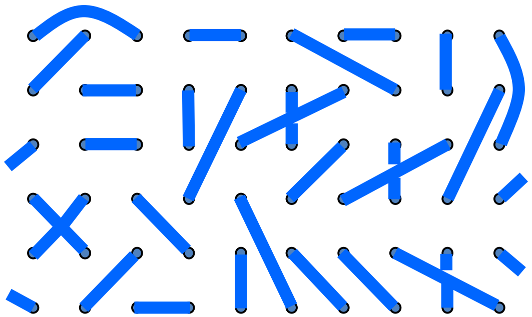
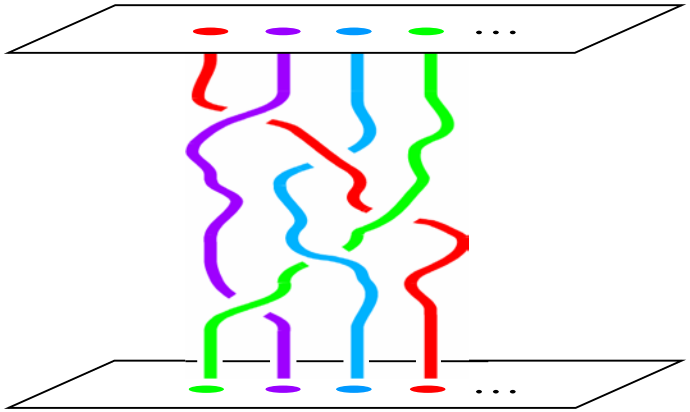
New Kinds of Ordered Matter
and
New Kinds of Quantum Machines

Nick Bonesteel, Dept. of Physics & NHMFL, Florida State University



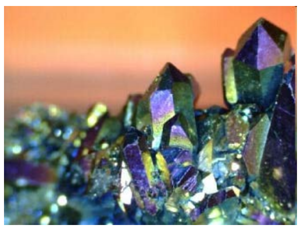


Two Big Questions

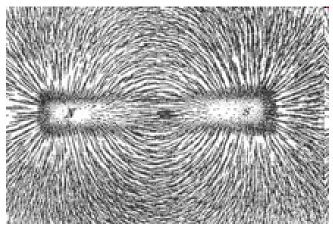
(1) What are the different ways matter can become ordered?

The classics…

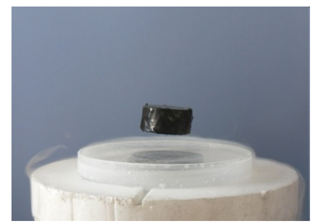
Crystals



Magnets



Superconductors

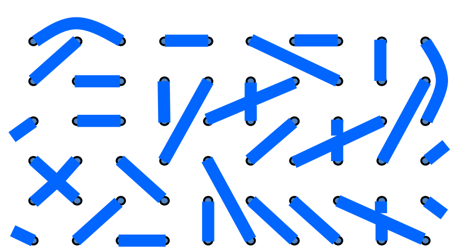


…

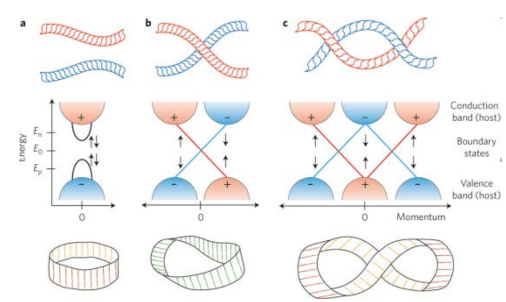
~ 30 years ago, a new kind of order was discovered…

Quantum Hall States

Spin Liquids



Topological Insulators



Two Big Questions

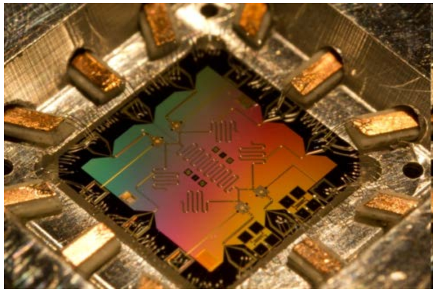
(2) What are the fundamental limits on the machines we can build?

Today's state of the art: The digital computer

Fundamental building block: The Bit

0 or 1

~ 20 years ago, people realized a qualitatively new kind of computer was possible: **A quantum computer**

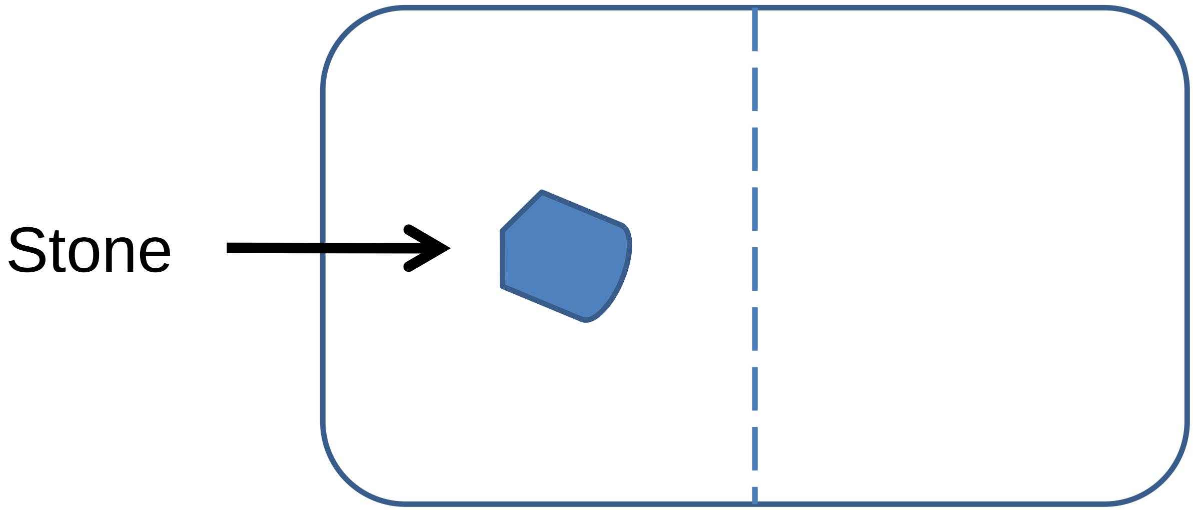


Fundamental building block: The Qubit

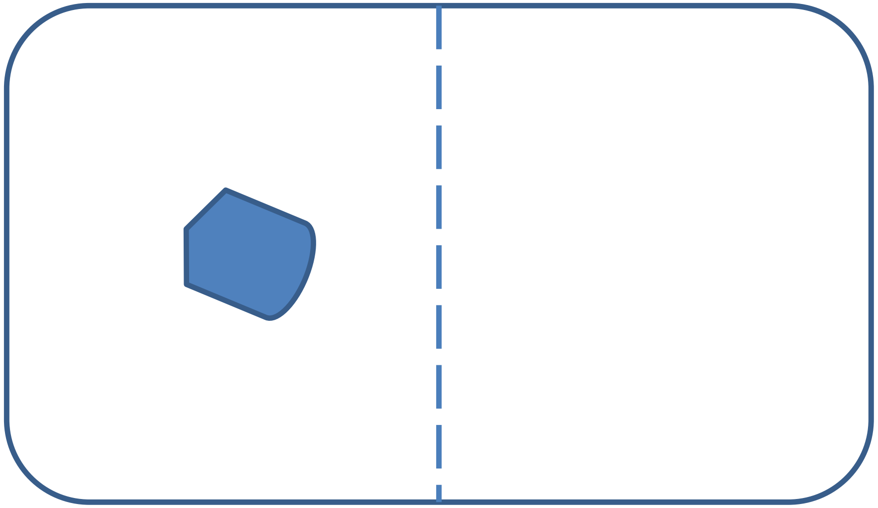
$$\alpha\left|0\right\rangle + \beta\left|1\right\rangle$$

http://web.physics.ucsb.edu/~martinisgroup/

Early Digital Memory

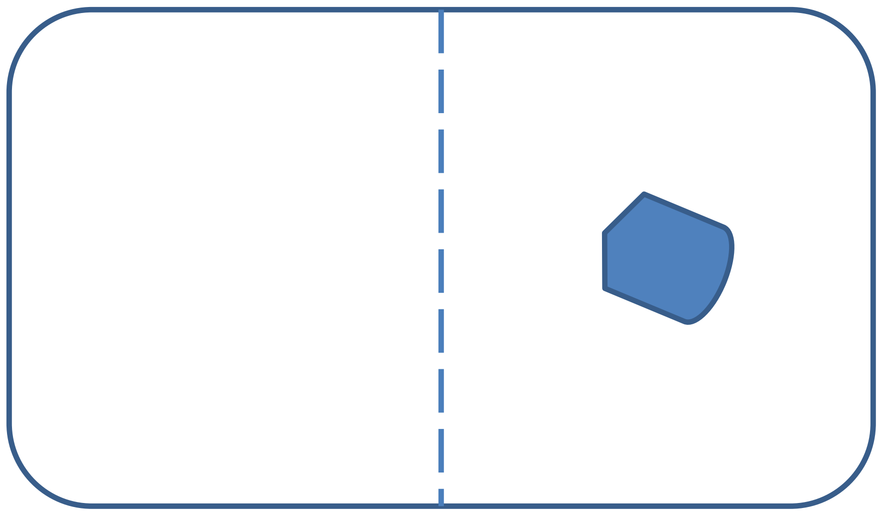


Early Digital Memory



= 0

Early Digital Memory



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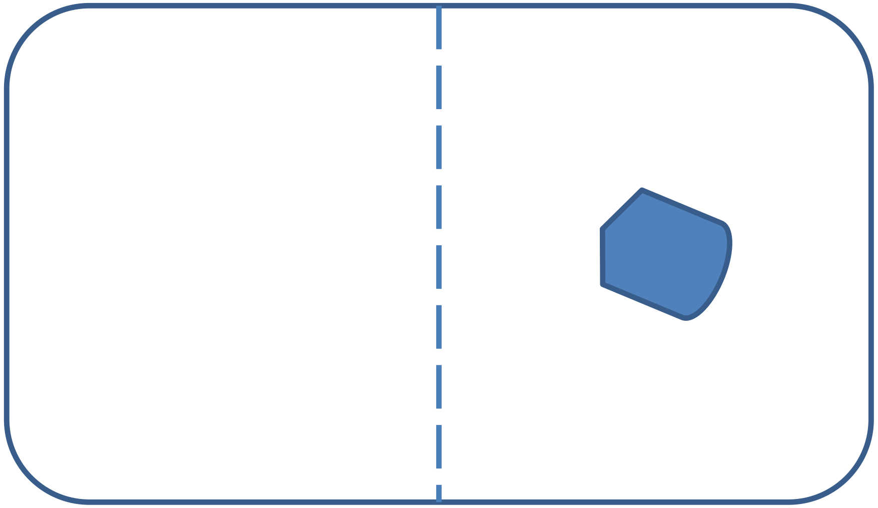
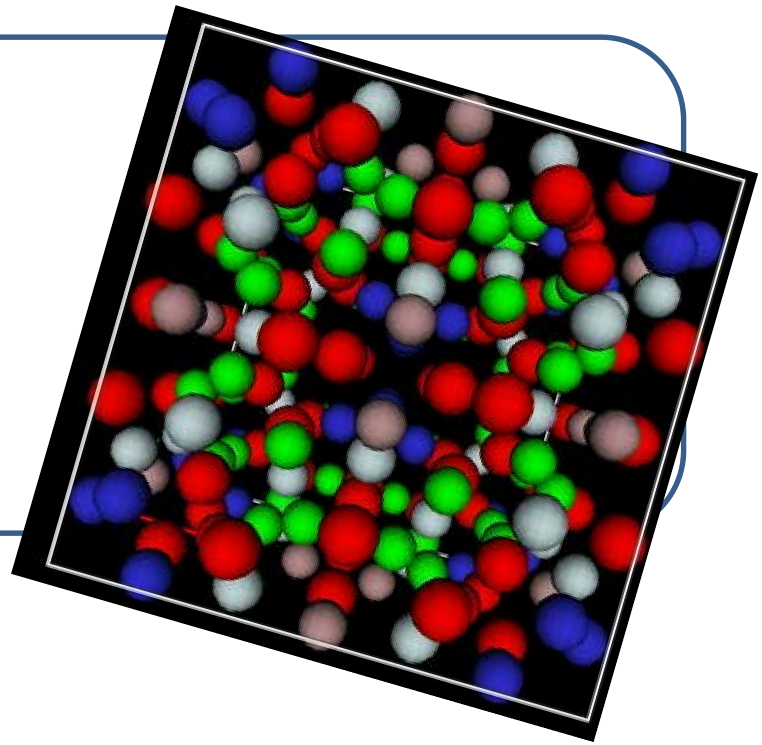
Early Digital Memory



= 1

The iStone



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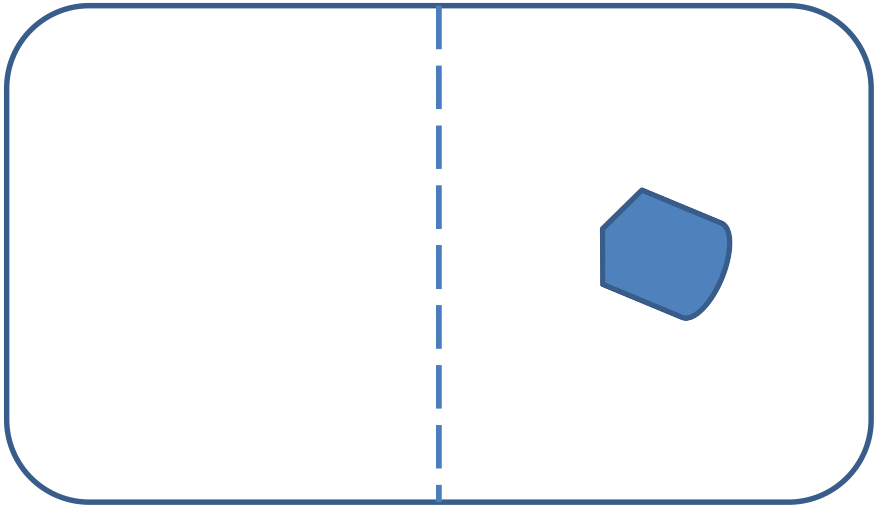
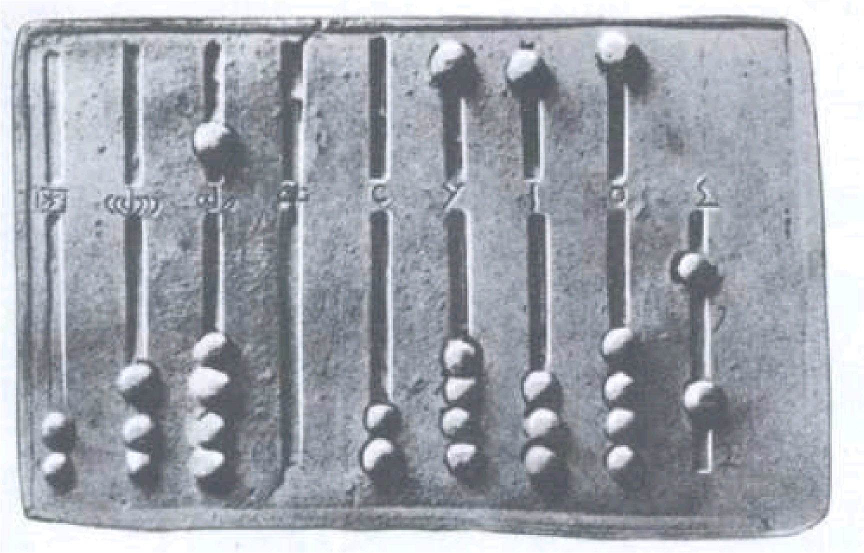


