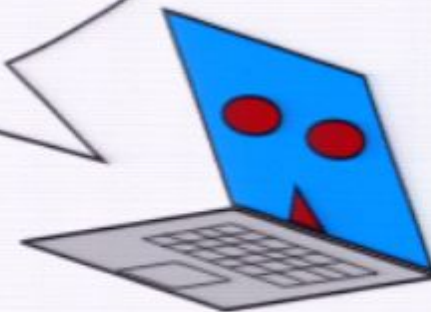
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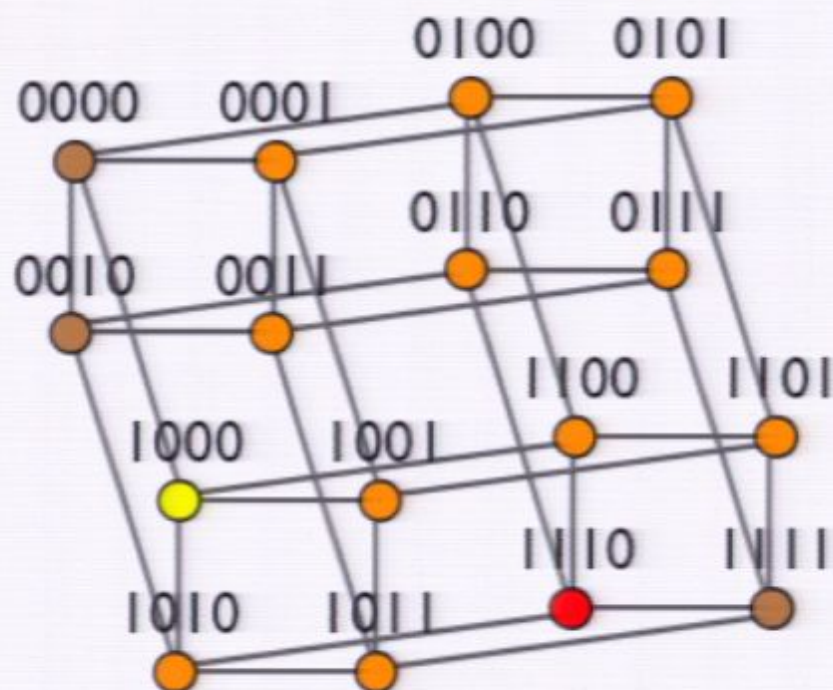


Spin Systems and NP-Completeness

Finding the ground state of a classical spin system can be an NP-complete problem.

For any Boolean formula, we can write down a Hamiltonian, with energy = # unsatisfied clauses.

$$H = ABC + (I-A)(I-D) + (I-B)(I-C)D + (I-A)(I-B)(I-D) + CD + B(I-C)D + AC(I-D) + AB(I-D)$$



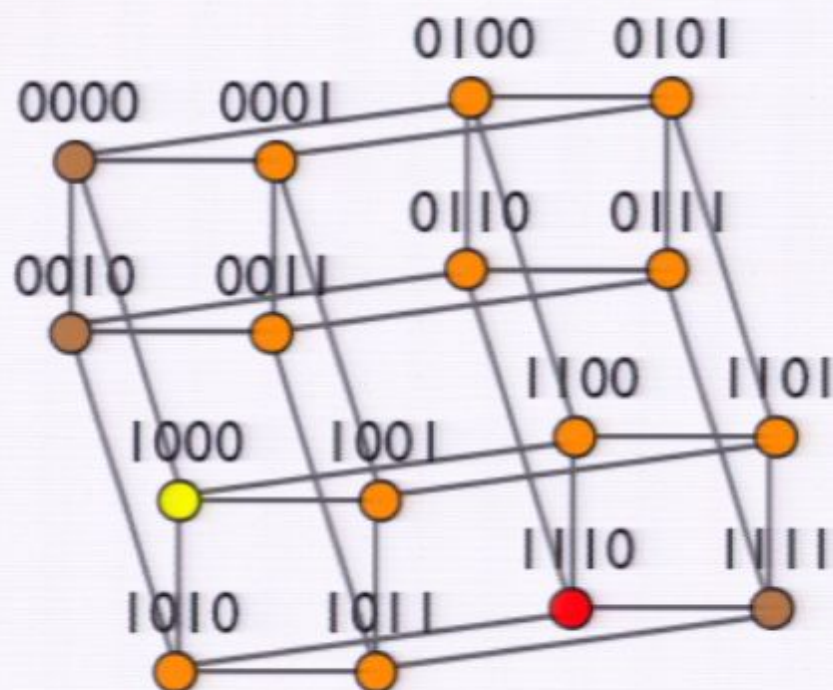
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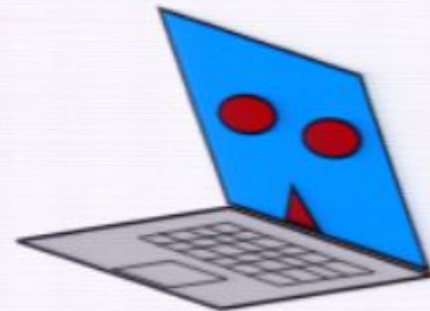


