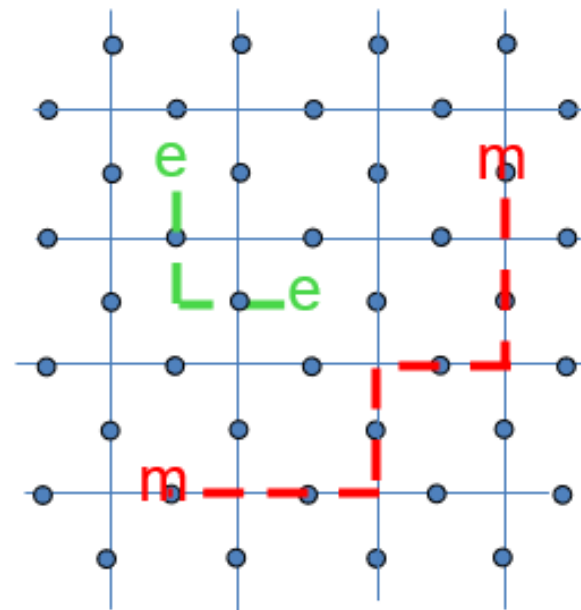
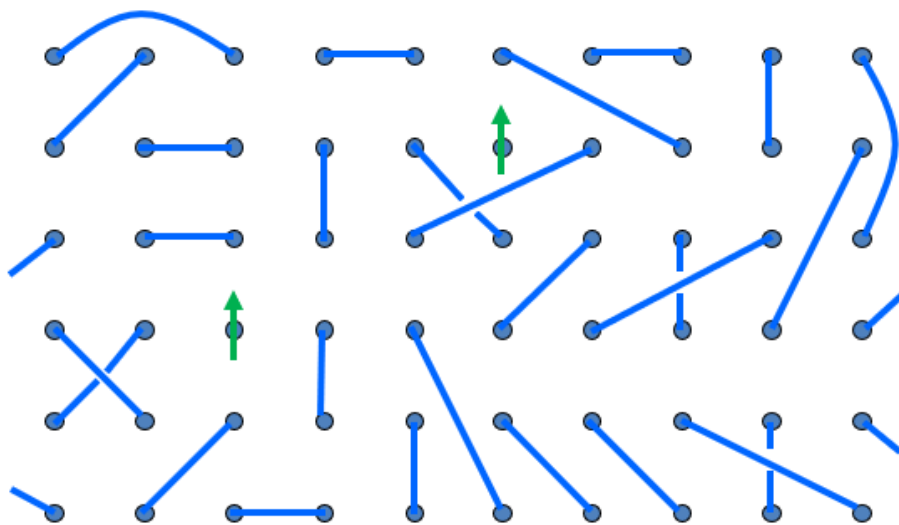


Quantum Computing, Quantum Matter, and a Little AI

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



MagX, NHMFL, May 5, 2026

Two Big Questions

Two Big Questions

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

Two Big Questions

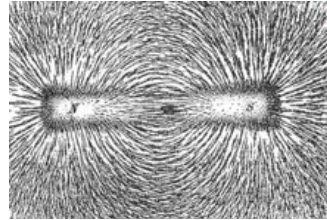
(1) What are the different ways matter can become ordered?

The classics...

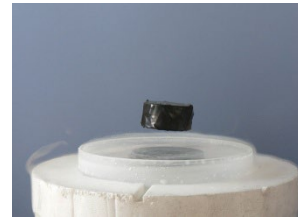
Crystals



Magnets



Superconductors



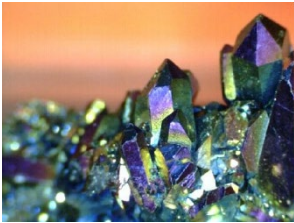
...

Two Big Questions

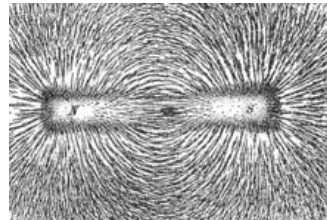
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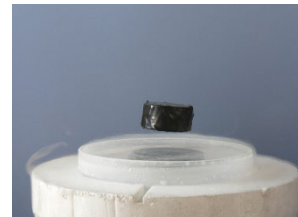
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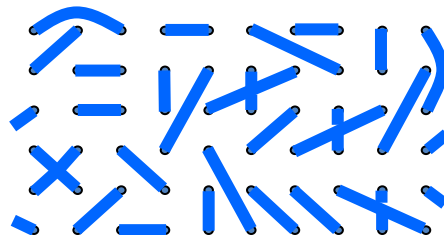
...

~ 45 years ago, a different kind of order was discovered...

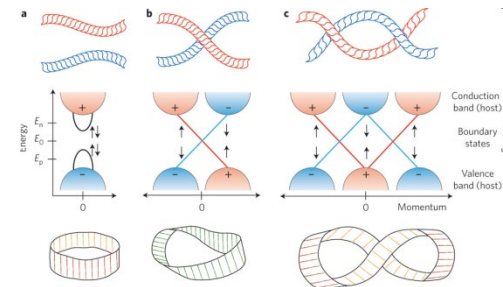
Quantum Hall States



Spin Liquids



Topological Insulators



Two Big Questions

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

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Today's state of the art: The digital computer



Fundamental building block: The Bit

0 or 1

Two Big Questions

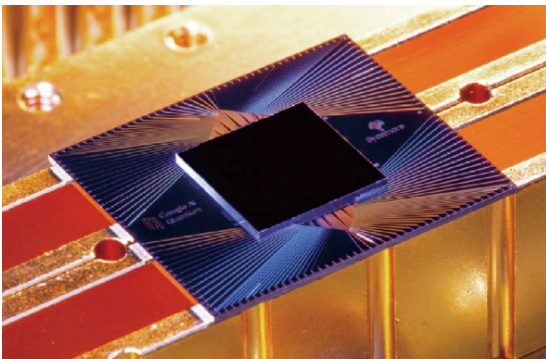
(2) What are the fundamental limits on the machines we can build?

Today's state of the art: The digital computer



Fundamental building block: The Bit
0 or 1

~ 30 years ago, people realized a qualitatively new kind of computer was possible: **A quantum computer**



Google's Sycamore Chip: 54 qubits

Fundamental building block: The Qubit

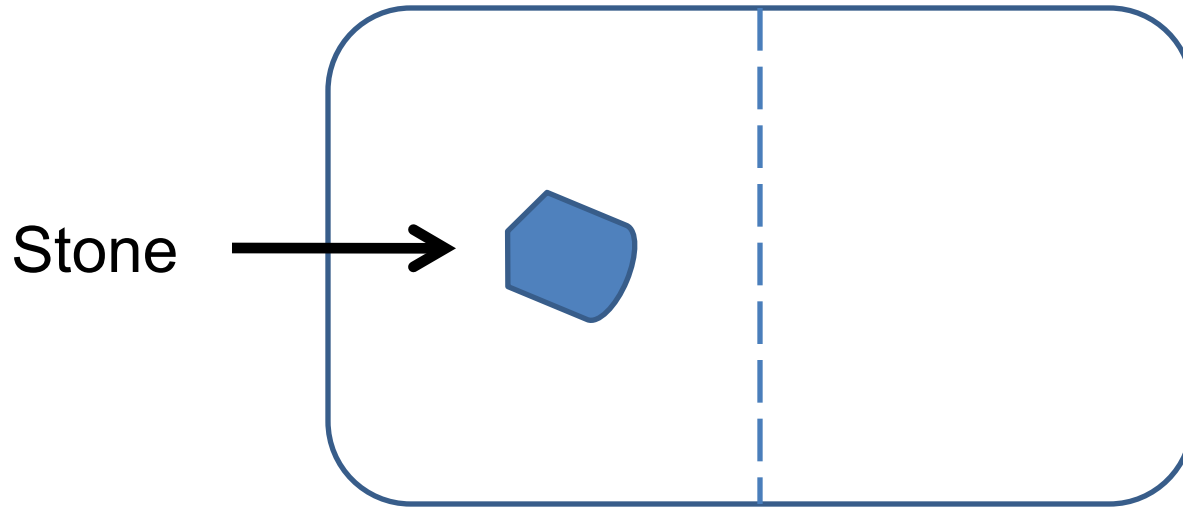
$$\alpha |0\rangle + \beta |1\rangle$$

Modern Digital Device



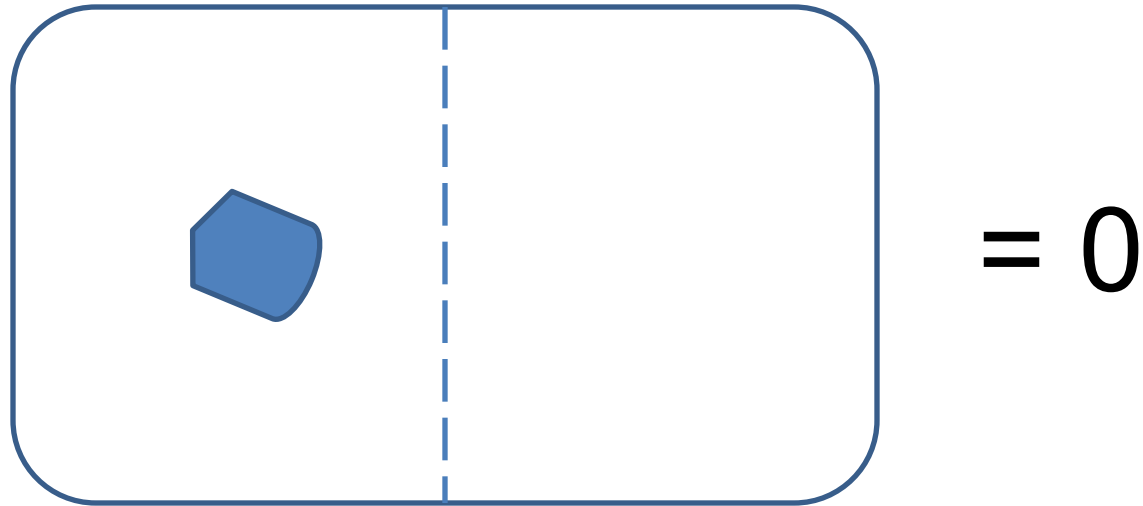
The iPhone 17: $\sim 2 \times 10^{12}$ bits

