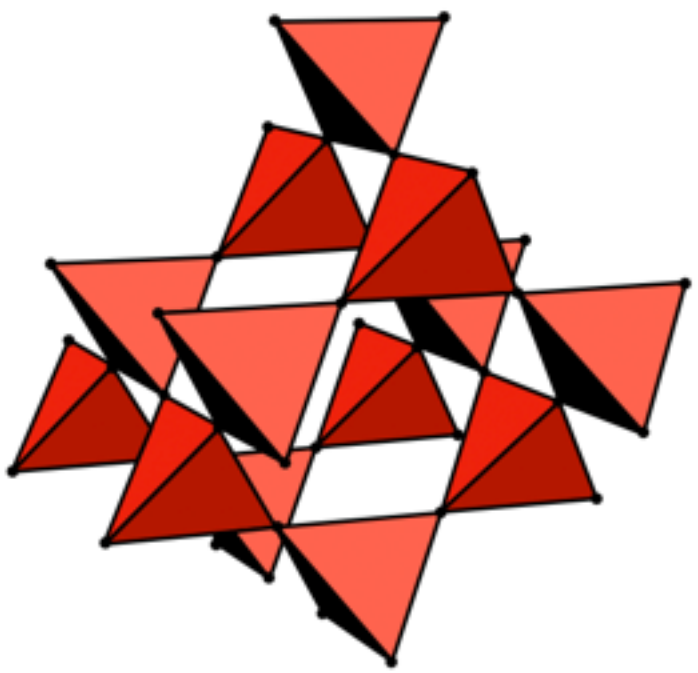
THE EMERGENT FINE STRUCTURE CONSTANT IN QUANTUM SPIN ICE

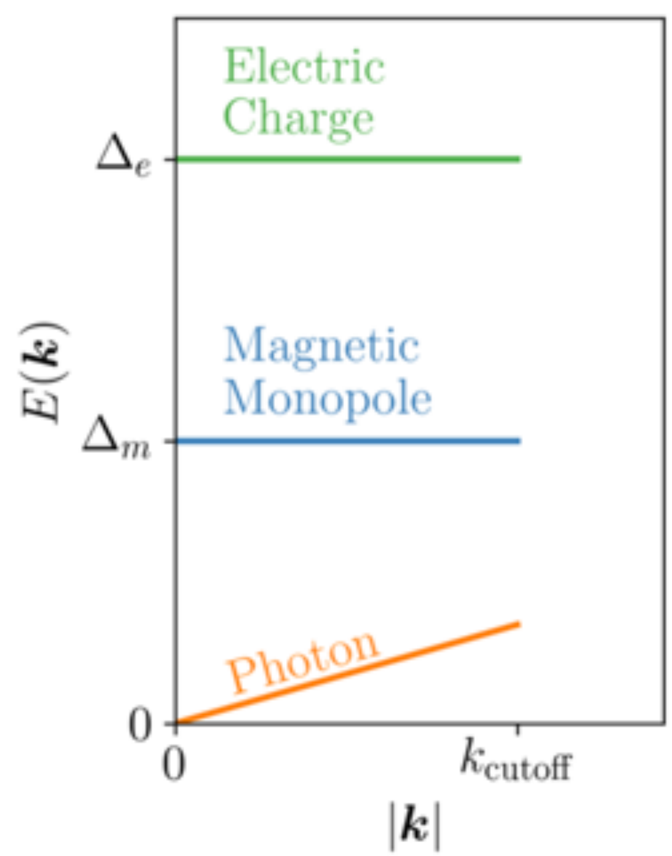
Sal Pace

OUR JOURNEY

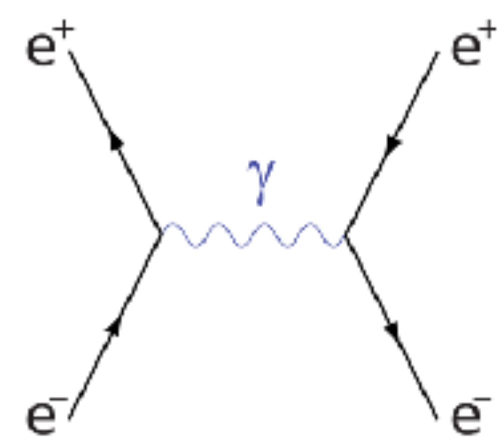
1) Quantum Spin Ice



2) Emergent QED



3) Calculating the emergent fine structure constant



$\sim \quad \alpha$

QUANTUM CONDENSED MATTER PHYSICS

- Known UV degrees of freedom
- Many-body problem complex and intractable

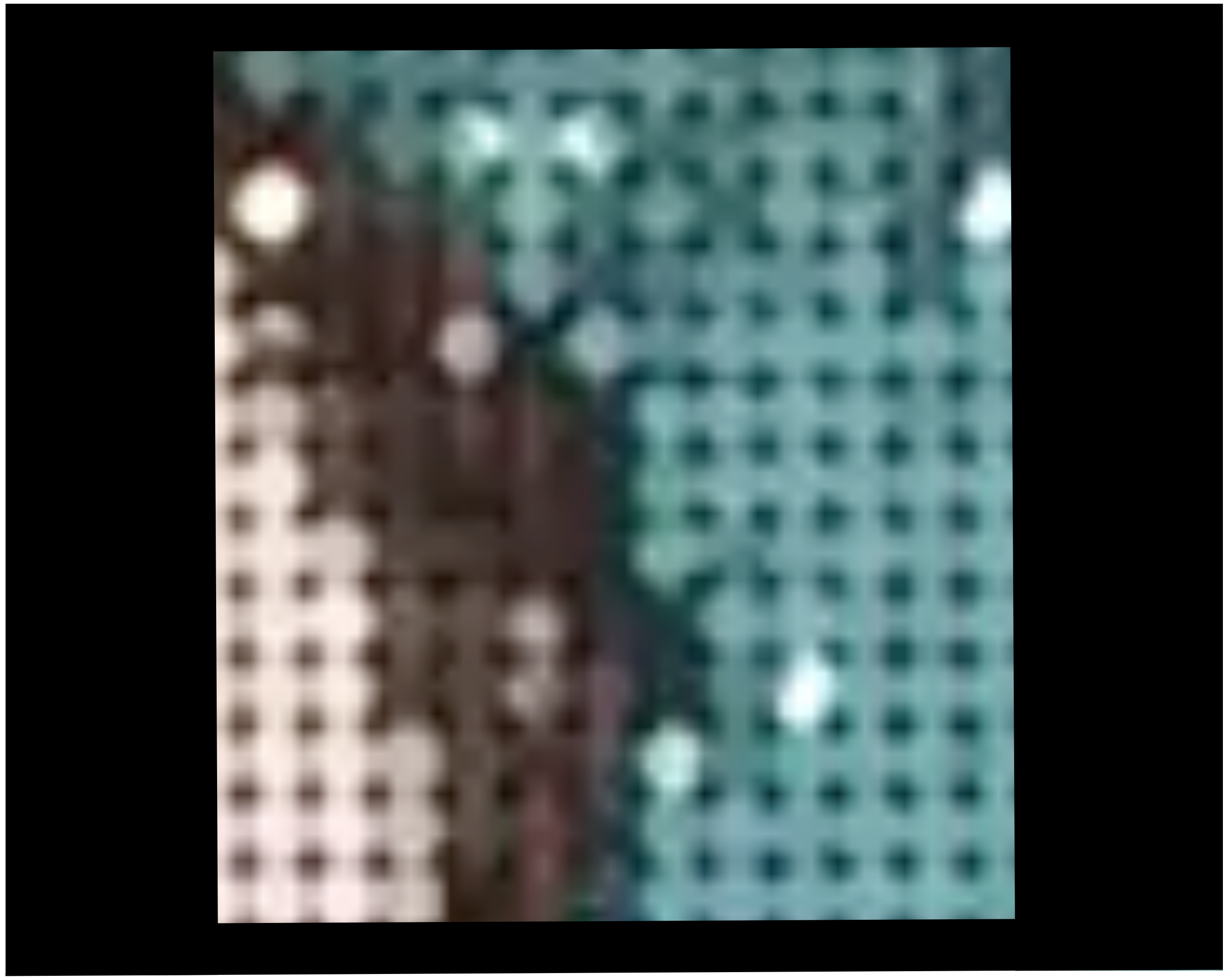
Short Distances (High Energy)

Long Distances (Low Energy)

- IR degrees of freedom emerge
- Effective description of many-body problem

EMERGENCE

Short Distances (High Energy)



Long Distances (Low Energy)

EMERGENCE

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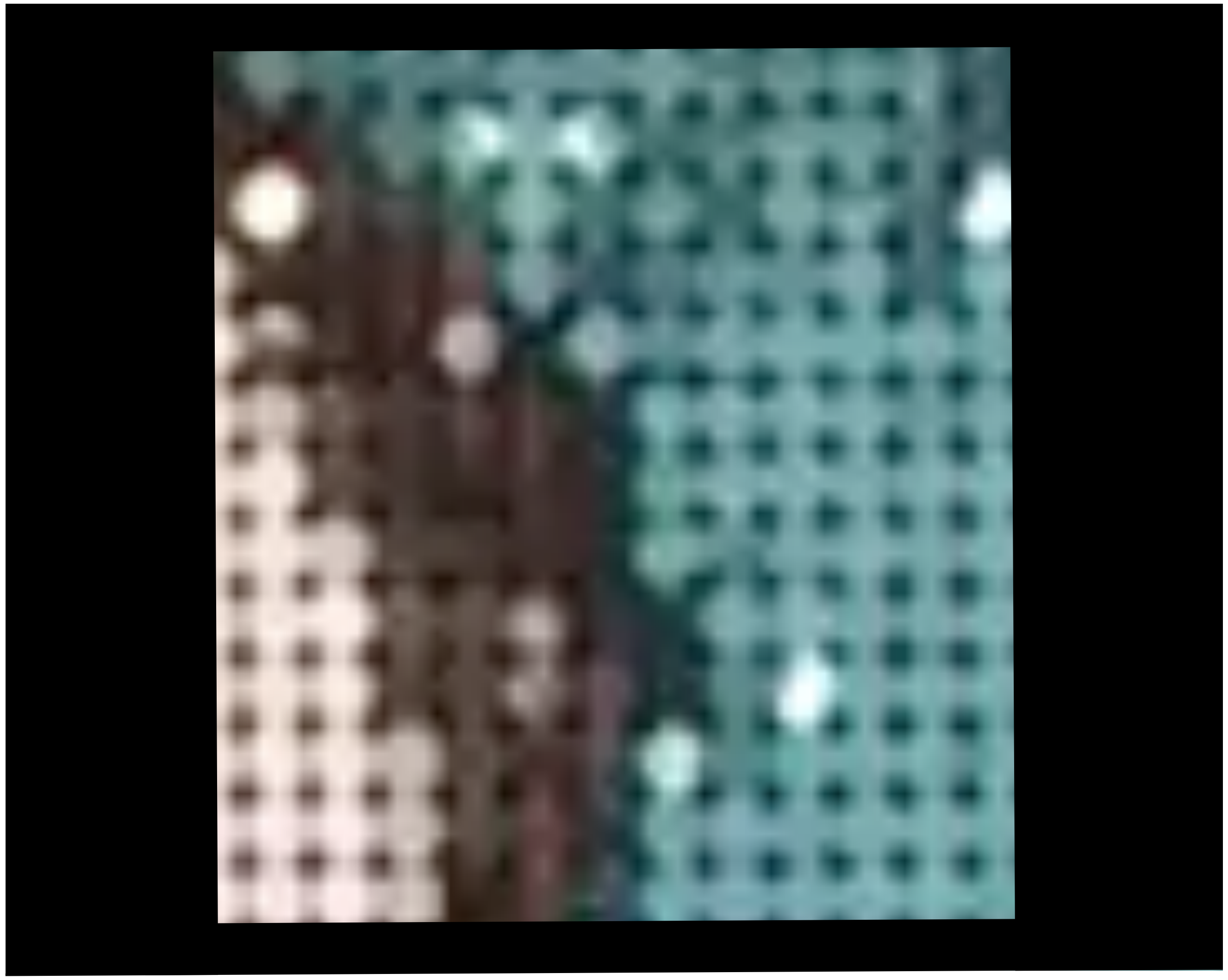

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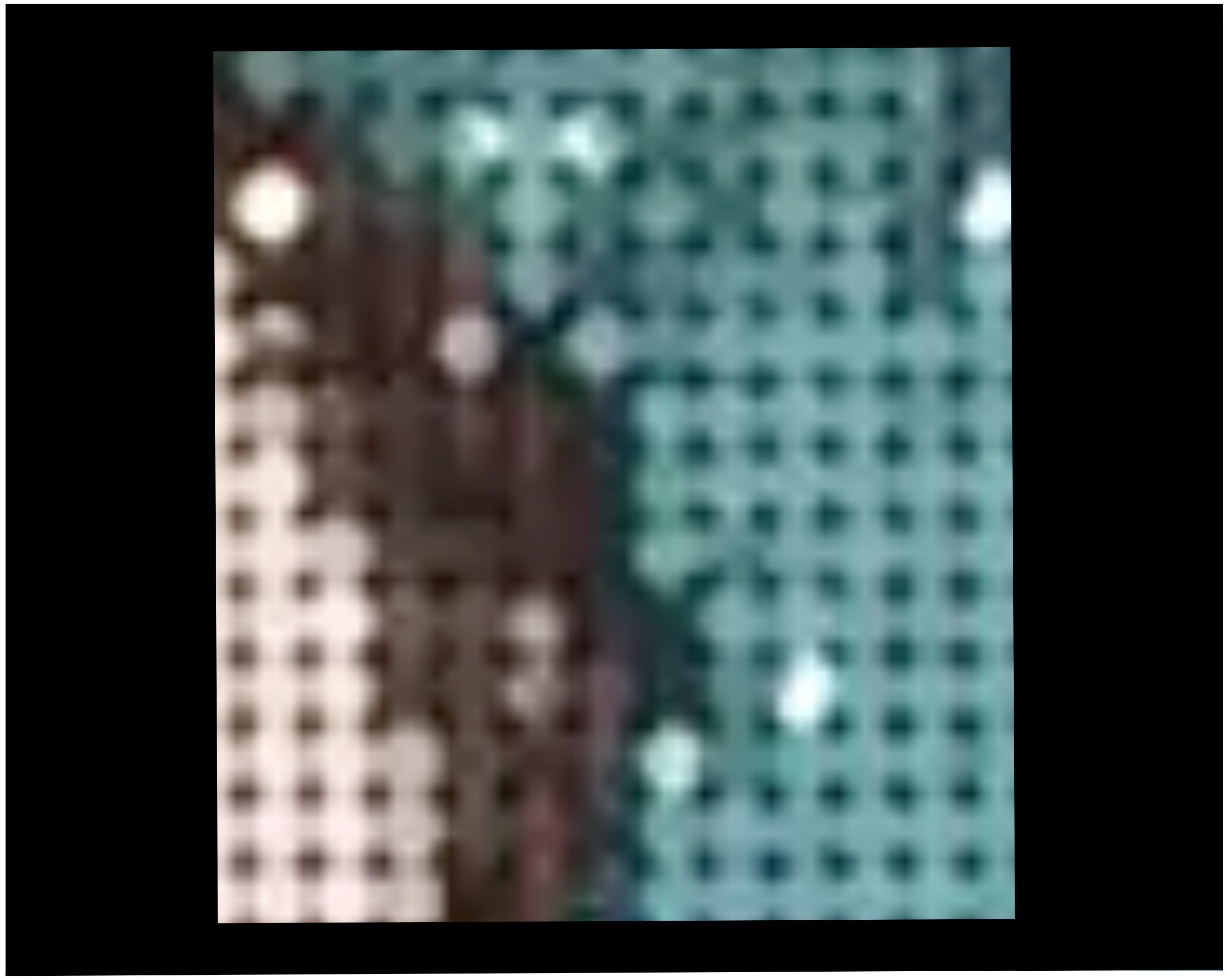