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Hardness and Spin Glasses

Given a Satisfiability problem, we can convert it into a Hamiltonian. If the Hamiltonian has ground state energy 0, then there is a configuration that satisfies all clauses in the Boolean formula. Finding the ground state energy of the Hamiltonian thus allows us to solve Satisfiability.

Since Satisfiability is NP-complete, it follows that finding the ground-state energy of a Hamiltonian is also NP-complete.



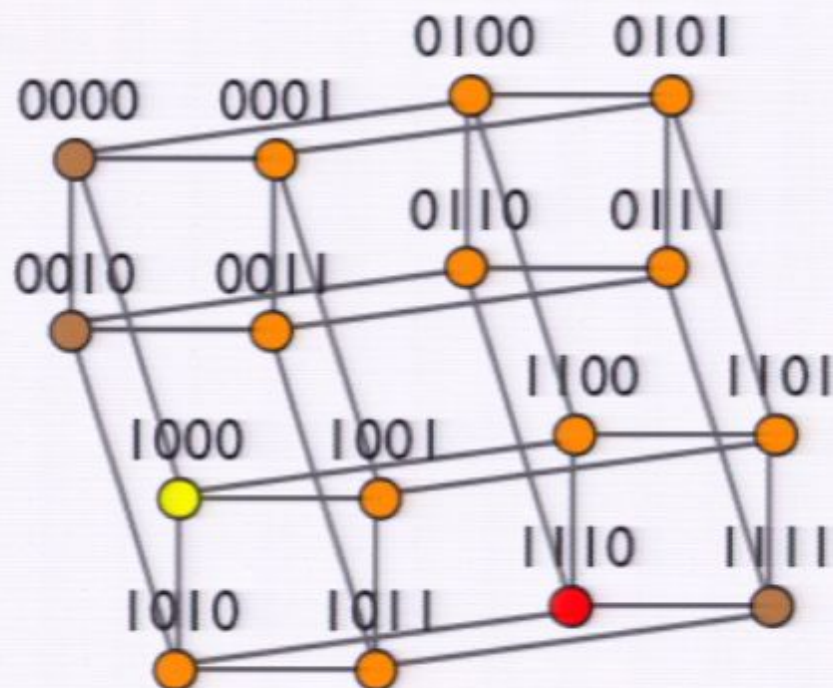
But given a Hamiltonian corresponding to a hard instance of Satisfiability, there cannot be any reasonable environment and cooling strategy that will bring it to the ground state. Otherwise, we could find the ground state by simulating that cooling strategy on a computer (or quantum computer, if necessary).

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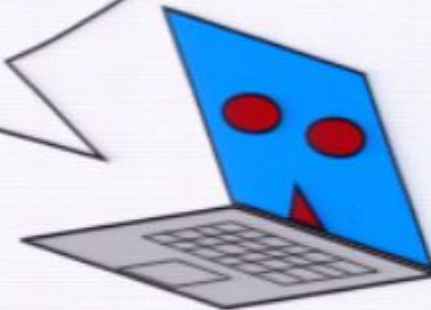
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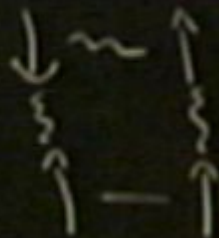
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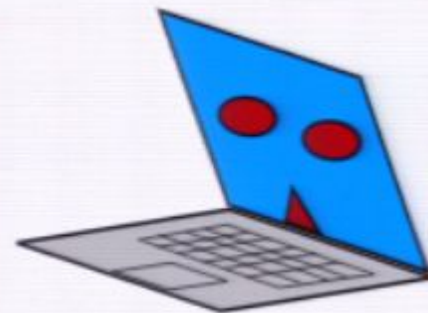