Early Digital Device



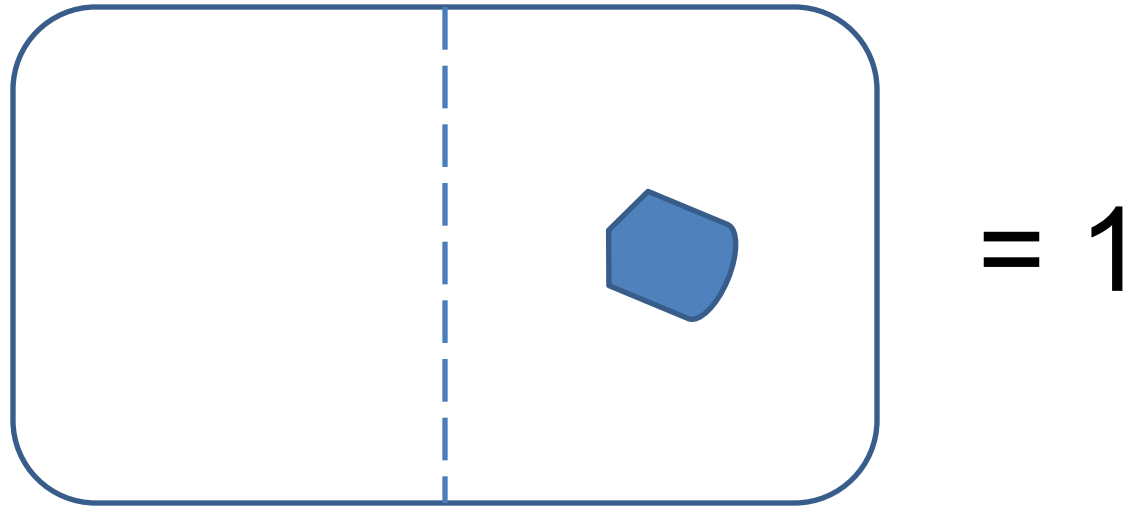
The iStone 1: 1 bit

Early Digital Device

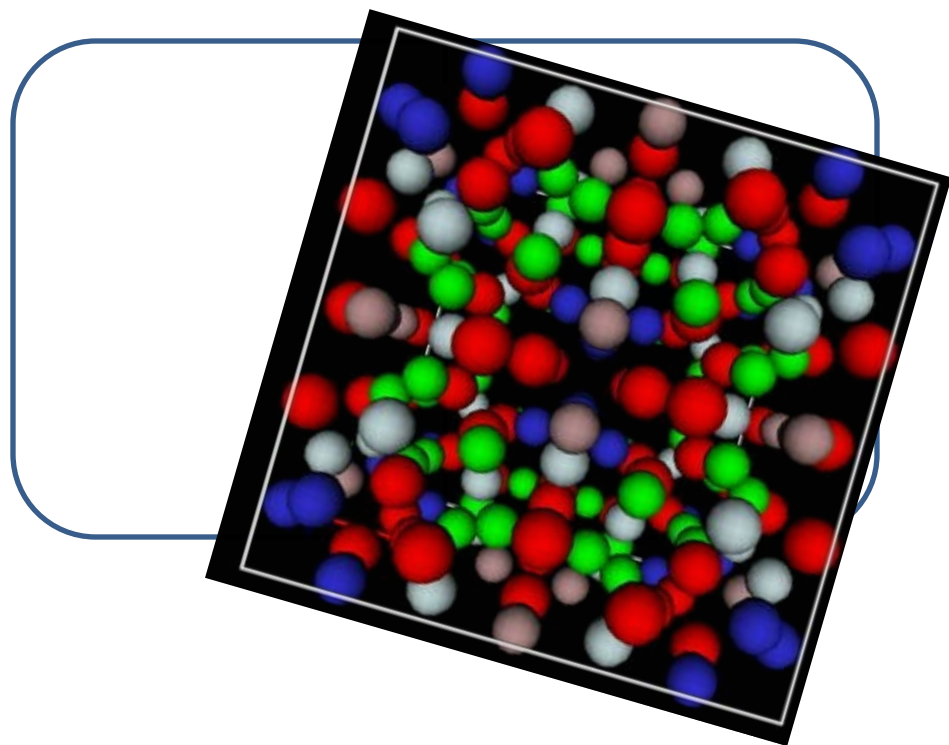


The iStone 1: 1 bit

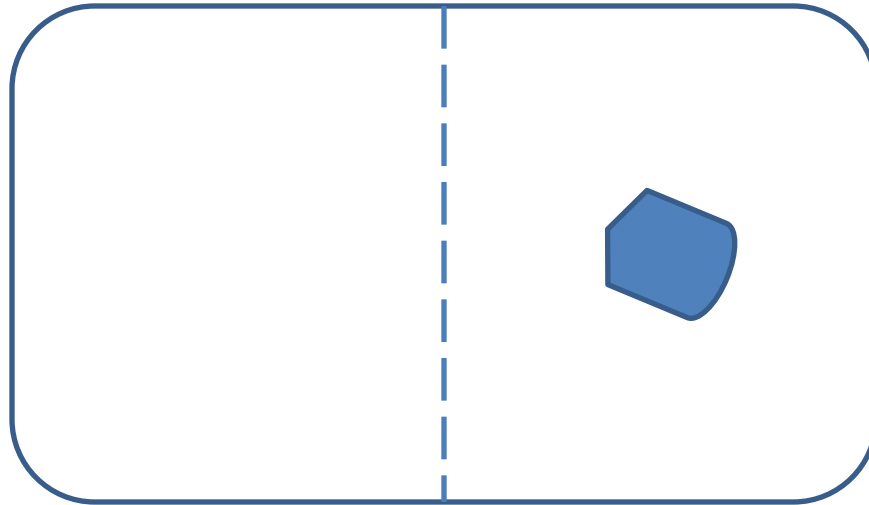
Early Digital Device



The iStone 1: 1 bit

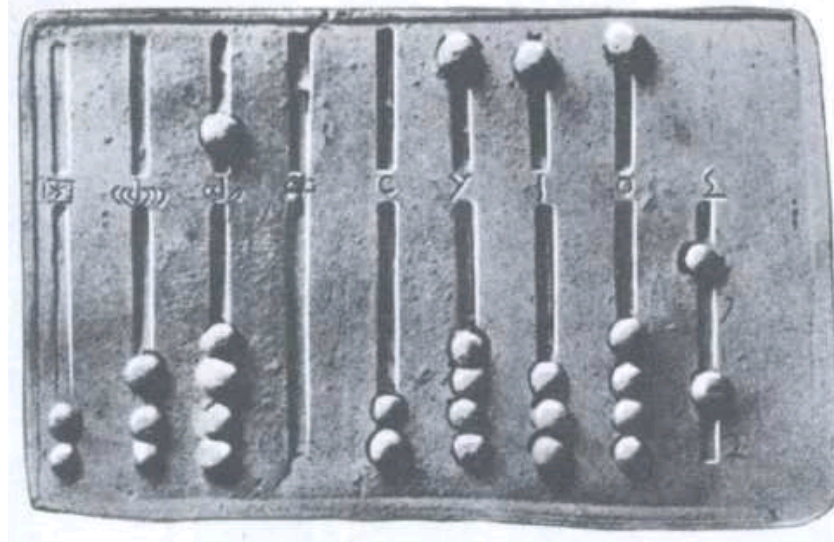


Early Digital Device



The iStone: 1 bit

Early Digital Device



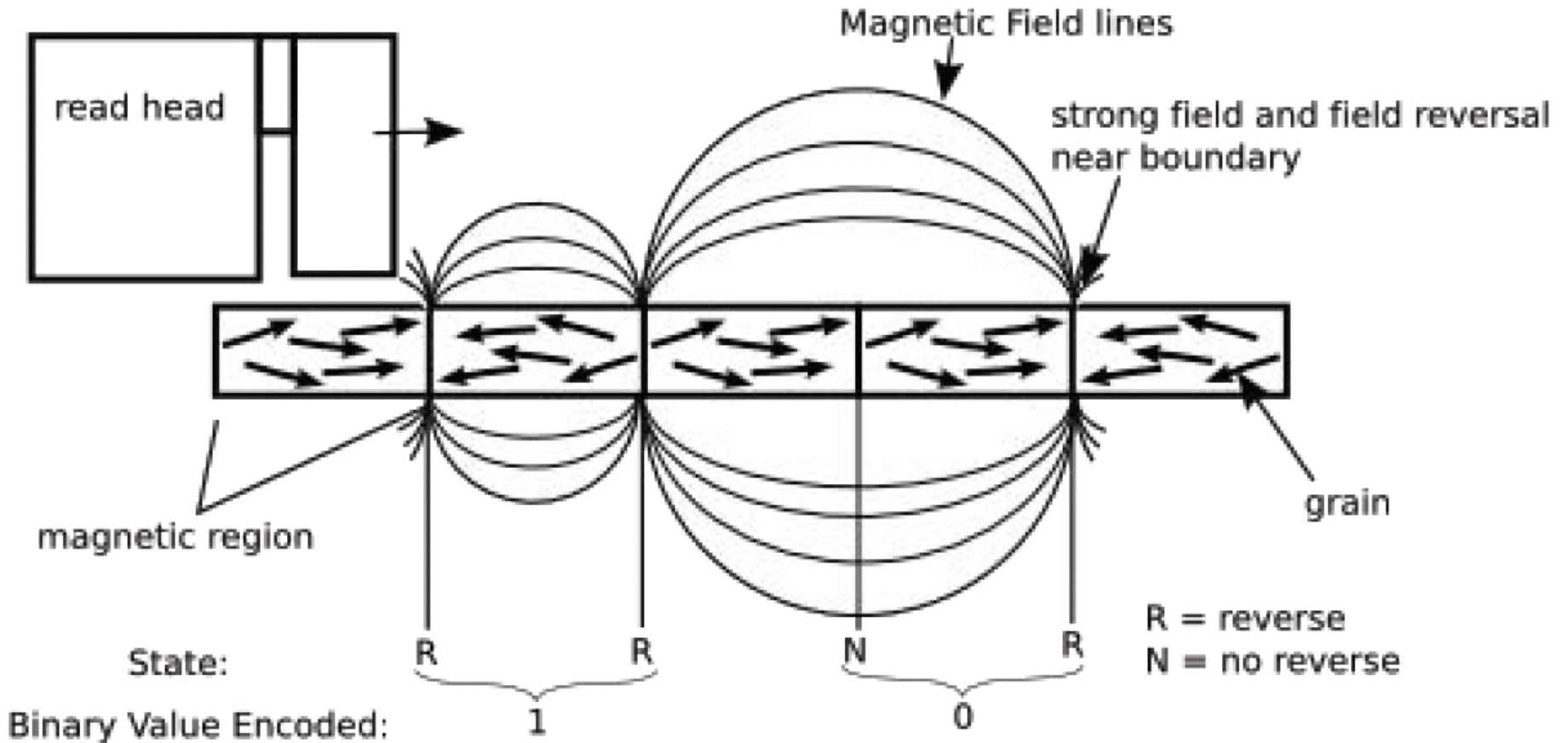
The iStone 5: ~ 20 bits

Modern Digital Device



The iPod: $\sim 1.4 \times 10^{12}$ bits

Modern Digital Memory



Magnetic Order

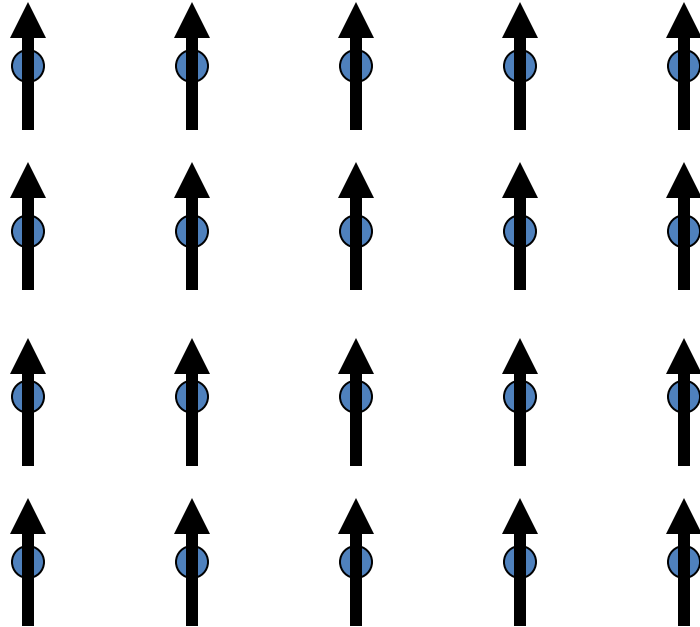
A spin-1/2 particle: ●



“spin up”

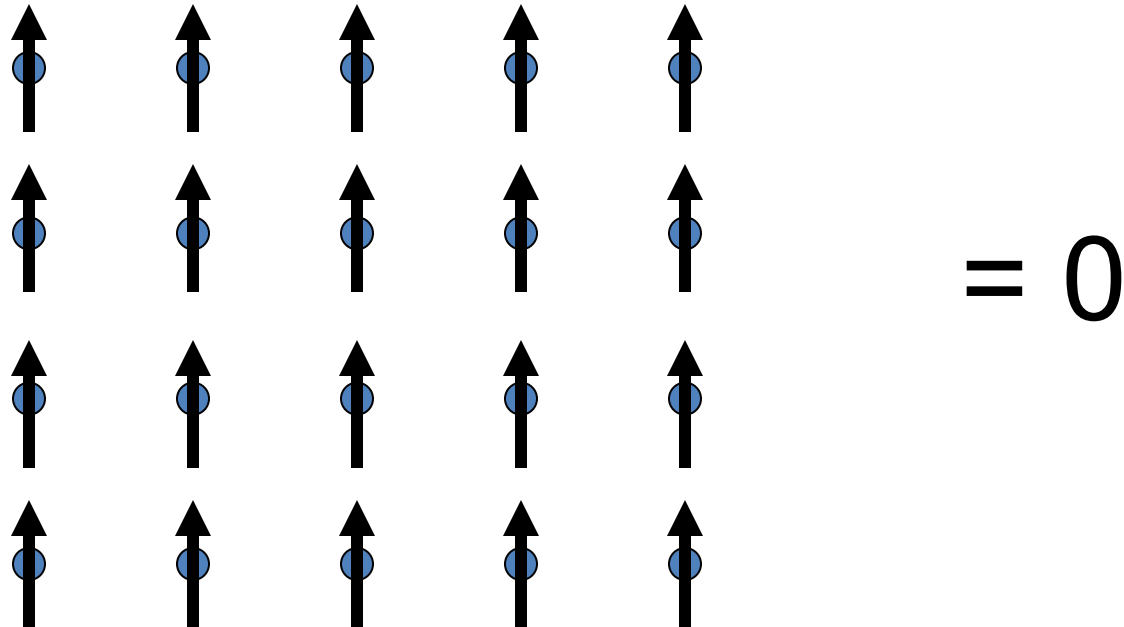
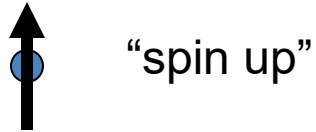


“spin down”



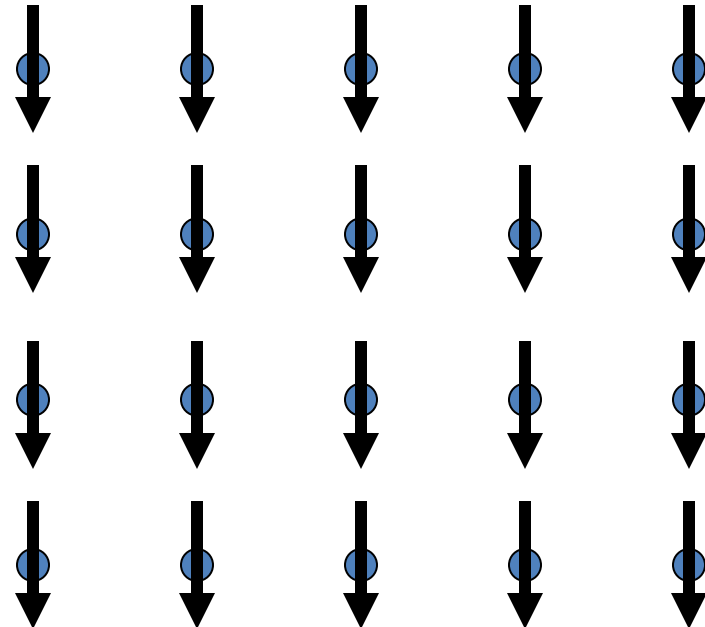
Magnetic Order

A spin-1/2 particle: ●



Magnetic Order

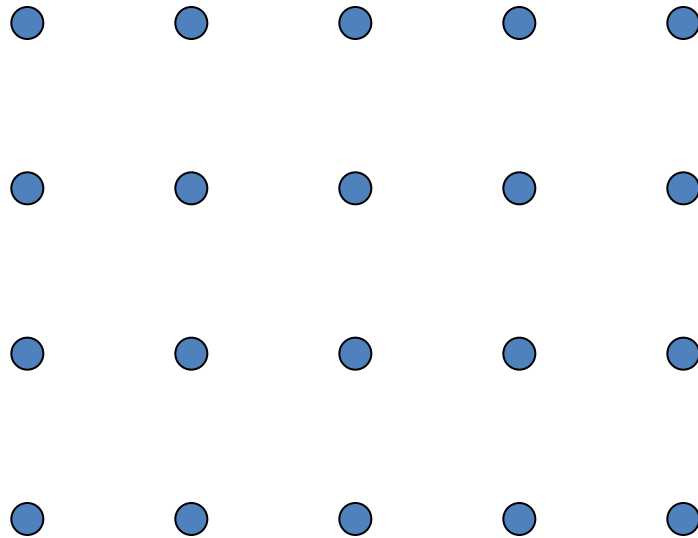
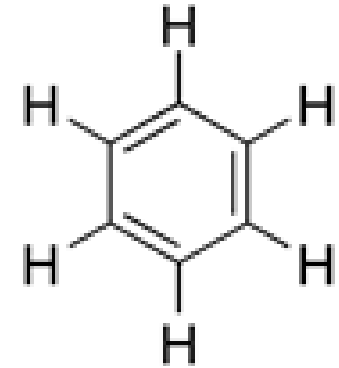
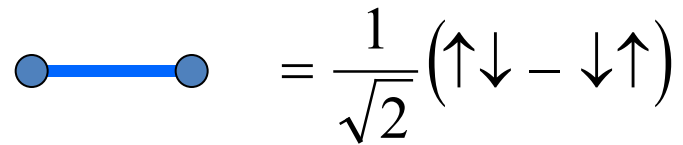
A spin-1/2 particle: ●



= 1

Another Kind of Order

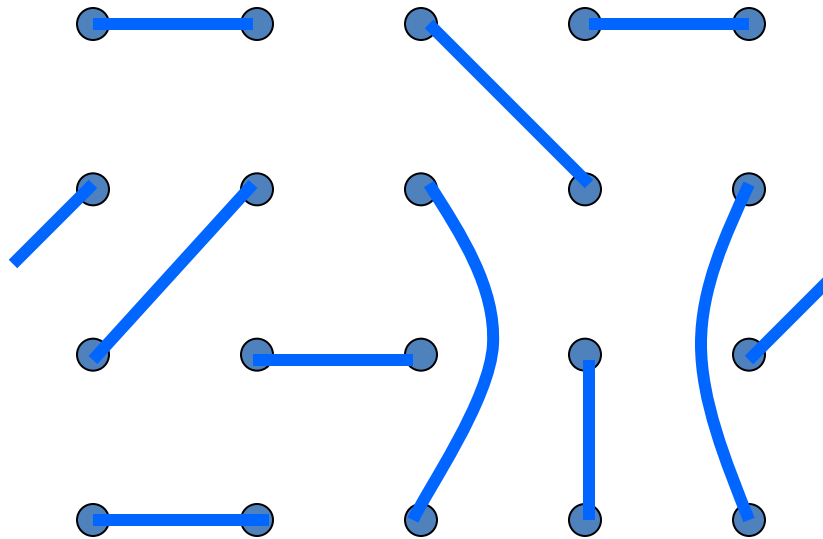
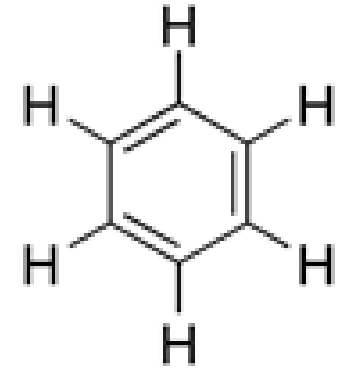
A valence bond:



Another Kind of Order

A valence bond:

$$\bullet \text{---} \bullet = \frac{1}{\sqrt{2}} (\uparrow\downarrow - \downarrow\uparrow)$$

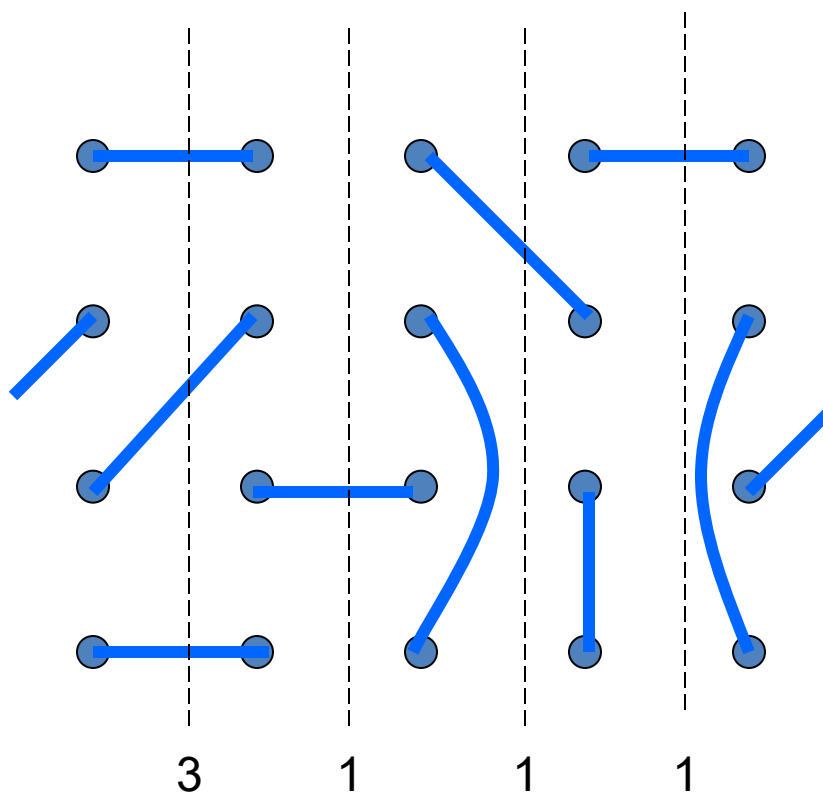
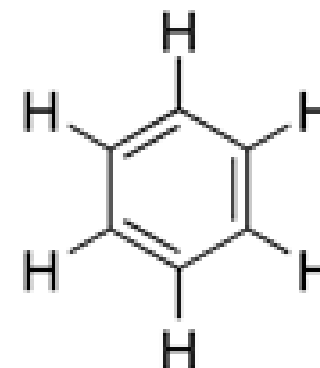