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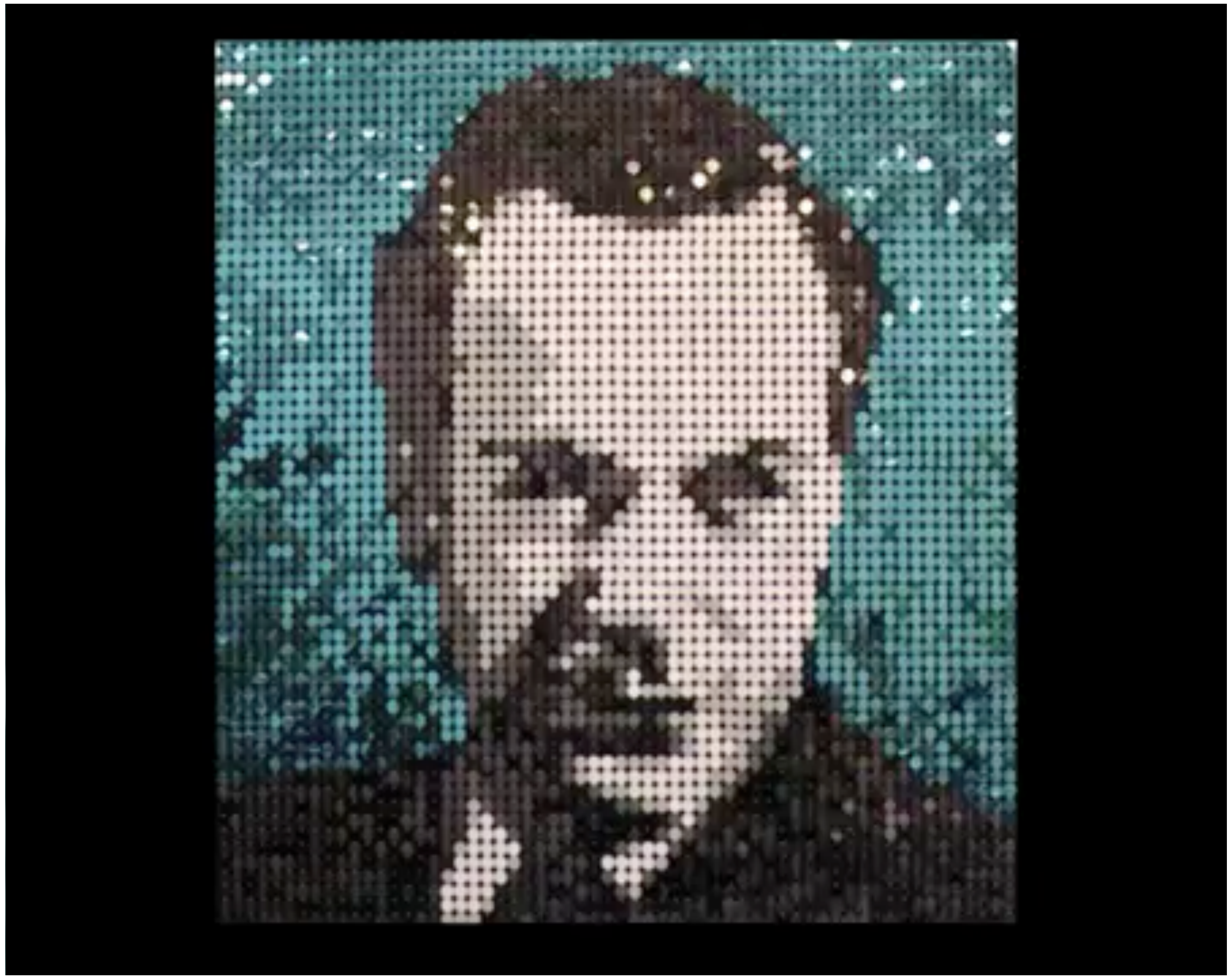

YouTube: "Richard Feynman FRS.mov," by Cheryl Field

EMERGENCE

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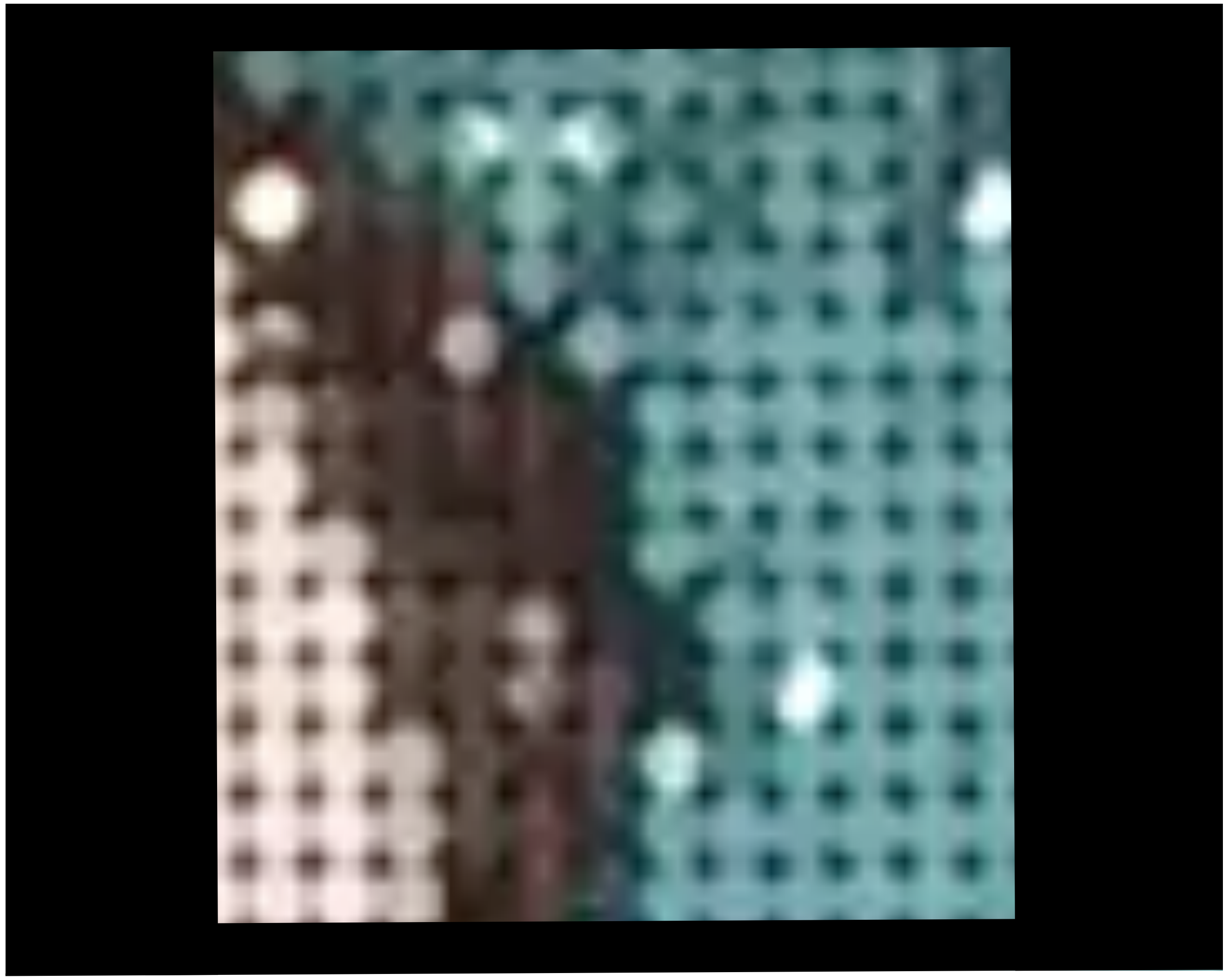

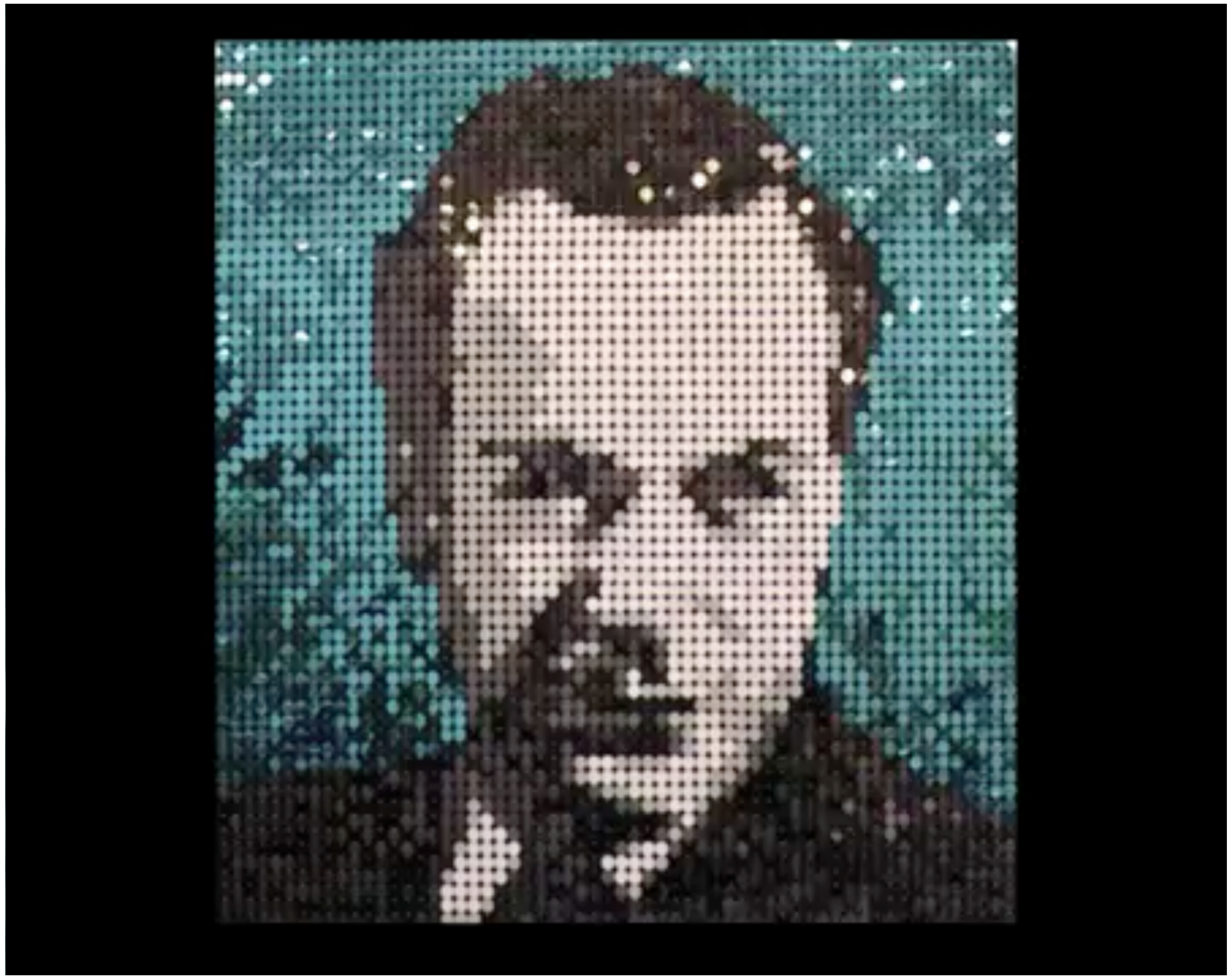

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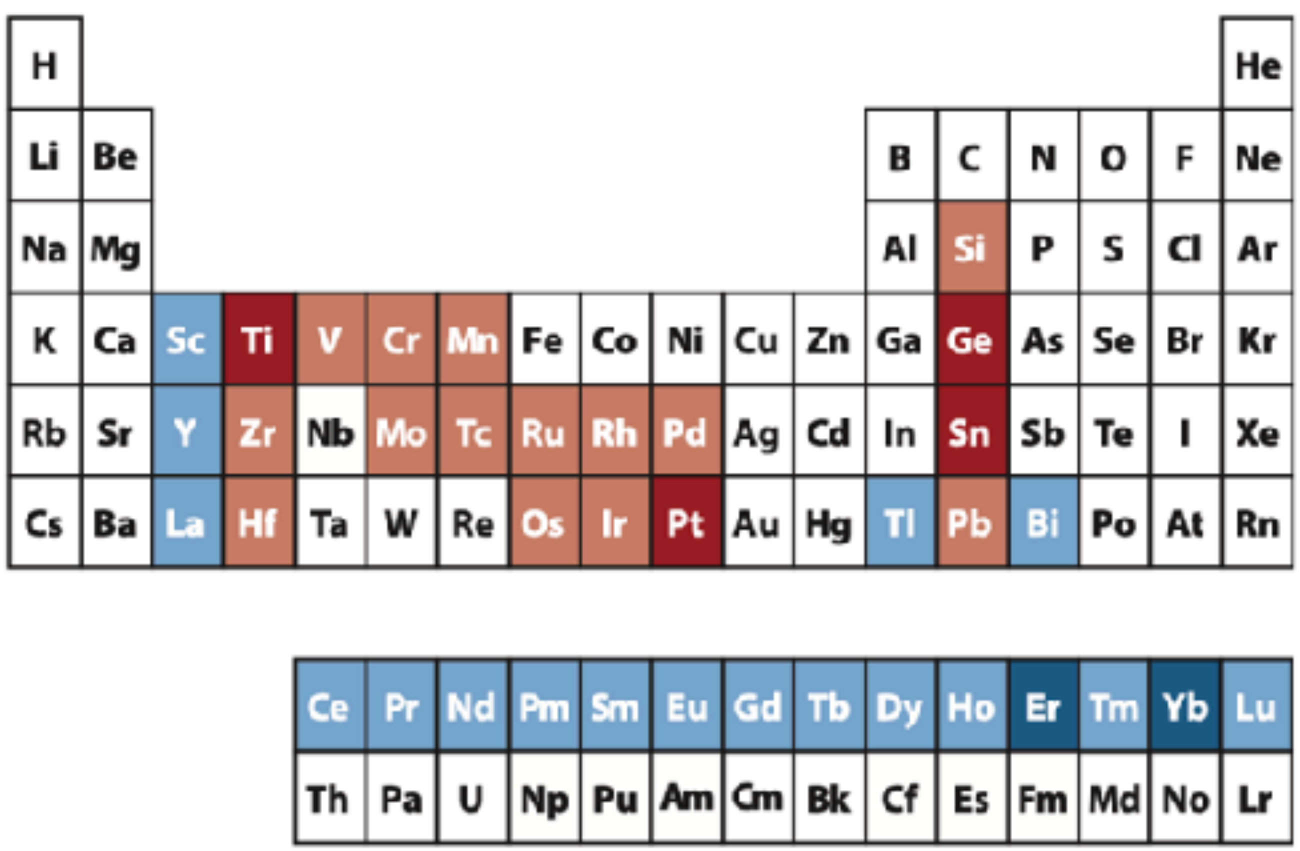
Emergent Quantum Electrodynamics???

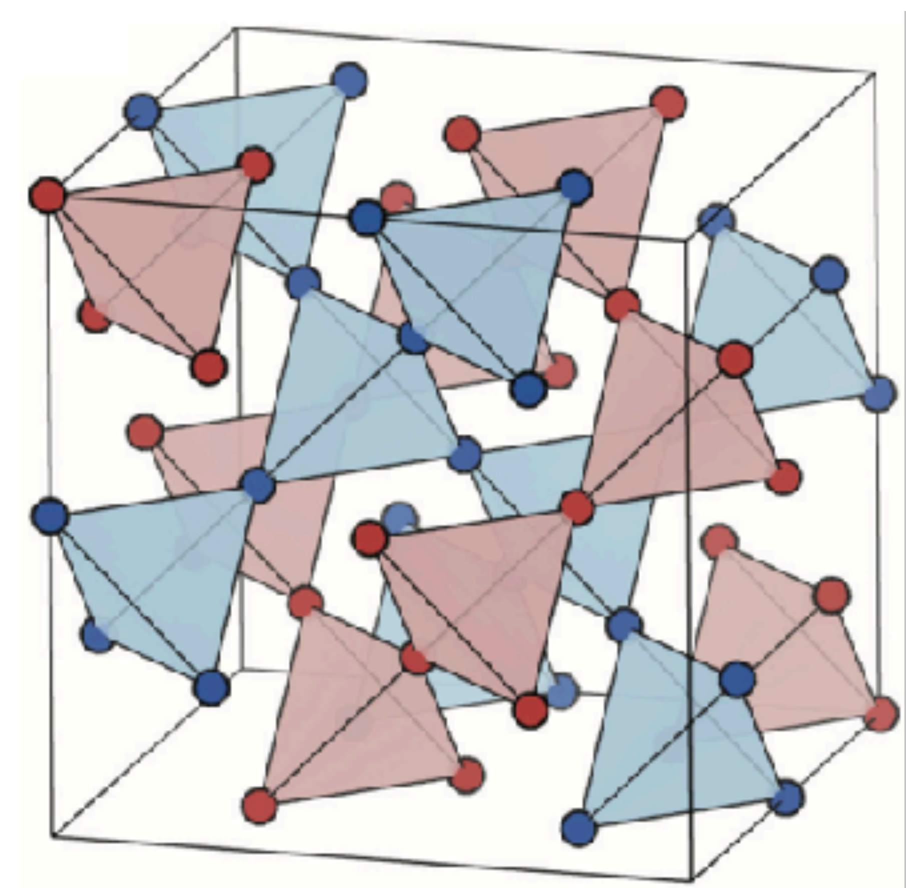
RARE-EARTH PYROCHLORE MAGNETS

$$A_2^{3+}B_2^{4+}O_7$$

Magnetic rare-earth ion

Non-magnetic





Hallas, Alannah M., Jonathan Gaudet, and Bruce D. Gaulin. *Annual Review of Condensed Matter Physics* 9 (2018): 105-124.