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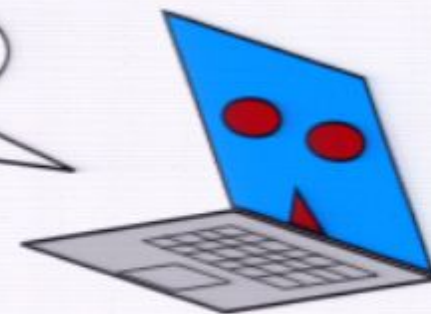
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Quantum Complexity Classes

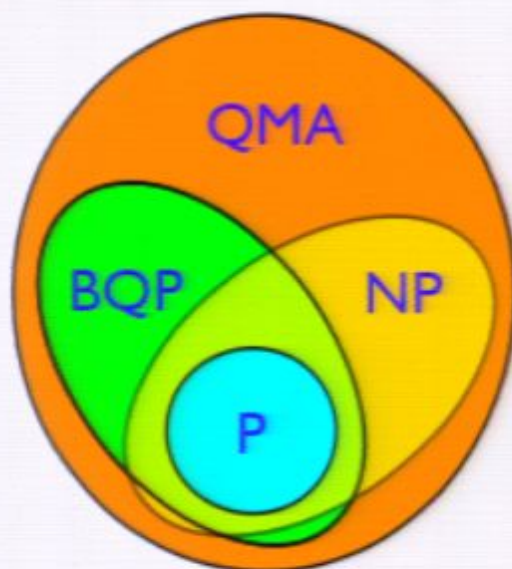


But don't you also need a set of quantum complexity classes?

I guess so. We want quantum analogues of P and NP.



BQP is the class of problems that can be solved in polynomial time on a quantum computer.



QMA is the class of problems which may be hard to solve, but are easy to check on a quantum computer.

We think, but cannot prove, that these classes are all different.

Spin Systems and QMA

QMA stands for “Quantum Merlin-Arthur”

Merlin is very powerful, but not very trustworthy.



He wishes to prove something to Arthur, who has limited computational power.

A **k-local Hamiltonian** is a Hamiltonian which is the sum of terms each of which acts on at most k spins.



The **k-Local Hamiltonian problem**: Given a **k-local Hamiltonian**, is the ground state energy below E or above $E + \Delta$?

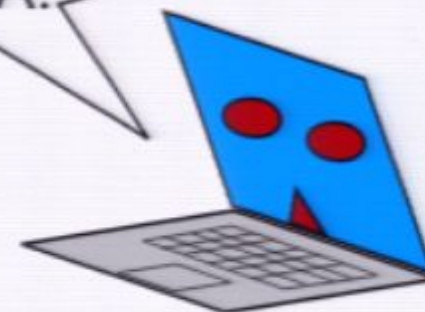
k -Local Hamiltonian is in QMA. Merlin must provide Arthur with a copy of the ground state.

QMA-Completeness

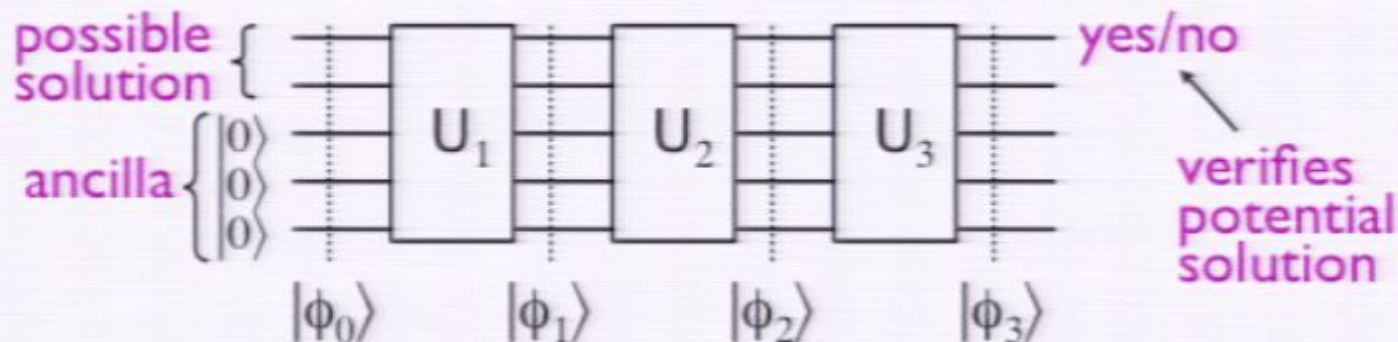
Kitaev showed that 5-Local Hamiltonian is QMA-complete.