Use periodic boundary conditions

Another Kind of Order

A valence bond:

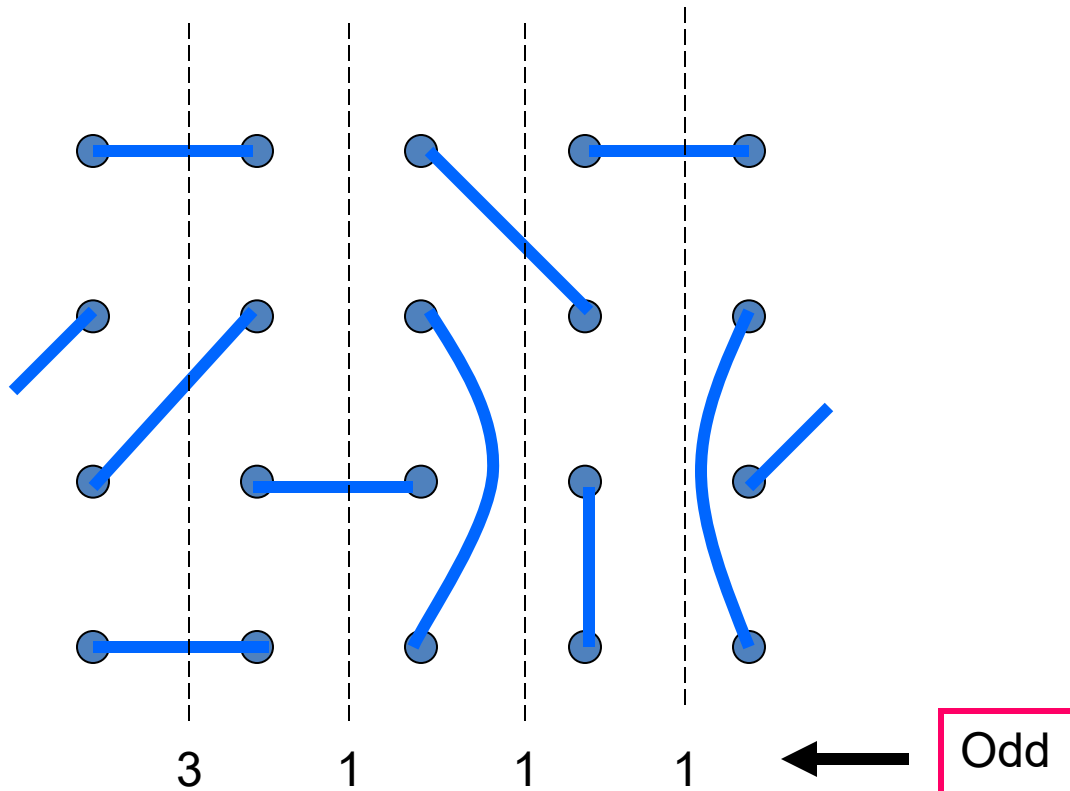
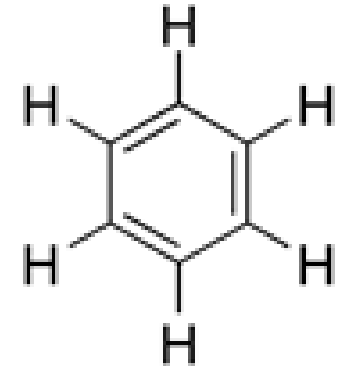
$$\bullet\text{---}\bullet = \frac{1}{\sqrt{2}}(\uparrow\downarrow - \downarrow\uparrow)$$



Another Kind of Order

A valence bond:

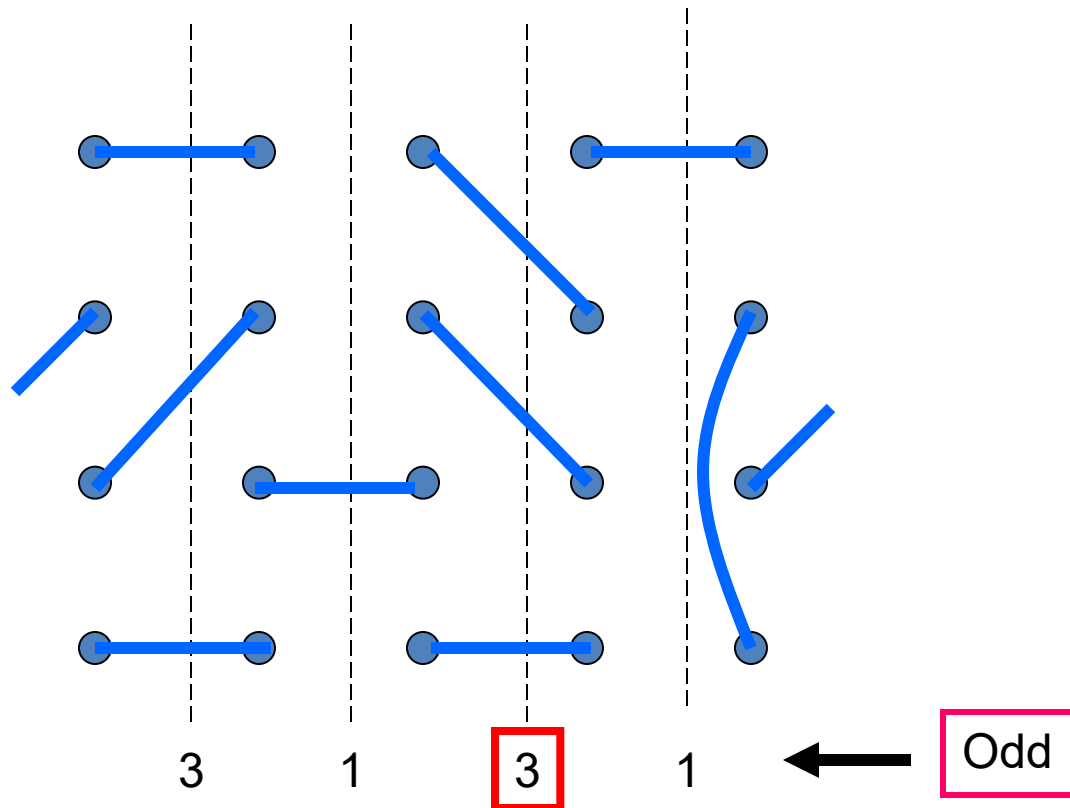
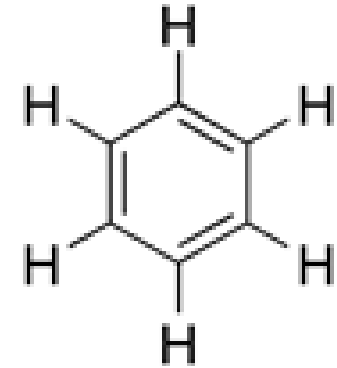
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Another Kind of Order

A valence bond:

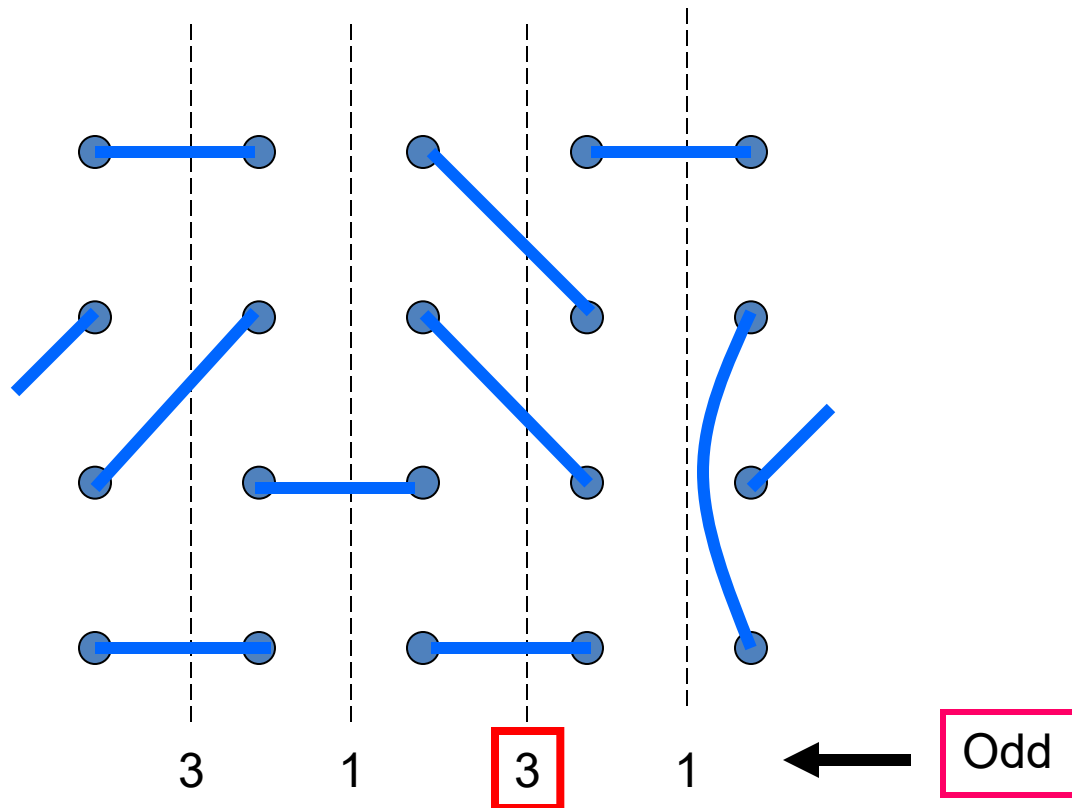
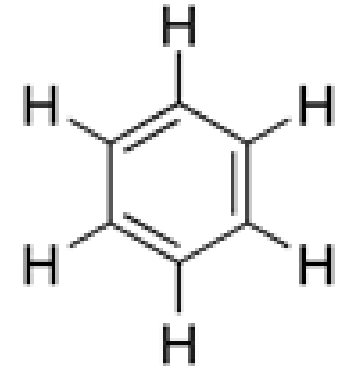
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Another Kind of Order

A valence bond:

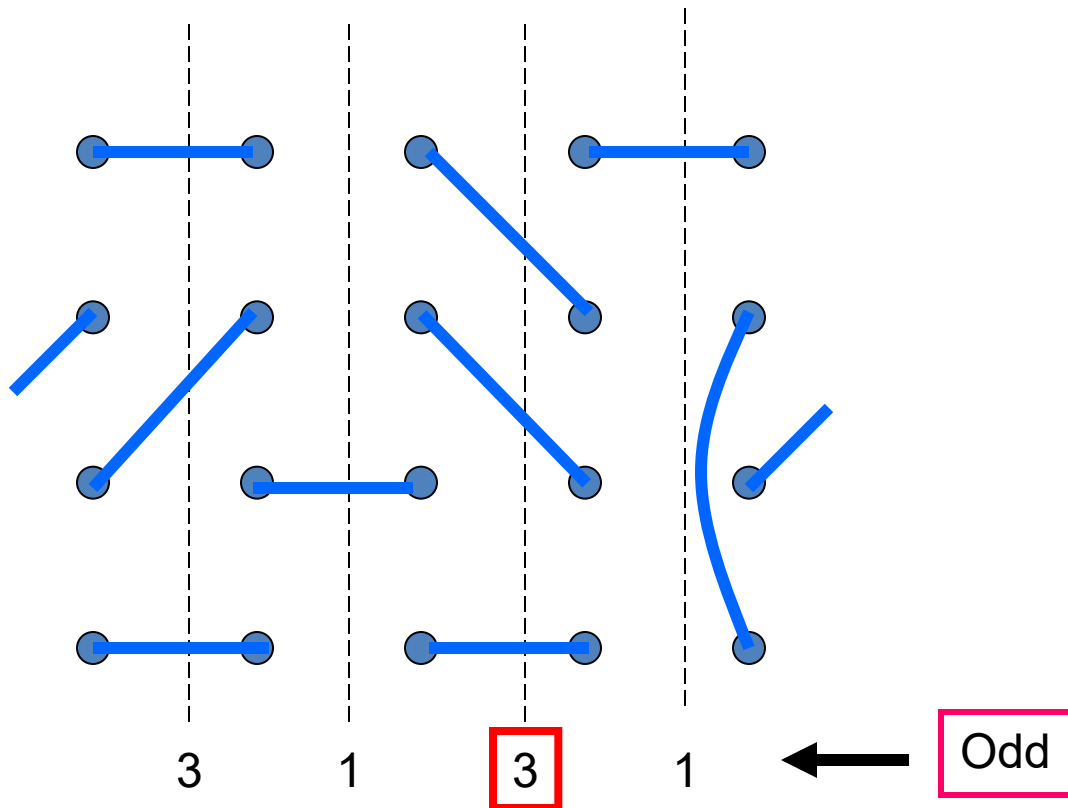
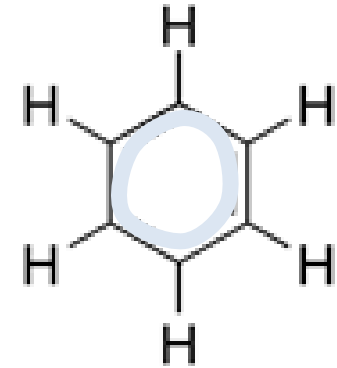
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Another Kind of Order

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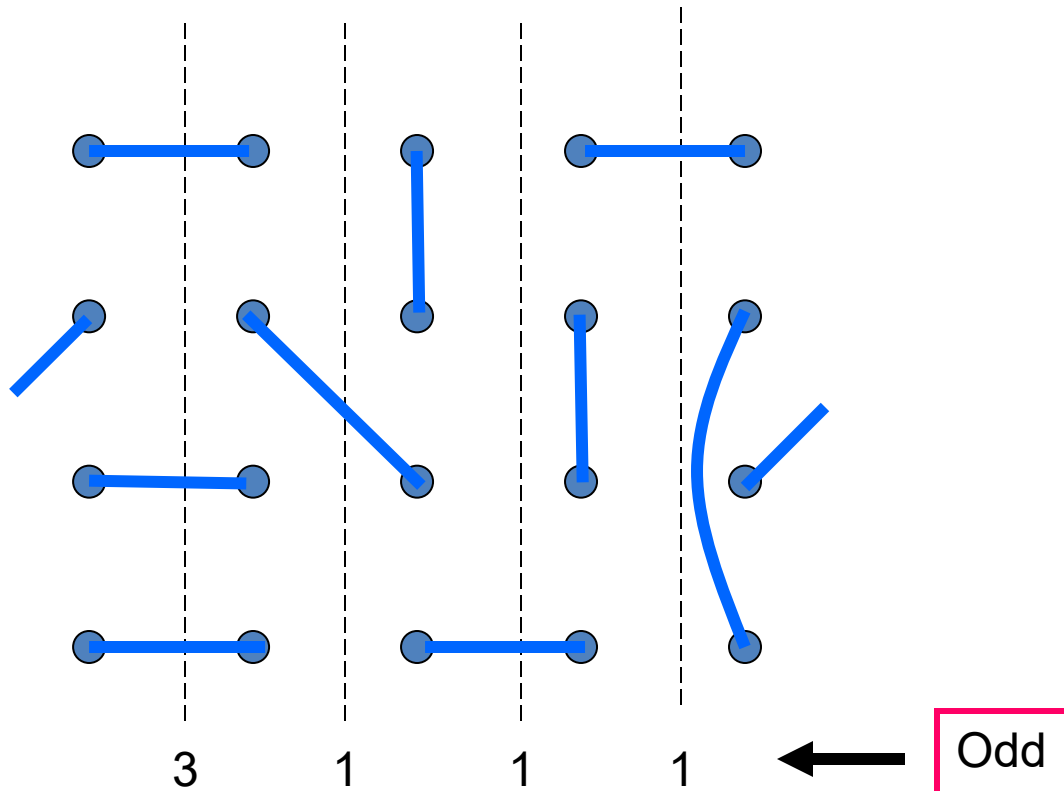
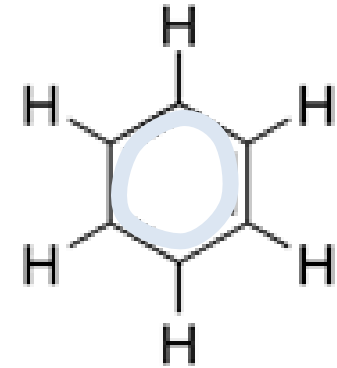
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Another Kind of Order