The iStone: 1 bit

Early Digital Memory



The iStone 4: ~ 20 bits

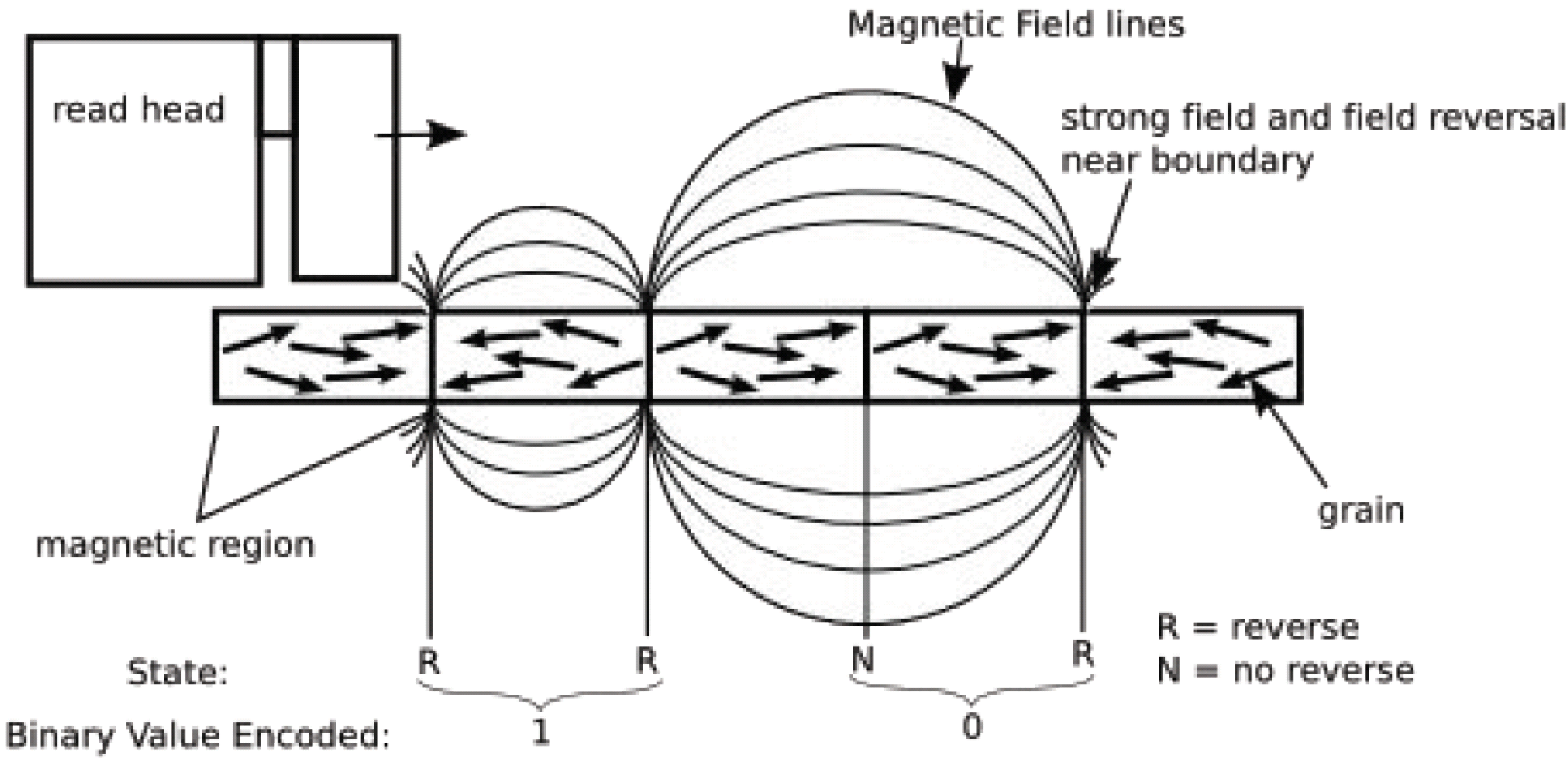
Modern Digital Memory

The iPhone 4: ~ 2.6×10^{11} bits

Modern Digital Memory

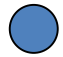
The iPod: ~ 1.4×10^{12} bits

Modern Digital Memory

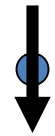


http://en.wikipedia.org/wiki/Hard_disk_drive

Magnetic Order

A spin-1/2 particle: 

“spin up”



“spin down”

Magnetic Order

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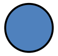
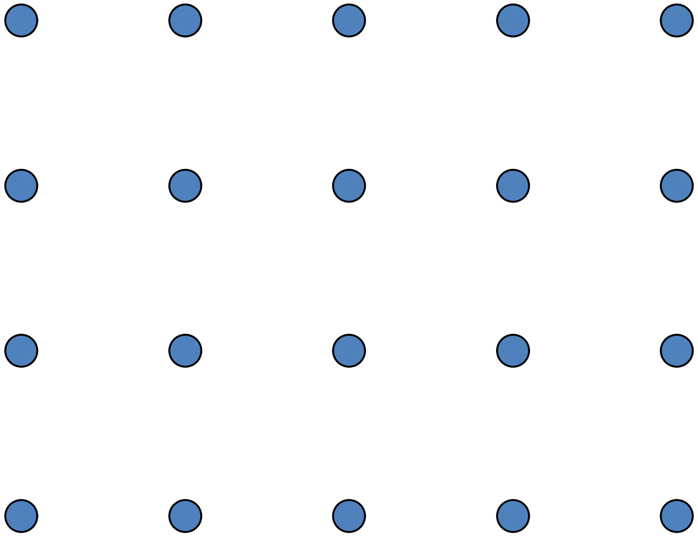


Many spin-1/2 particles:



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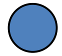
A spin-1/2 particle: 

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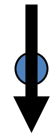 "spin down"

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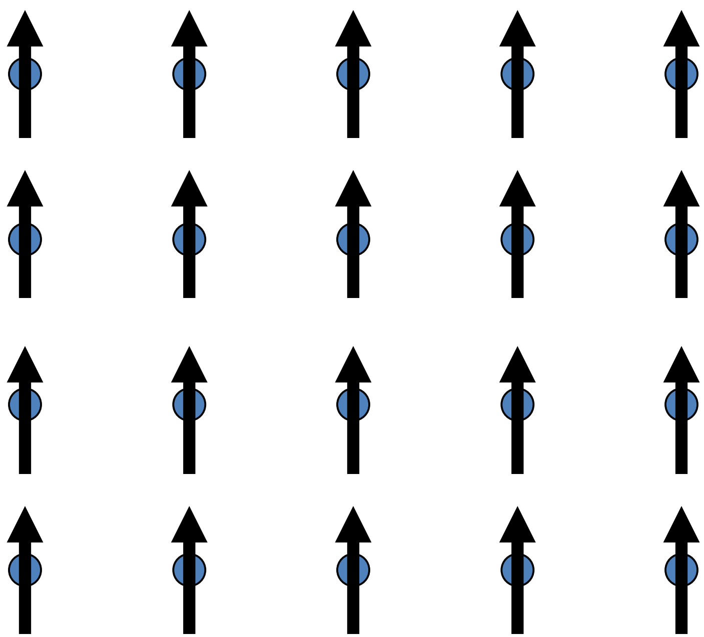

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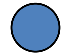
A spin-1/2 particle: 

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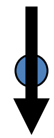
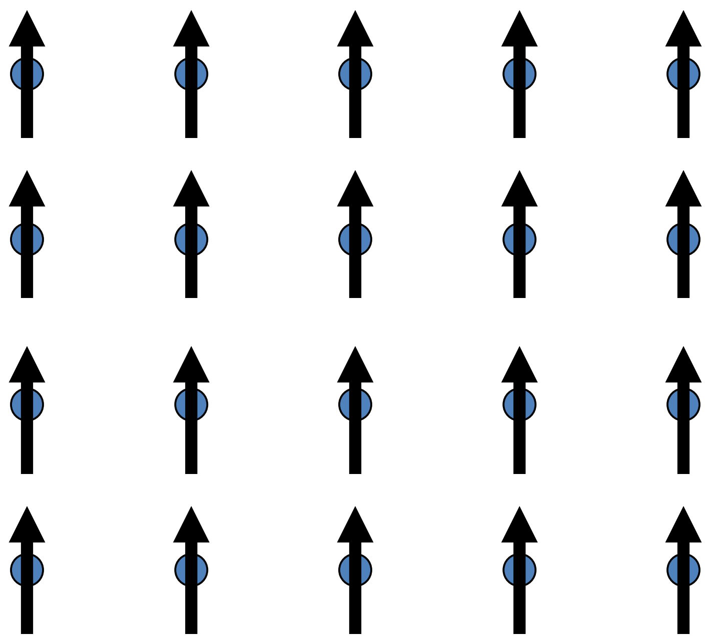
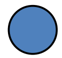
 "spin down"



Magnetic Order

$= 0$

Magnetic Order

A spin-1/2 particle: 

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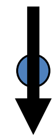 “spin down”

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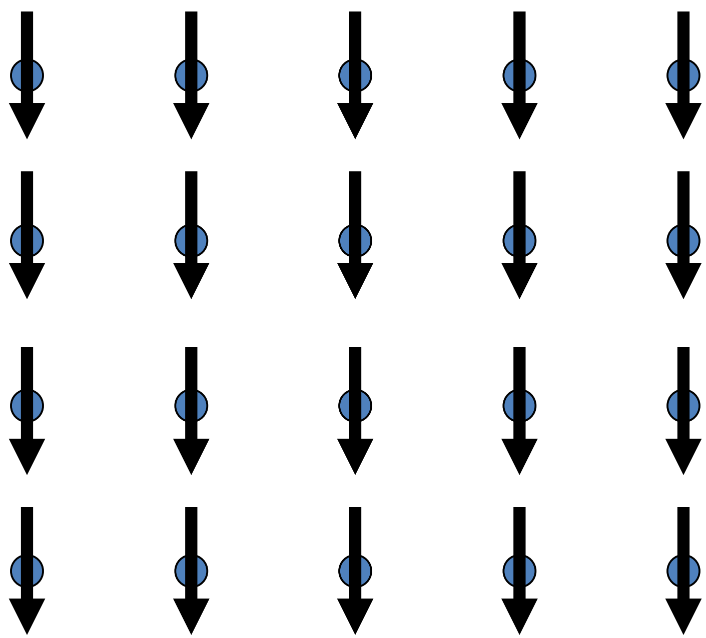

= 1

Another Kind of Order

A valence bond:

$$= \frac{1}{\sqrt{2}}\left(\uparrow\downarrow - \downarrow\uparrow\right)$$

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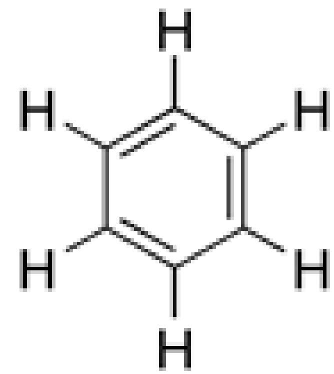

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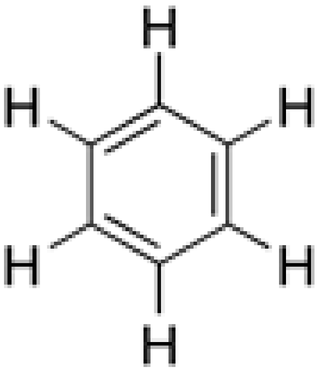

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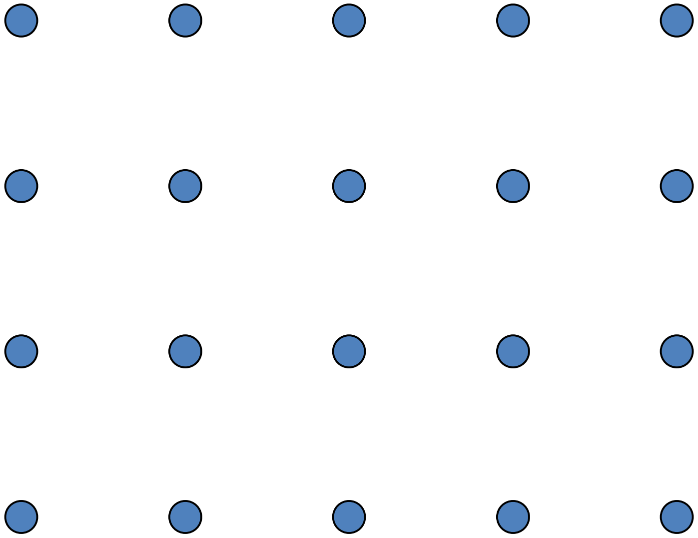

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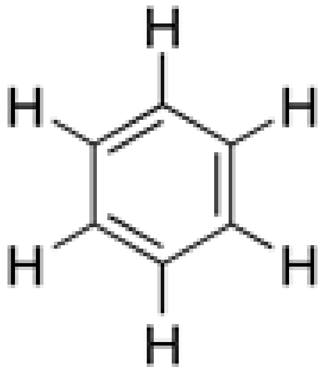

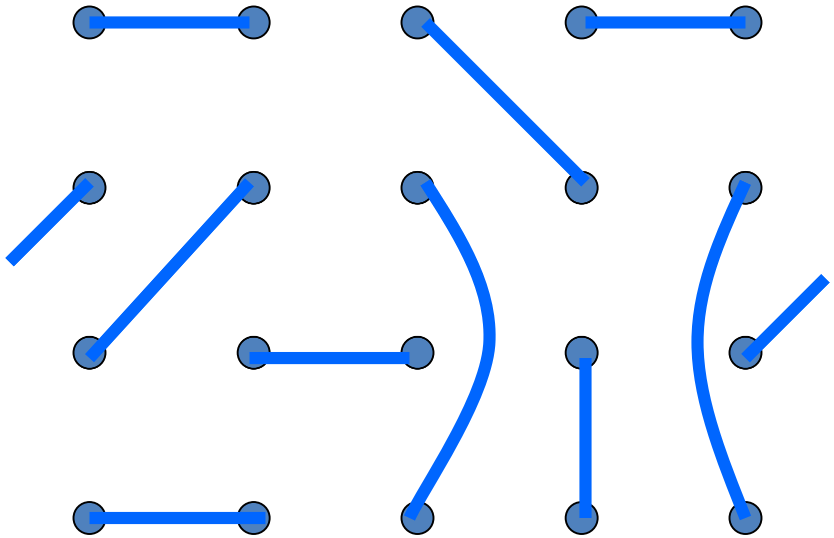

Use periodic boundary conditions

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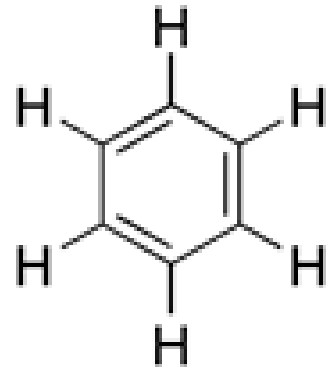

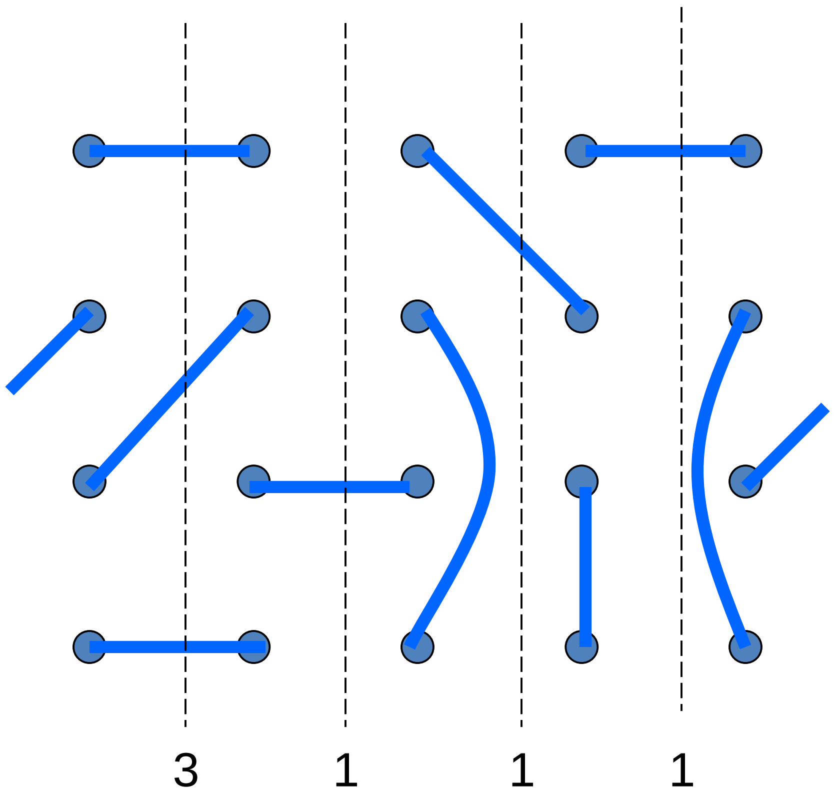

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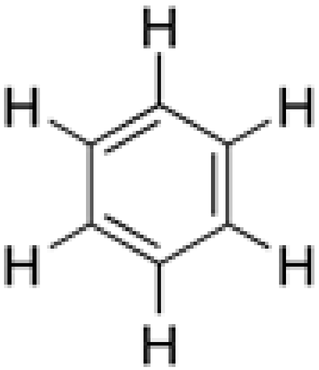