SPIN ICE MATERIALS

$$A_2^{3+}B_2^{4+}O_7$$

<u>Classical spin ice</u>

$Ho_2Ti_2O_7$

$Dy_2Ti_2O_7$

- Well established
- Order at low T

<u>Candidate quantum spin ice</u>

$Yb_2Ti_2O_7$ $Pr_2Sn_2O_7$ $Pr_2Hf_2O_7$

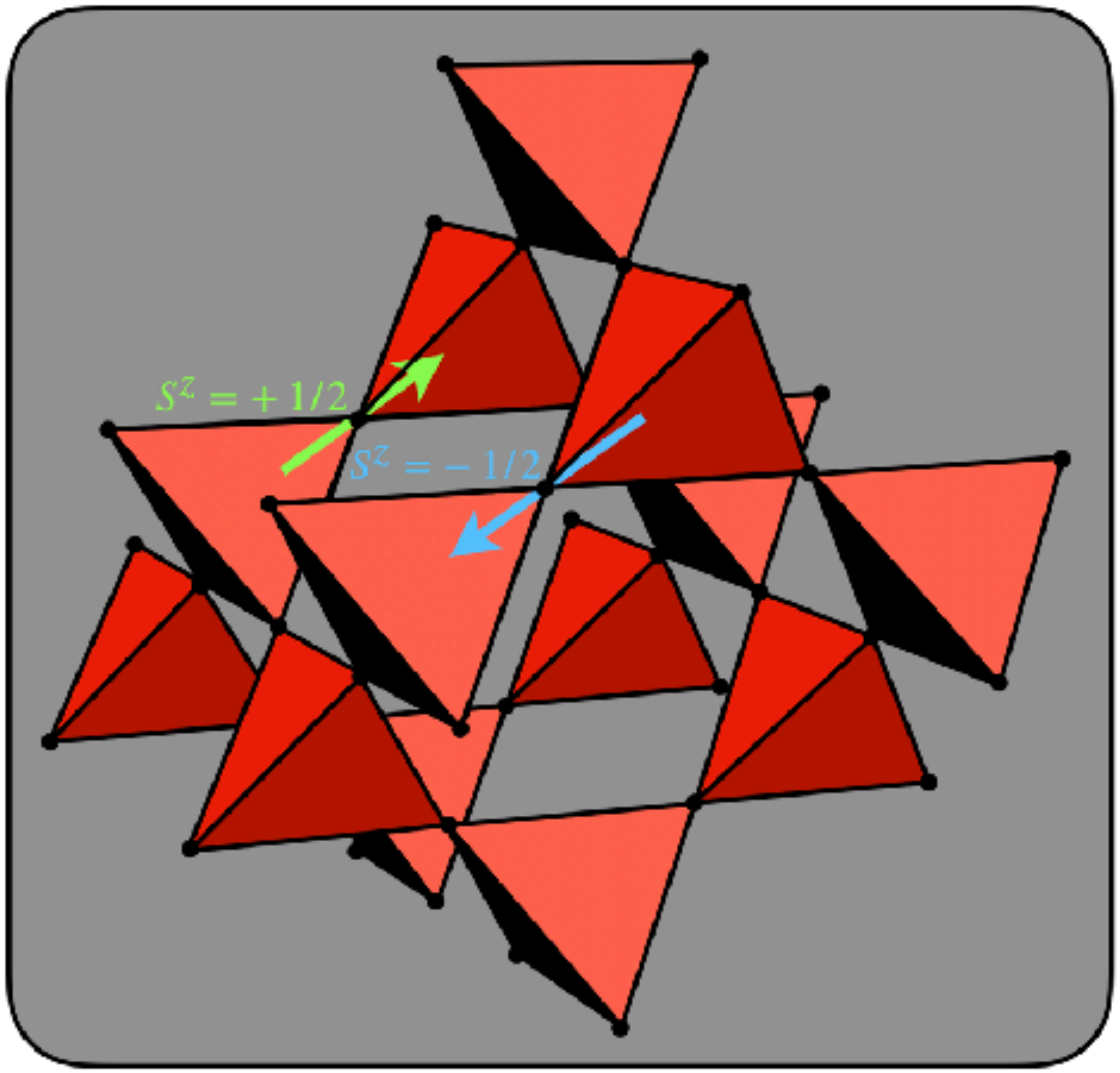
$Tb_2Ti_2O_7$ $Pr_2Zr_2O_7$

- Active area of experimental research
- No long-range order even at $T = 0$

Gardner, Jason S., Michel JP Gingras, and John E. Greedan. *Reviews of Modern Physics* 82.1 (2010): 53.
Hallas, Alannah M., Jonathan Gaudet, and Bruce D. Gaulin. *Annual Review of Condensed Matter Physics* 9 (2018): 105-124.
Rau, Jeffrey G., and Michel JP Gingras. *Annual Review of Condensed Matter Physics* (2019).

CLASSICAL SPIN ICE

Pyrochlore Lattice



$$H_{\mathrm{CSI}} = J_{zz} \sum_{\langle i,j \rangle} S_i^z S_j^z$$

- $\langle i, j \rangle$: Nearest neighbors
- $J_{zz} > 0$

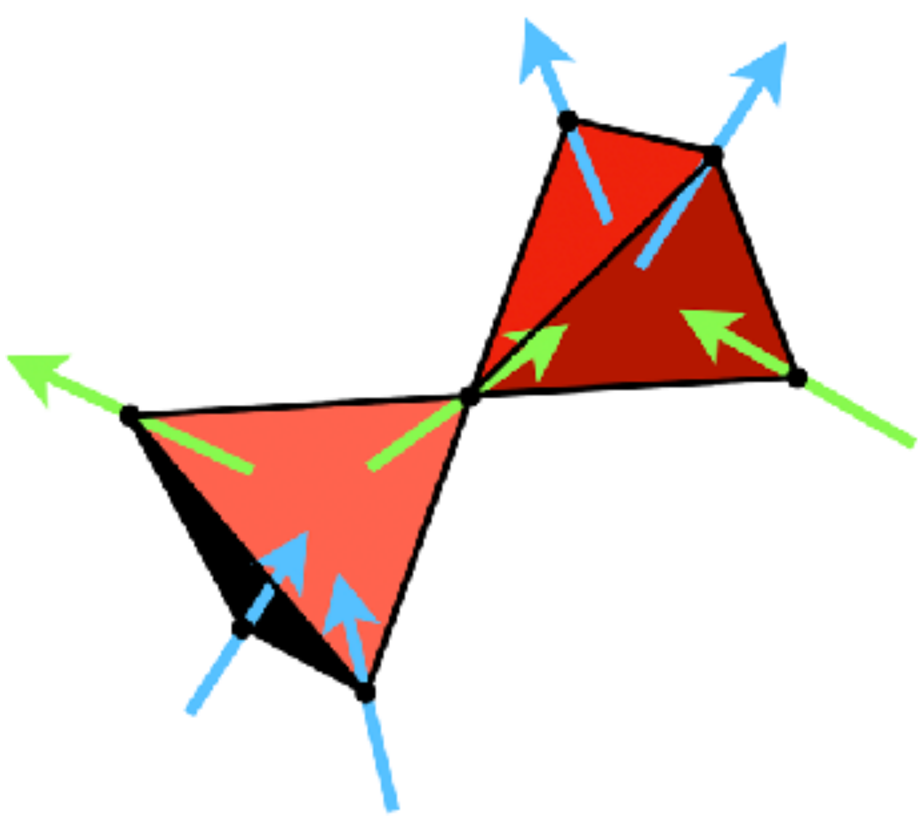
Anderson, Philip W. *Physical Review* 102.4 (1956): 1008.

CLASSICAL GROUND STATE AND EXCITATIONS

$$H_{\mathrm{CSI}} = J_{zz} \sum_{\langle i,j \rangle} S_i^z S_j^z$$

Ground state

Local 2-in 2-out constraint: ice rule



CLASSICAL GROUND STATE AND EXCITATIONS

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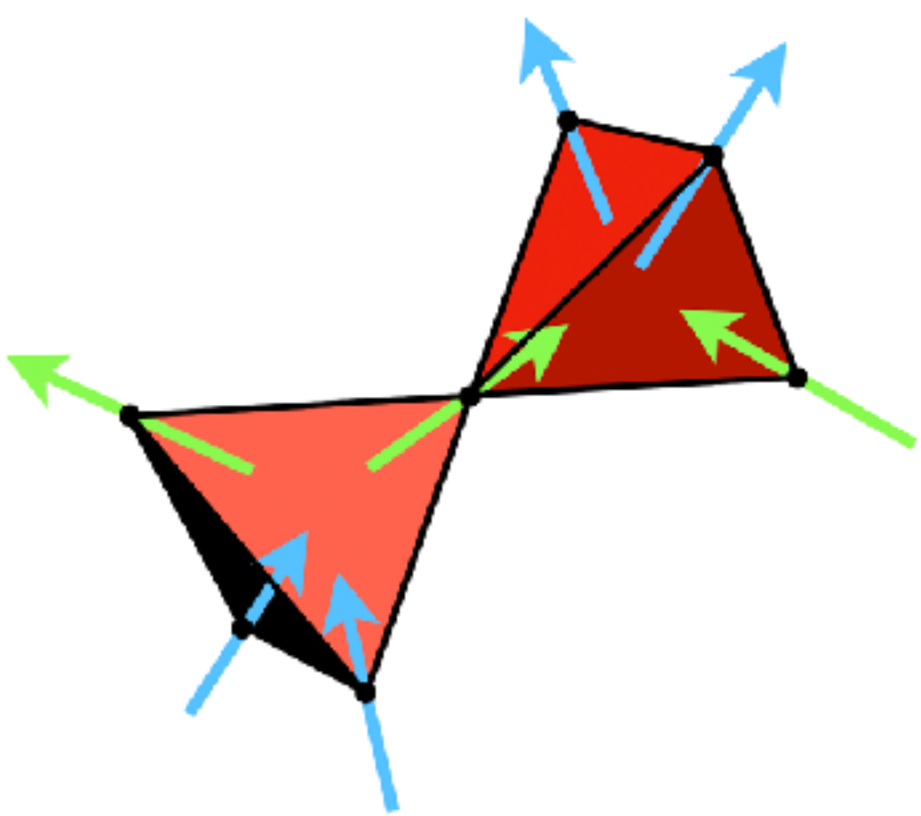
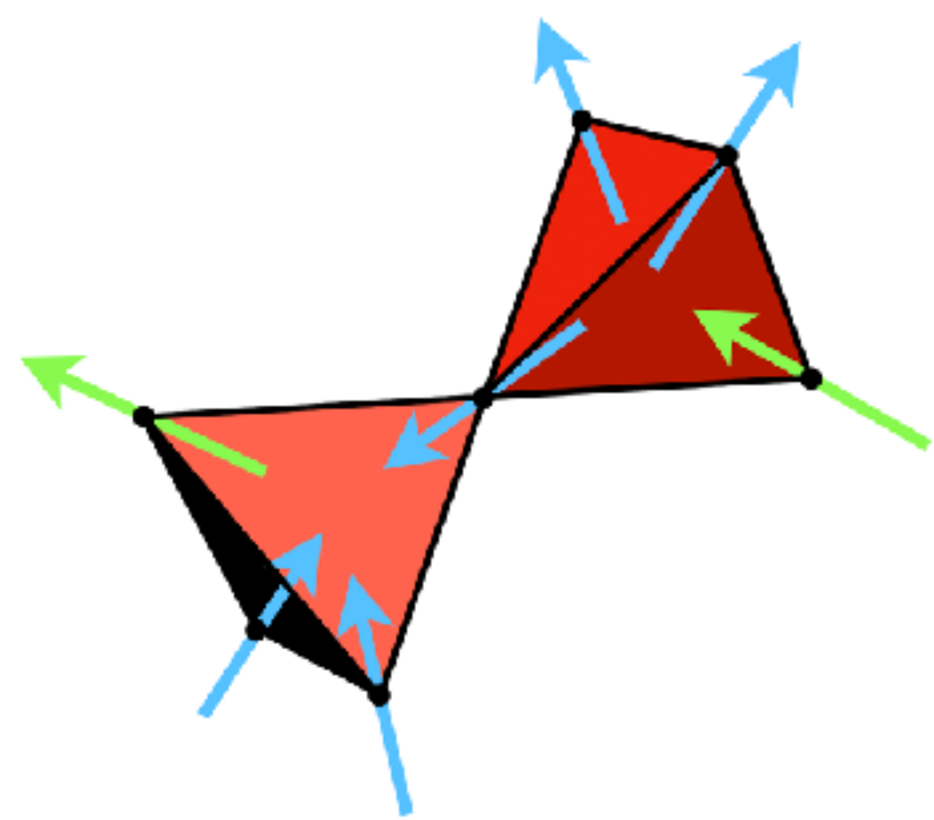


Excitation

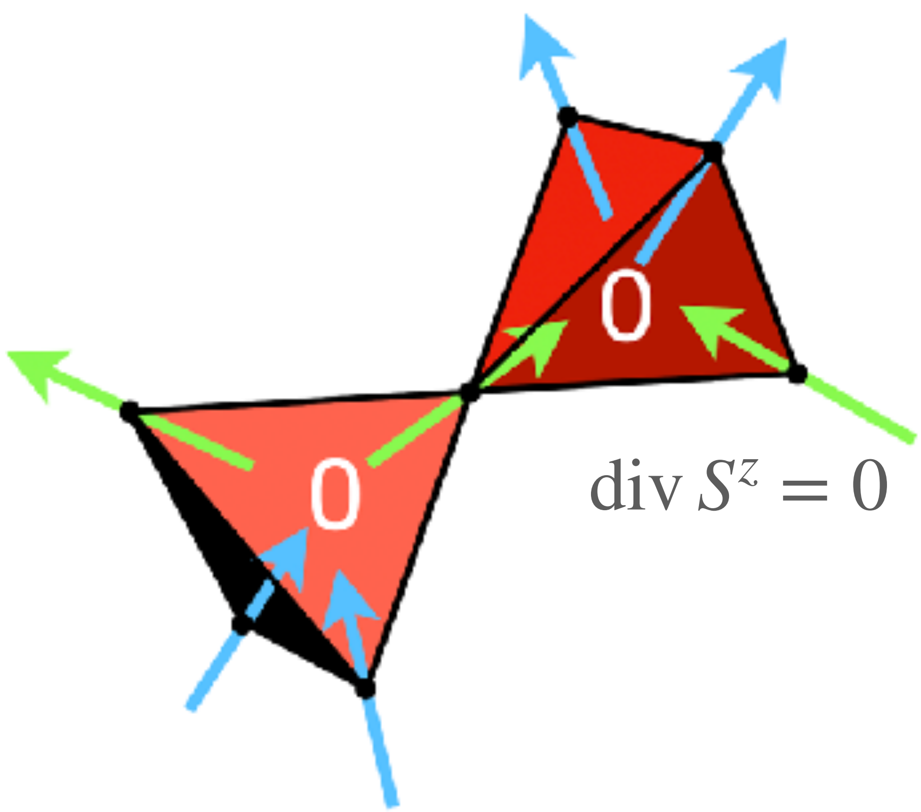
$2J_{zz}$ energy gap



AN EMERGENT GAUGE STRUCTURE

<u>Ground state</u>

Local constraint: 2-in 2-out



$\mathrm{div}\, S^z = 0$

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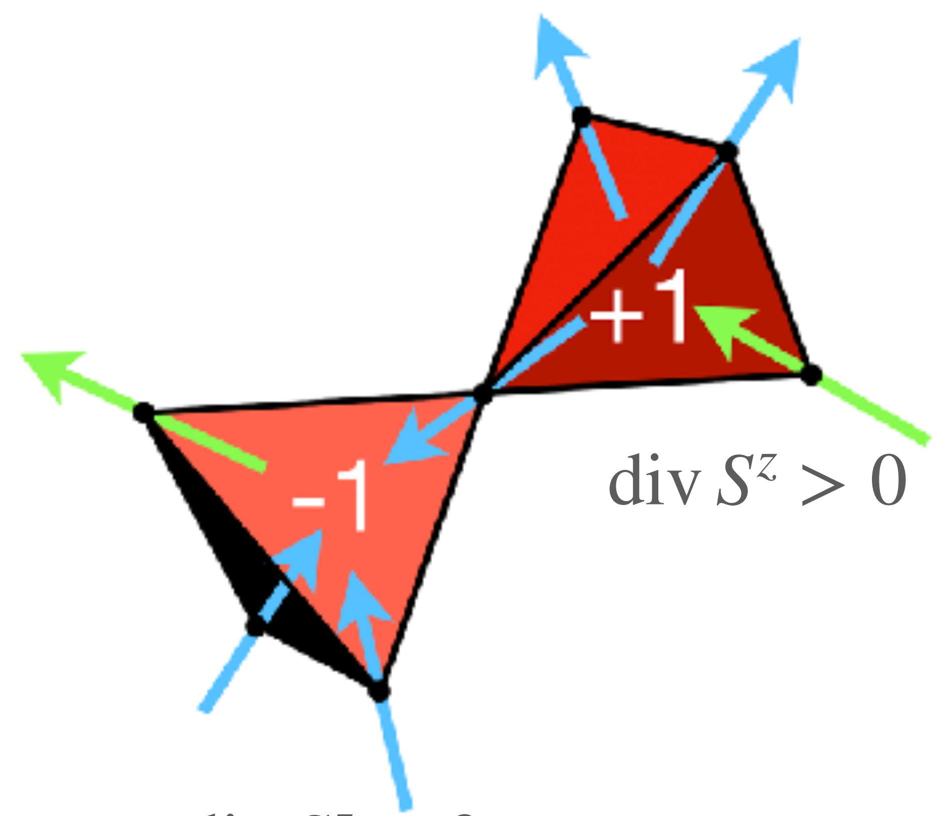
<u>Excitation</u>

$2J_{zz}$ energy gap



$\mathrm{div}\, S^z > 0$

$\mathrm{div}\, S^z < 0$

Castelnovo, Claudio, Roderich Moessner, and Shivaji L. Sondhi. *Nature* 451.7174 (2008): 42-45.