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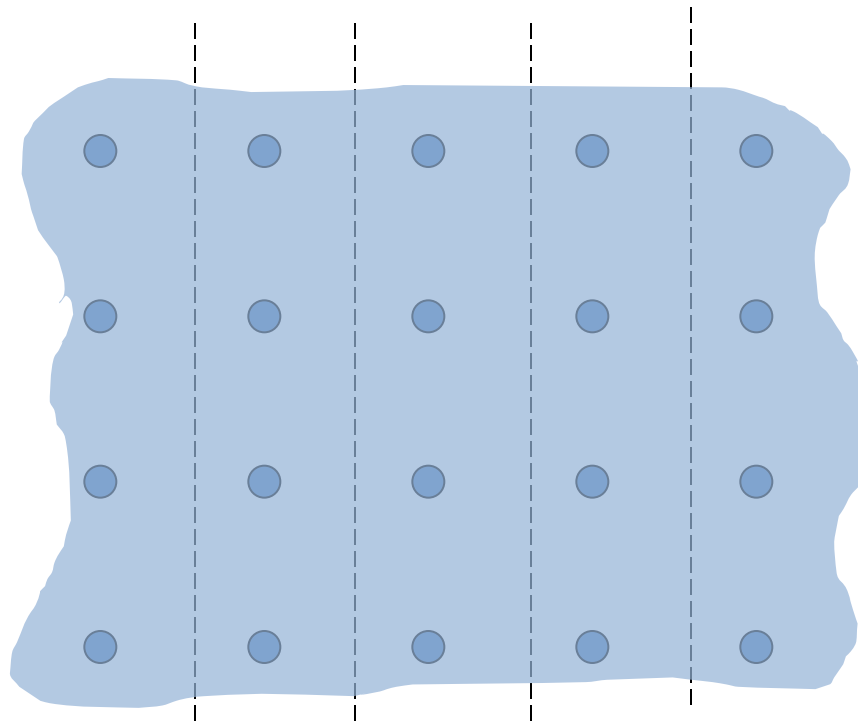
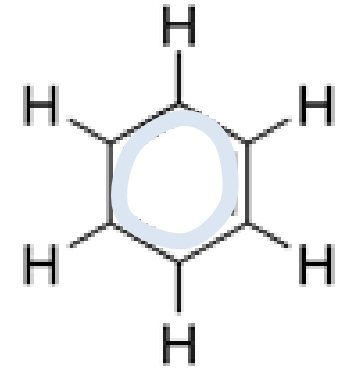
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Another Kind of Order

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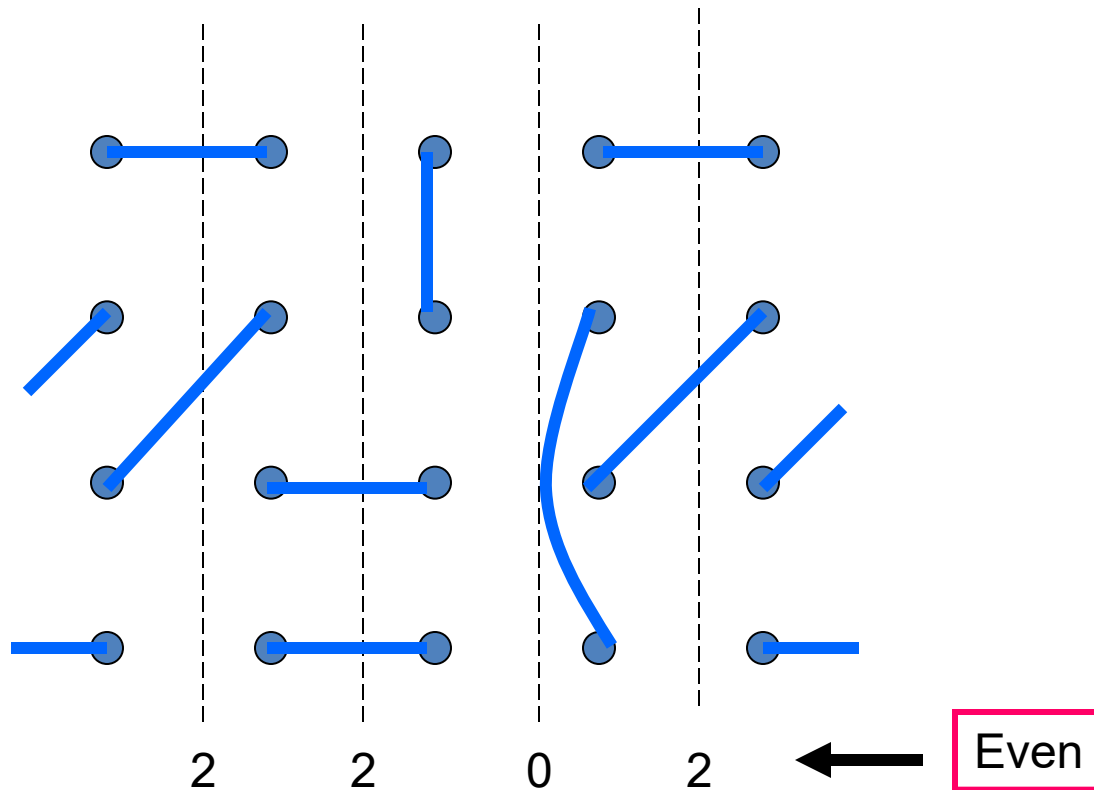
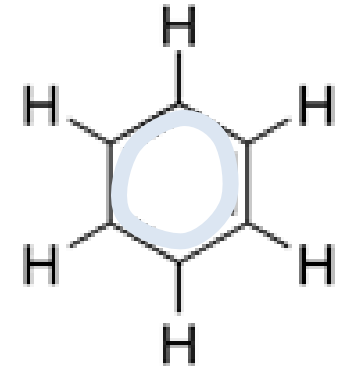
Quantum superposition
of valence-bond states.
A “**spin liquid**.”

Odd

Another Kind of Order

A valence bond:

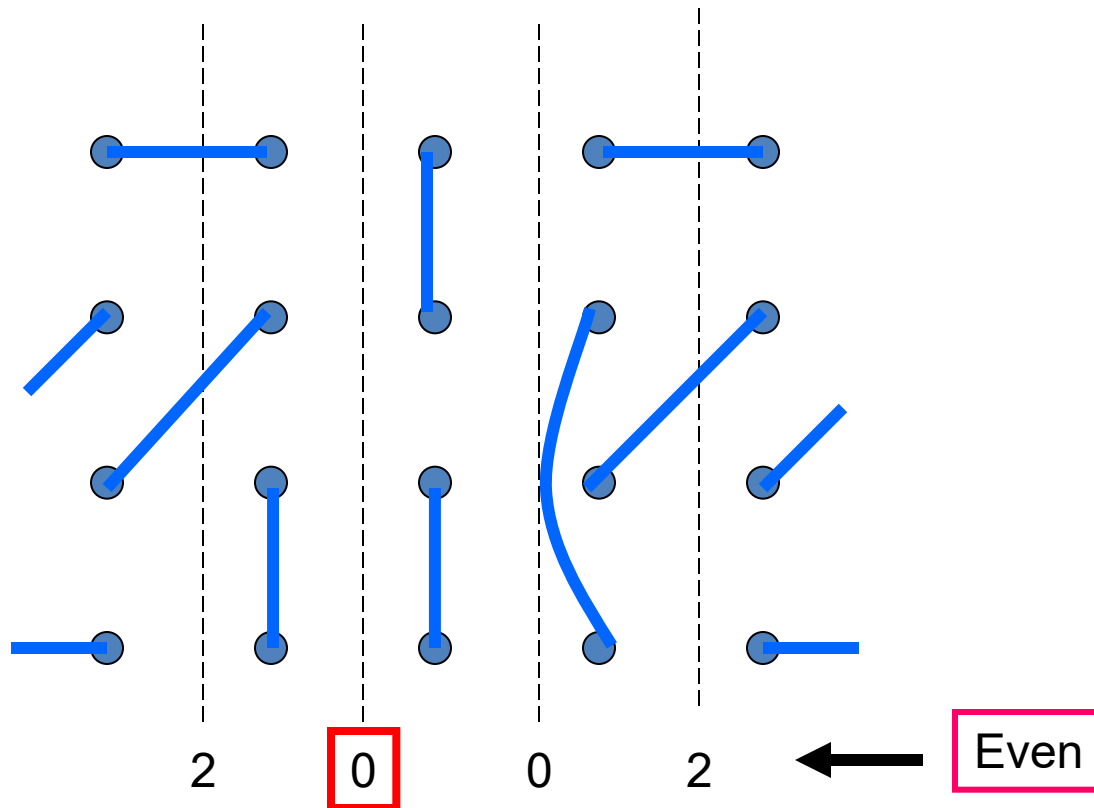
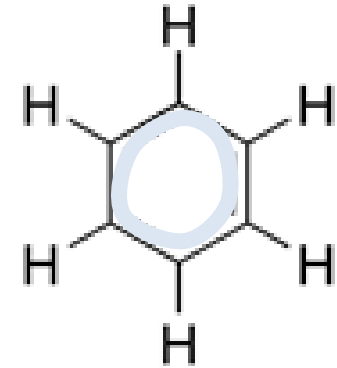
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Another Kind of Order

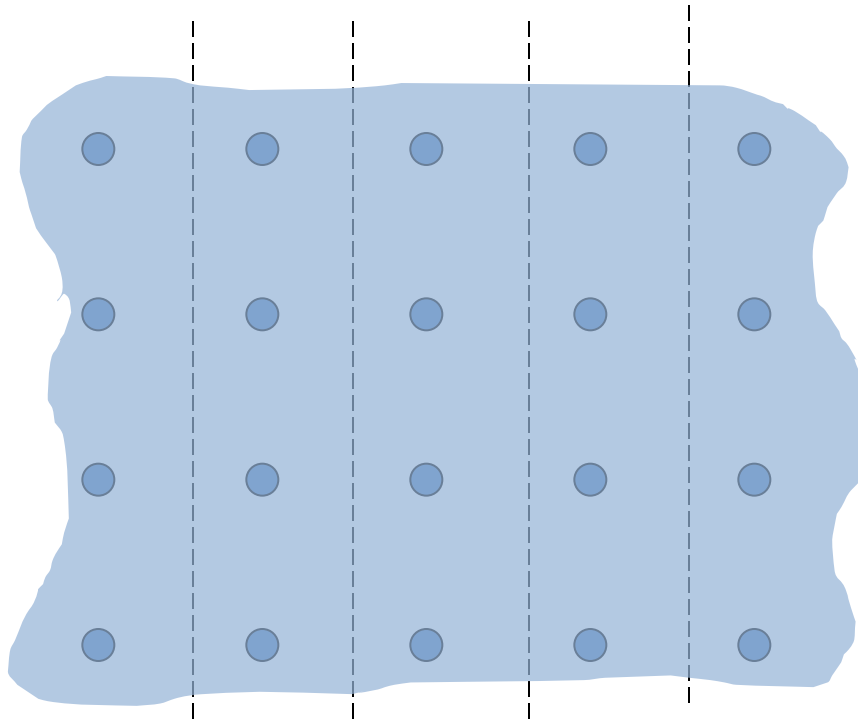
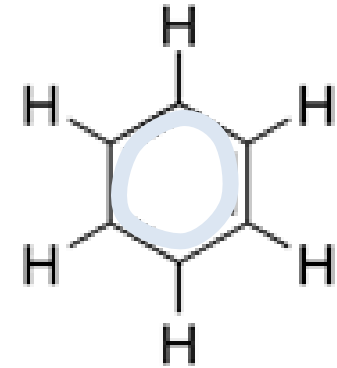
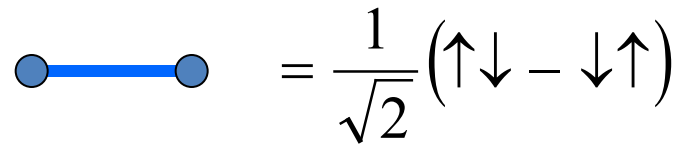
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Another Kind of Order

A valence bond:

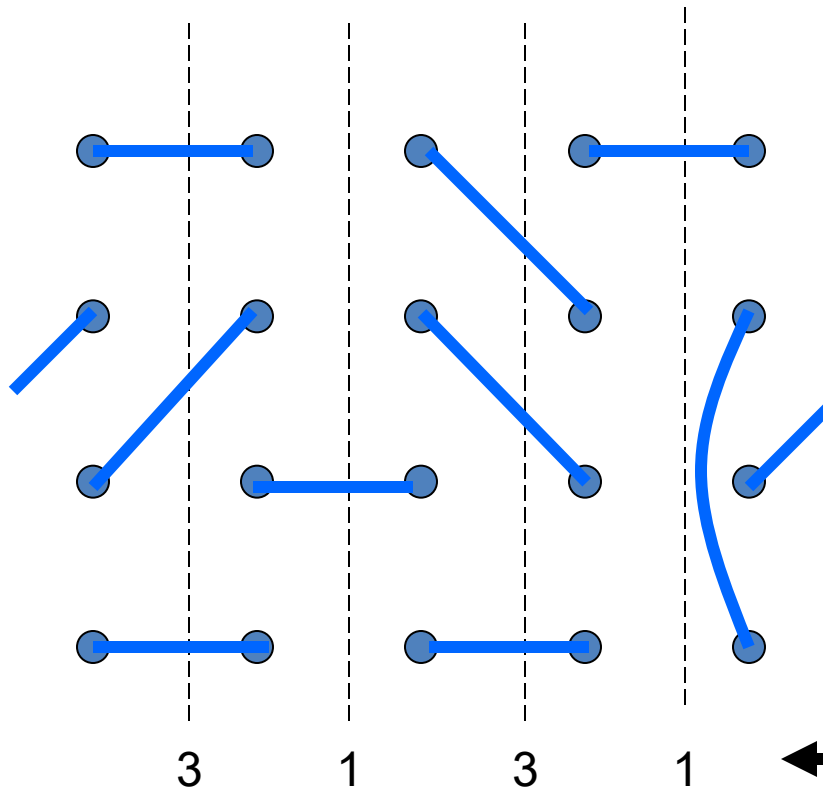
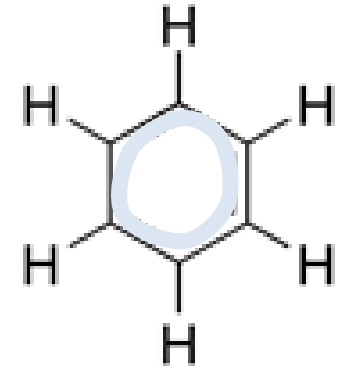


Even

Another Kind of Order

A valence bond:

$$\bullet\text{---}\bullet = \frac{1}{\sqrt{2}}(\uparrow\downarrow - \downarrow\uparrow)$$