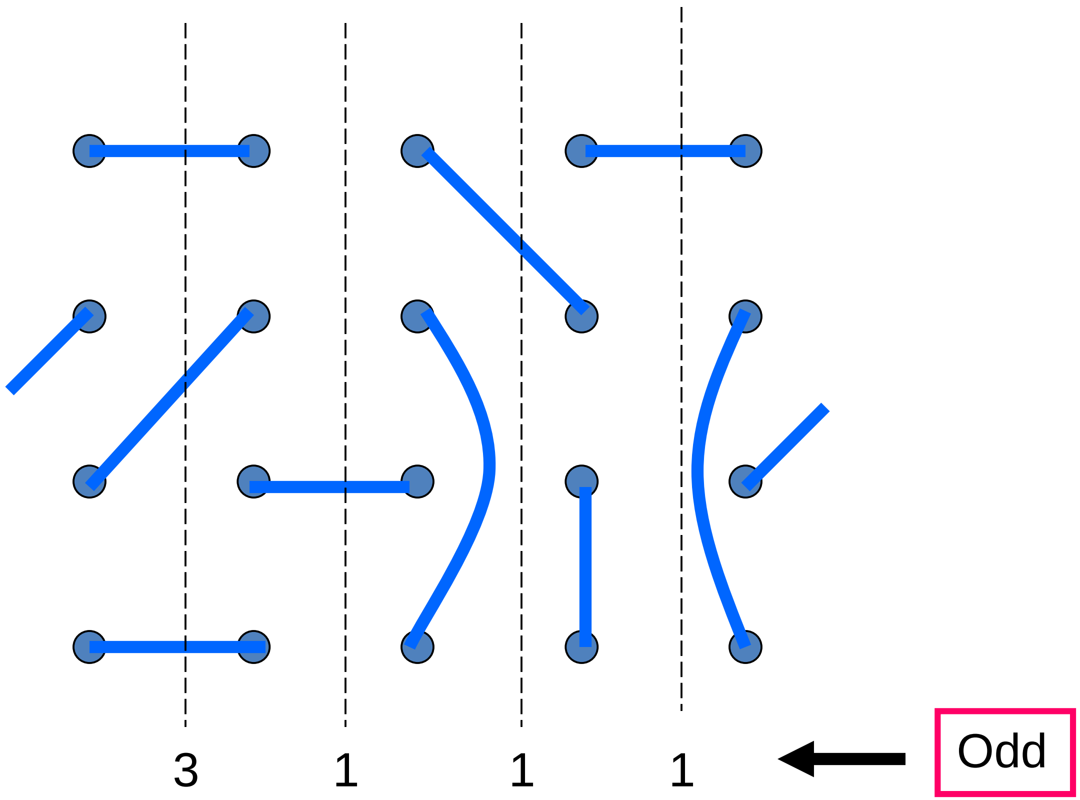

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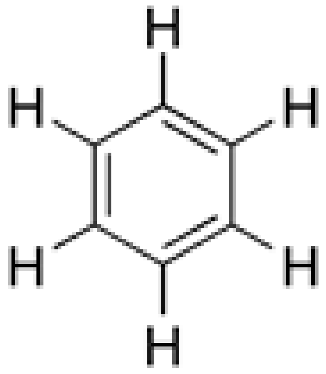

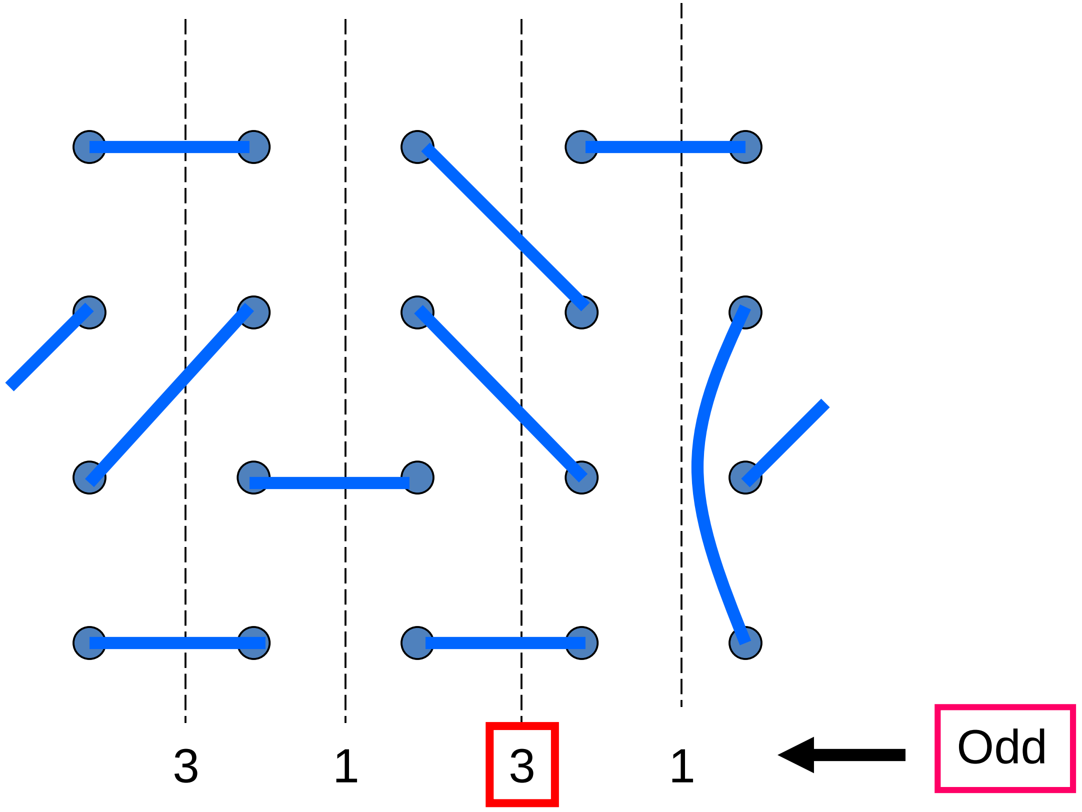

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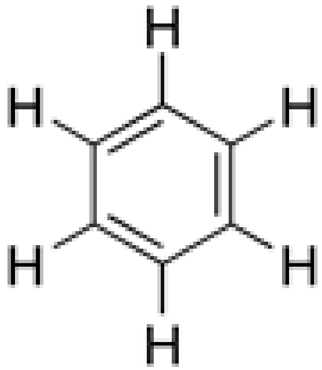

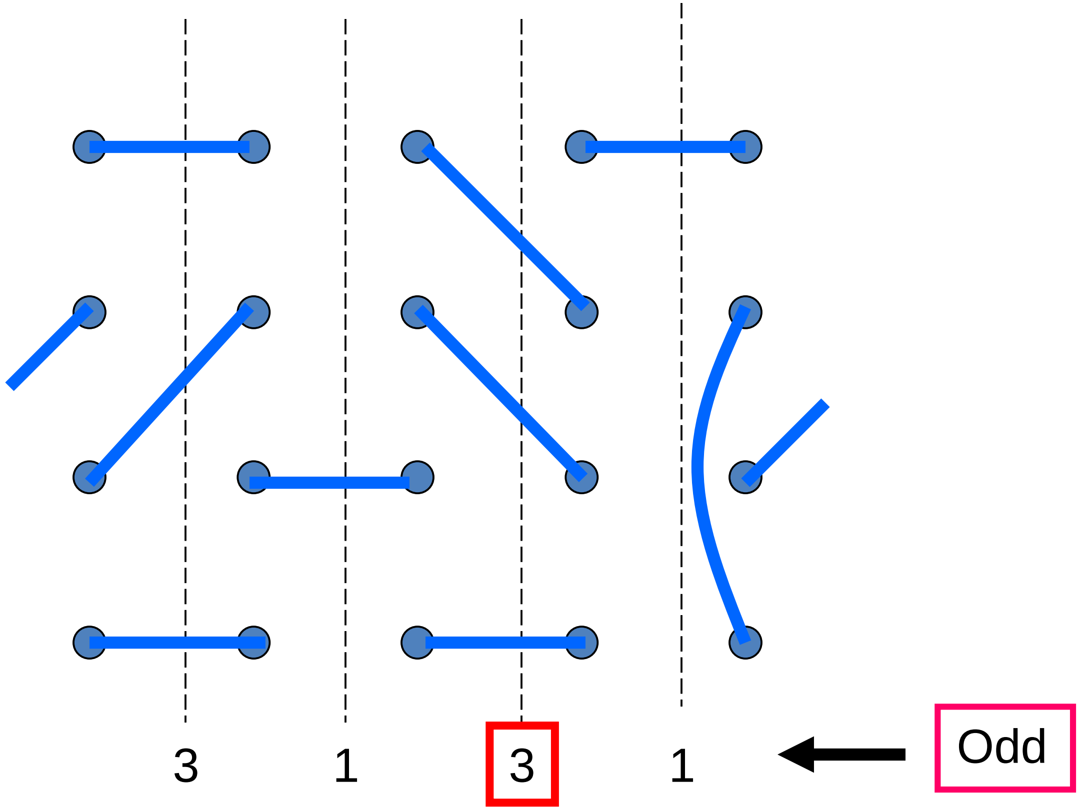

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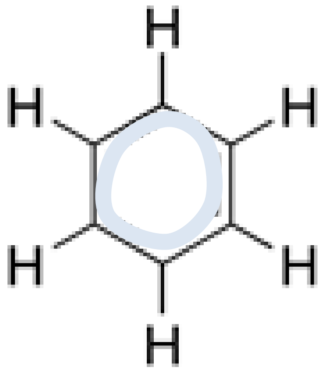

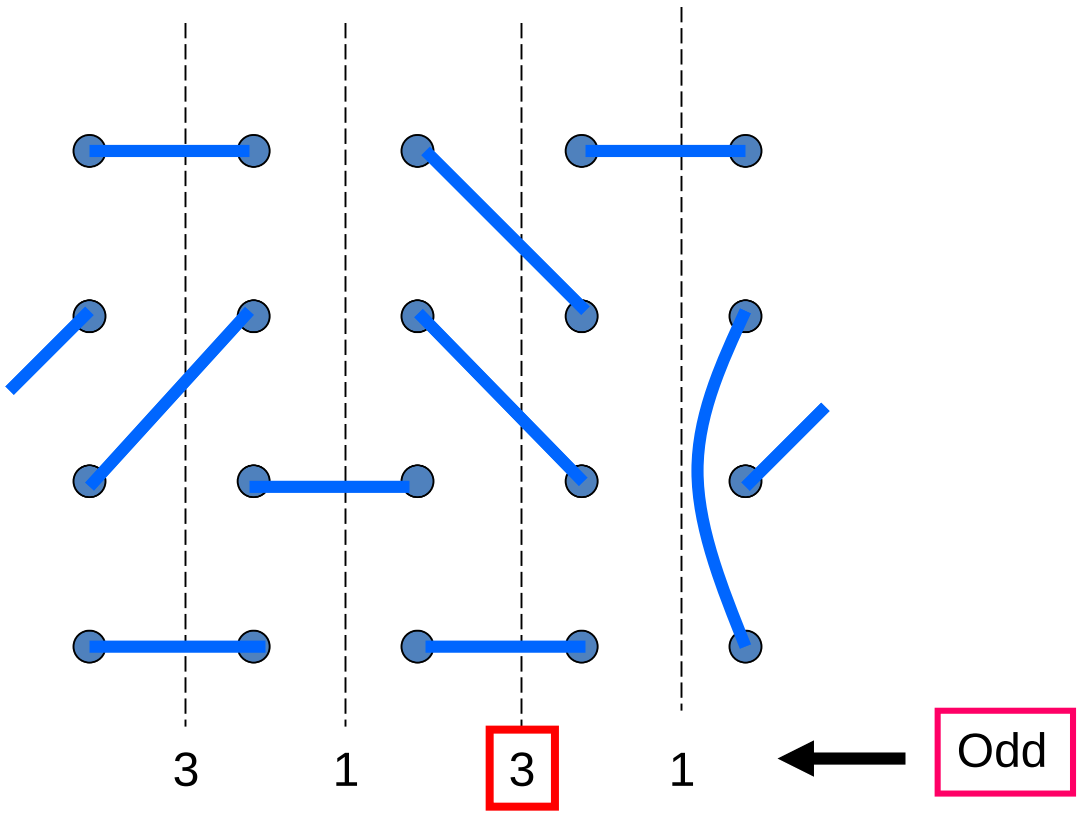

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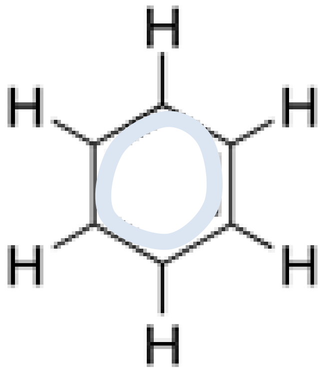

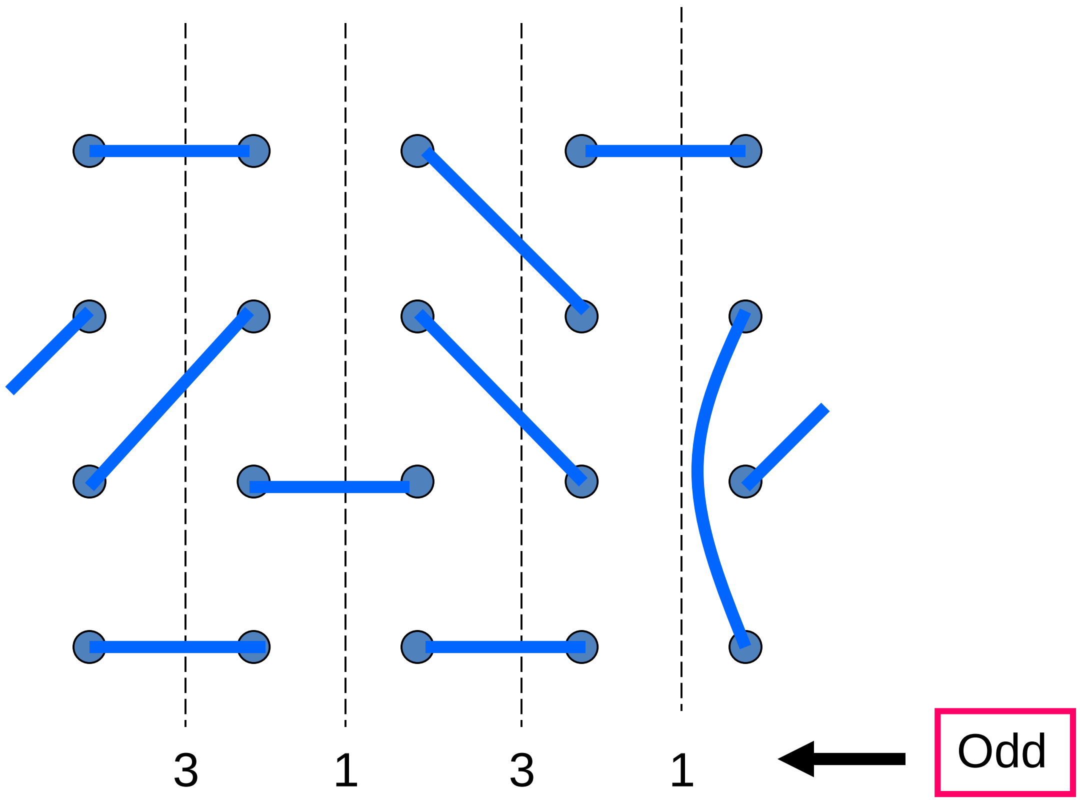

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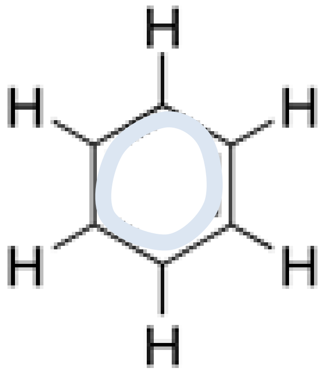