If you can solve a QMA-complete problem, you can solve all of QMA!

For any QMA problem x , we must find a Hamiltonian H with low ground state energy if and only if the answer to x is “yes”.



Checking circuit for the input x :



Kitaev writes down a Hamiltonian whose ground state corresponds to the “history” $|\psi\rangle = \sum |\phi_t\rangle |t\rangle$ of the checking circuit.

Who Cares if Spin Systems are Hard?



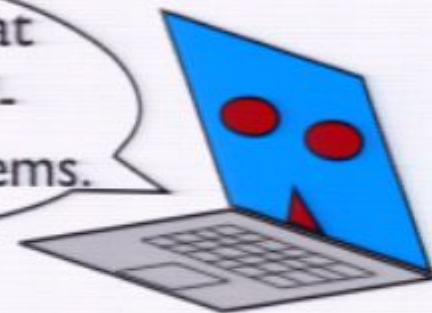
I would like to be able to find the ground state energy of spin systems.

I can find algorithms that will do that for some systems -- but not for NP-complete or QMA-complete problems.

Maybe this viewpoint will help me understand spin glasses better.

I can prove some other problems are QMA-complete now.

These techniques can be useful for other spin problems.



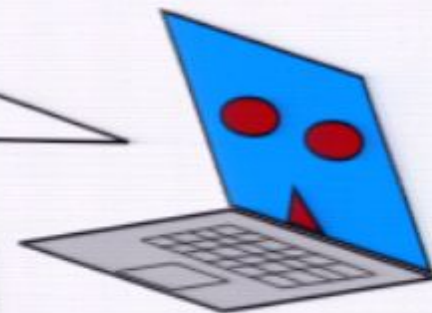
Which Spin Systems are Hard?



So which Hamiltonians are hard and which are easy?

That's the wrong question. A single Hamiltonian either has a low ground state energy or it doesn't. You have to ask about a *class* of Hamiltonians so that I can study the scaling of difficulty with the number of particles.

Fine. What are the hard *classes* of Hamiltonians?



Hardness of Classical Spin Systems



Let's look at classical spin systems first.



3-Satisfiability (3-Local Ham.)

Hard (NP-complete)

2-Satisfiability (w/ bits)

Easy (P)

Hardness of Classical Spin Systems



3-Satisfiability (3-Local Ham.)

Hard (NP-complete)

Classical 2-Local Hamiltonian

Hard (NP-complete)



2-Satisfiability (w/ bits)

Easy (P)

Hardness of Classical Spin Systems



But these examples have no geometry.



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Hardness of Classical Spin Systems



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2-Local Ham. in 2D (Tiling)

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Hardness of Classical Spin Systems



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2-Local Ham. in 1D

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Hardness of Classical Spin Systems



I'm interested in translation-invariant systems.



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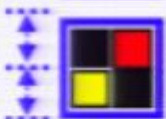
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Translationally-Invariant Tiling

Hard (NEXP-complete)



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Translationally-Invariant Tiling

Hard (NEXP-complete)



2-Local Ham. in 1D

Easy (P)



Trans. Inv. 1D Ham.

Easy (P, as a function of $\log N$)

2-Satisfiability (w/ bits)

Easy (P)

NEXP vs. NP

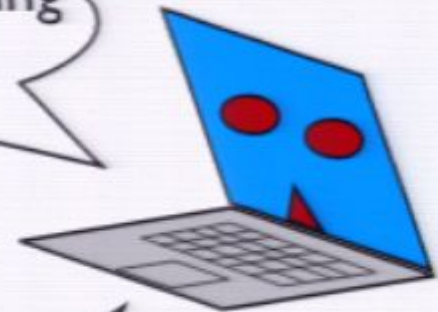


NEXP? What's that?

It's like NP, but we allow the checking circuit to take exponentially long.

So NEXP-complete problems are very hard.

Yes, but for a translationally-invariant system, the only input is n , the number of spins. Thus, the input **size** is just $\log n$, so the checking time is polynomial in n .



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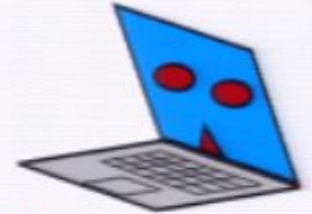
Hard vs. Easy Quantum Spin Systems



What about quantum spin systems?