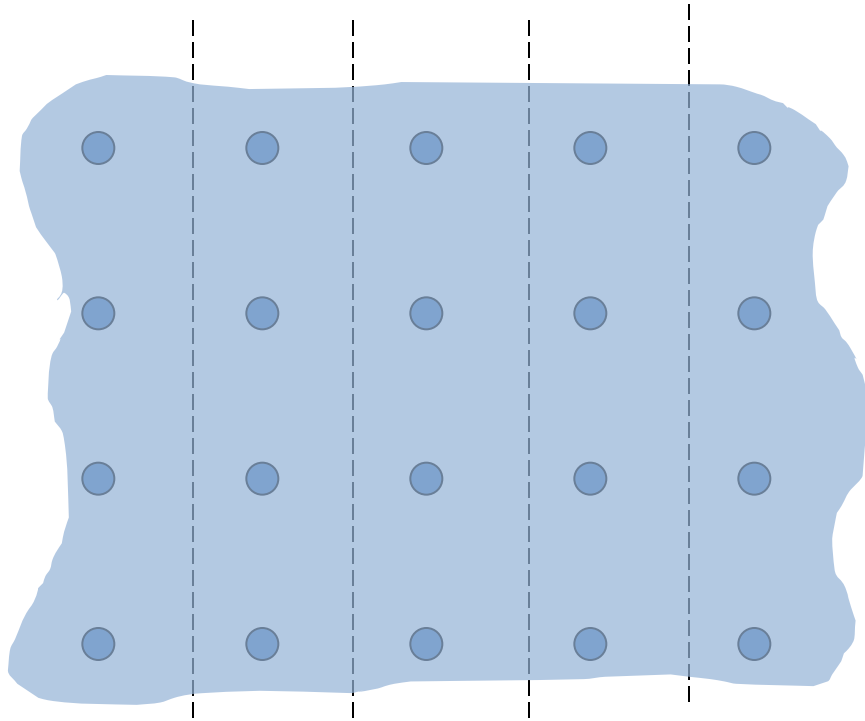
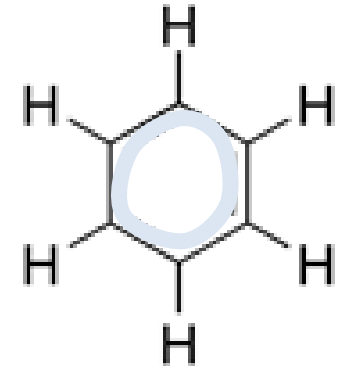
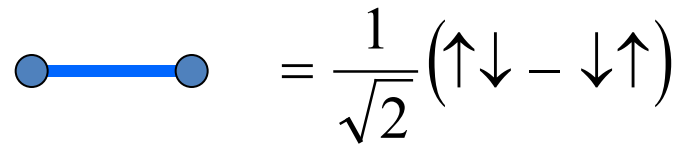


$|0\rangle$

← Odd

Another Kind of Order

A valence bond:



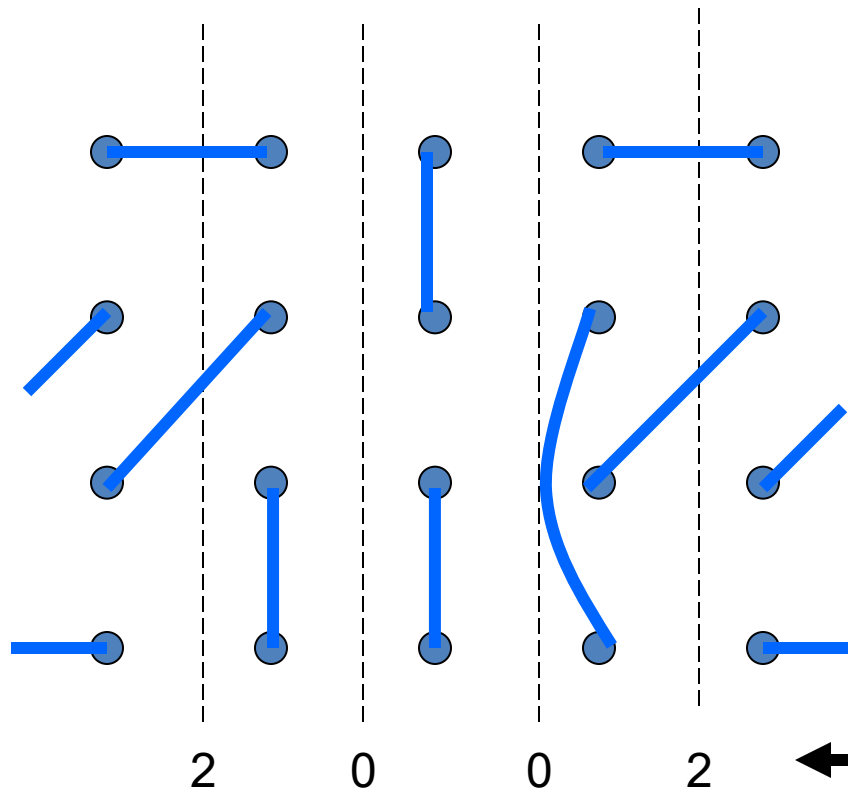
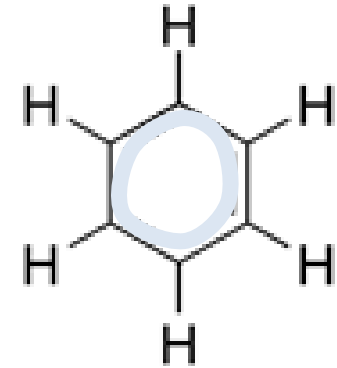
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← Odd

Another Kind of Order

A valence bond:

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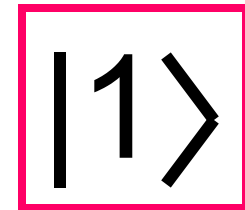
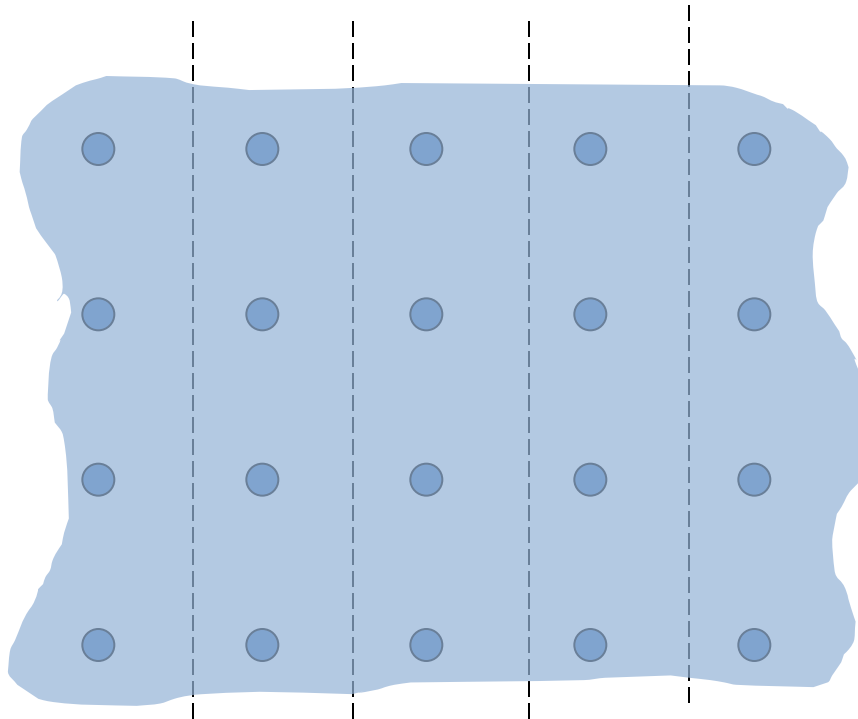
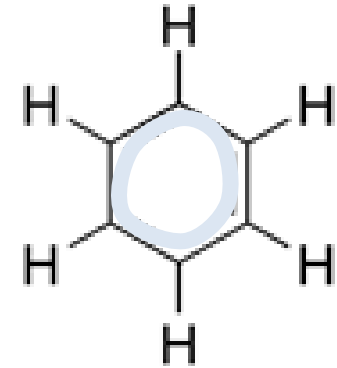
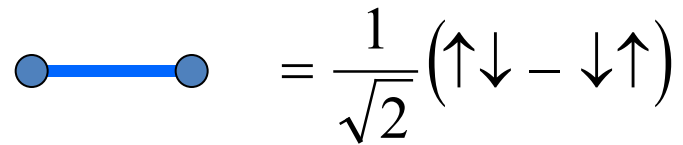


$|1\rangle$

Even

Another Kind of Order

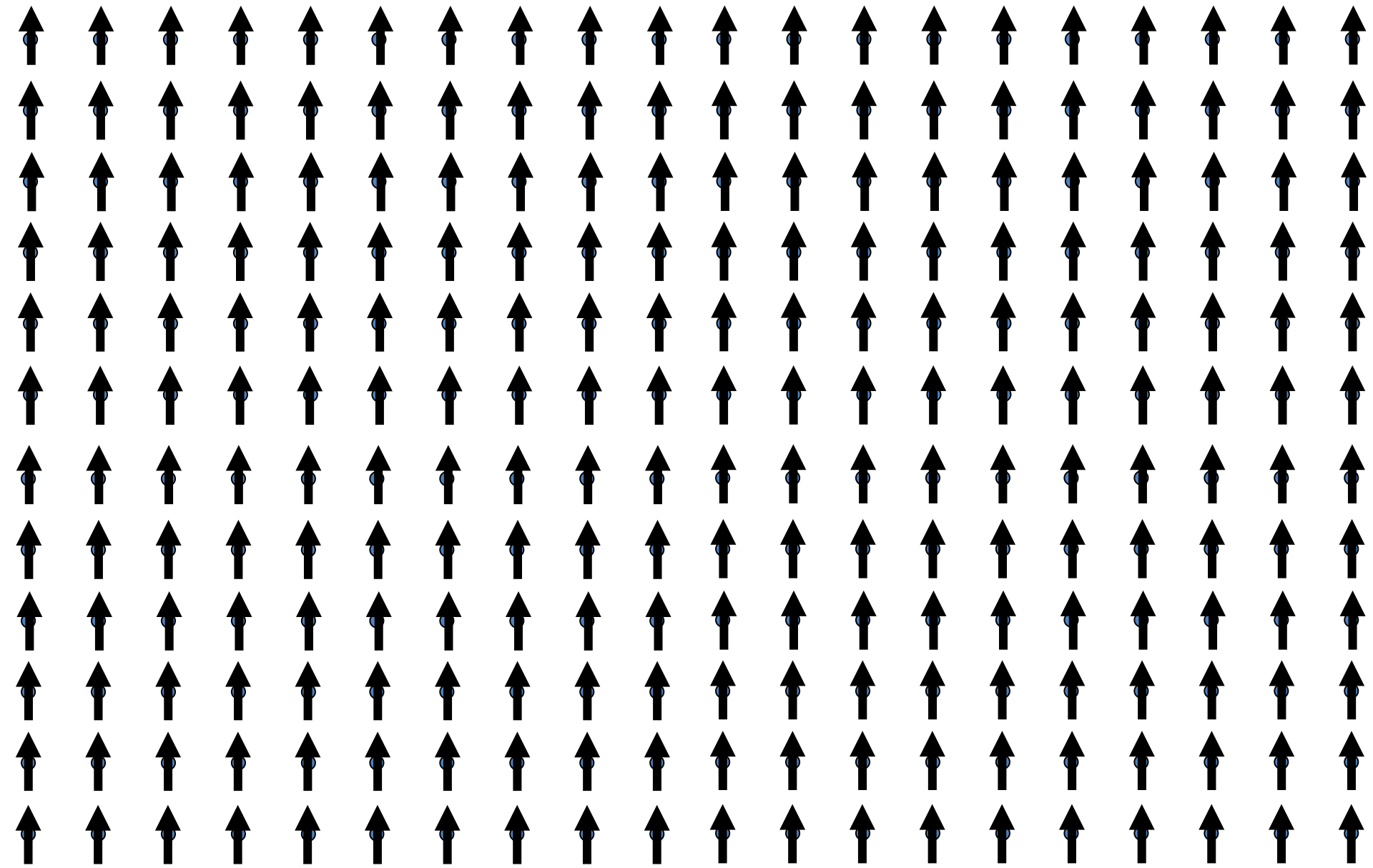
A valence bond:



← Even

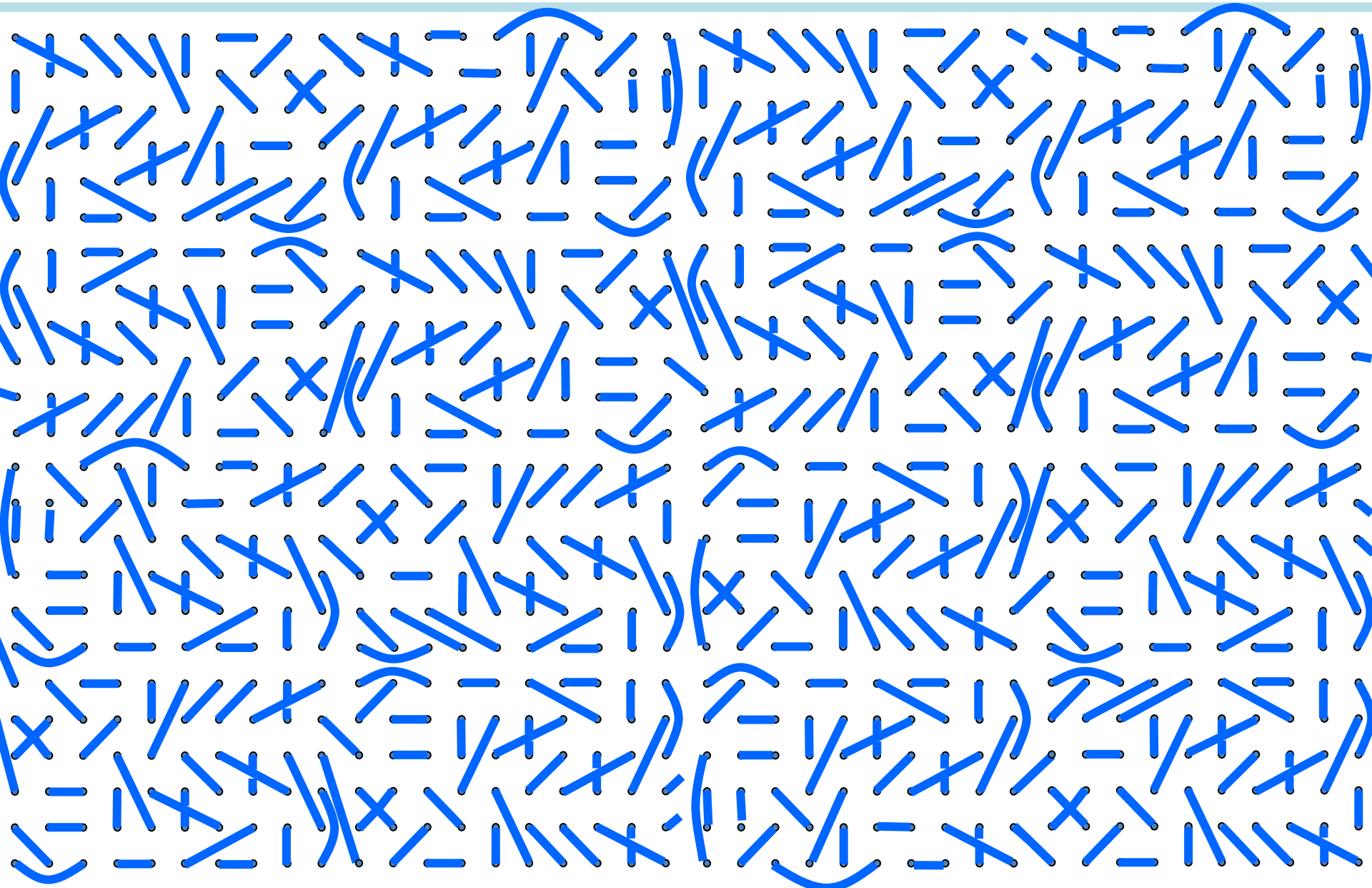
Is it a 0 or a 1?