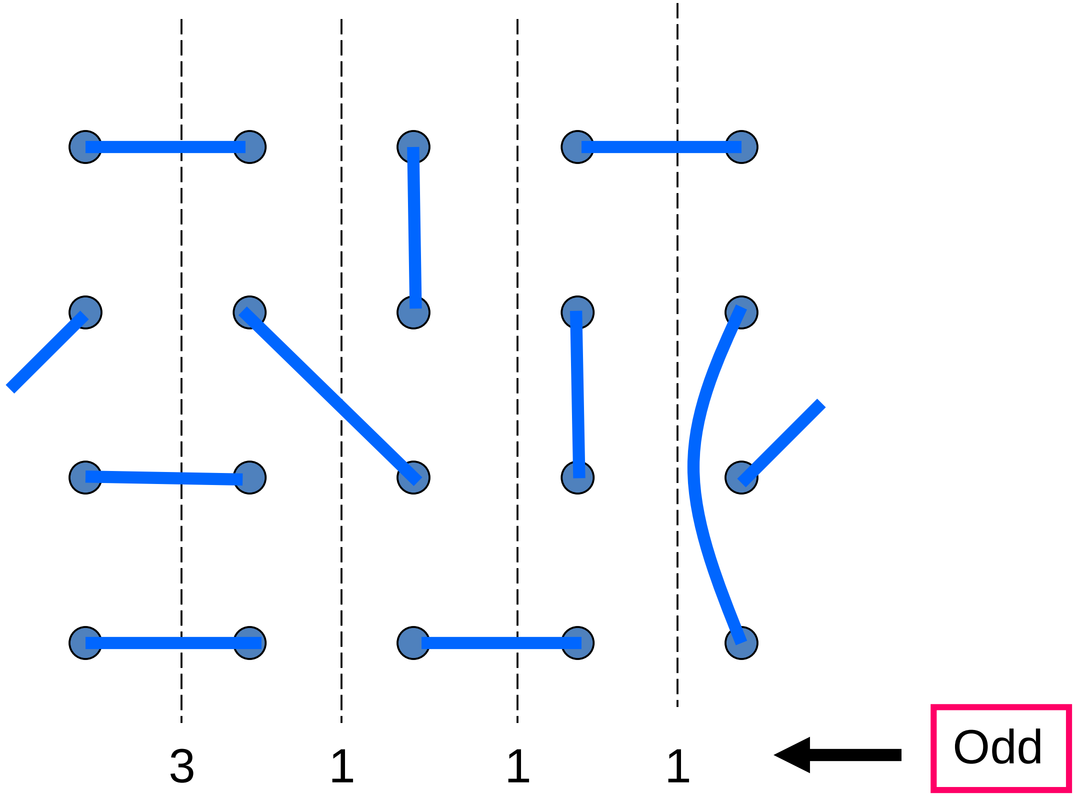

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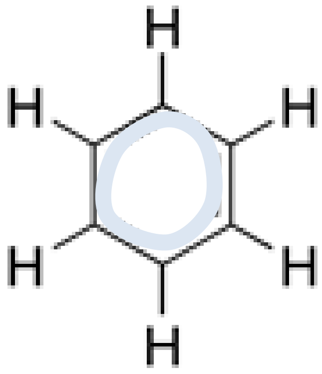
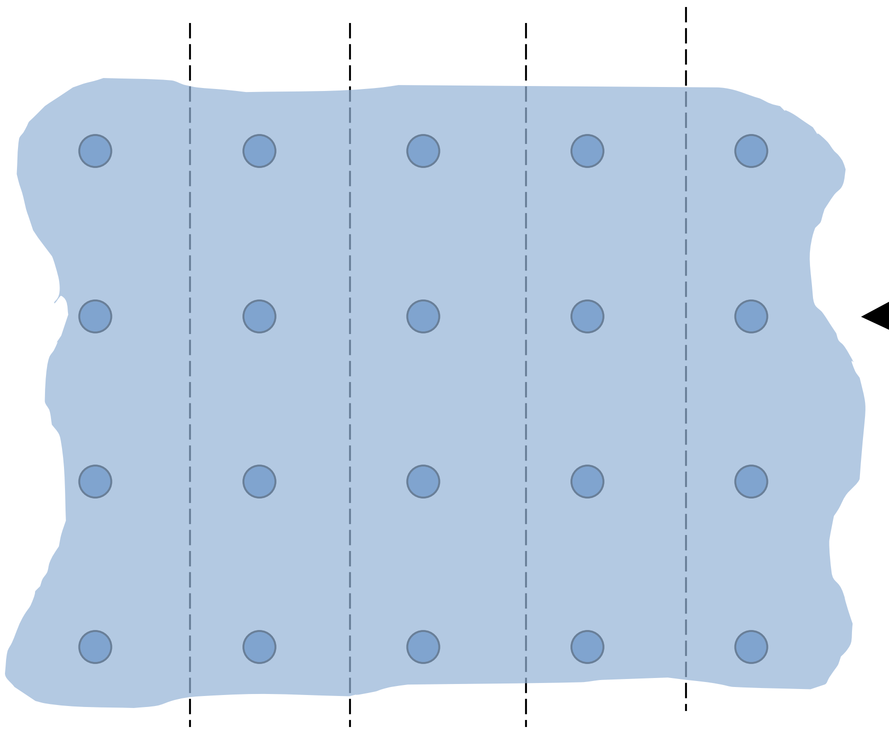




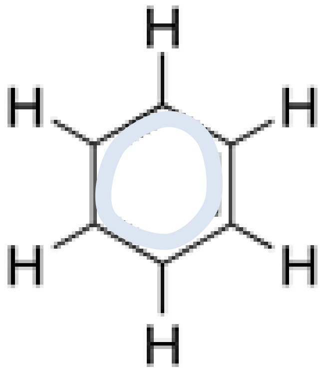
Quantum superposition of valence-bond states. A "**spin liquid**."

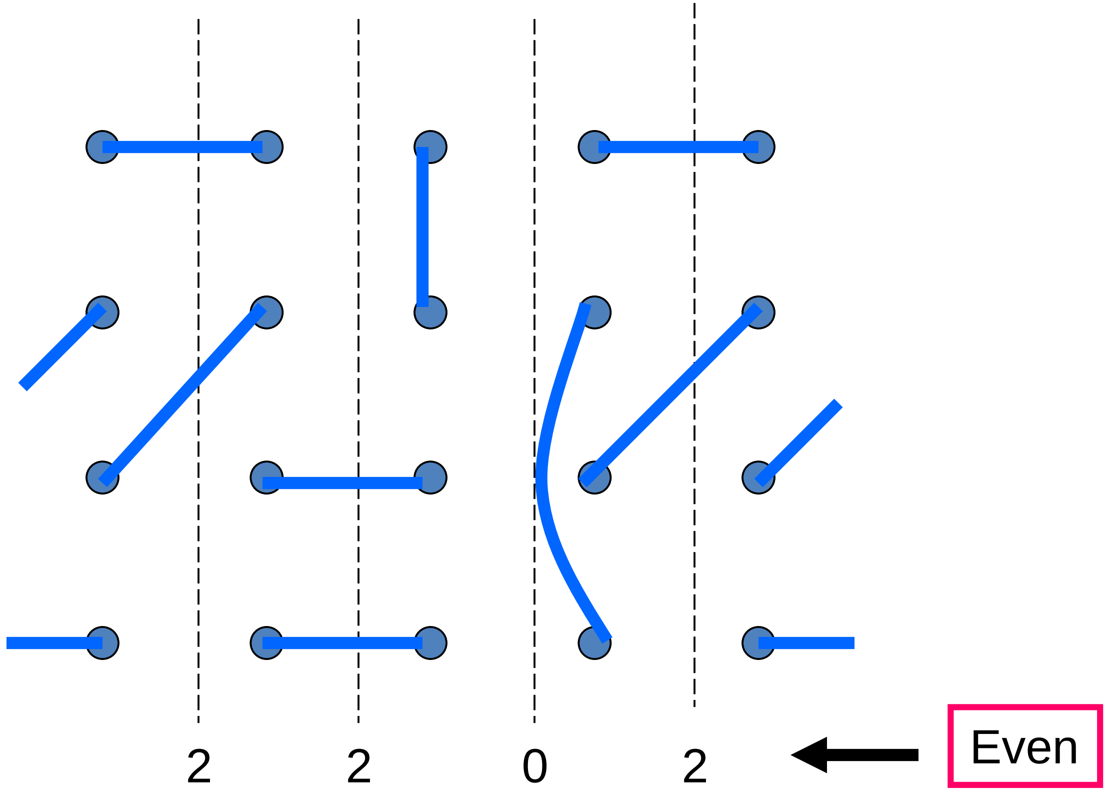
Odd

Another Kind of Order

A valence bond:

$$\bullet\!\!-\!\!\bullet \;=\; \frac{1}{\sqrt{2}}\left(\uparrow\downarrow - \downarrow\uparrow\right)$$





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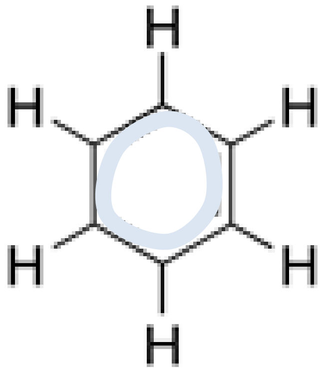

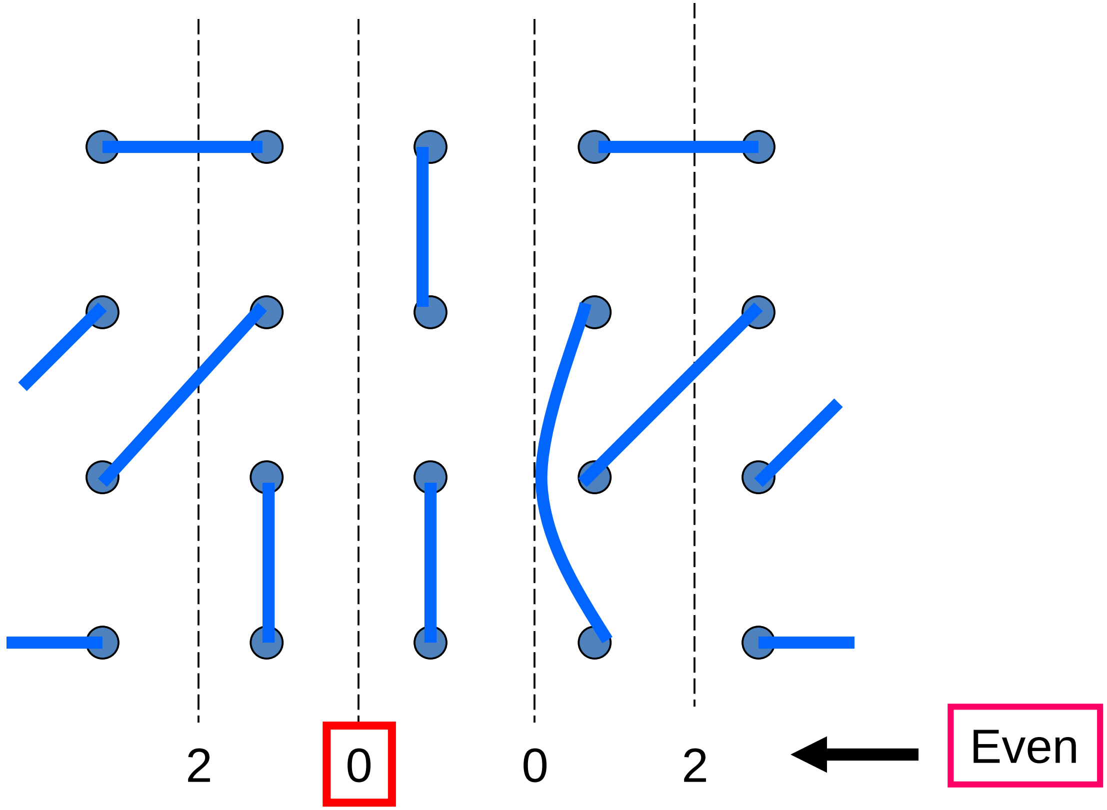

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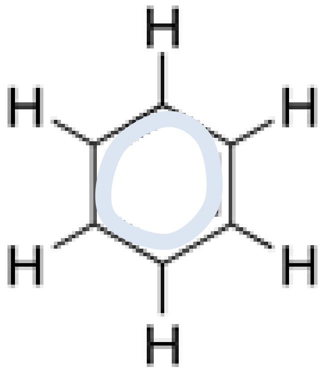

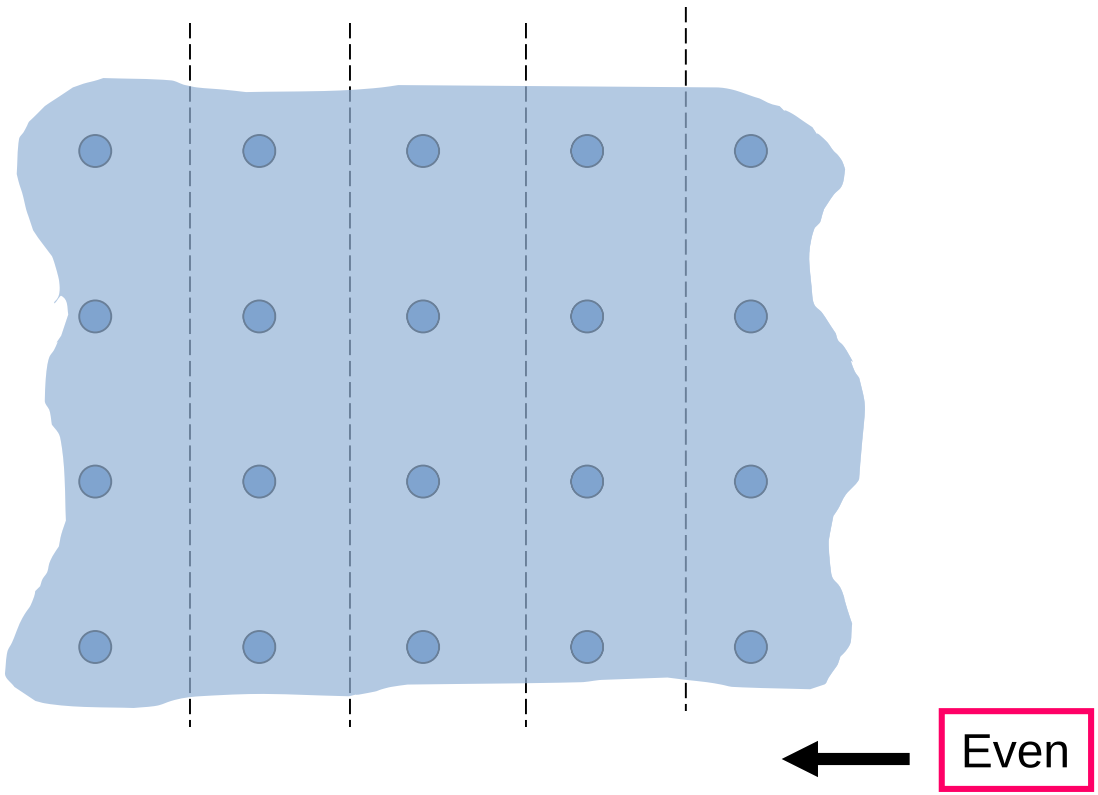

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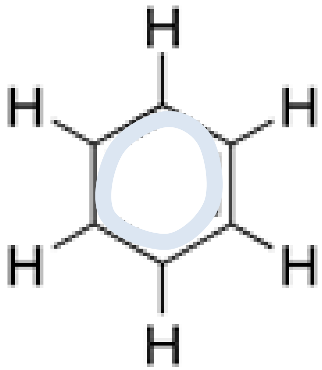

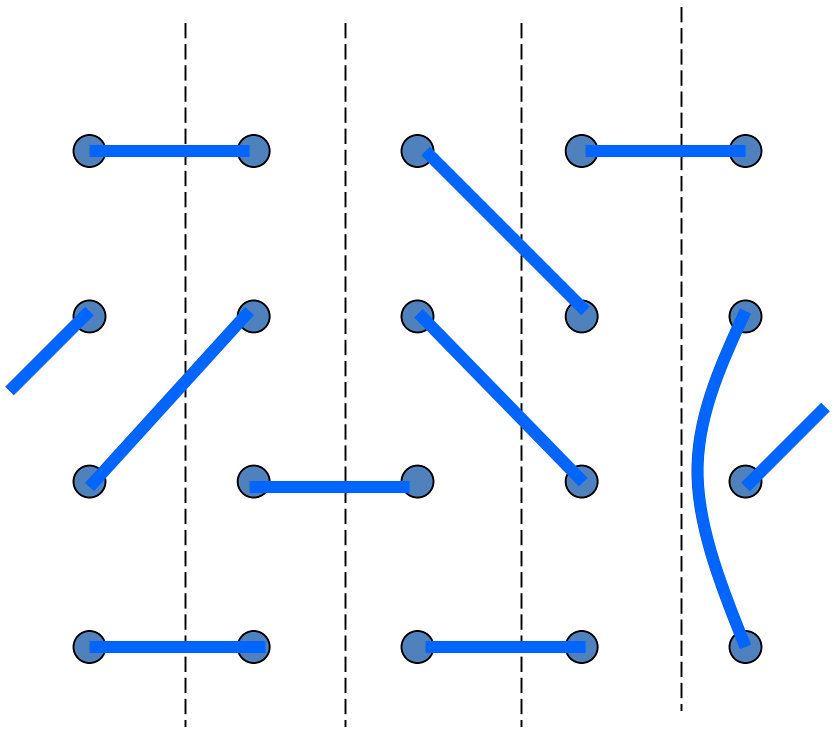

$|0\rangle$

Odd

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A valence bond:

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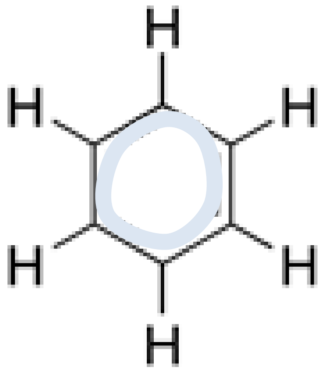