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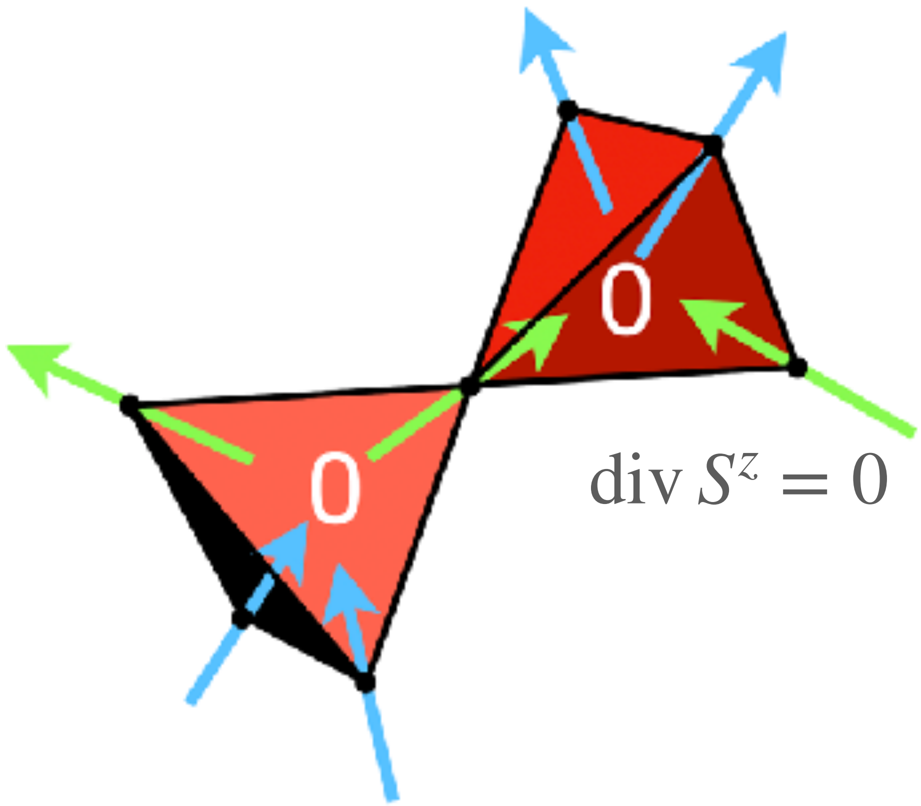

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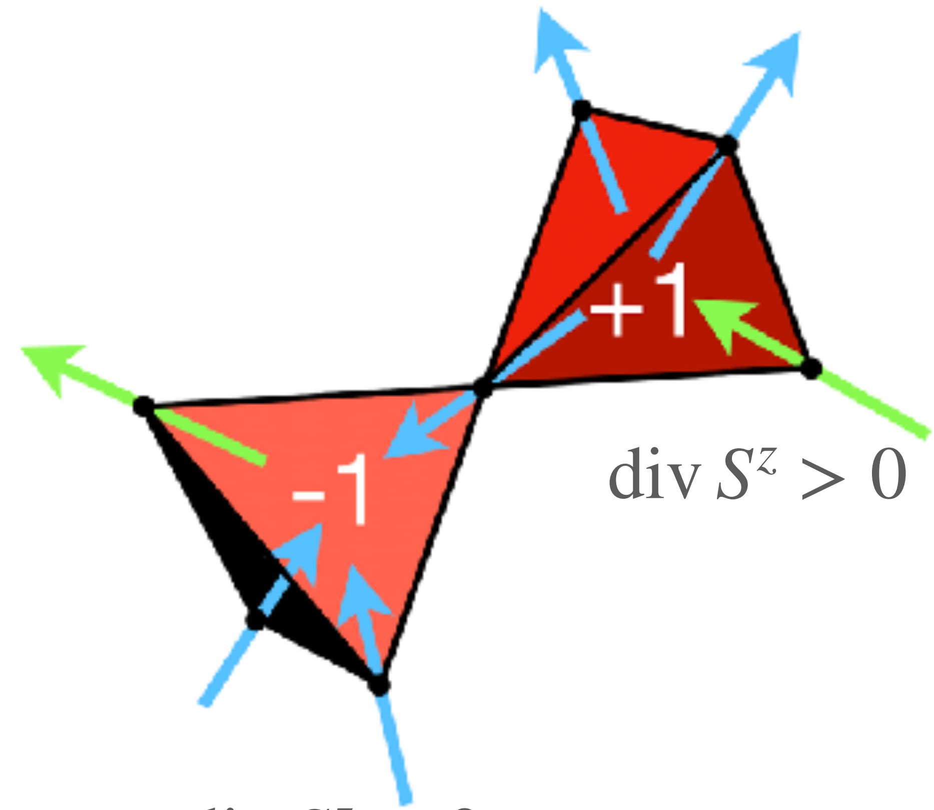

$\operatorname{div} S^z > 0$

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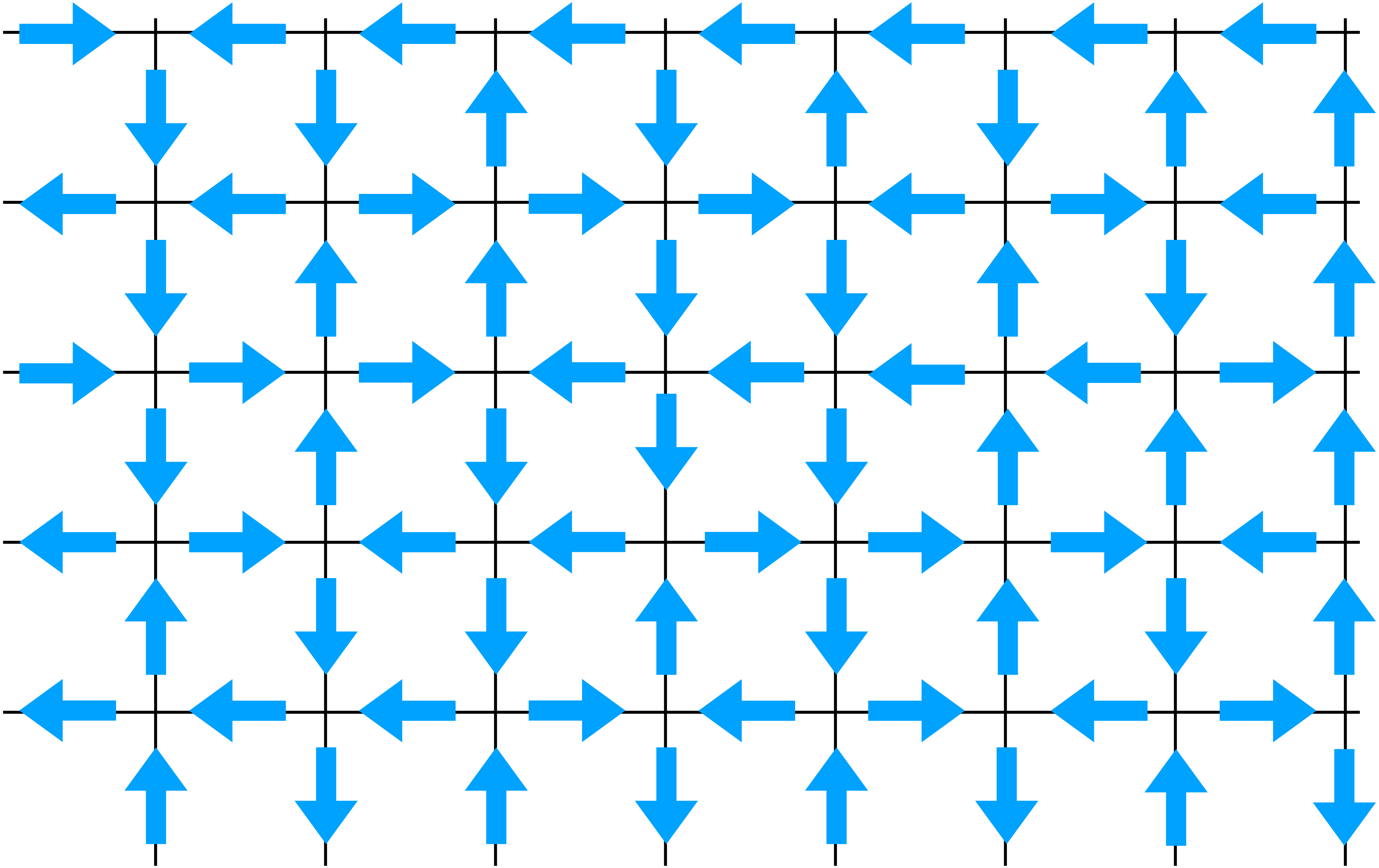
Emergent Gauss's Law: $\operatorname{div}_t S^z = q$

Castelnovo, Claudio, Roderich Moessner, and Shivaji L. Sondhi. *Nature* 451.7174 (2008): 42-45.

EMERGENT ELECTRODYNAMICS



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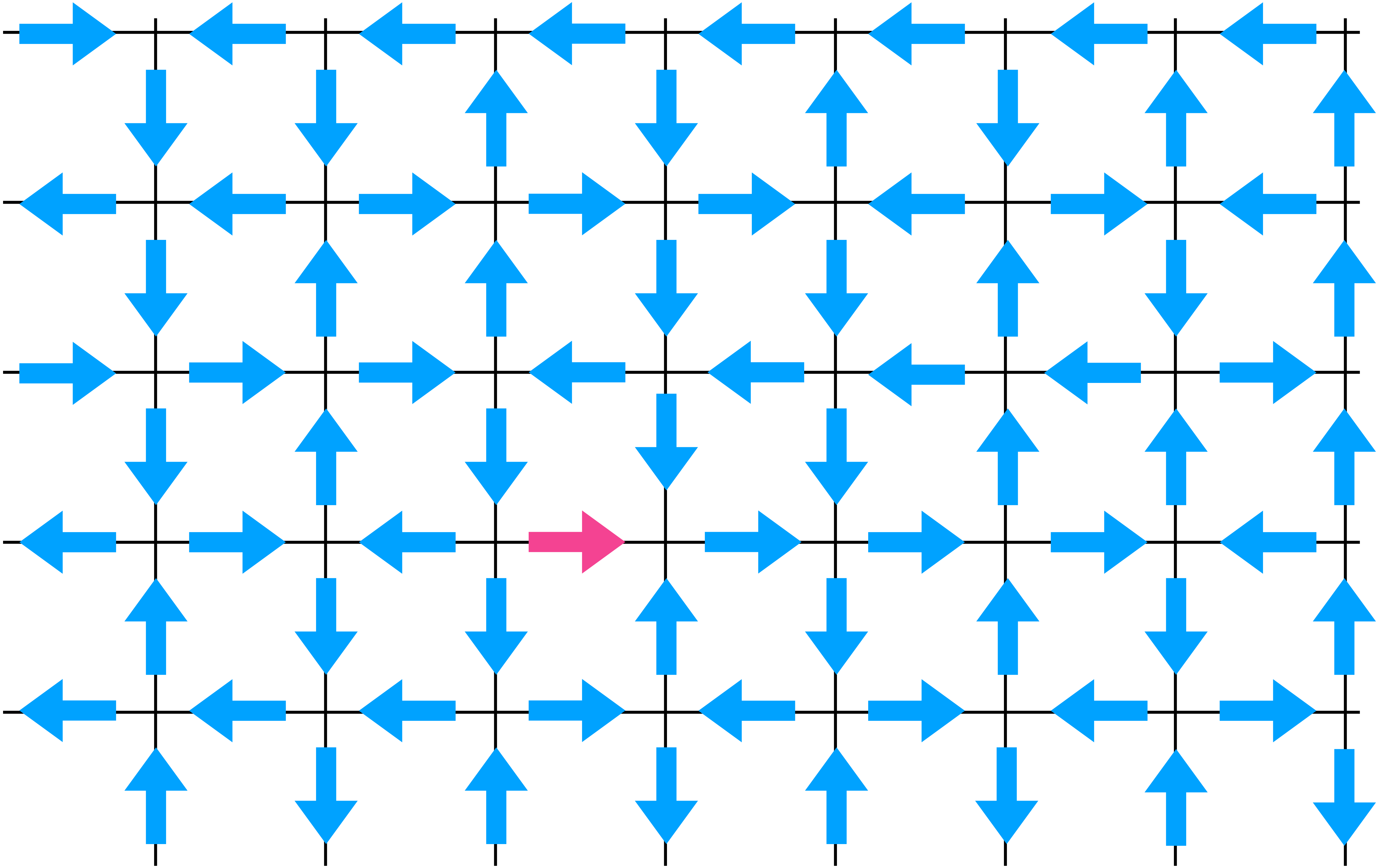

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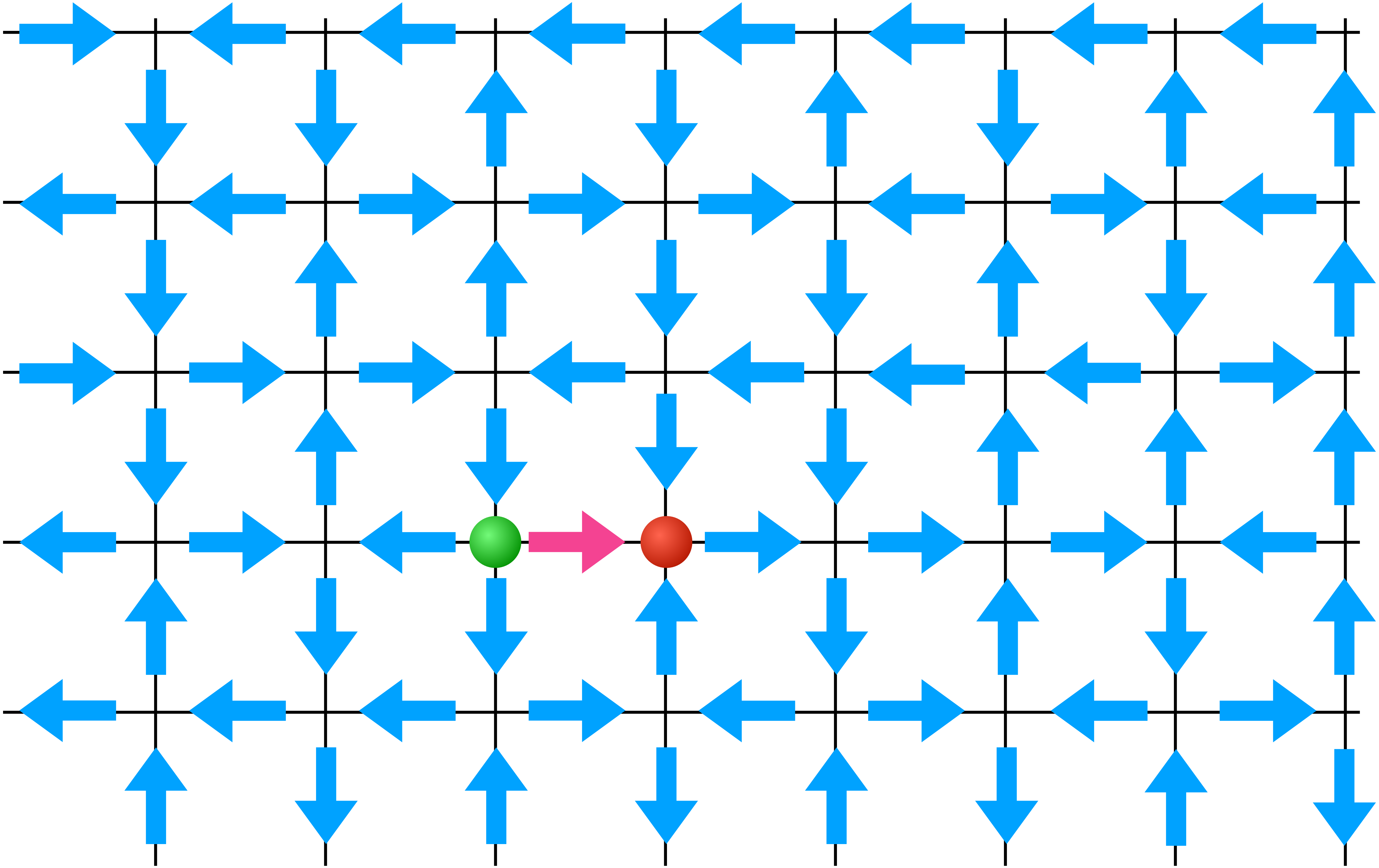