Is it a 0 or a 1?

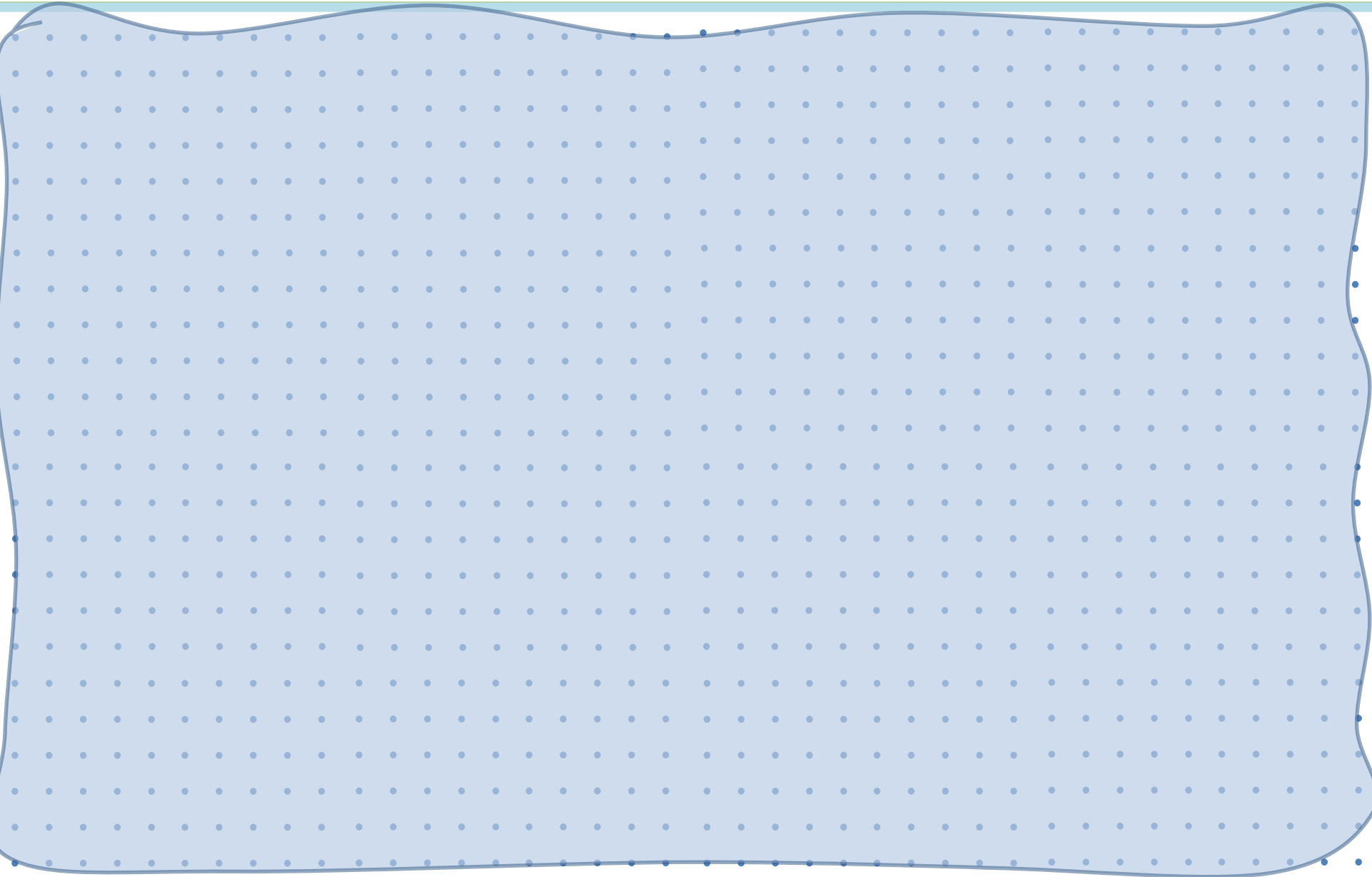


Is it a $|0\rangle$ or a $|1\rangle$?

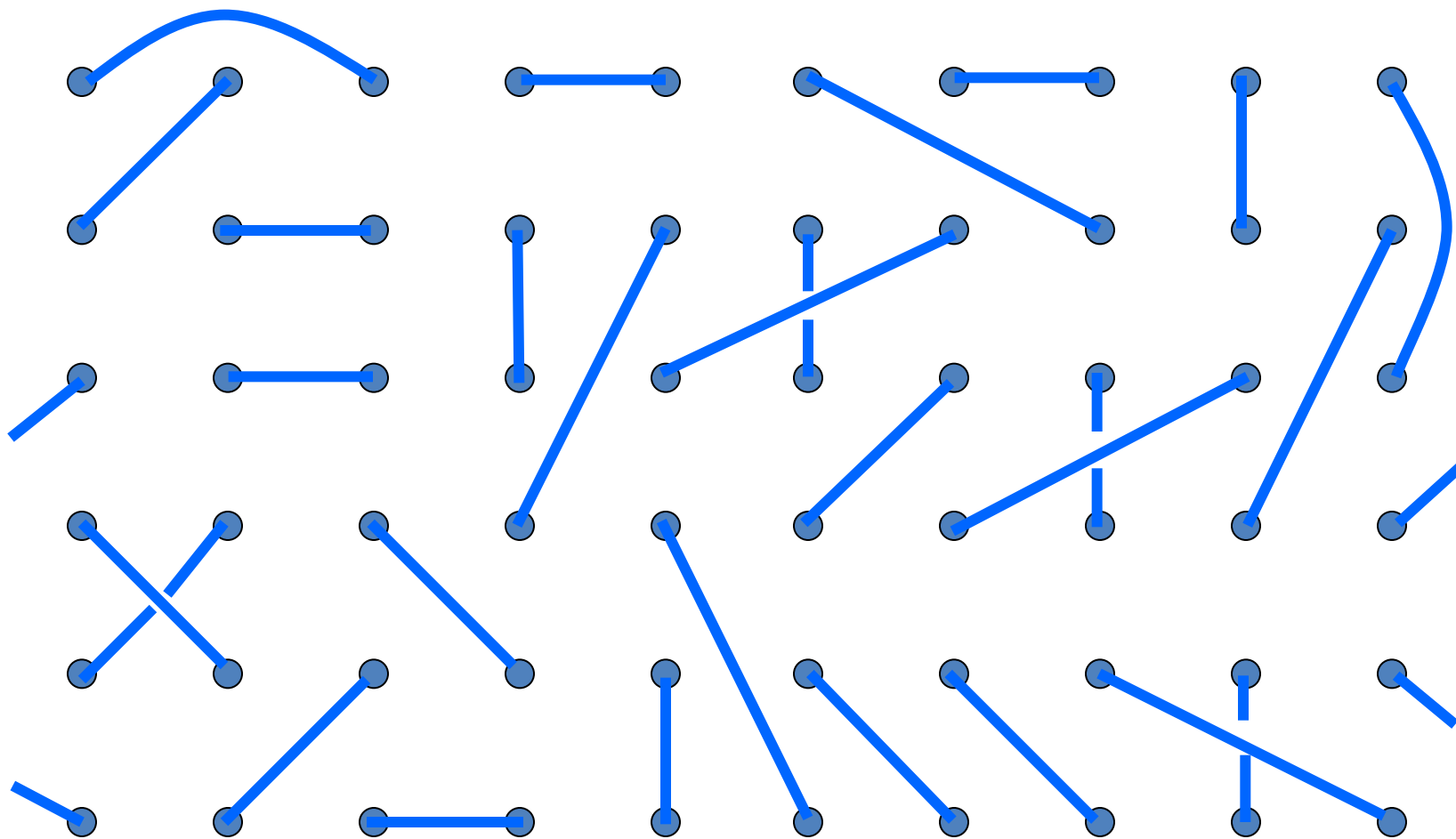
Is it a $|0\rangle$ or a $|1\rangle$?



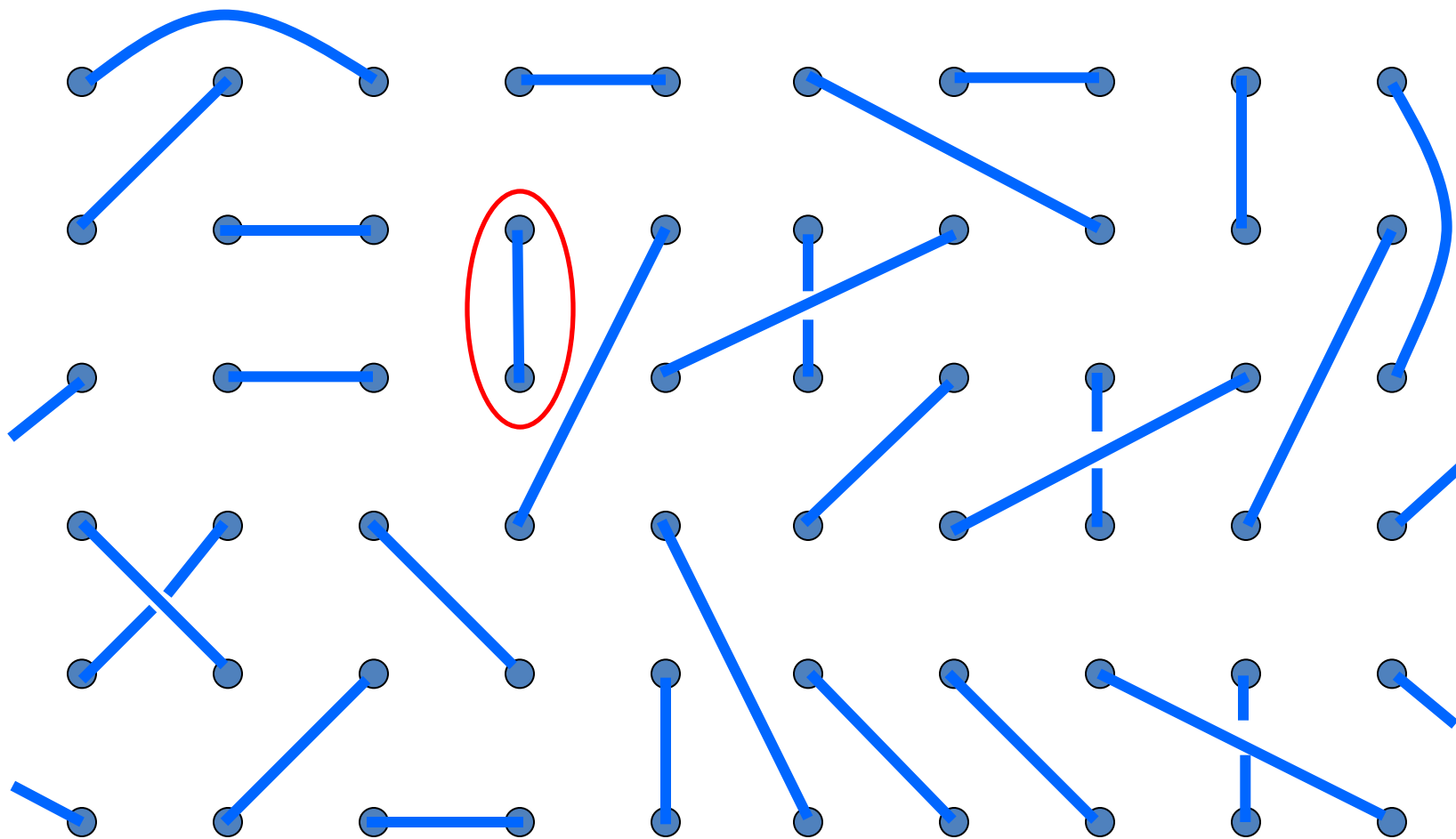
Is it a $|0\rangle$ or a $|1\rangle$?