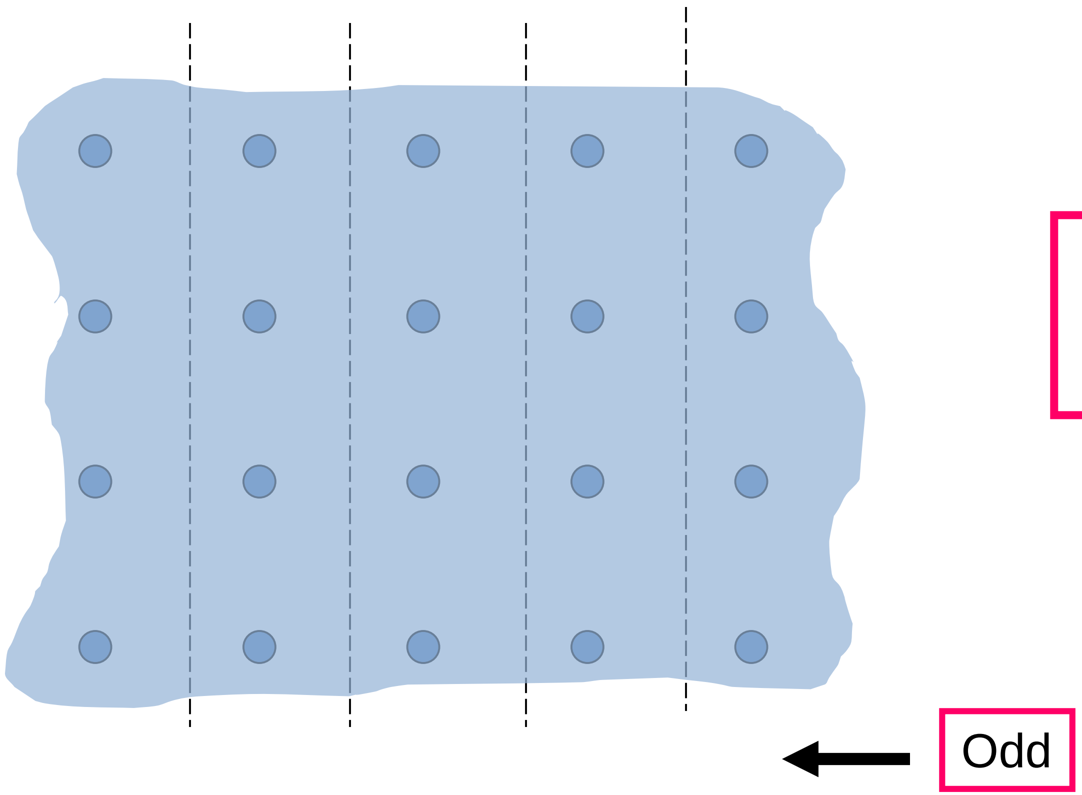

$$|0\rangle$$

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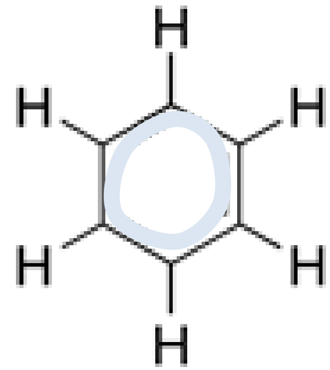
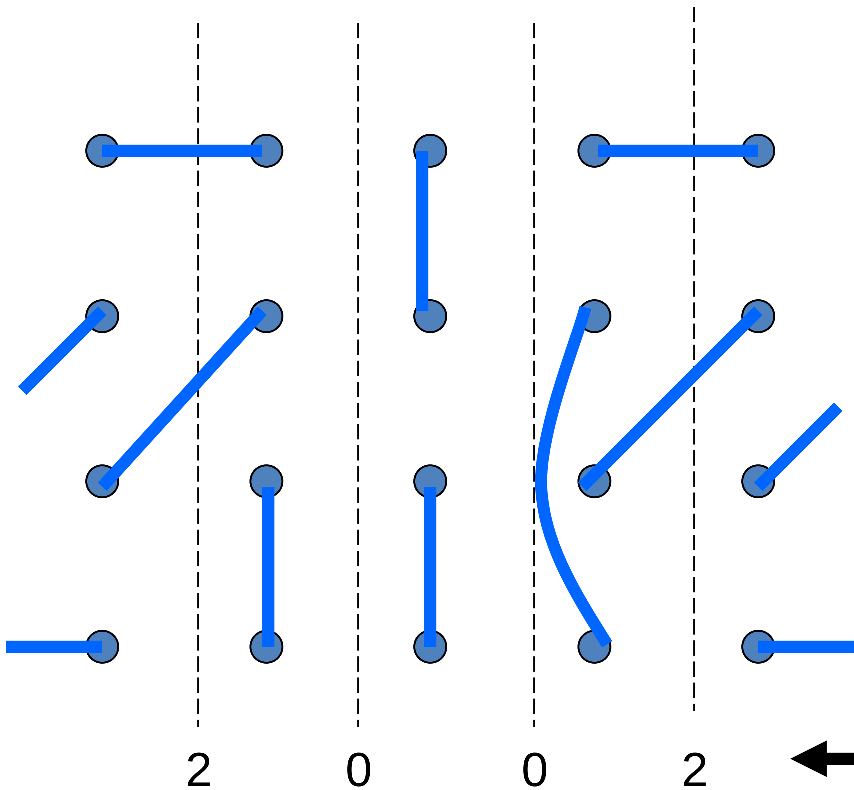




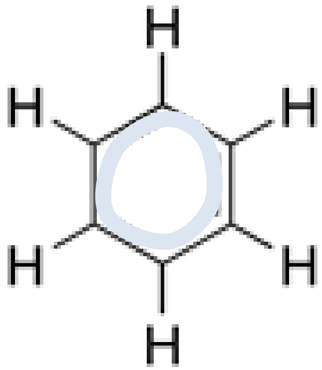
$|1\rangle$

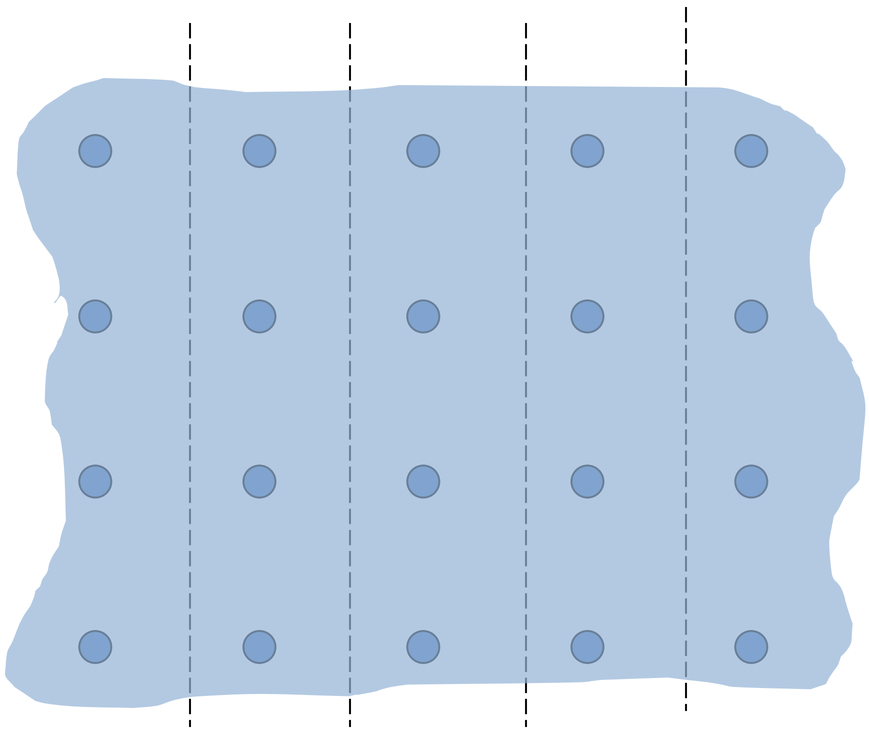
← Even

Another Kind of Order

A valence bond:

$$= \frac{1}{\sqrt{2}}\left(\uparrow\downarrow - \downarrow\uparrow\right)$$



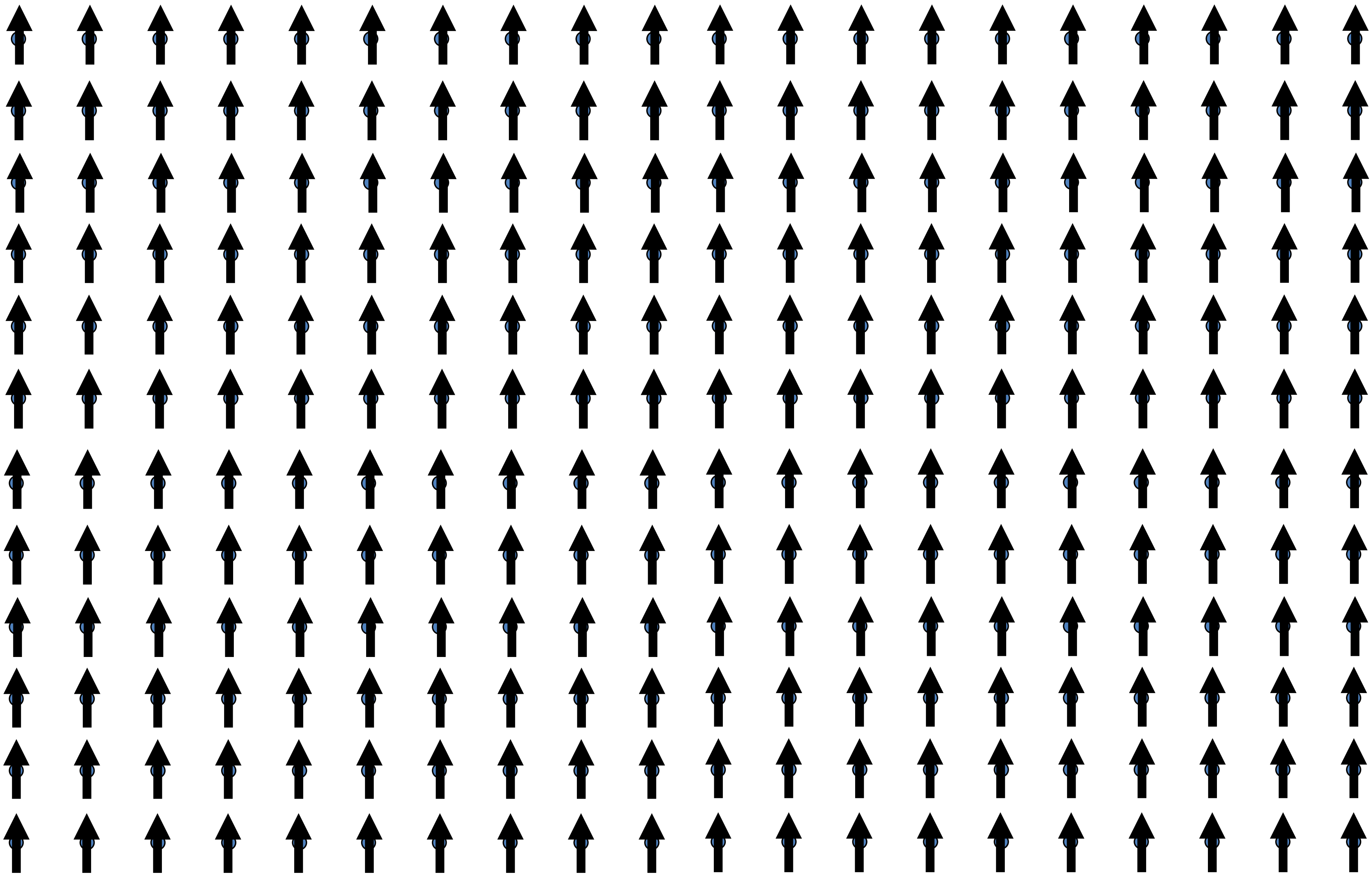


$|1\rangle$

← Even

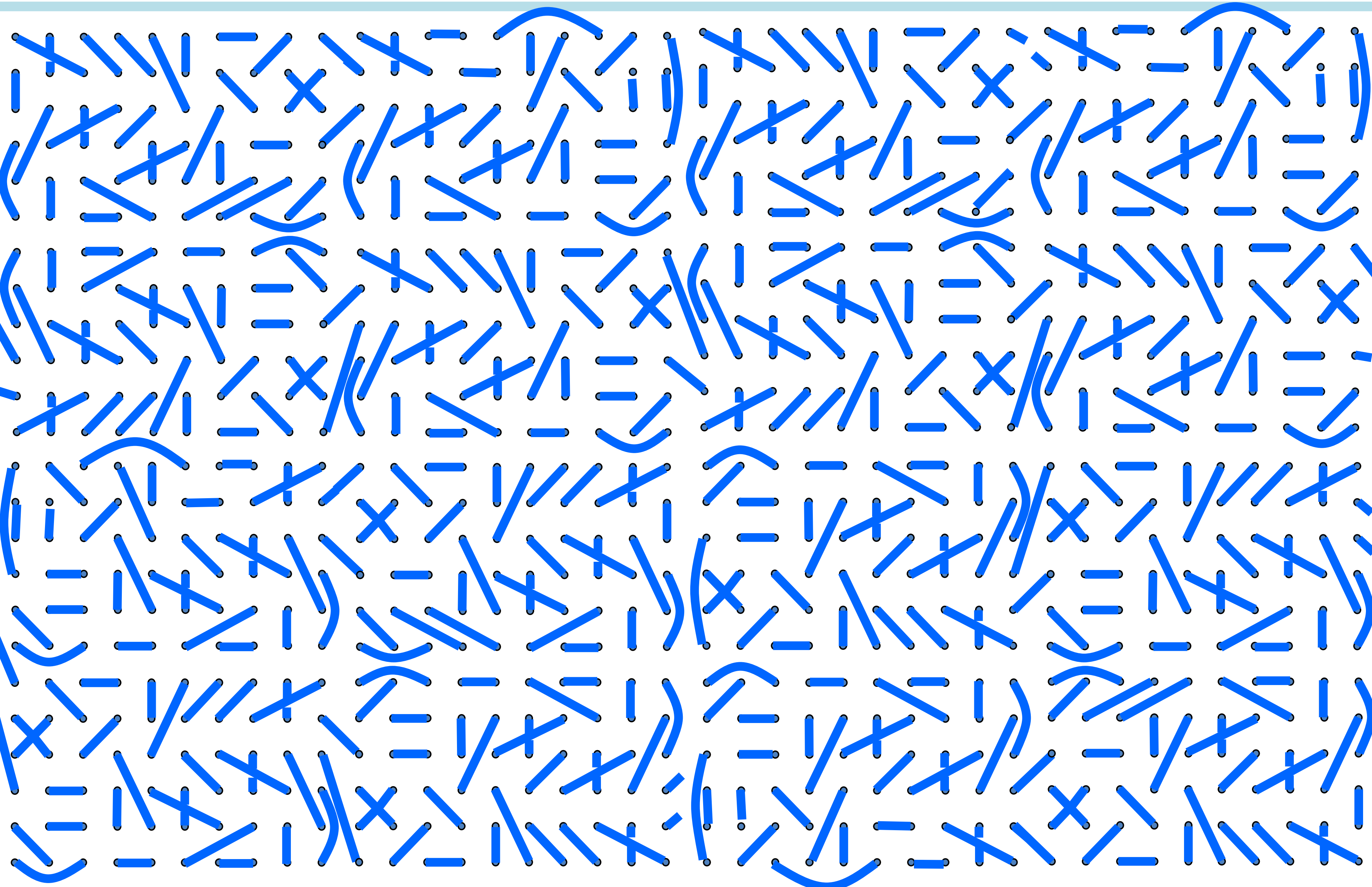
Is it a 0 or a 1?

Is it a 0 or a 1?



Is it a $|0\rangle$ or a $|1\rangle$?

Is it a |0⟩ or a |1⟩?