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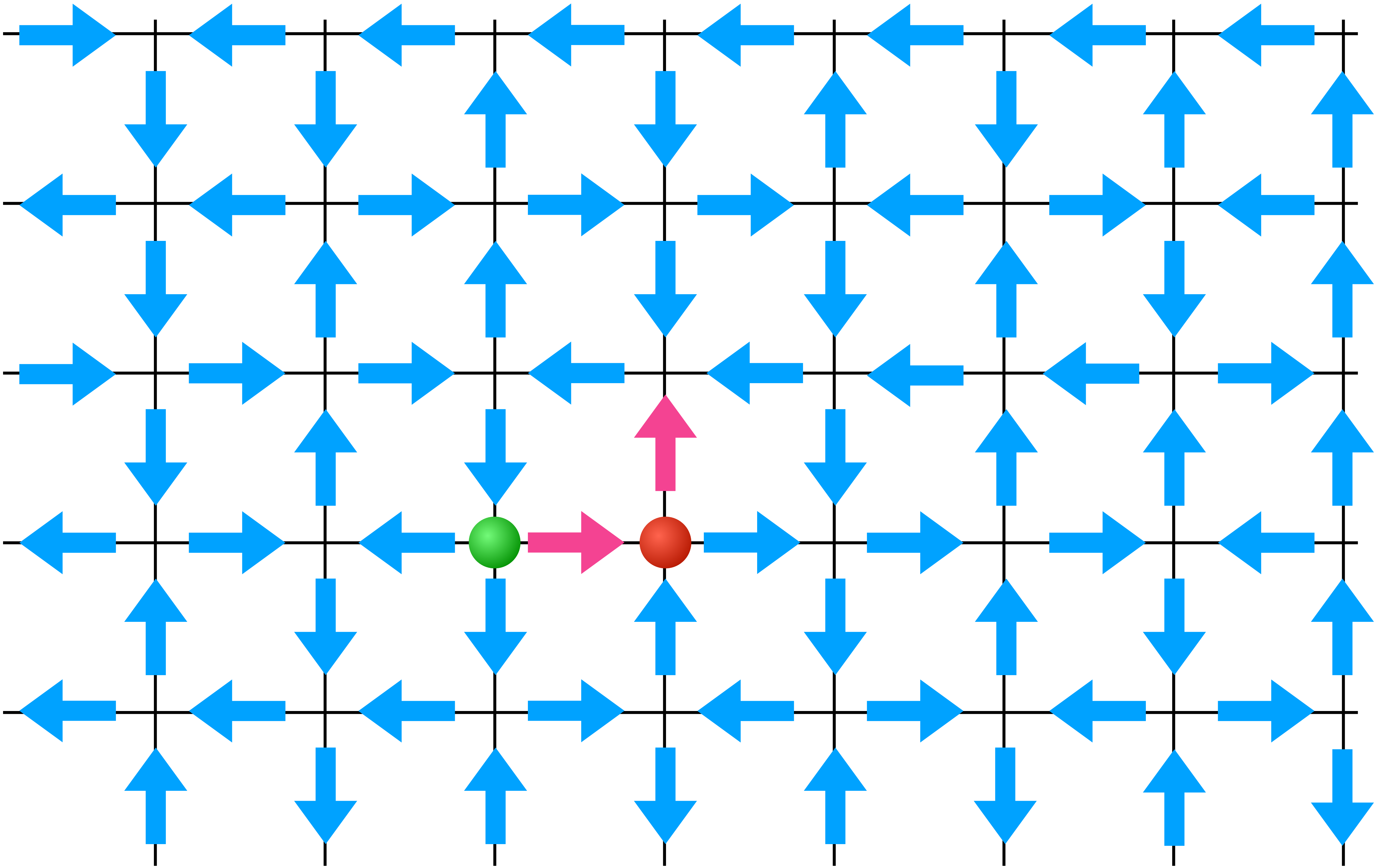

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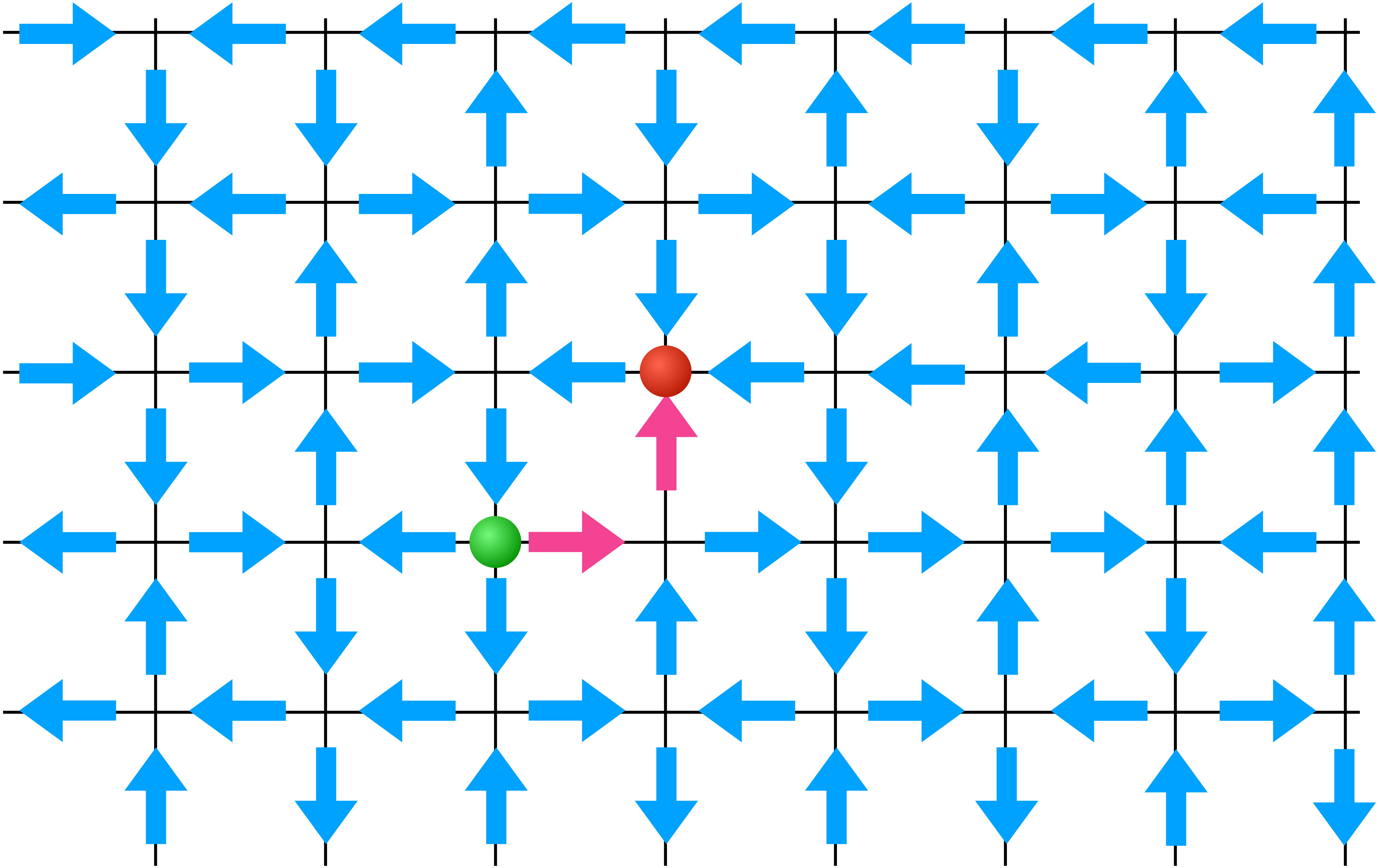

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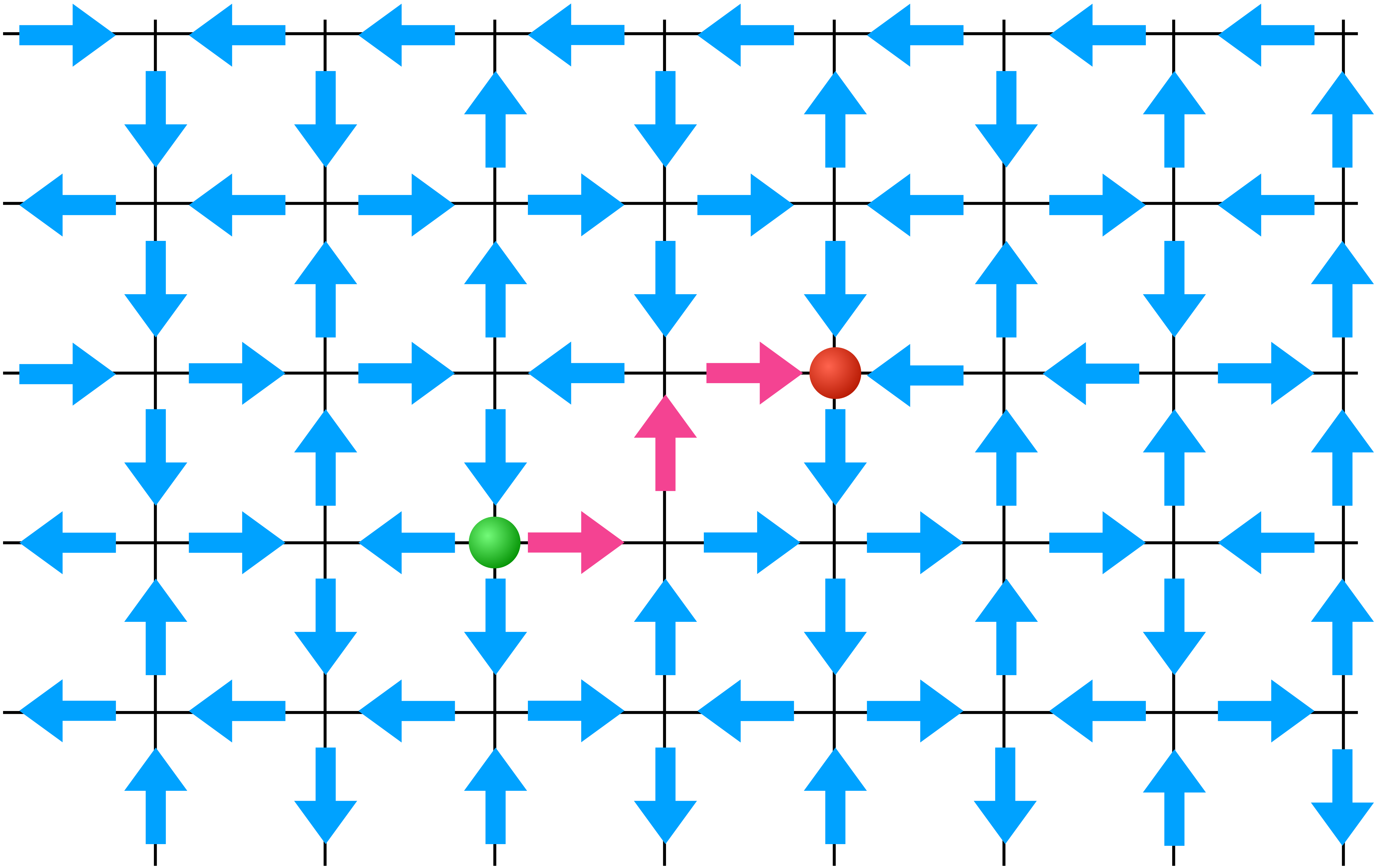

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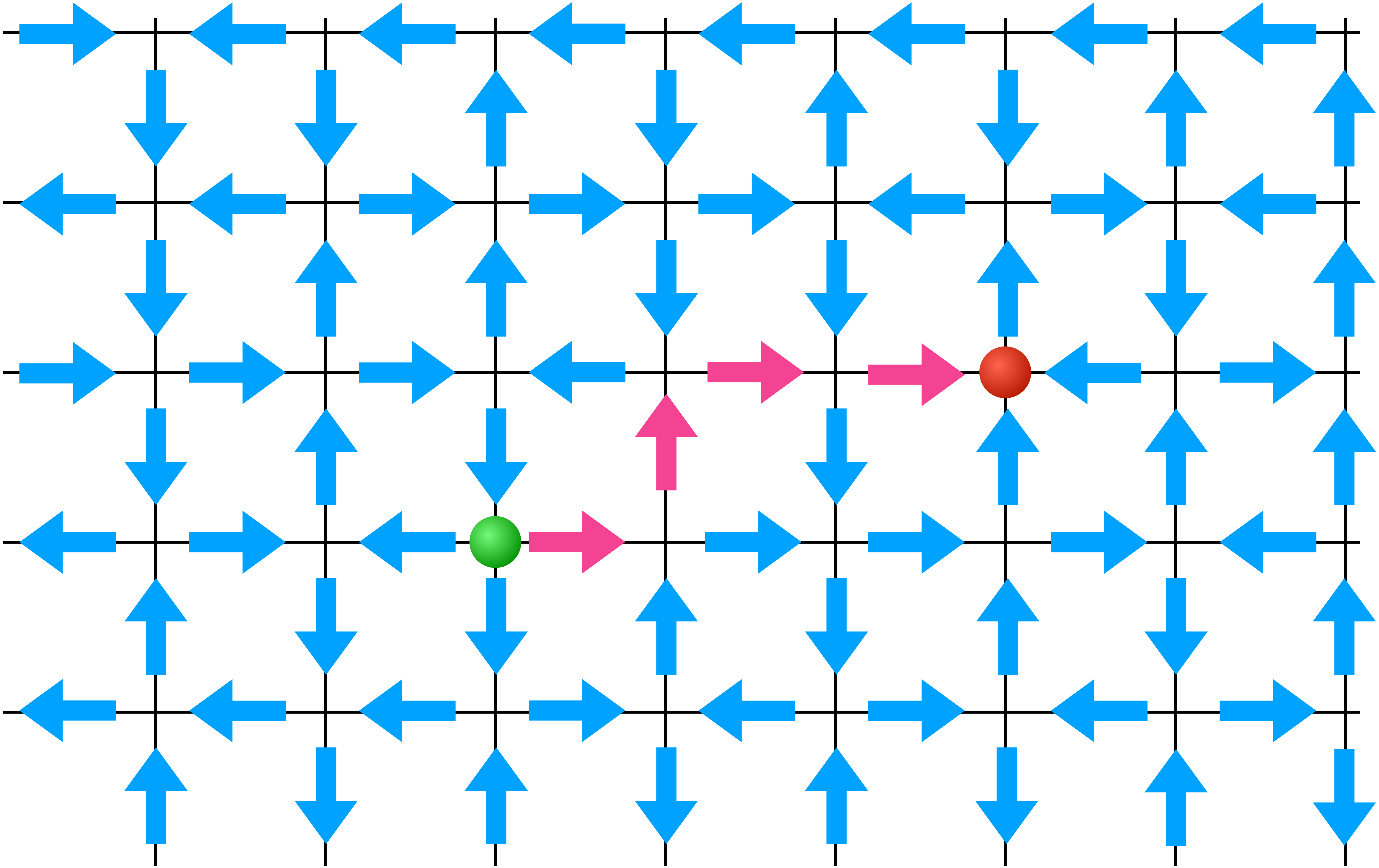