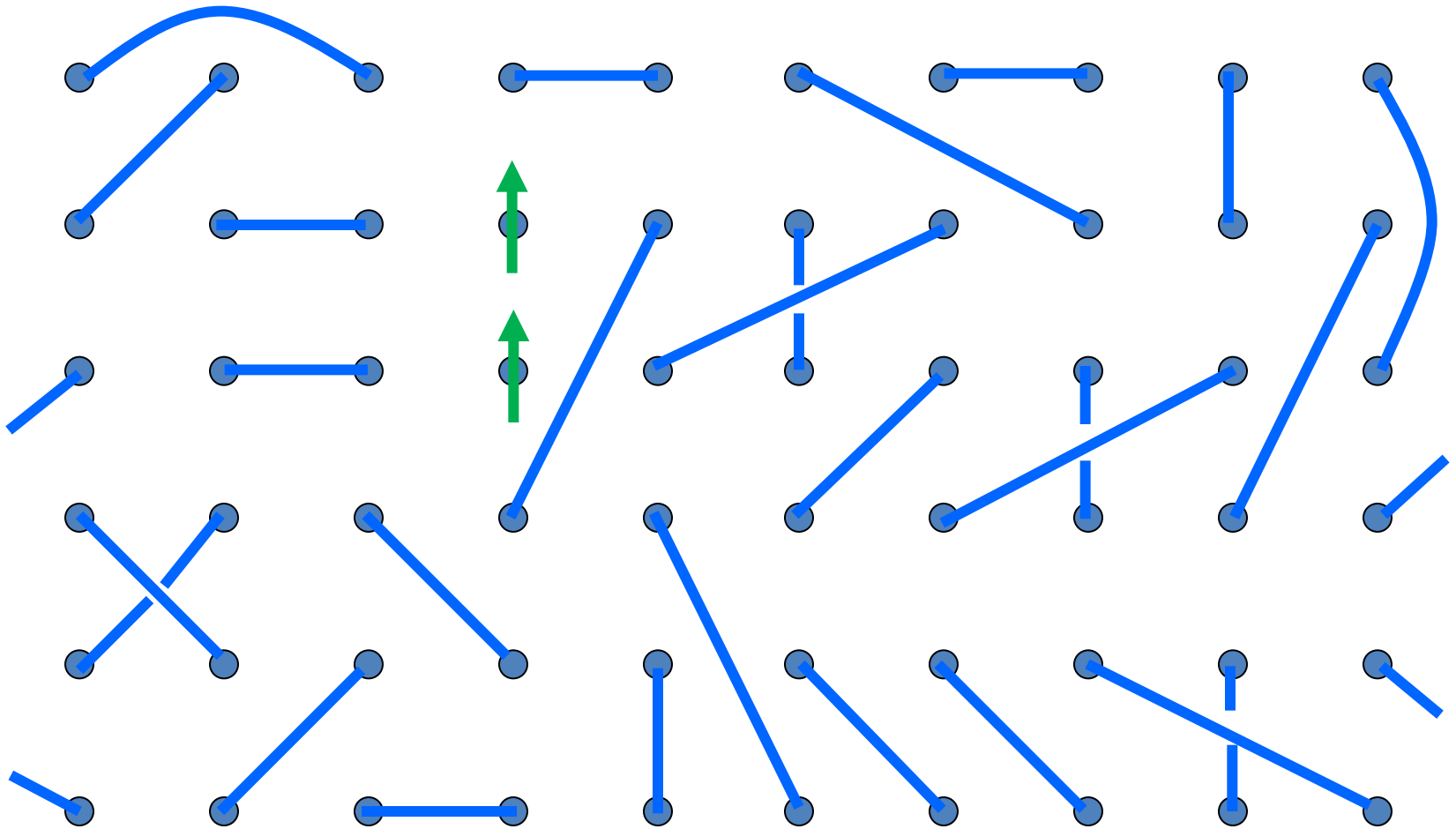
Topological Order: Excitations



Topological Order: Excitations

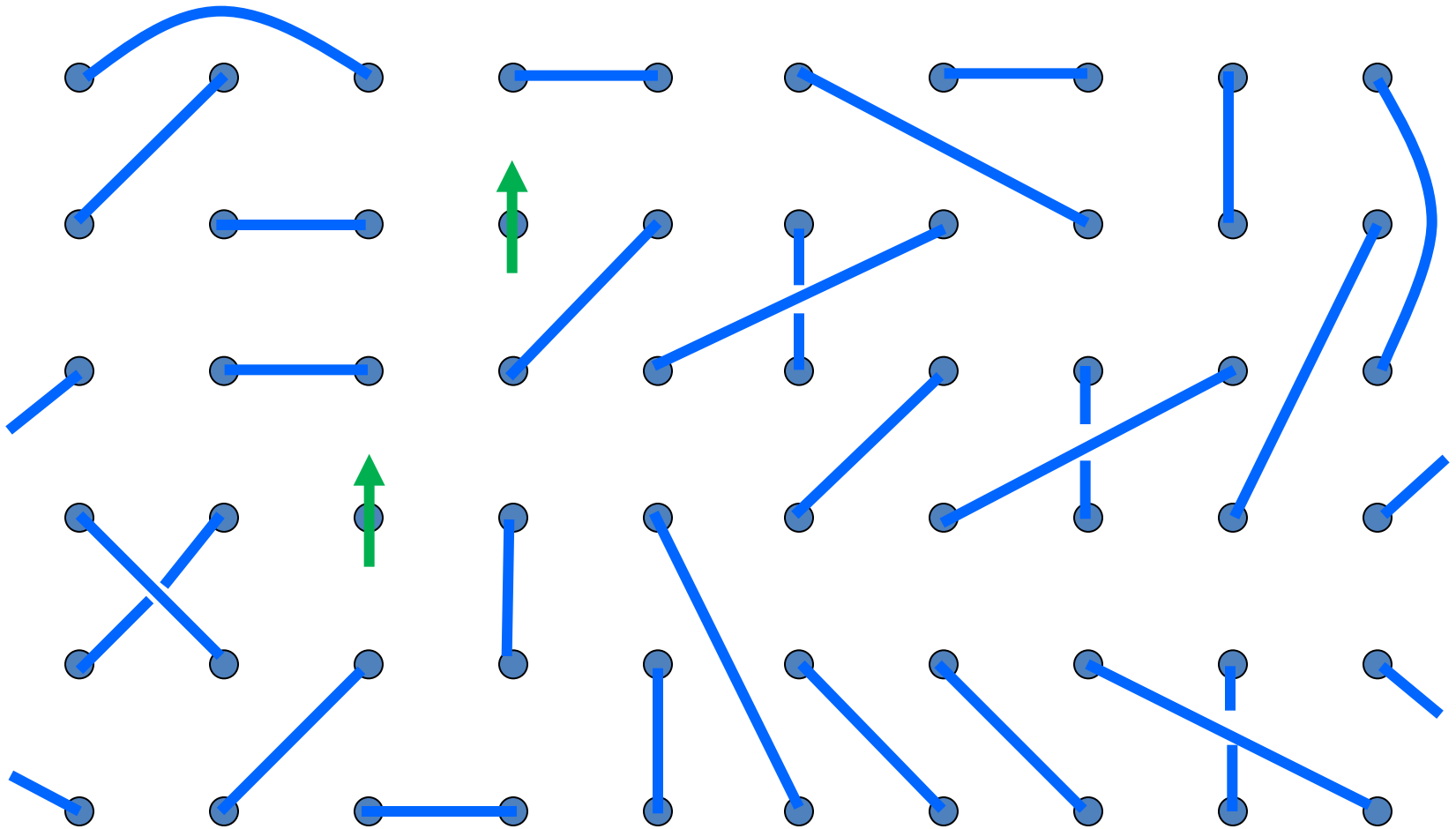


Topological Order: Excitations



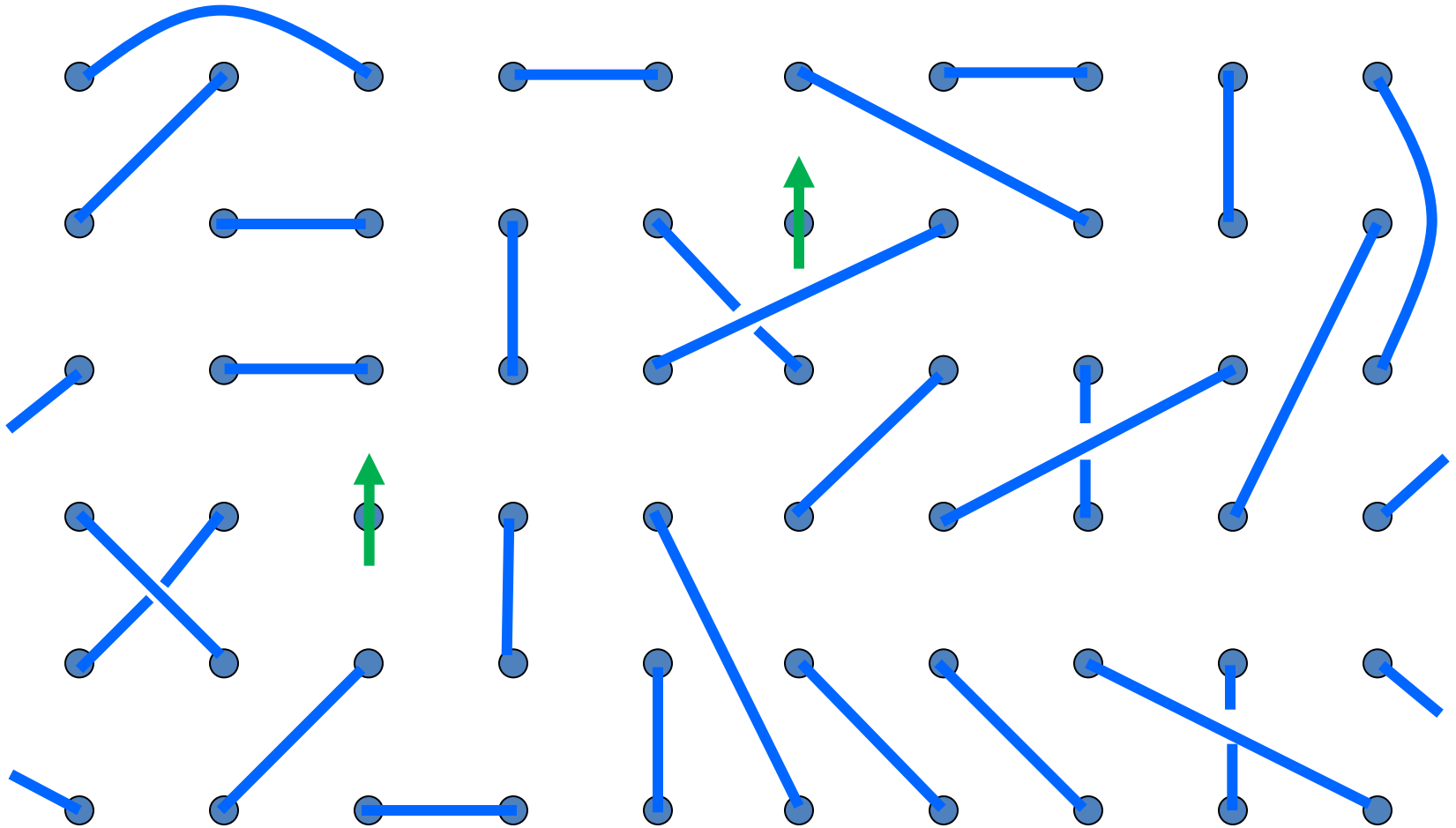
Breaking a bond creates an excitation with $S_z = 1$

Topological Order: Excitations



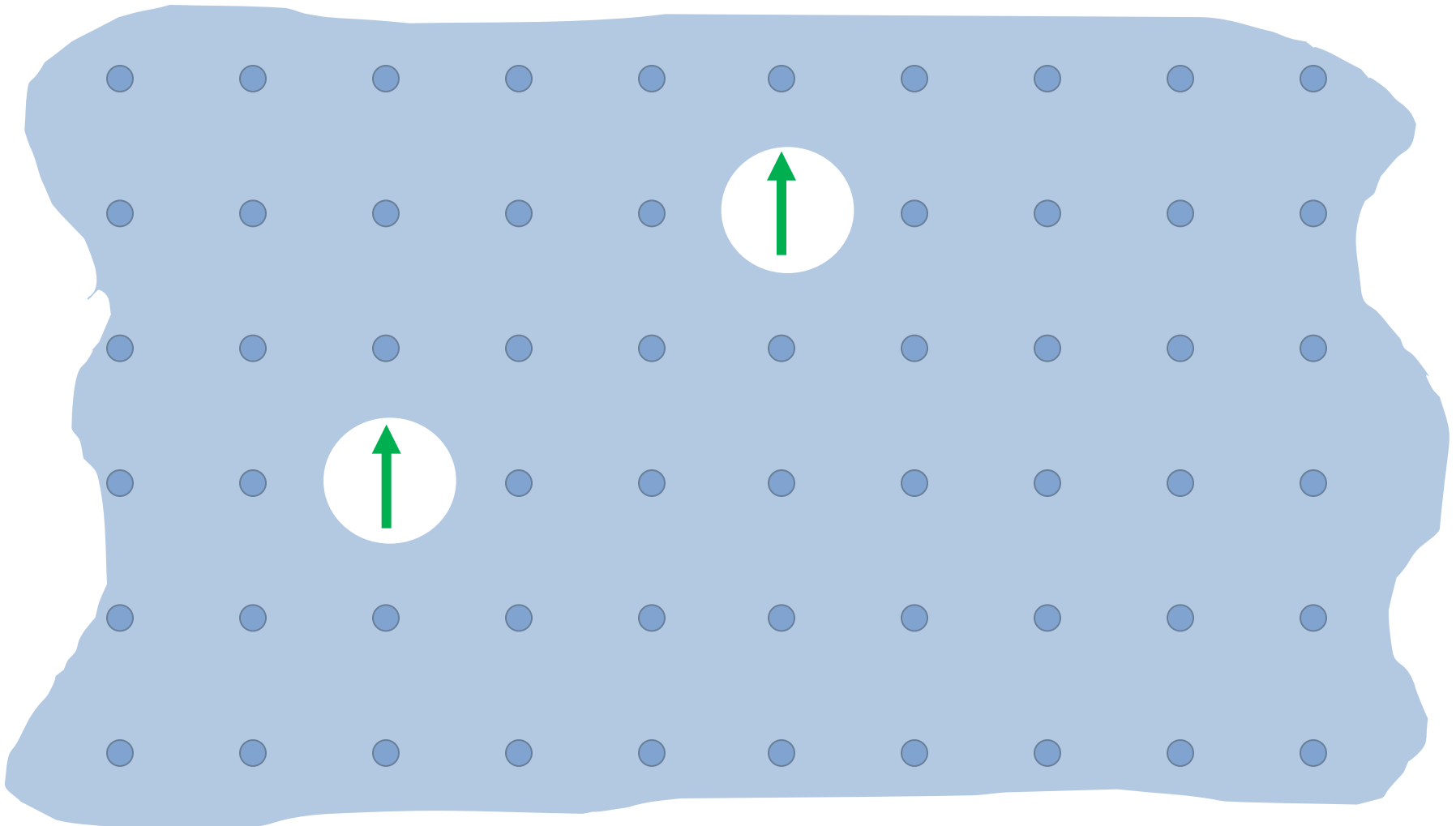
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Topological Order: Excitations



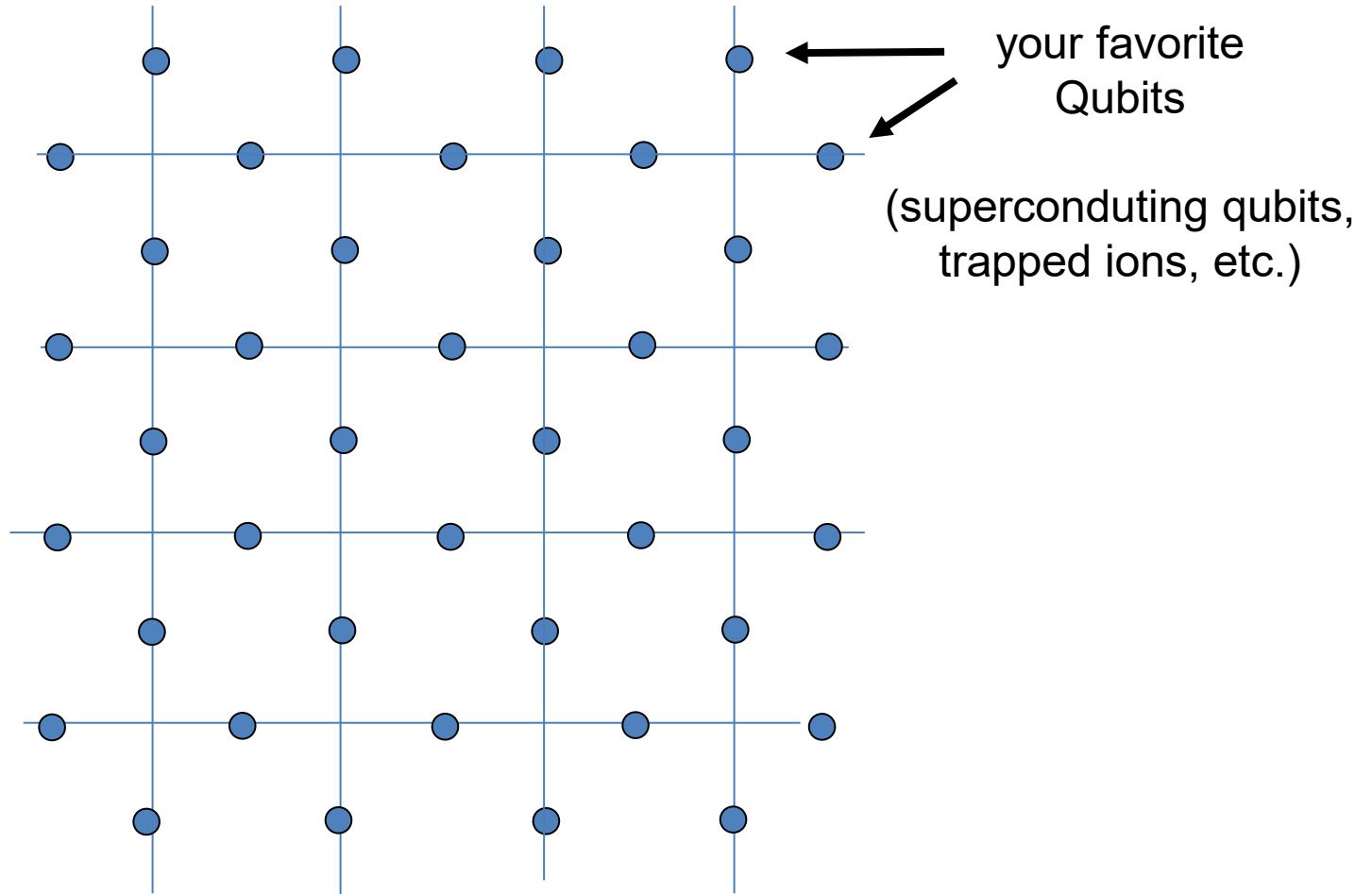
Breaking a bond creates an excitation with $S_z = 1$