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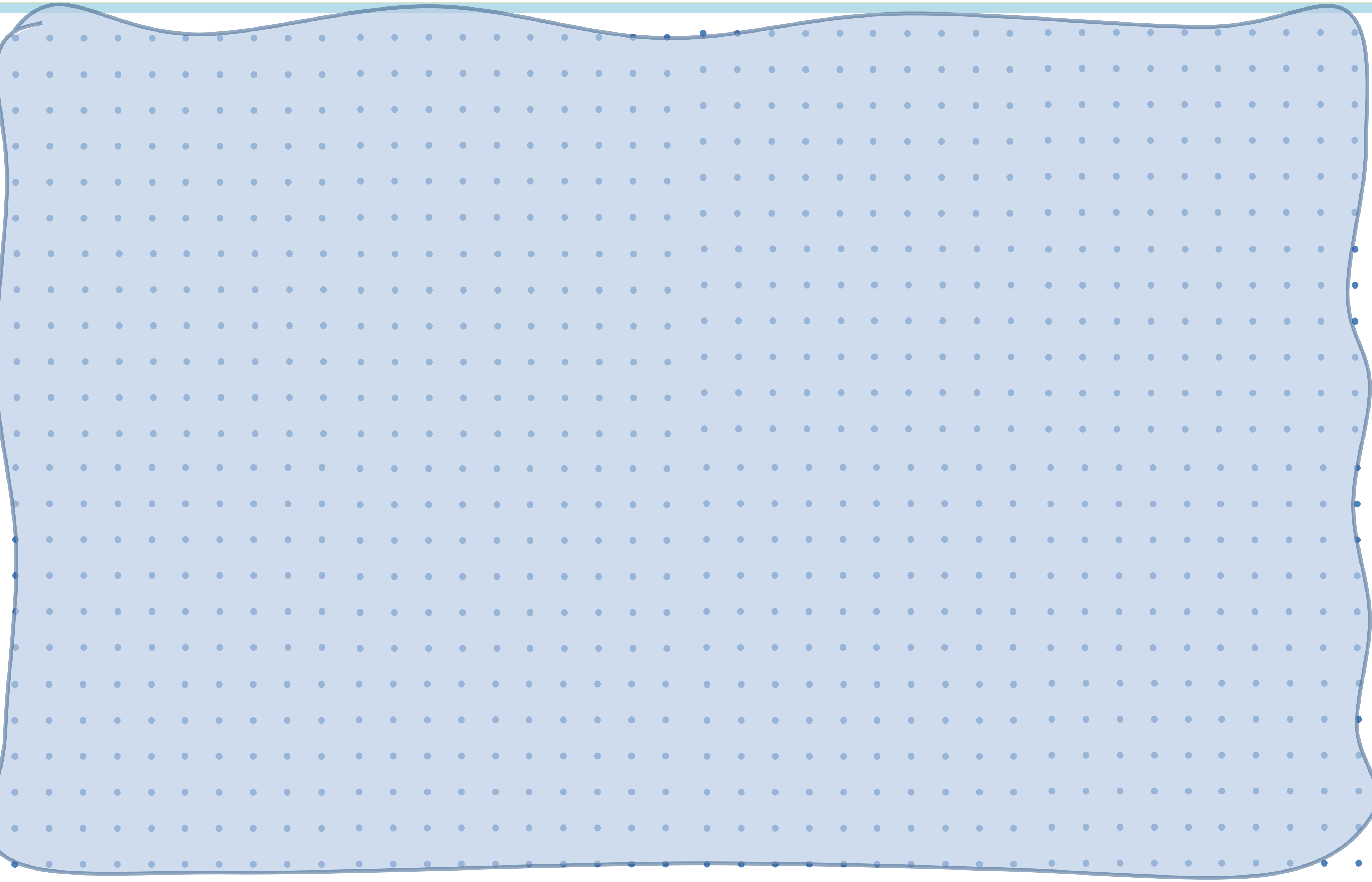
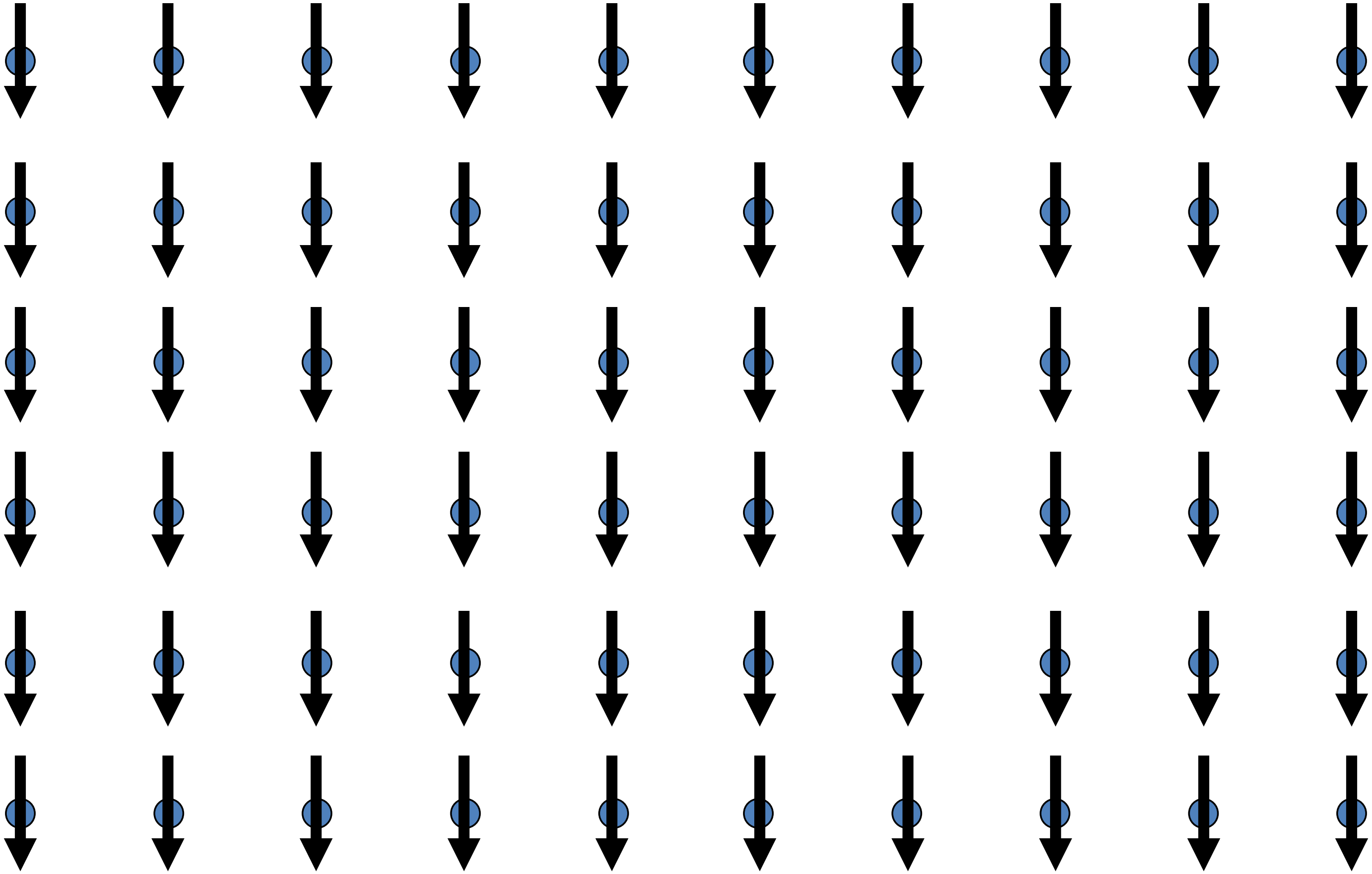
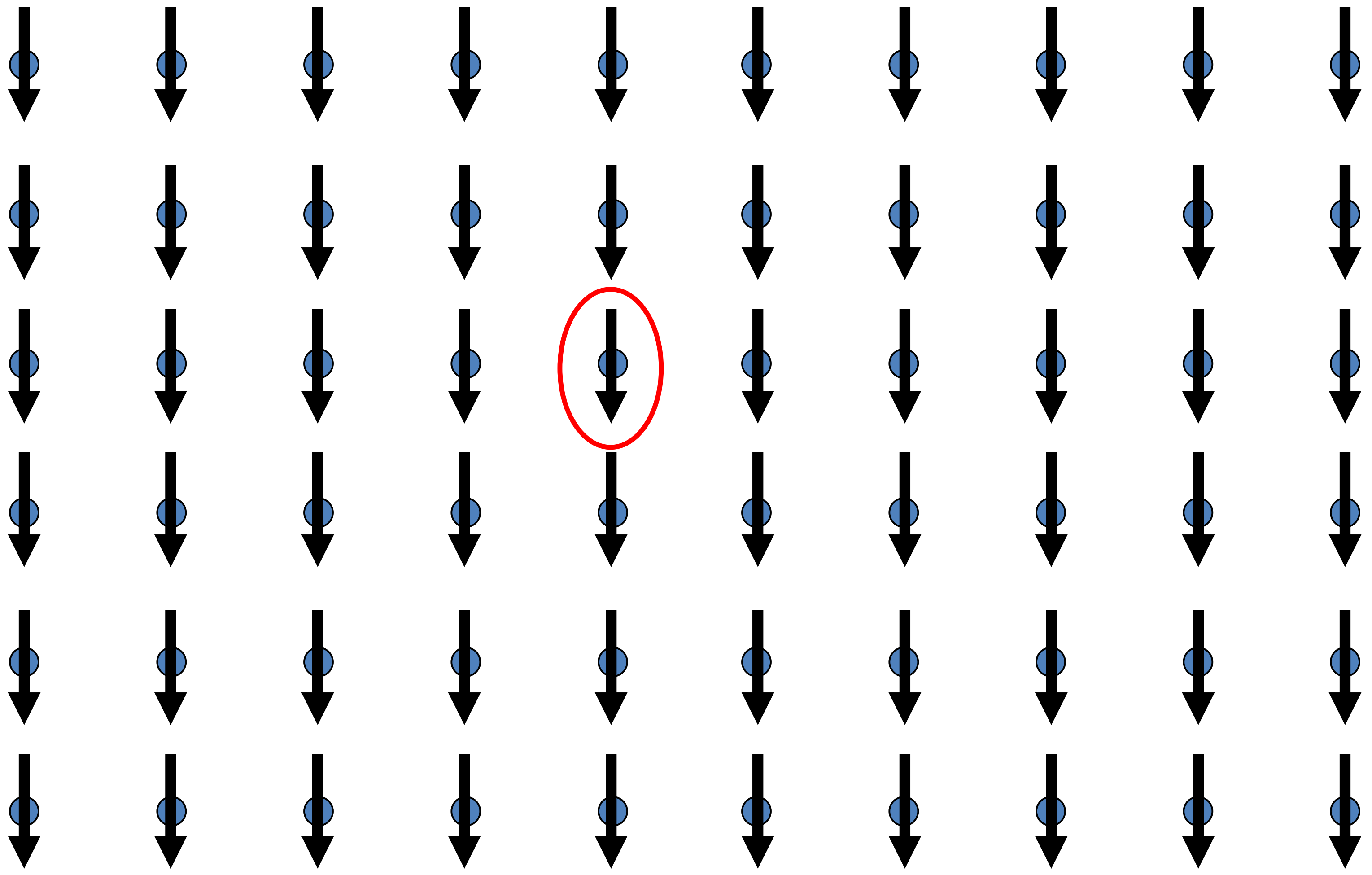