5-Local Hamiltonians

Hard (QMA-complete)



Hard vs. Easy Quantum Spin Systems



What about quantum spin systems?



5-Local Hamiltonians

Hard (QMA-complete)



2-Local Hamiltonians

Hard (QMA-complete)

Specific 1D Systems

Easy (P)

Hard vs. Easy Quantum Spin Systems



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Hamiltonians in 2D

Hard (QMA-complete)

Hard vs. Easy Quantum Spin Systems



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Hamiltonians in 1D with qubits ?

?

Hard vs. Easy Quantum Spin Systems



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Hamiltonians in 1D with qubits

?



Translationally-Invariant Ham.

Hard (QMA_{EXP}-complete)

Hard vs. Easy Quantum Spin Systems



What about quantum spin systems?



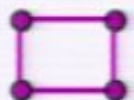
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2-Local Hamiltonians

Hard (QMA-complete)



Hamiltonians in 2D

Hard (QMA-complete)



Hamiltonians in 1D

Hard (QMA-complete)



Hamiltonians in 1D with qubits

?



Translationally-Invariant Ham.

Hard (QMA_{EXP}-complete)



Trans. & Reflection-Inv. Ham.

Hard (QMA_{EXP}-complete)

Specific 1D Systems

Easy (P)

Translational Invariance and QMA_{EXP}

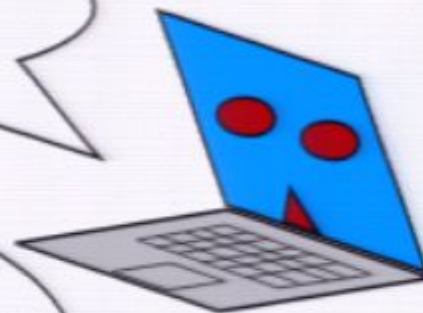


And QMA_{EXP} ?

Again, like QMA , but with an exponential checking circuit.

You said we can only measure the hardness of classes of Hamiltonians, but with translationally-invariant Hamiltonians, the only input is n .

You're right! Now we can talk about the complexity of individual Hamiltonian terms!

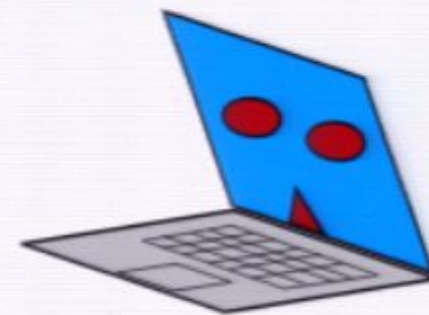


Summary and Open Questions



- Even Hamiltonians in 1D with an enormous amount of symmetry -- translational and reflection invariance -- can give spin glasses.
- Such Hamiltonians have no quenched disorder. Instead, the disorder is “self-induced” or emergent.
- We can prove these Hamiltonians are computationally hard problems (given some basic complexity-theoretic assumptions).

- What are the simplest Hamiltonian systems that are computationally hard? Existing examples use large values of spin.
- More generally, which Hamiltonians are easy and which are hard?
- What precision do we require in the energy?
- Can we constrain the spectral gap or other properties of the Hamiltonian?



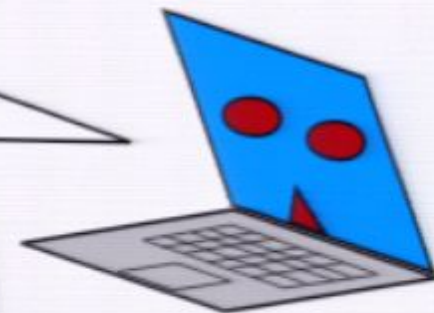
Which Spin Systems are Hard?



So which Hamiltonians are hard and which are easy?

That's the wrong question. A single Hamiltonian either has a low ground state energy or it doesn't. You have to ask about a *class* of Hamiltonians so that I can study the scaling of difficulty with the number of particles.

Fine. What are the hard *classes* of Hamiltonians?



Hardness of Classical Spin Systems



I'm interested in translation-invariant systems.



3-Satisfiability (3-Local Ham.)

Hard (NP-complete)

Classical 2-Local Hamiltonian

Hard (NP-complete)



2-Local Ham. in 2D (Tiling)

Hard (NP-complete)



Translationally-Invariant Tiling

Hard (NEXP-complete)



2-Local Ham. in 1D

Easy (P)

2-Satisfiability (w/ bits)

Easy (P)

NEXP vs. NP



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