Fractionalization

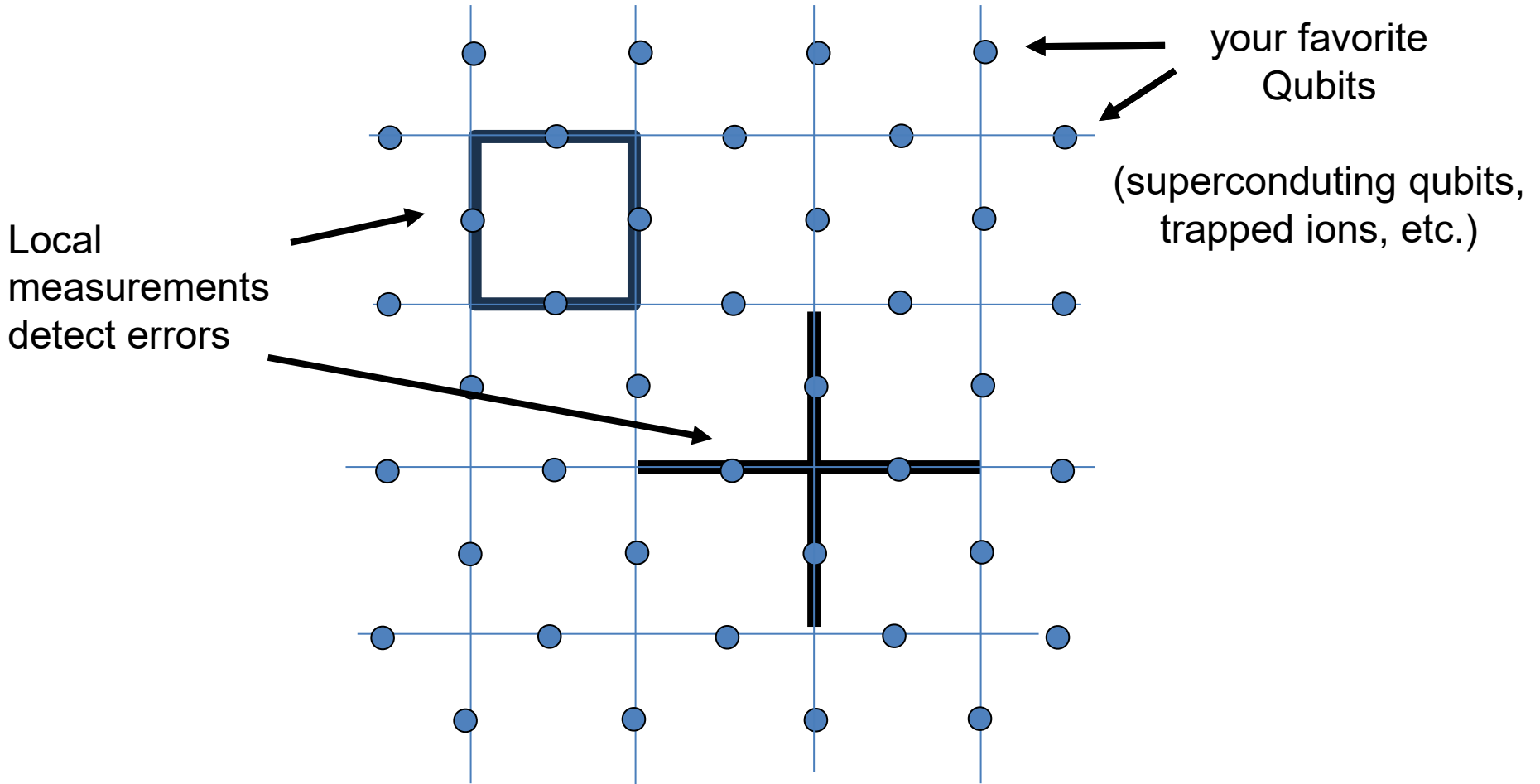


$S_z = 1$ excitation **fractionalizes** into two $S_z = \frac{1}{2}$ excitations

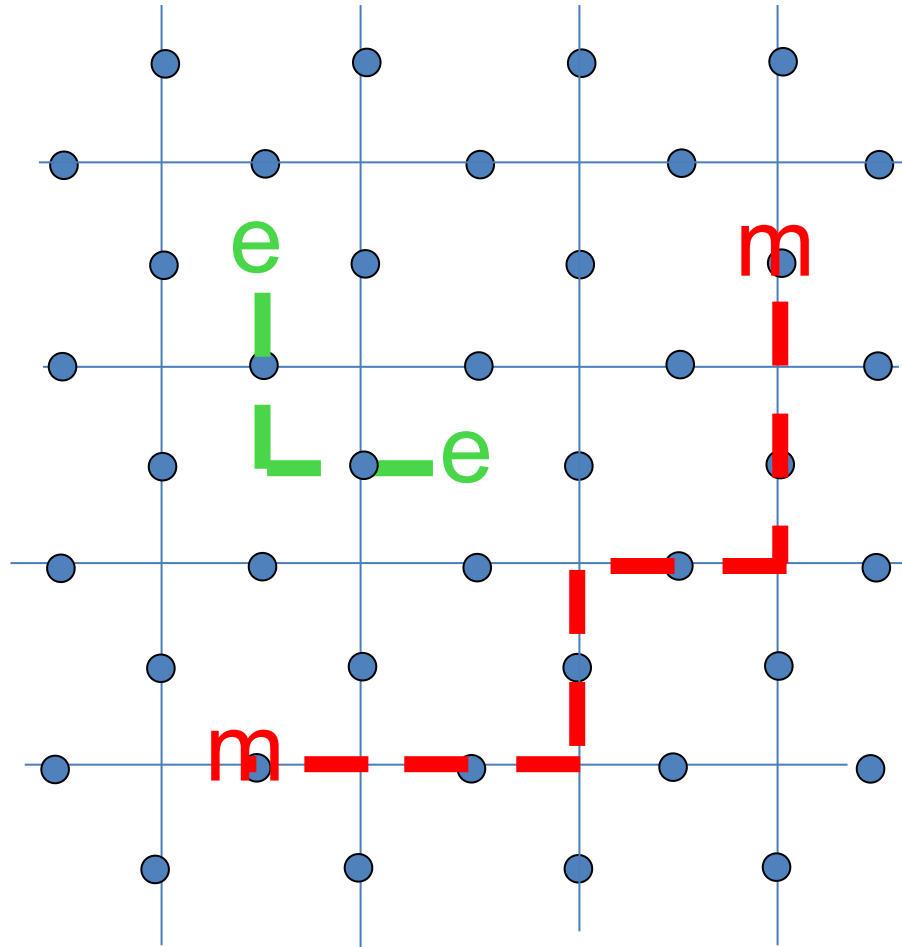
Surface Code



Surface Code

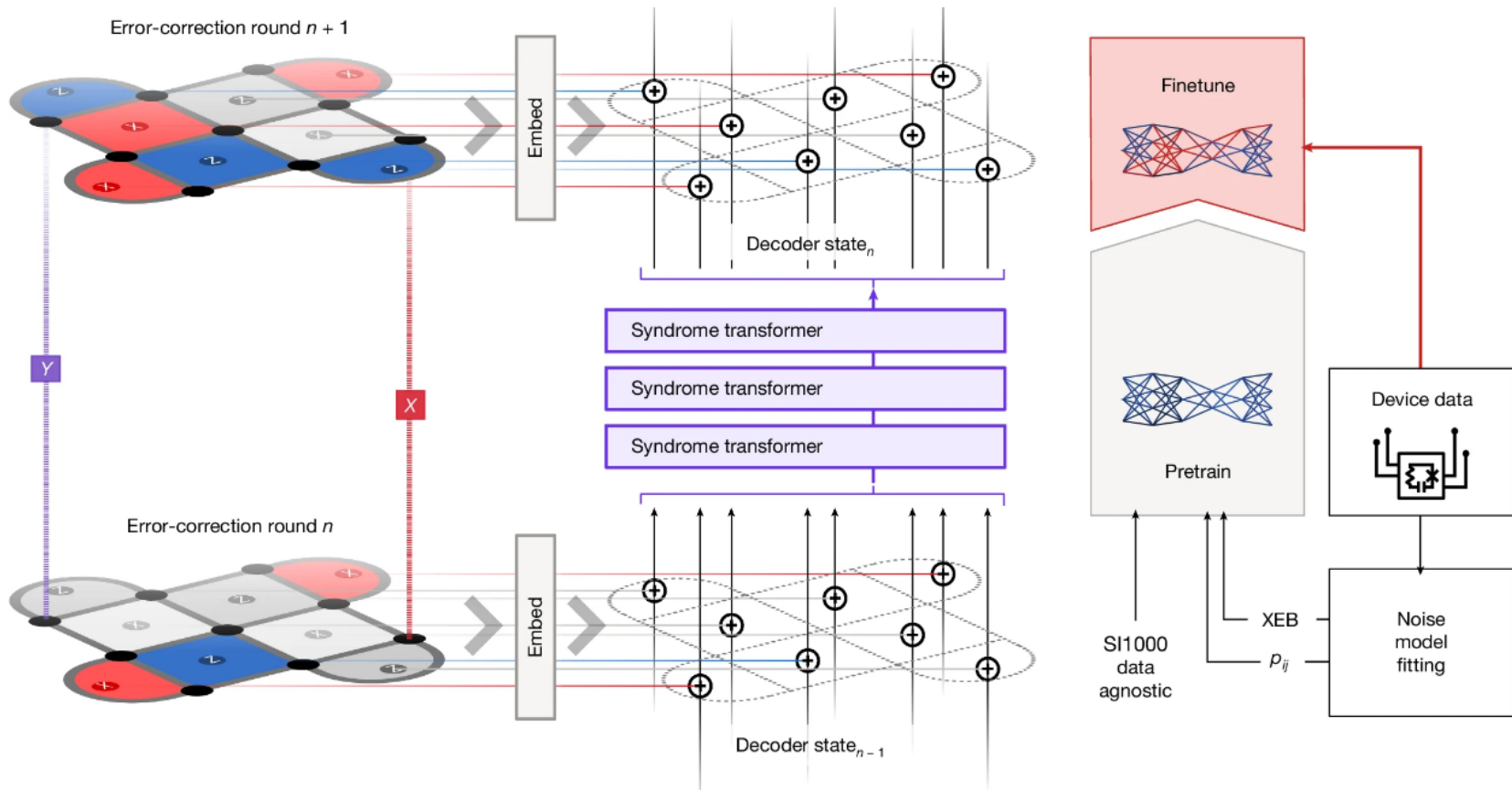


Surface Code



Errors appear as pairs of defects (just like the spin liquid)

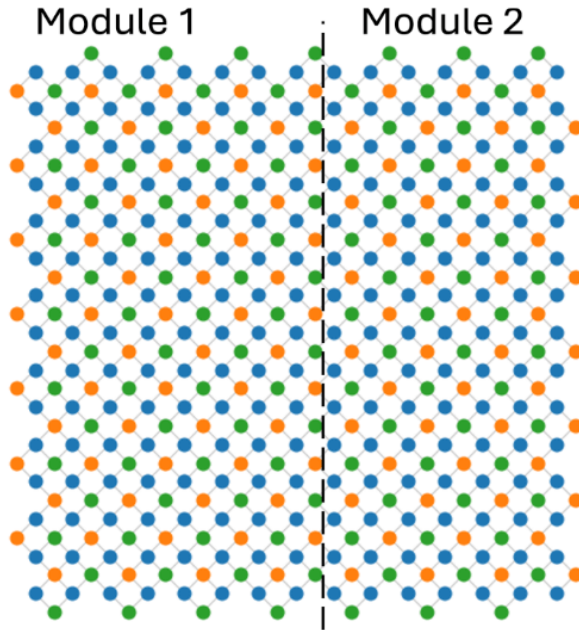
Decoding Errors with AI: AlphaQubit



Bausch et al. (Google DeepMind and Google Quantum AI), "Learning high-accuracy error decoding for quantum processors," *Nature* 635, 834 (2024).

Beyond the Surface Code

Surface Code



qLDPC Code

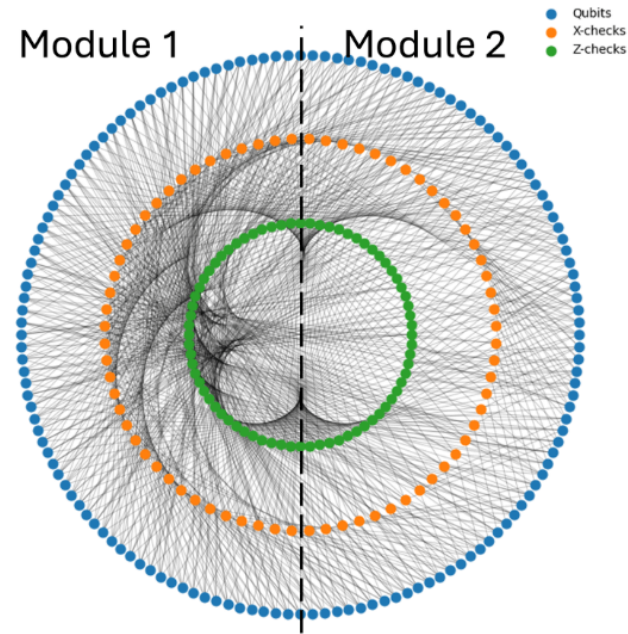


Image from “Reimagining Error Correction for Modular Quantum Computing”, IonQ blog (2025)
<https://www.ionq.com/blog/reimagining-error-correction-for-modular-quantum-computing>

- $\sim 10\times$ fewer qubits per logical qubit at same protection
- Shor resource estimate: 20M \rightarrow 1M (past few years)

Quantum Hardware Landscape (early 2026)

- **Superconducting** — IBM (transitioning surface code → qLDPC; *Starling* FTQC target 2029) · Google (Willow, surface code below threshold) · China (Zuchongzhi 3.2)
- **Trapped ions** — Quantinuum · IonQ + Oxford Ionics (99.99% gate fidelity); shuttling enables surface, color, and qLDPC codes
- **Neutral atoms** — QuEra · Atom Computing · Pasqal; movable atoms are a natural fit for qLDPC
- **Photonics** — PsiQuantum · Xanadu (fusion-based codes, distinct from surface/qLDPC)
- **Cat qubits** — Alice & Bob · Amazon; superconducting microwave resonators; bias-preserving qubits suppress bit-flips, reducing QEC overhead
- **Silicon spin qubits** — Diraq · Silicon Quantum Computing (99.99% two-qubit fidelity); CMOS-compatible, no logical qubits yet
- **Topological** — Microsoft Majorana 1 (early-stage; physics still debated)

Multiple below-threshold demonstrations on small surface codes; no verified large-scale fault-tolerant logical qubit yet. Credible roadmaps target late 2020s – early 2030s.

Quantum Spin Liquids: Experimental Status

- **The challenge** — defined by what's *absent* (no order) and what's *non-local* (fractionalized excitations); no local order parameter to measure
- **Kagome antiferromagnets** — herbertsmithite $\text{ZnCu}_3(\text{OH})_6\text{Cl}_2$; spinon continuum in neutron scattering; disorder vs. intrinsic gaplessness still debated
- **Kitaev candidates** — $\alpha\text{-RuCl}_3$; field-induced regime, controversial thermal Hall signatures of Majorana edge modes
- **Triangular organics** — $\kappa\text{-(ET)}_2\text{Cu}_2(\text{CN})_3$; long-standing candidate, recent questions about glassy alternatives
- **Quantum spin ice** — rare-earth pyrochlores; cerium compounds ($\text{Ce}_2\text{Zr}_2\text{O}_7$) emerging as cleanest candidates
- **Synthetic systems** — Rydberg arrays, superconducting simulators; topological signatures *directly* measurable

After ~20 years: serious candidates in several families, no single confirmed example. The same non-locality that makes spin liquids hard to detect is what would make them robust quantum memories.

Selected Reviews and Key References

Quantum spin liquids — Savary & Balents, *Rep. Prog. Phys.* **80**, 016502 (2017); Broholm et al., *Science* **367**, eaay0668 (2020)

•**Surface code & topological QEC** — Fowler, Mariantoni, Martinis, Cleland, *Phys. Rev. A* **86**, 032324 (2012); Terhal, *Rev. Mod. Phys.* **87**, 307 (2015)

•**Surface code experiments** — Acharya et al. (Google, Willow), *Nature* **638**, 920 (2025); Zuchongzhi 3.2 (USTC), *Phys. Rev. Lett.* (2025)

•**qLDPC codes** — Breuckmann & Eberhardt, *PRX Quantum* **2**, 040101 (2021); Bravyi et al., *Nature* **627**, 778 (2024)

•**qLDPC experiments** — Reichardt et al. (Quantinuum, $[[25,4,3]]$ code), arXiv:2406.02666 (2024); IBM Kookaburra roadmap (2026)

•**AI decoders (surface)** — Bausch et al. (AlphaQubit), *Nature* **635**, 834 (2024); Senior et al. (AlphaQubit 2), arXiv:2512.07737 (2025)

•**AI decoders (qLDPC)** — Maan & Paler (Astra), *npj Quantum Information* (2025); Blue et al., arXiv:2504.13043 (2025)

(And something I would have talked about if I had more than 20 minutes...)

•**Non-Abelian anyons & topological QC** — Nayak, Simon, Stern, Freedman, Das Sarma, *Rev. Mod. Phys.* **80**, 1083 (2008); Hormozi, Zikos, NEB, Simon, *Phys. Rev. B* **75**, 165310 (2007), NEB, DiVincenzo, *Phys Rev. B* **86**, 165113 (2012)