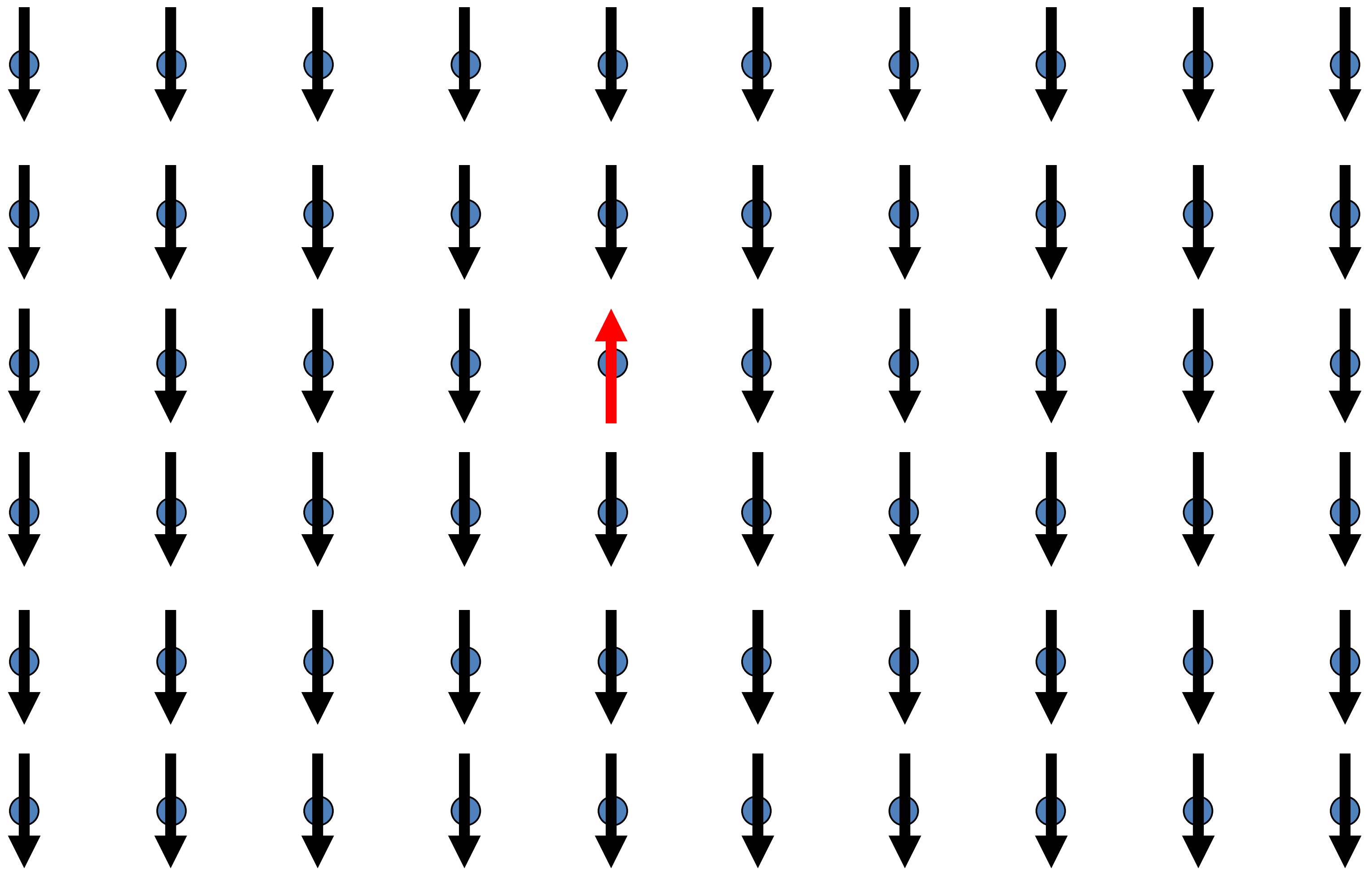
Conventional Order: Excitations



Conventional Order: Excitations

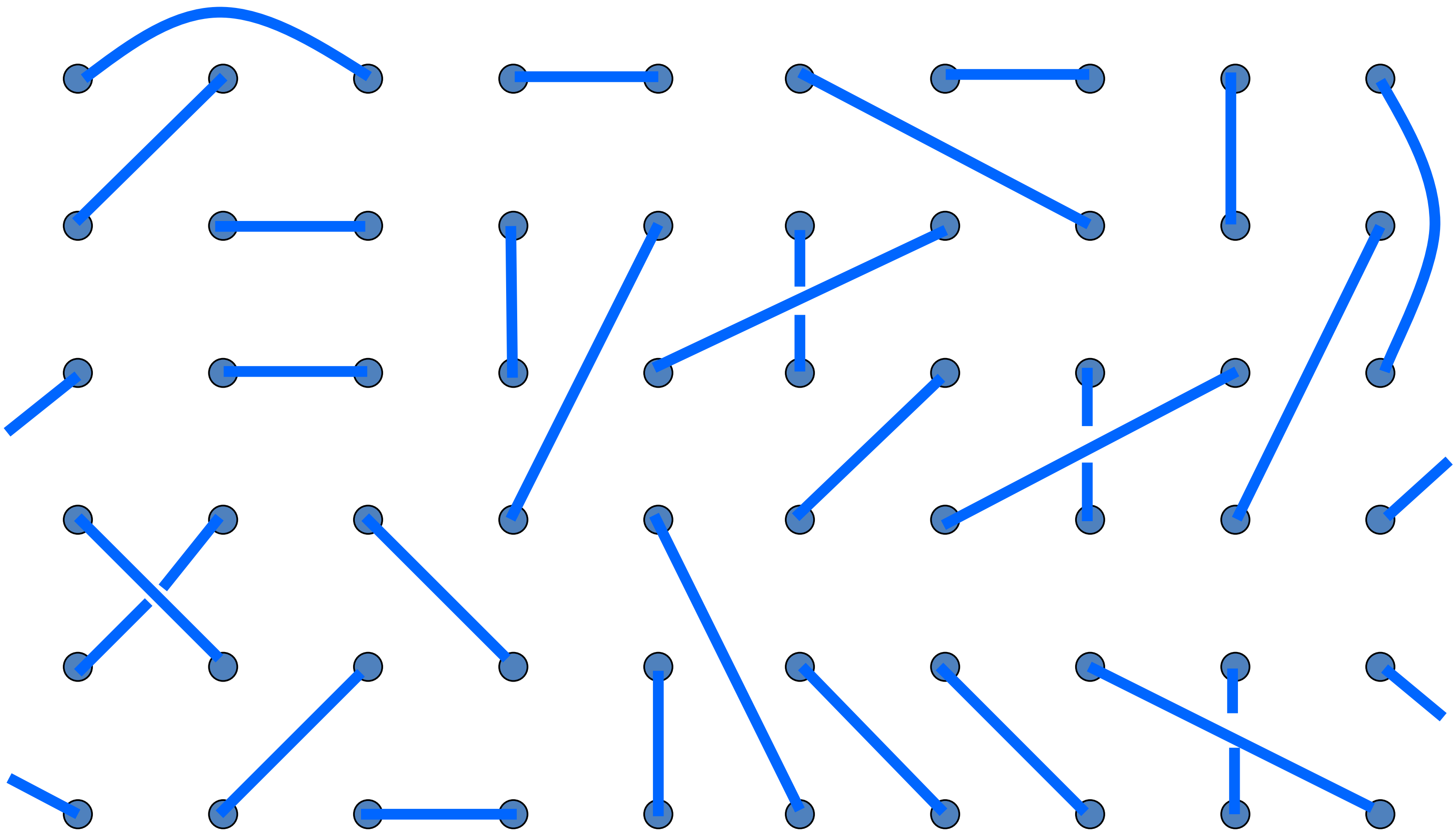


Conventional Order: Excitations

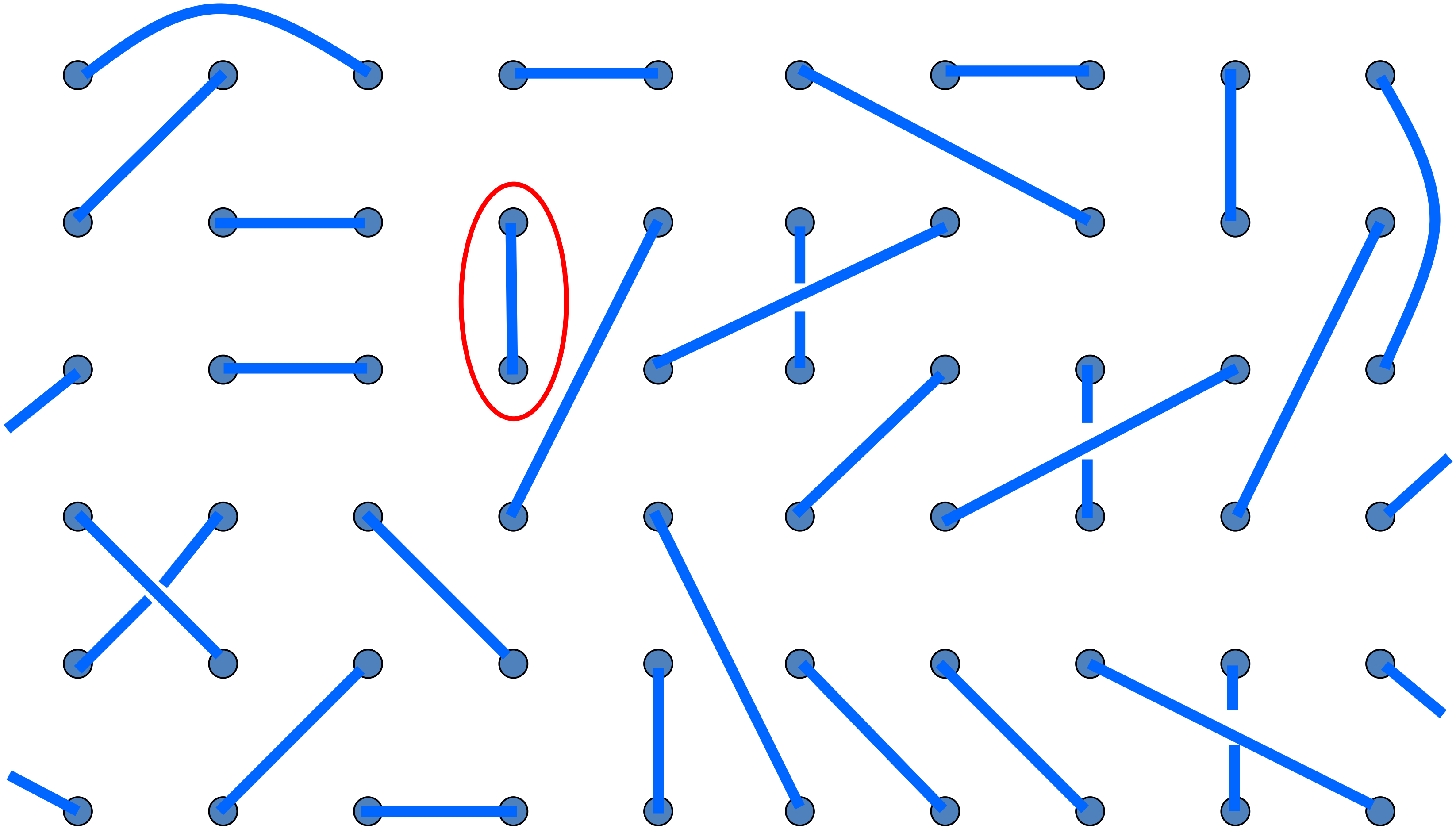


Magnon = one spin flip: Total S_z changes by +1

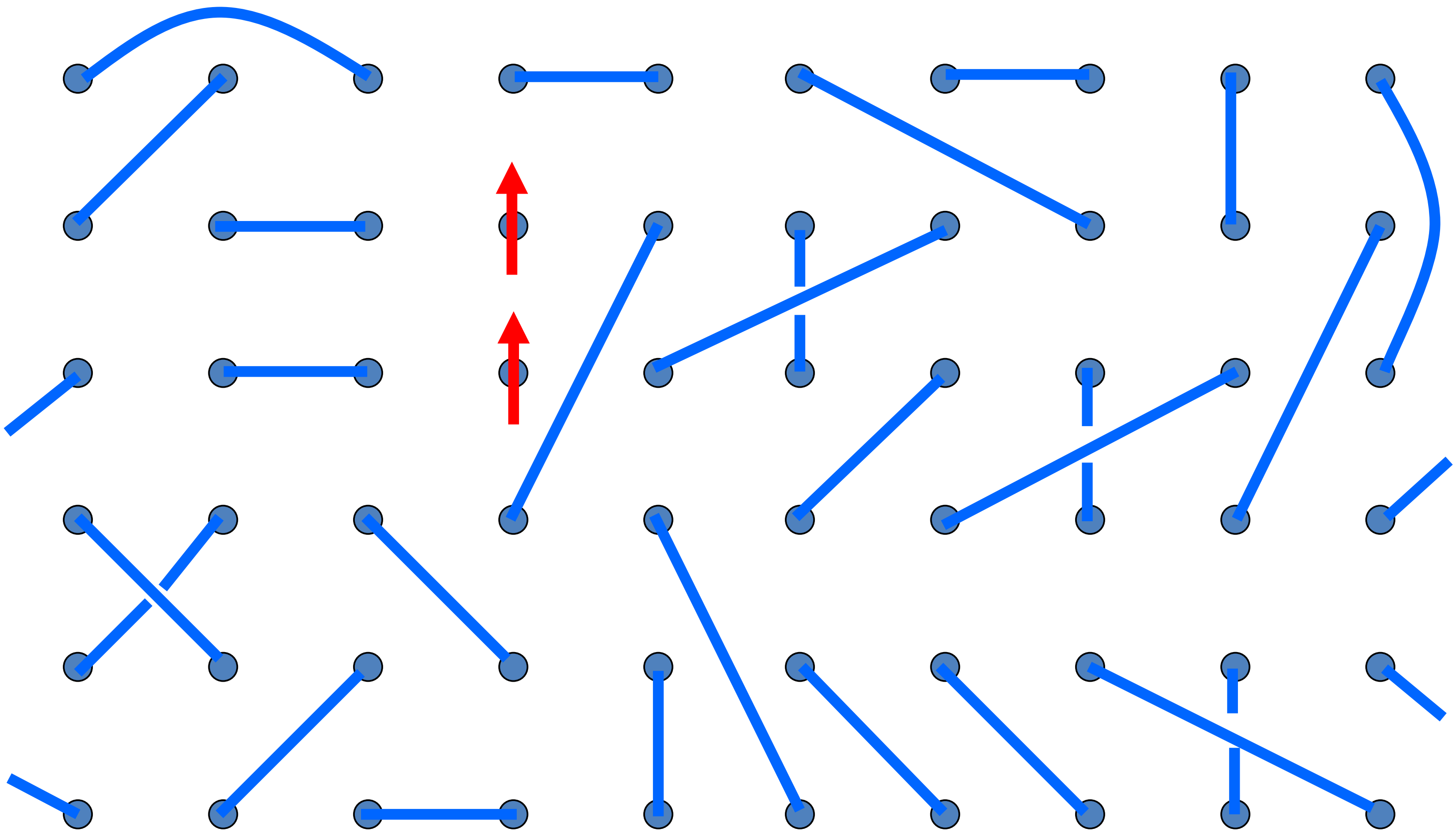
Topological Order: Excitations



Topological Order: Excitations

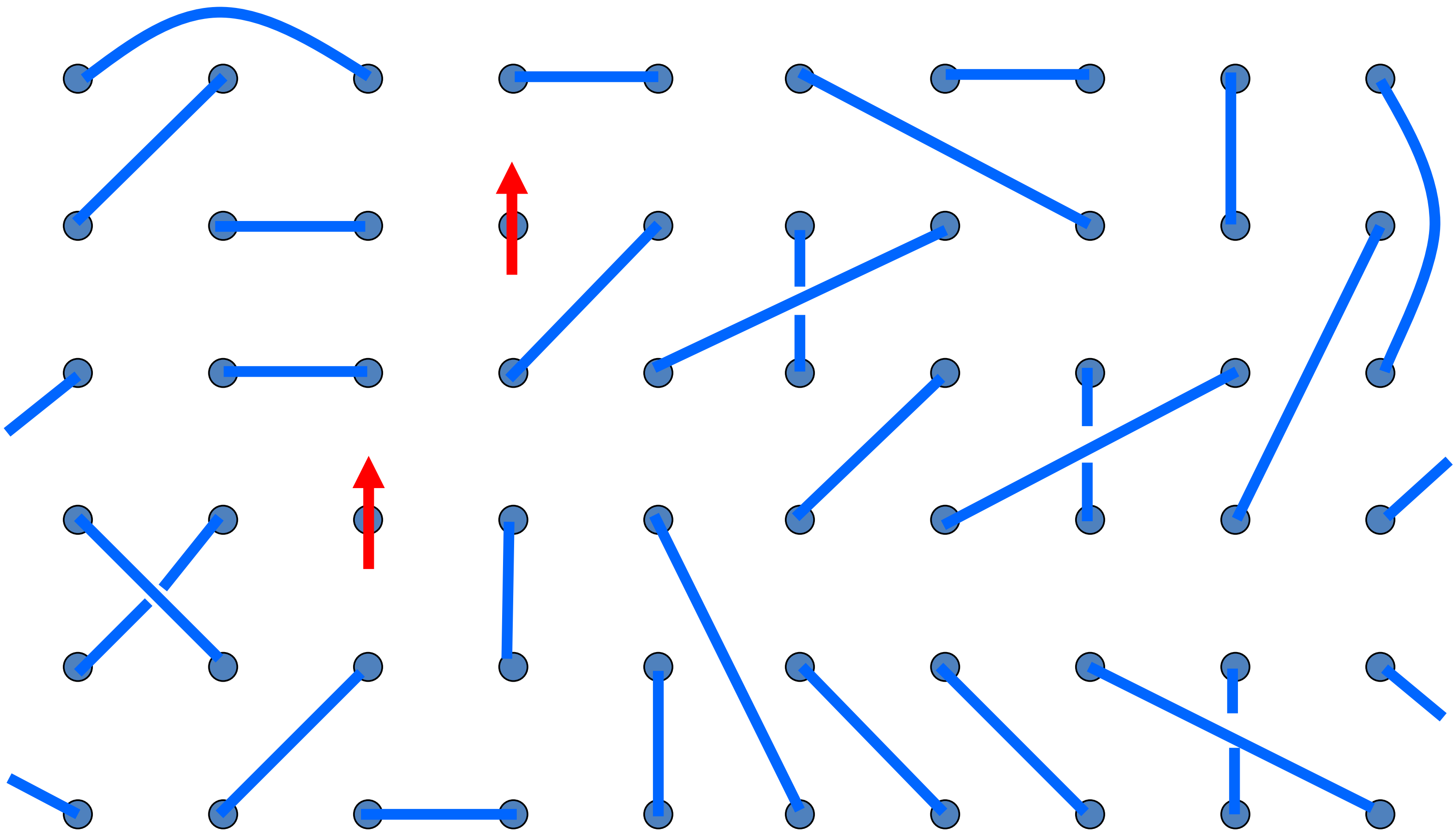


Topological Order: Excitations



Breaking a bond creates an excitation with $S_z = 1$

Topological Order: Excitations



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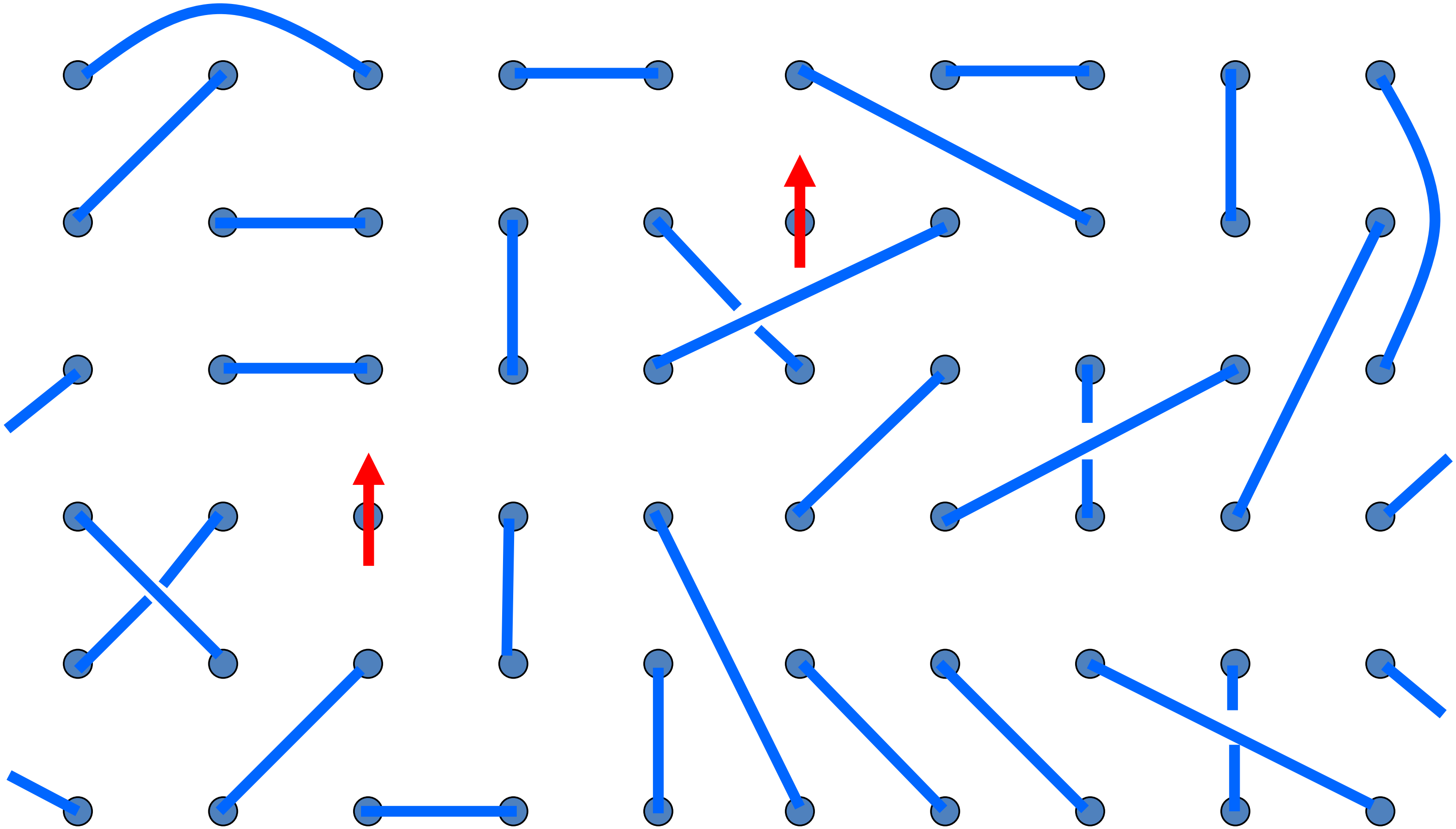
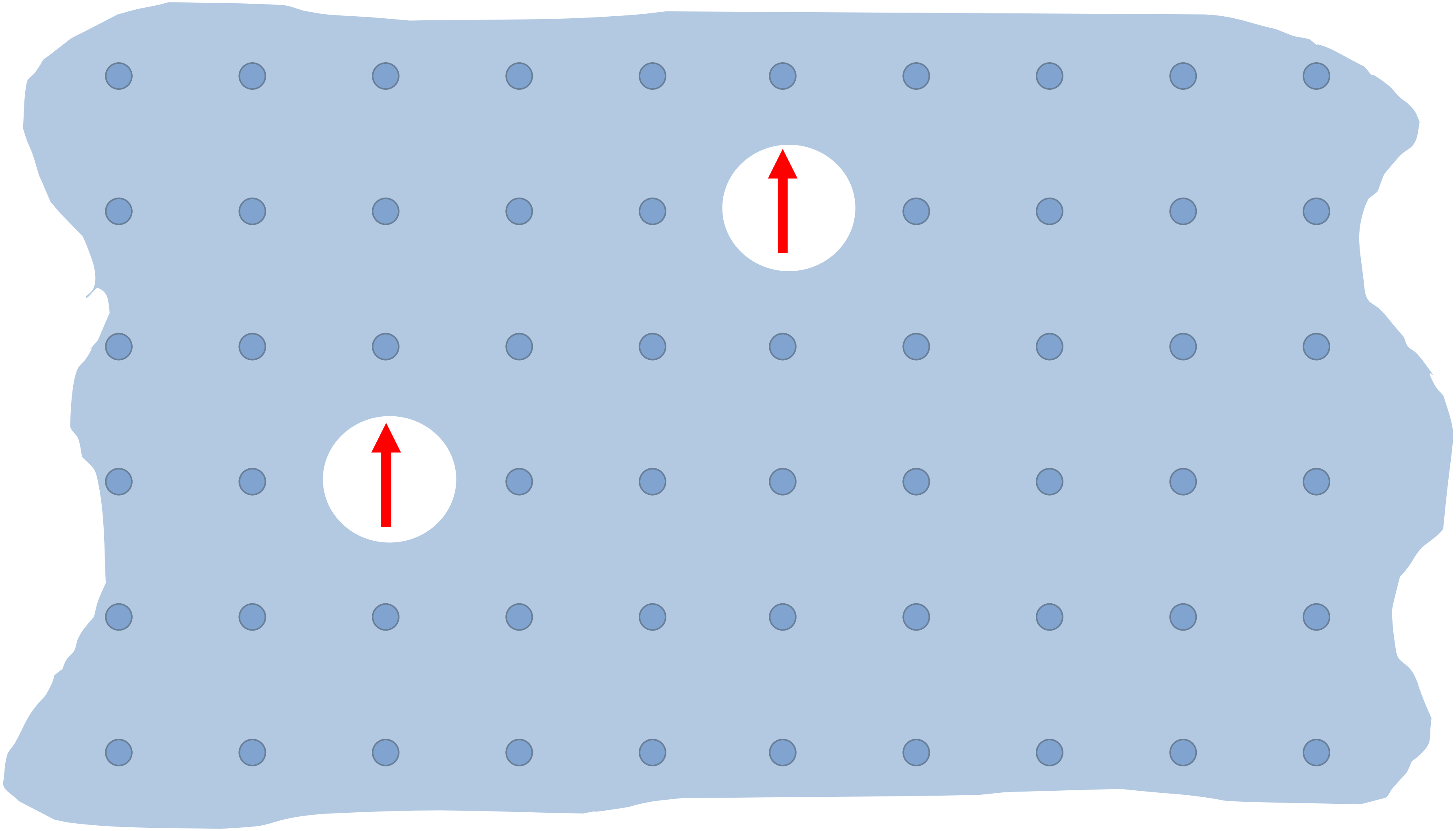
Topological Order: Excitations