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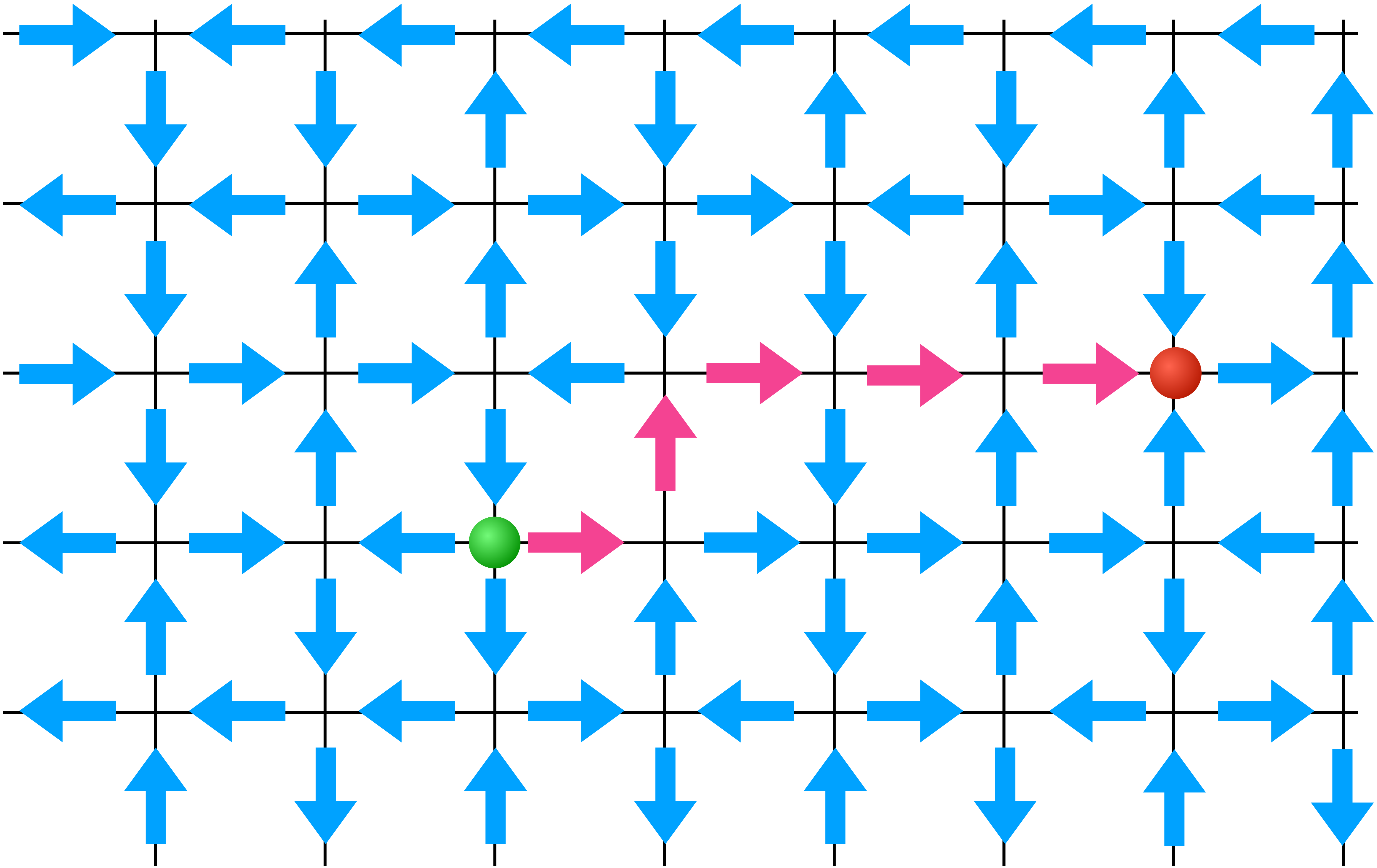

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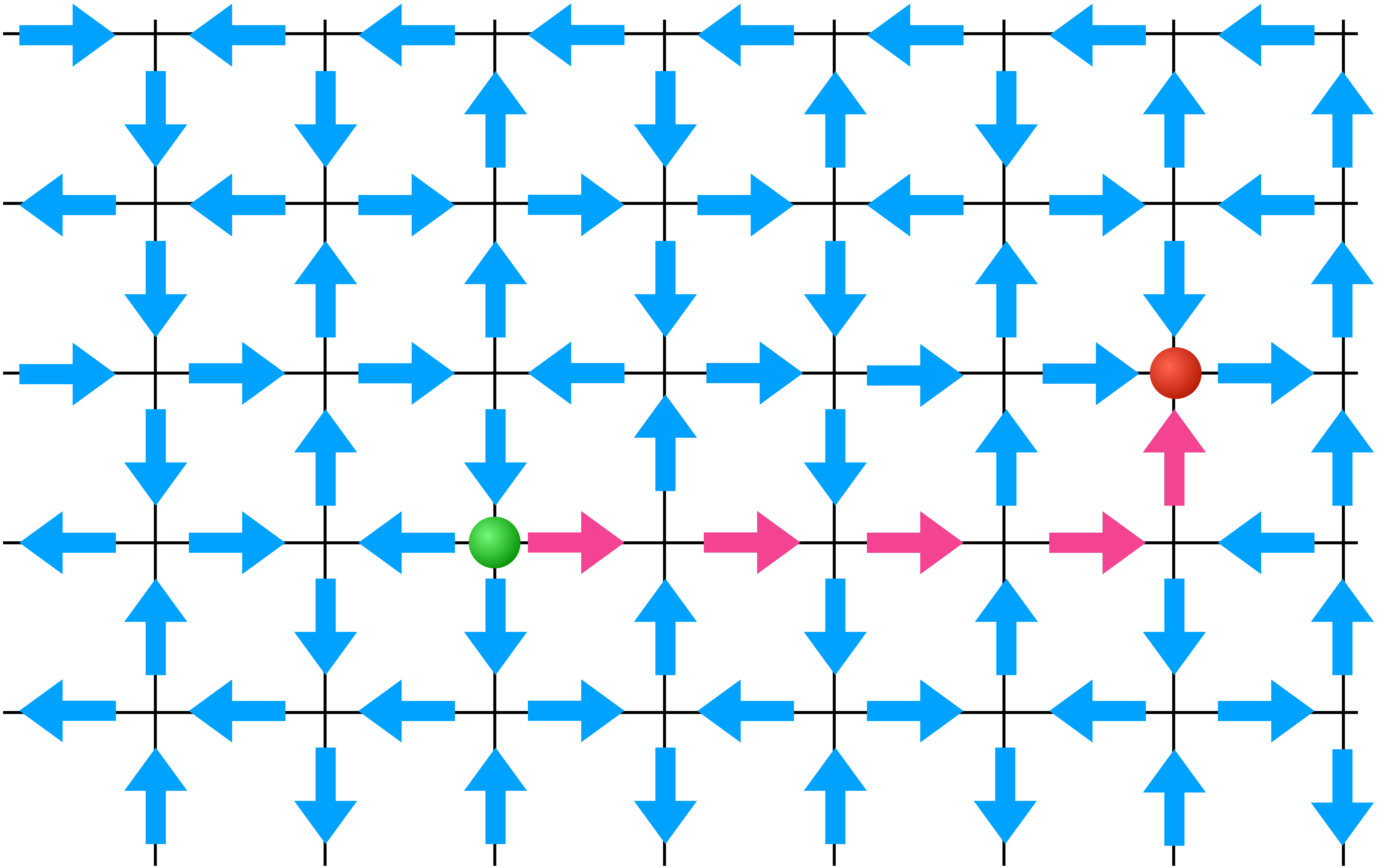

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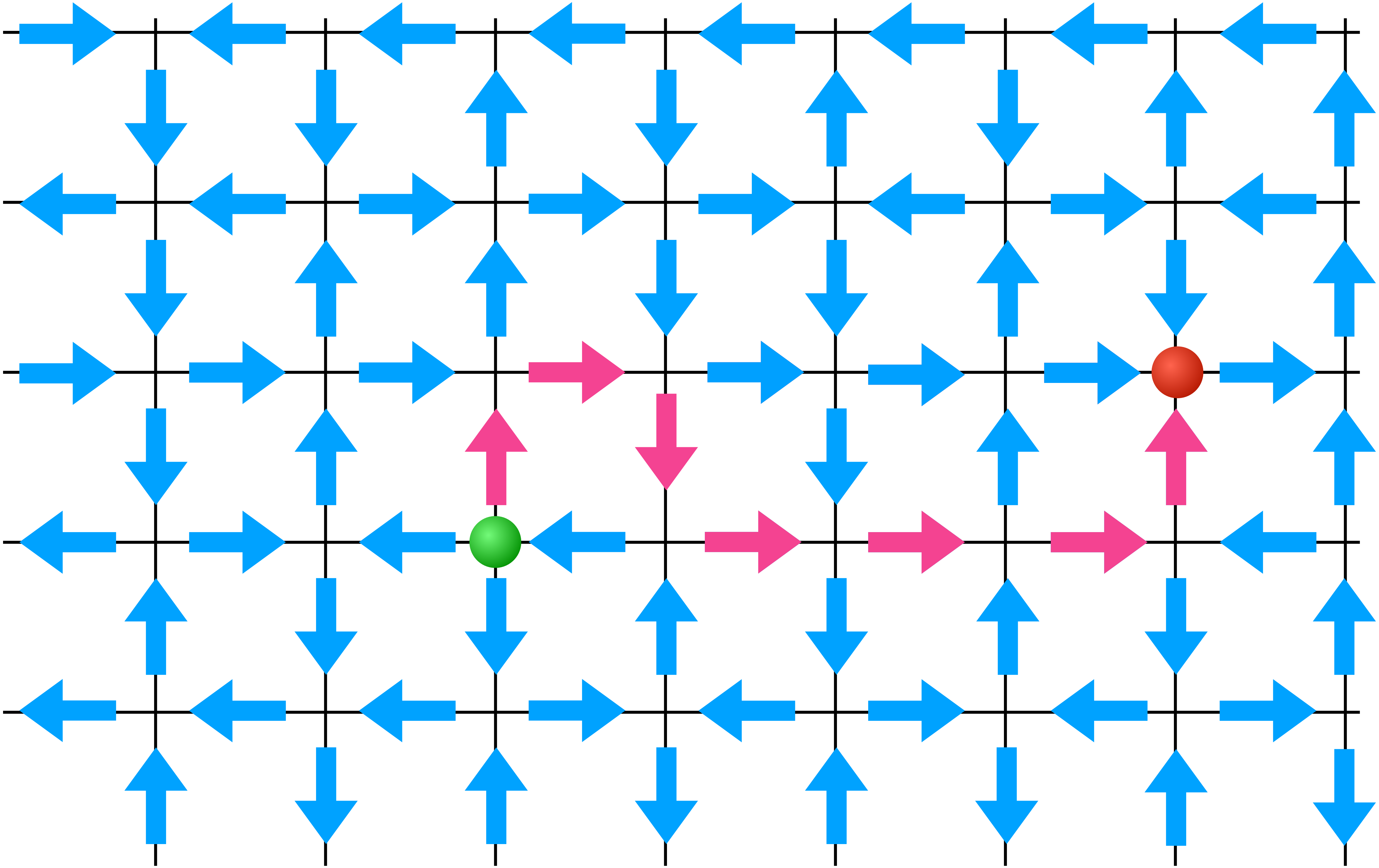

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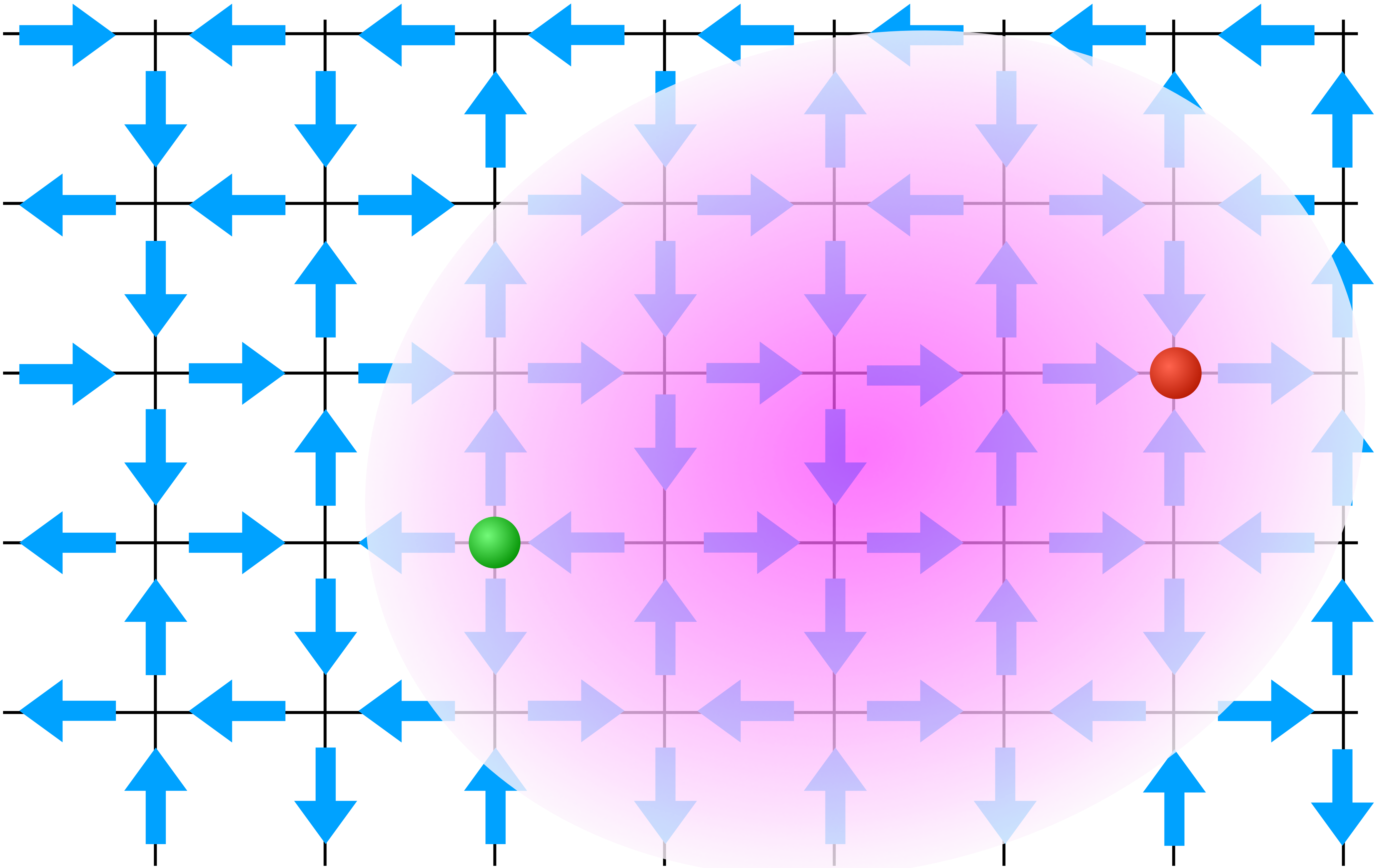

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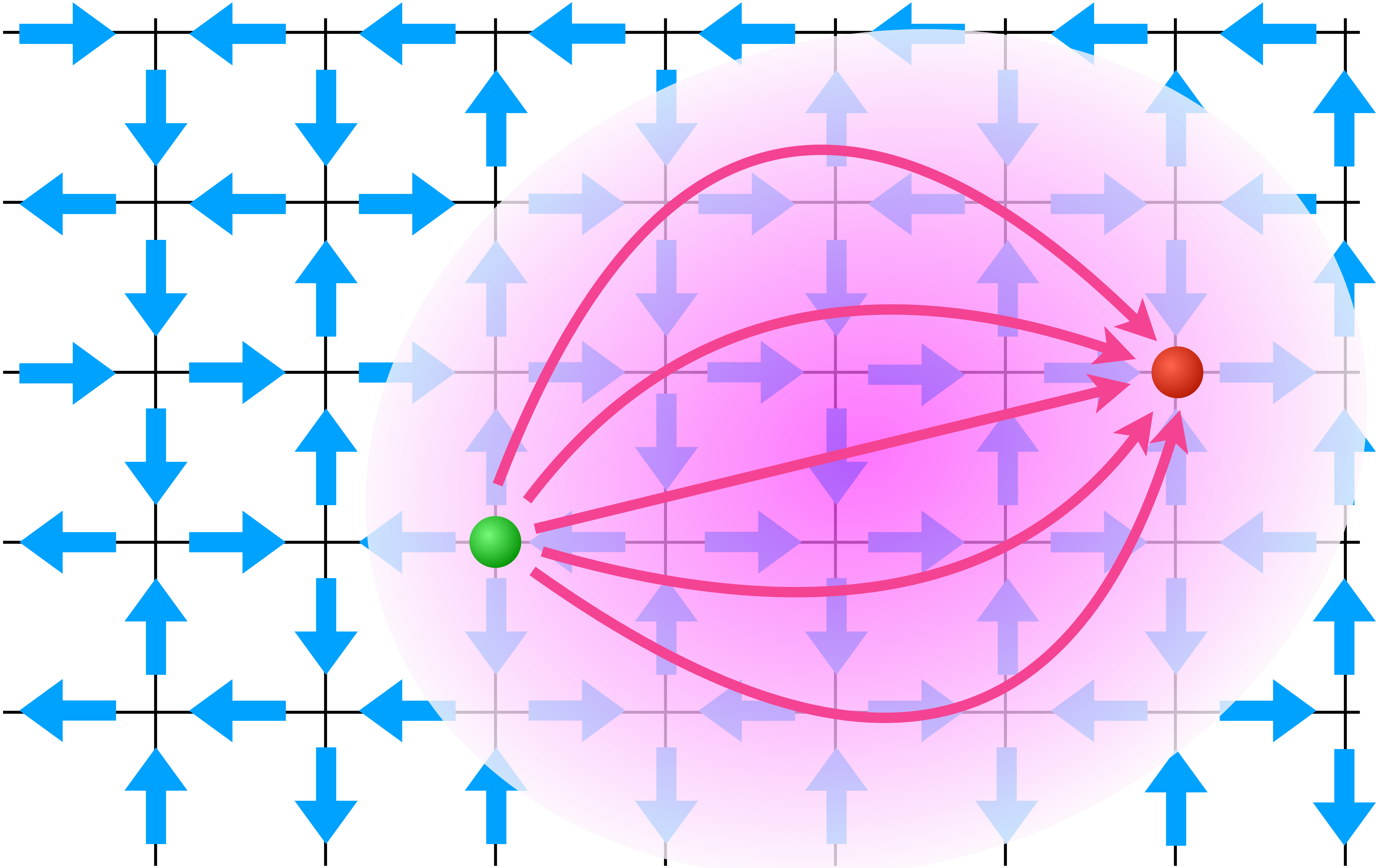

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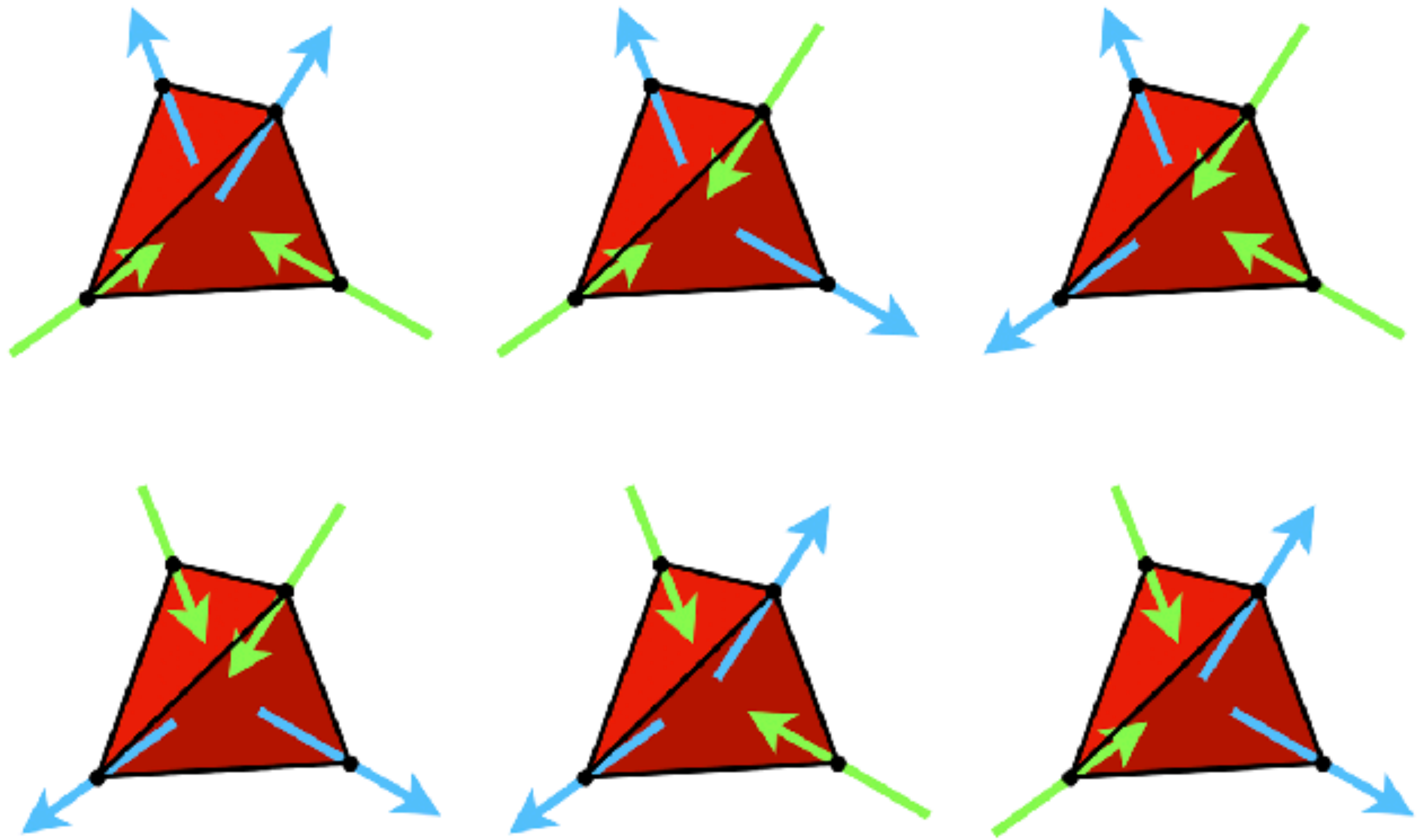
GEOMETRICAL FRUSTRATION

- Classical ground state is highly degenerate

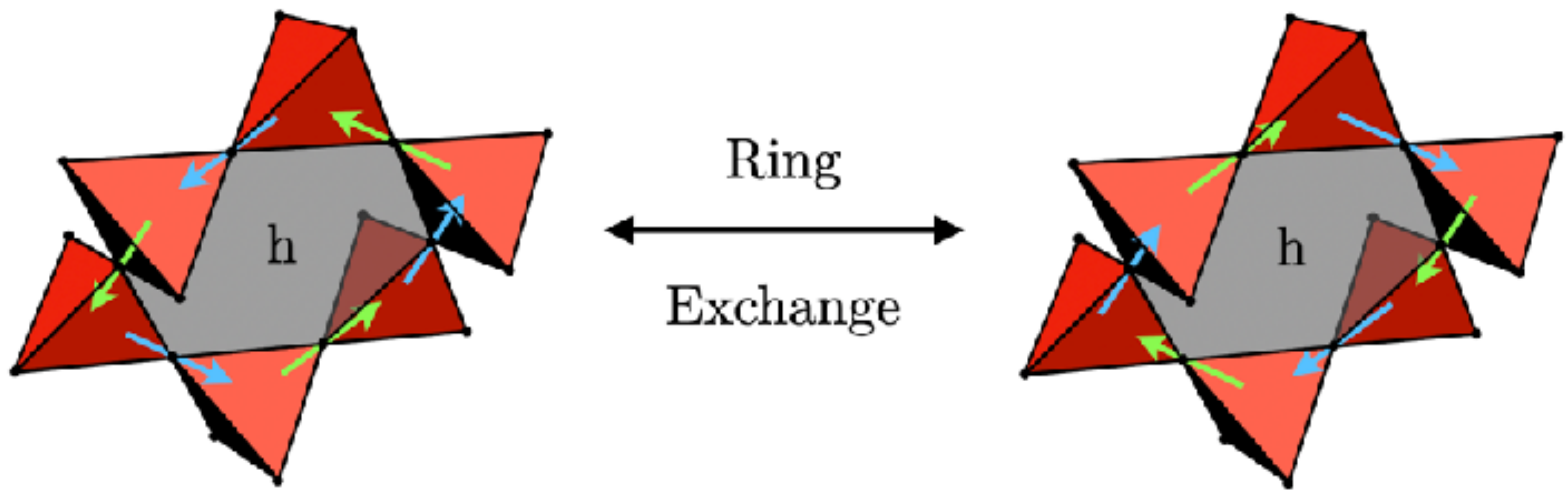


Residual Entropy $\approx N \ln 3/2$

Pauling, Linus. *Journal of the American Chemical Society* 57.12 (1935): 2680-2684.

QUANTUM SPIN ICE: CANONICAL MODEL

- Define operator: $\hat{W}_{\mathrm{h}} = \hat{S}^{+}_{\mathrm{h},1}\hat{S}^{-}_{\mathrm{h},2}\hat{S}^{+}_{\mathrm{h},3}\hat{S}^{-}_{\mathrm{h},4}\hat{S}^{+}_{\mathrm{h},5}\hat{S}^{-}_{\mathrm{h},6}$



$$\hat{H}_{\mathrm{QSI}} = J_{zz}\sum_{\langle i,j\rangle}\hat{S}^{z}_{i}\hat{S}^{z}_{j} - g\sum_{\mathrm{h}}\left(\hat{W}_{\mathrm{h}} + \hat{W}^{\dagger}_{\mathrm{h}}\right)$$

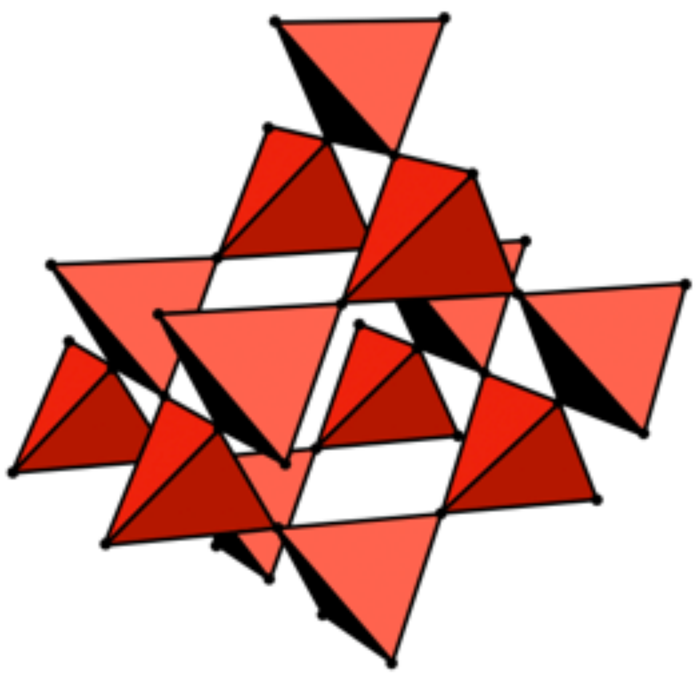
- $J_{zz} \gg g > 0$

Hermele, Michael, Matthew PA Fisher, and Leon Balents. *Physical Review B* 69.6 (2004): 064404.

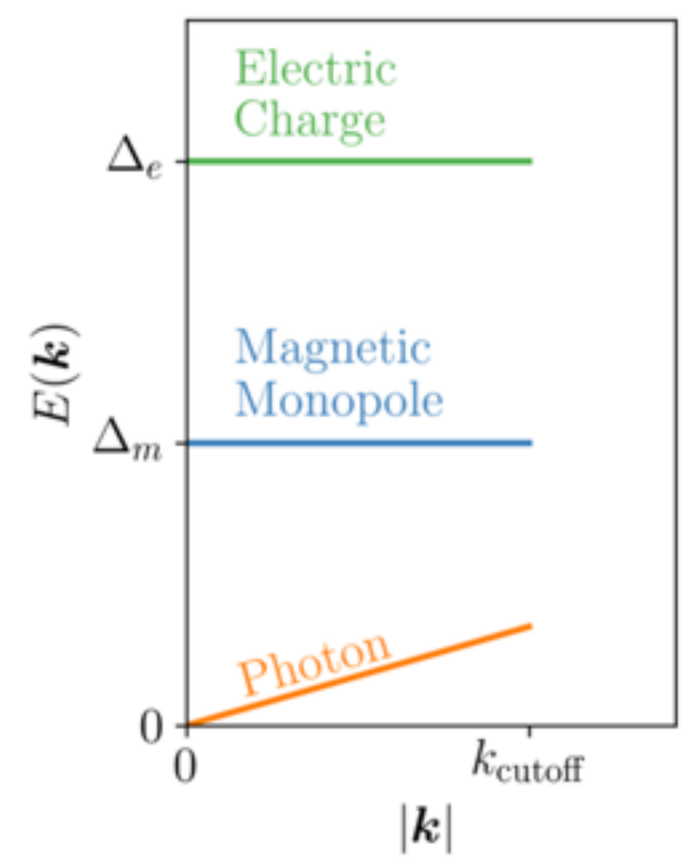
EMERGENT QED IN QUANTUM SPIN ICE

Short Distances (High Energy)

$$\hat{H}_{\mathrm{QSI}} = J_{zz} \sum_{\langle i,j \rangle} \hat{S}_i^z \hat{S}_j^z - g \sum_{\mathrm{h}} \left(\hat{W}_{\mathrm{h}} + \hat{W}_{\mathrm{h}}^\dagger \right)$$



$$\hat{H}_{\mathrm{Maxwell}} = \int d^3\boldsymbol{x} \left(\frac{\epsilon_{\mathrm{QSI}}}{2} \left| \hat{\boldsymbol{E}}(\boldsymbol{x}) \right|^2 + \frac{1}{2\mu_{\mathrm{QSI}}} \left| \hat{\boldsymbol{B}}(\boldsymbol{x}) \right|^2 \right)$$



Long Distances (Low Energy)

Hermele, Michael, Matthew PA Fisher, and Leon Balents. *Physical Review B* 69.6 (2004): 064404.
Banerjee, Argha, et al. *Physical review letters* 100.4 (2008): 047208.
Shannon, Nic, et al. *Physical review letters* 108.6 (2012): 067204.
Kato, Yasuyuki, and Shigeki Onoda. *Physical review letters* 115.7 (2015): 077202.
Huang, Chun-Jiong, et al. *Physical review letters* 120.16 (2018): 167202.
Szabó, Attila, and Claudio Castelnovo. *Physical Review B* 100.1 (2019): 014417.