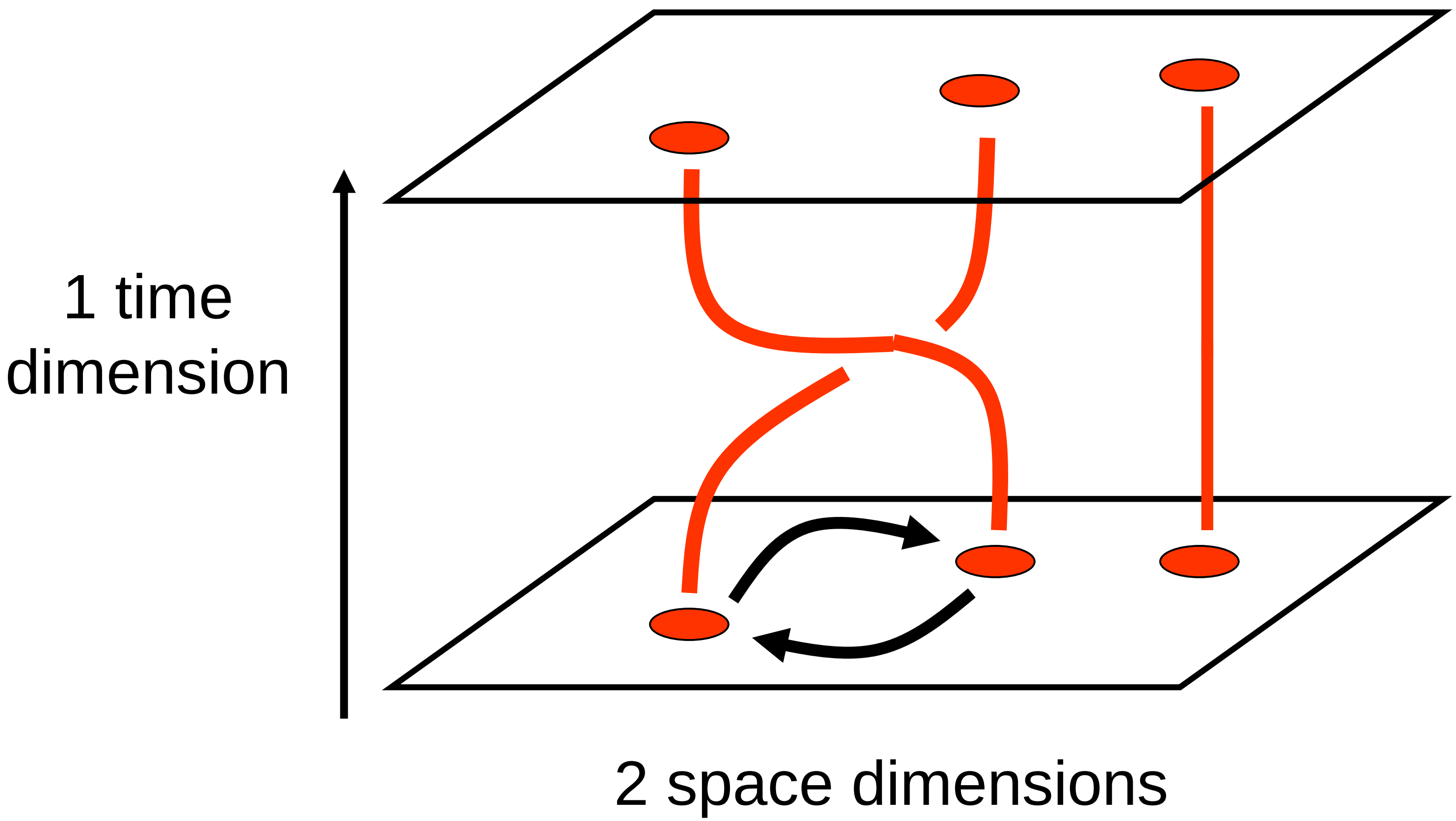
Breaking a bond creates an excitation with $S_z = 1$

Fractionalization



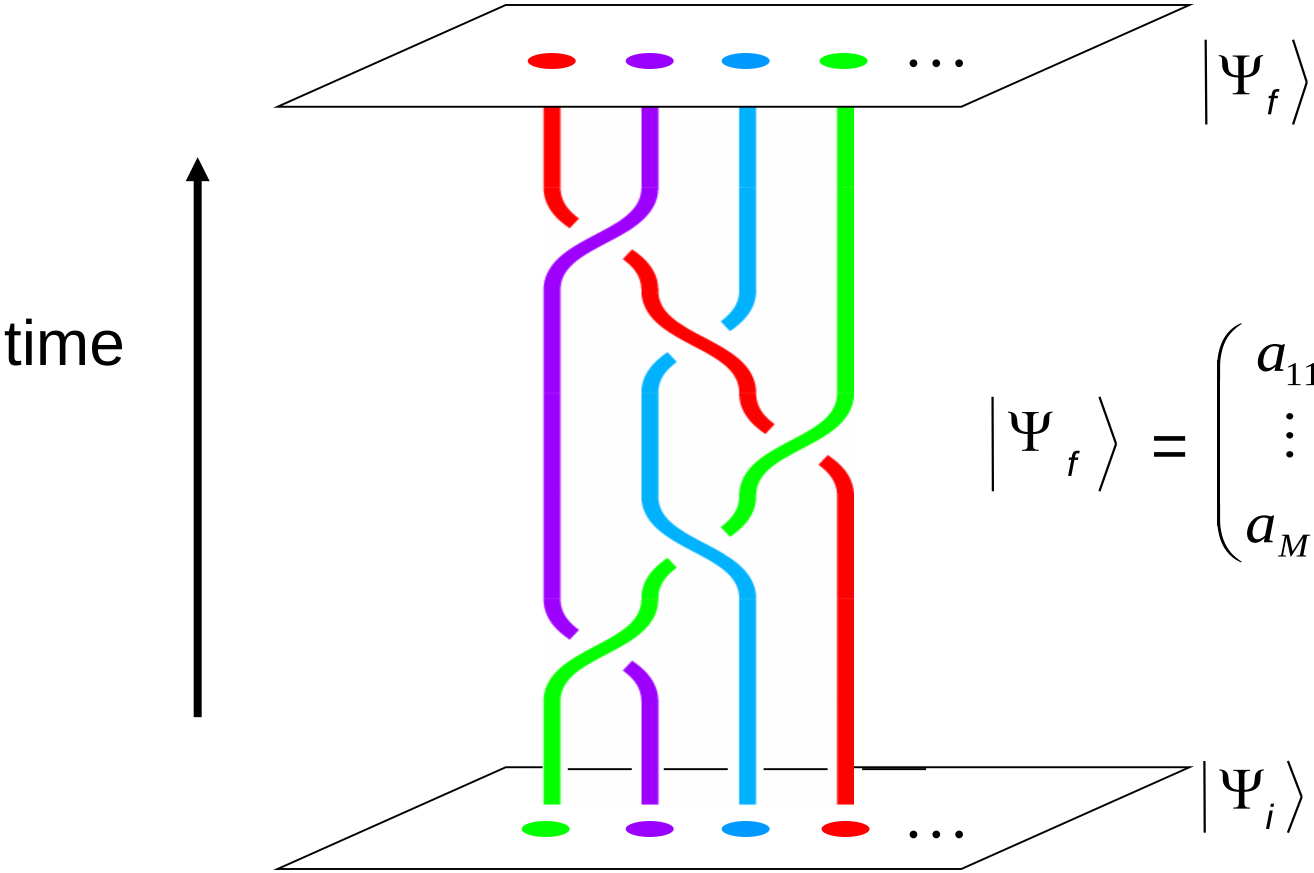
S_z = 1 excitation ***fractionalizes*** into two S_z = ½ excitations

Particle Exchange in 2+1 Dimensions



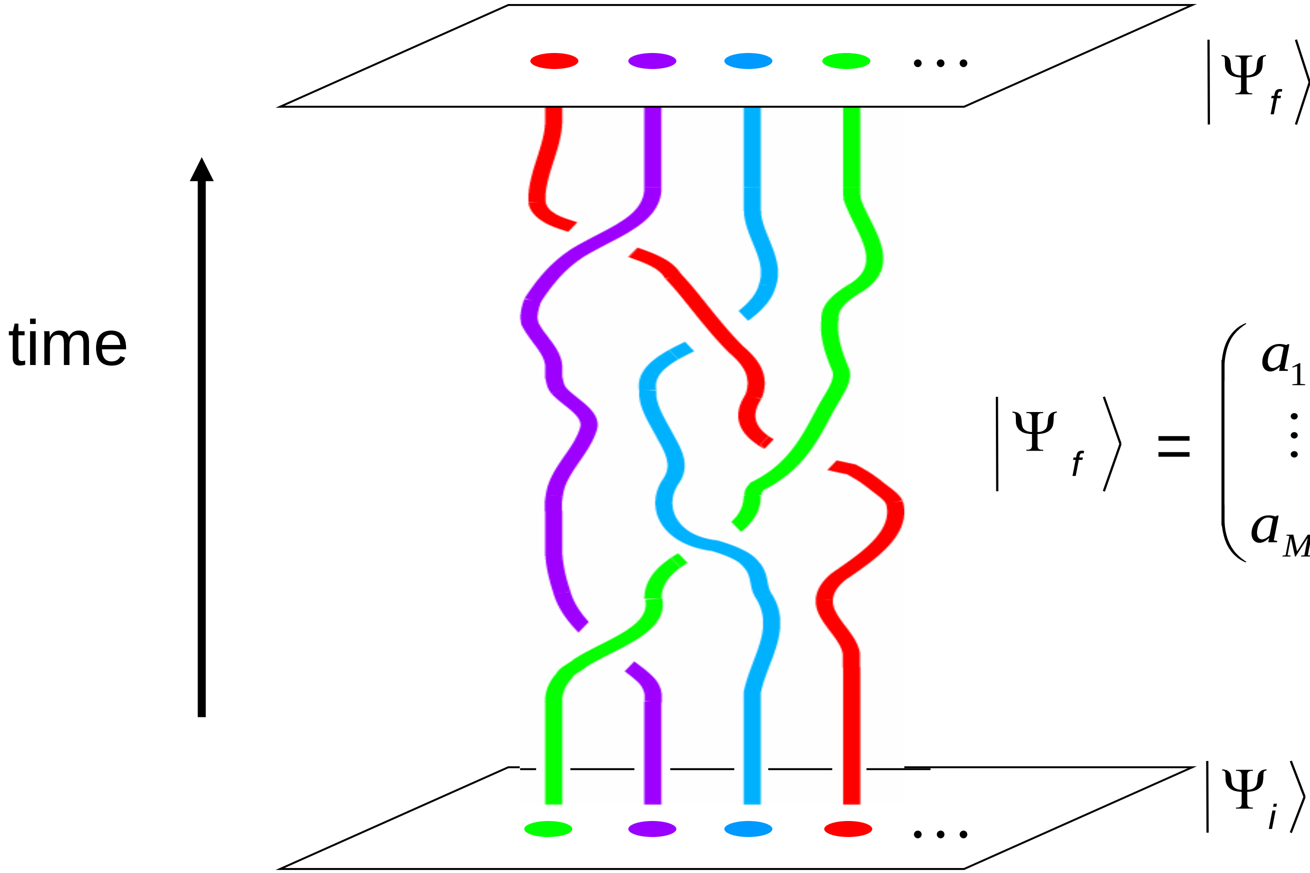
Particle “world-lines” form **braids** in 2+1 (=3) dimensions

Topological Quantum Computing



$$|\Psi_f\rangle = \begin{pmatrix} a_{11} & \cdots & a_{1M} \\ \vdots & \ddots & \vdots \\ a_{M1} & \cdots & a_{MM} \end{pmatrix} |\Psi_i\rangle$$

Topological Quantum Computing



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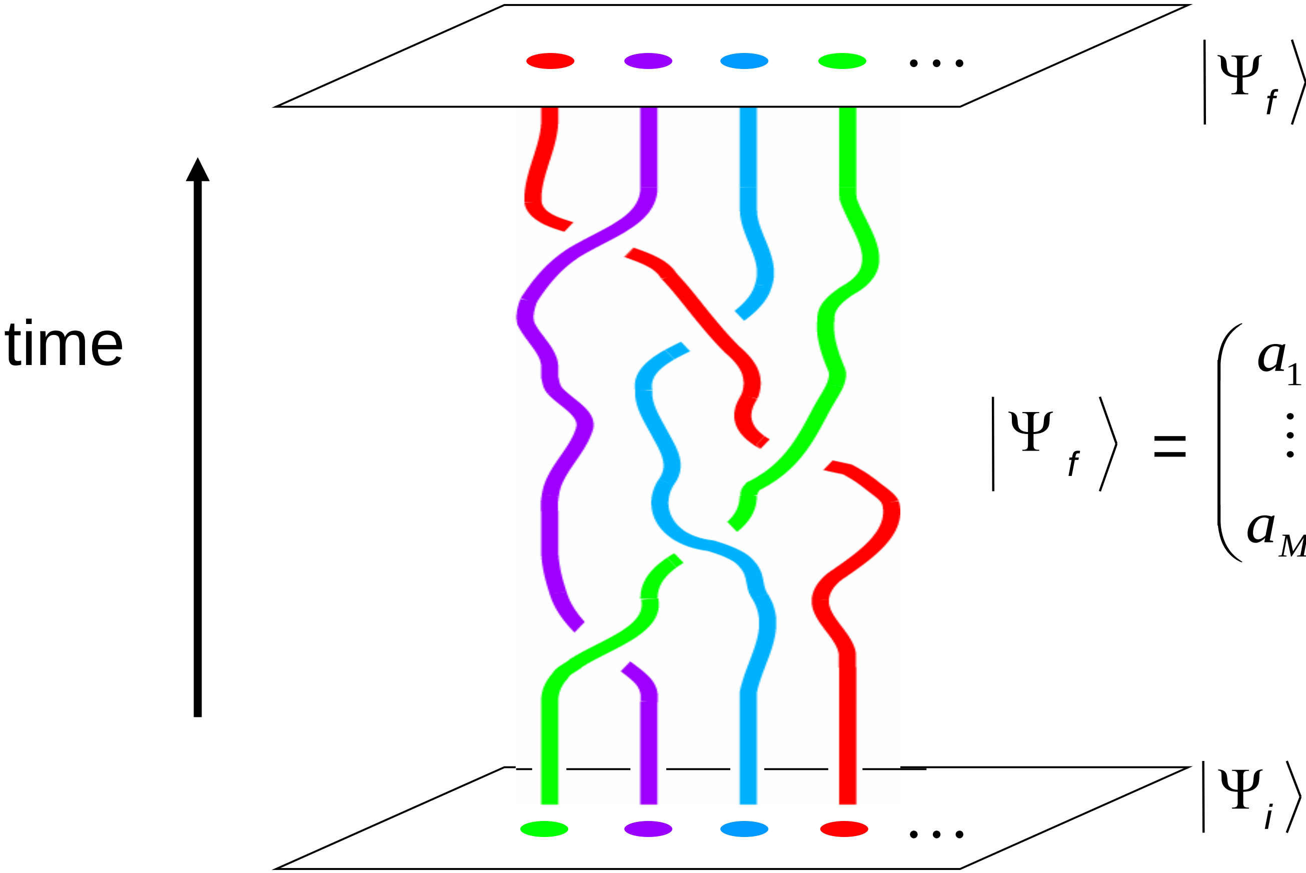
Topological Quantum Computing



$$|\Psi_f\rangle = \begin{pmatrix} a_{11} & \cdots & a_{1M} \\ \vdots & \ddots & \vdots \\ a_{M1} & \cdots & a_{MM} \end{pmatrix} |\Psi_i\rangle$$

Matrix depends only on the topology of the braid swept out by anyon world lines!

Kitaev '97, Freedman, Larsen, and Wang '03

Where do things stand now?

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I.B.M. Researchers Inch Toward Quantum Computer

By KENNETH CHANG
Published: February 28, 2012

"In the past, people have said, maybe it's 50 years away, it's a dream, maybe it'll happen sometime," said Mark B. Ketchen, manager of the physics of information group at I.B.M.'s Thomas J. Watson Research Center in Yorktown Heights, N.Y. "I used to think it was 50. Now I'm thinking like it's 15 or a little more. It's within reach. It's within our lifetime. It's going to happen."

Recent progress toward building a quantum computer, together with the growing body of experimental work on topologically ordered states is teaching us new and surprising things about how matter can order and what we can do with it.

Exciting times are ahead!