EMERGENT FINE STRUCTURE CONSTANT

Quest: Use exact diagonalization (ED) techniques on

$$\hat{H}_{\mathrm{QSI}} = J_{zz} \sum_{\langle i,j \rangle} \hat{S}_i^z \hat{S}_j^z - g \sum_{\mathrm{h}} \left(\hat{W}_{\mathrm{h}} + \hat{W}_{\mathrm{h}}^{\dagger} \right)$$

to find the low-energy spectra and measure:

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to find the low-energy spectra and measure:

$$\frac{e_{\mathrm{QSI}}^2}{\epsilon_{\mathrm{QSI}}}$$

$$c_{\mathrm{QSI}}$$

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to find the low-energy spectra and measure:

$$\boxed{\frac{e_{\mathrm{QSI}}^2}{\epsilon_{\mathrm{QSI}}}} \qquad \boxed{c_{\mathrm{QSI}}}$$

$$\boxed{\alpha_{\mathrm{QSI}} = \frac{e_{\mathrm{QSI}}^2}{4\pi \epsilon_{\mathrm{QSI}} \hbar c_{\mathrm{QSI}}}}$$

NUMERICAL PLAN OF ATTACK

Perform ED on systems with up to 96 spins

- Project to constrained Hilbert space satisfying ice rules

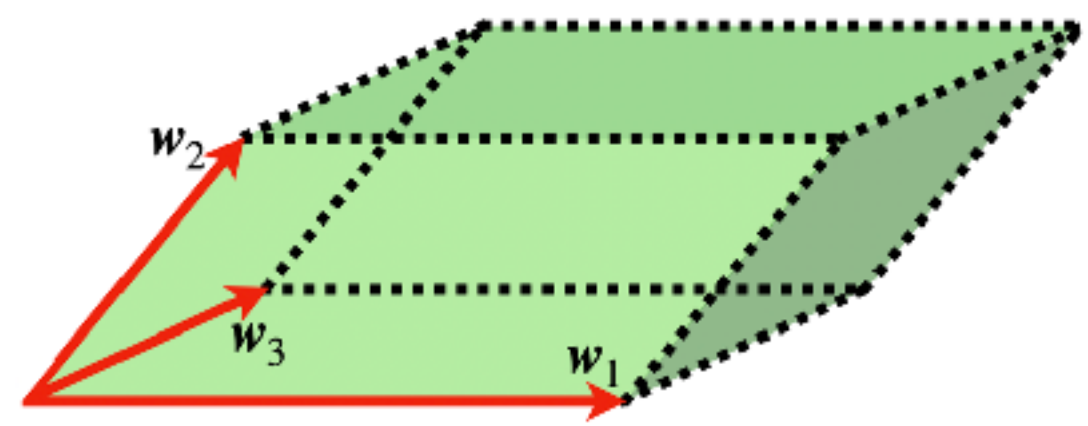
- Periodic Boundary Conditions allows additional projections

  A) Electric topological sectors

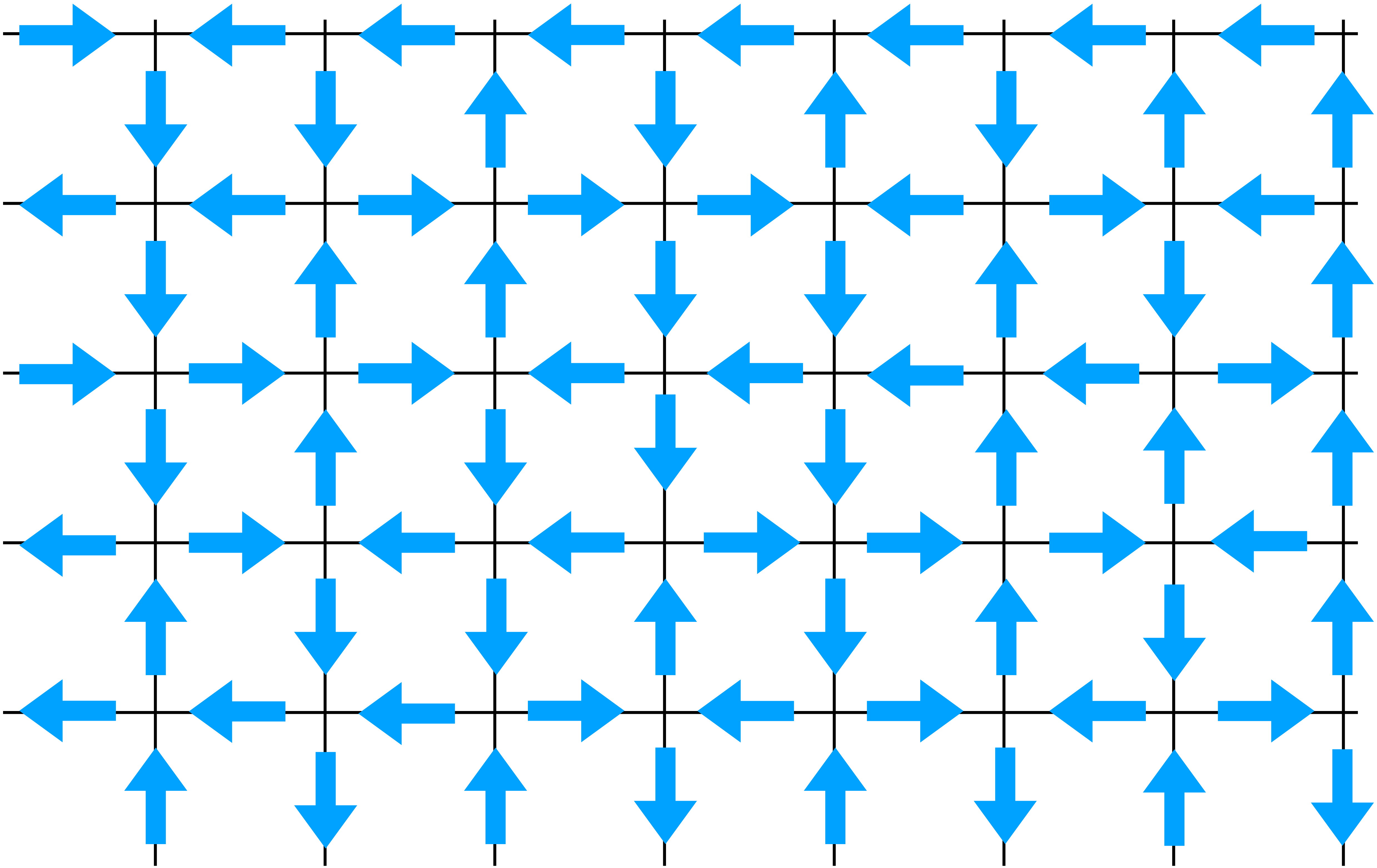
  B) Momentum sectors

	Before Projections	After Projections
$\dim \mathscr{H}$	$2^{96} \approx 8 \times 10^{28}$	$2^{22.7} \approx 7 \times 10^{6}$

- Vary shape of periodic unit



ELECTRIC TOPOLOGICAL SECTORS



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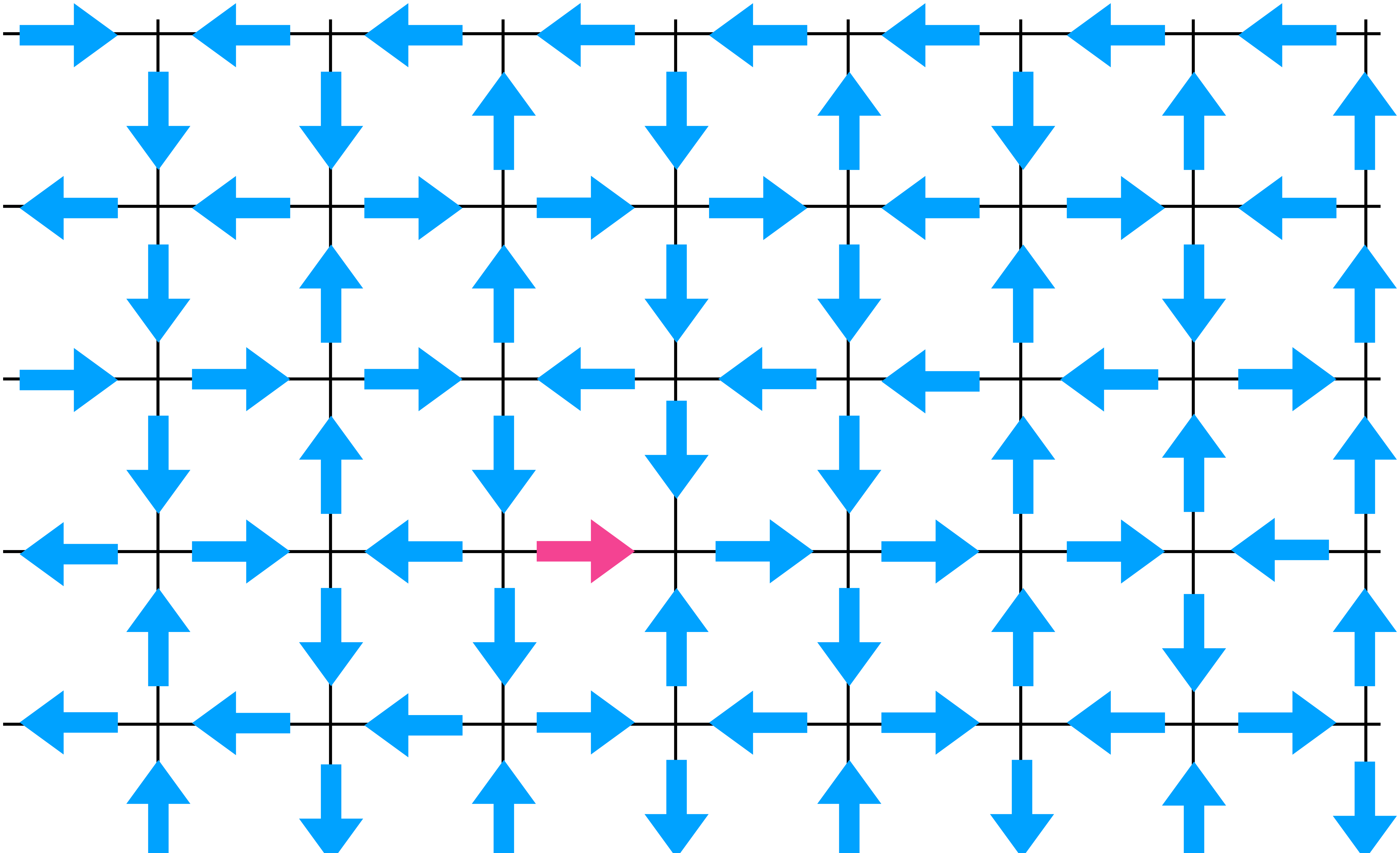

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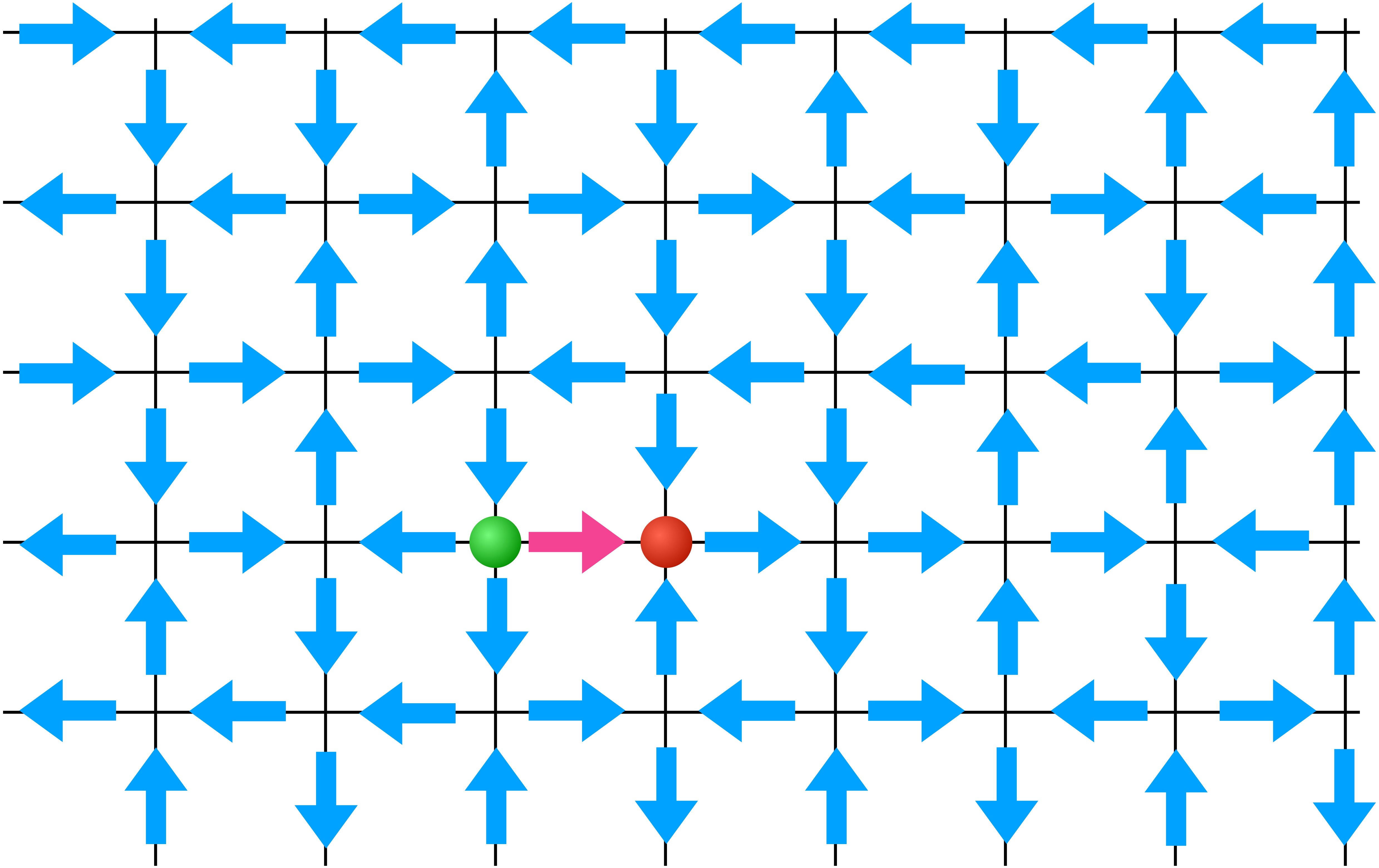

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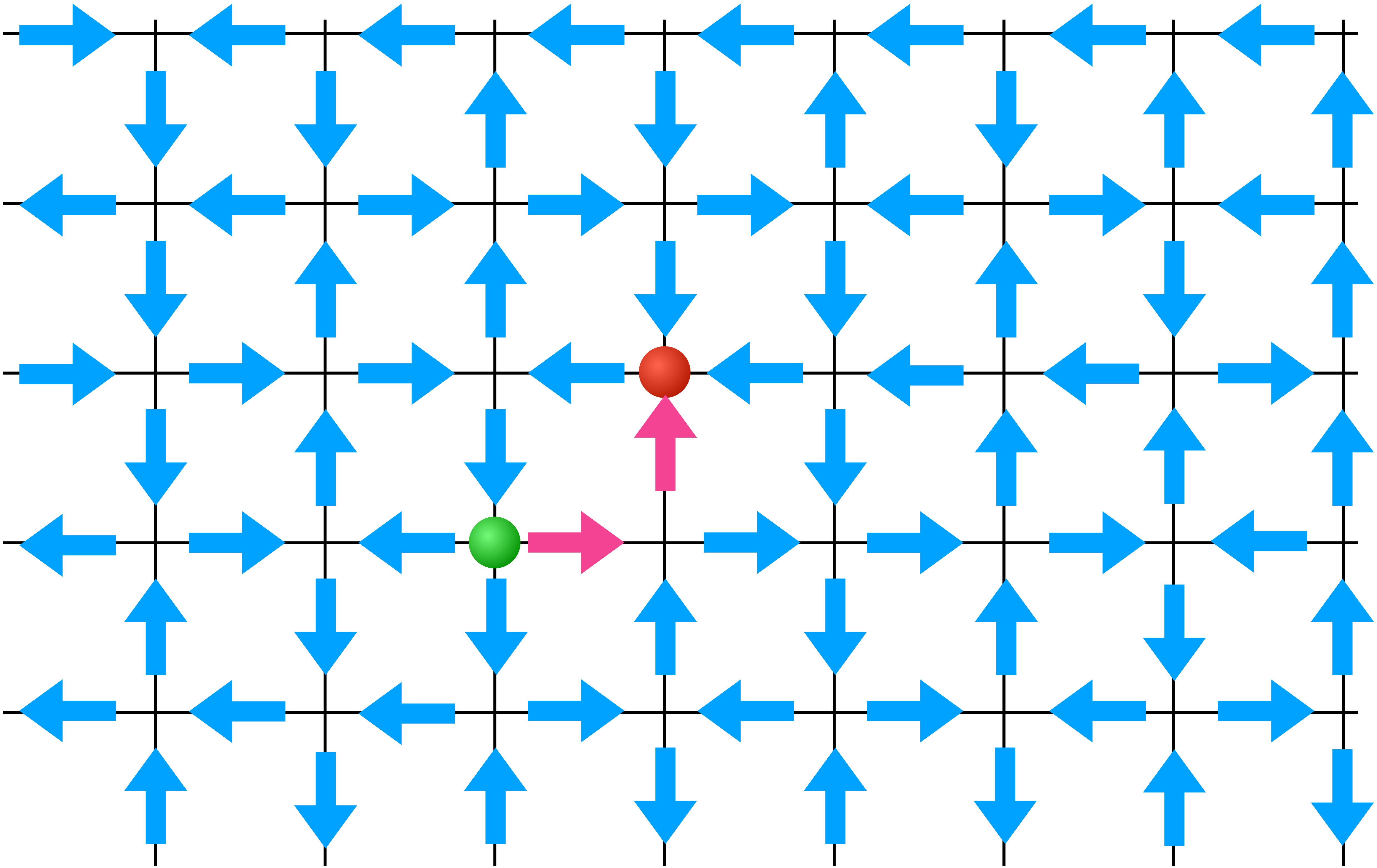

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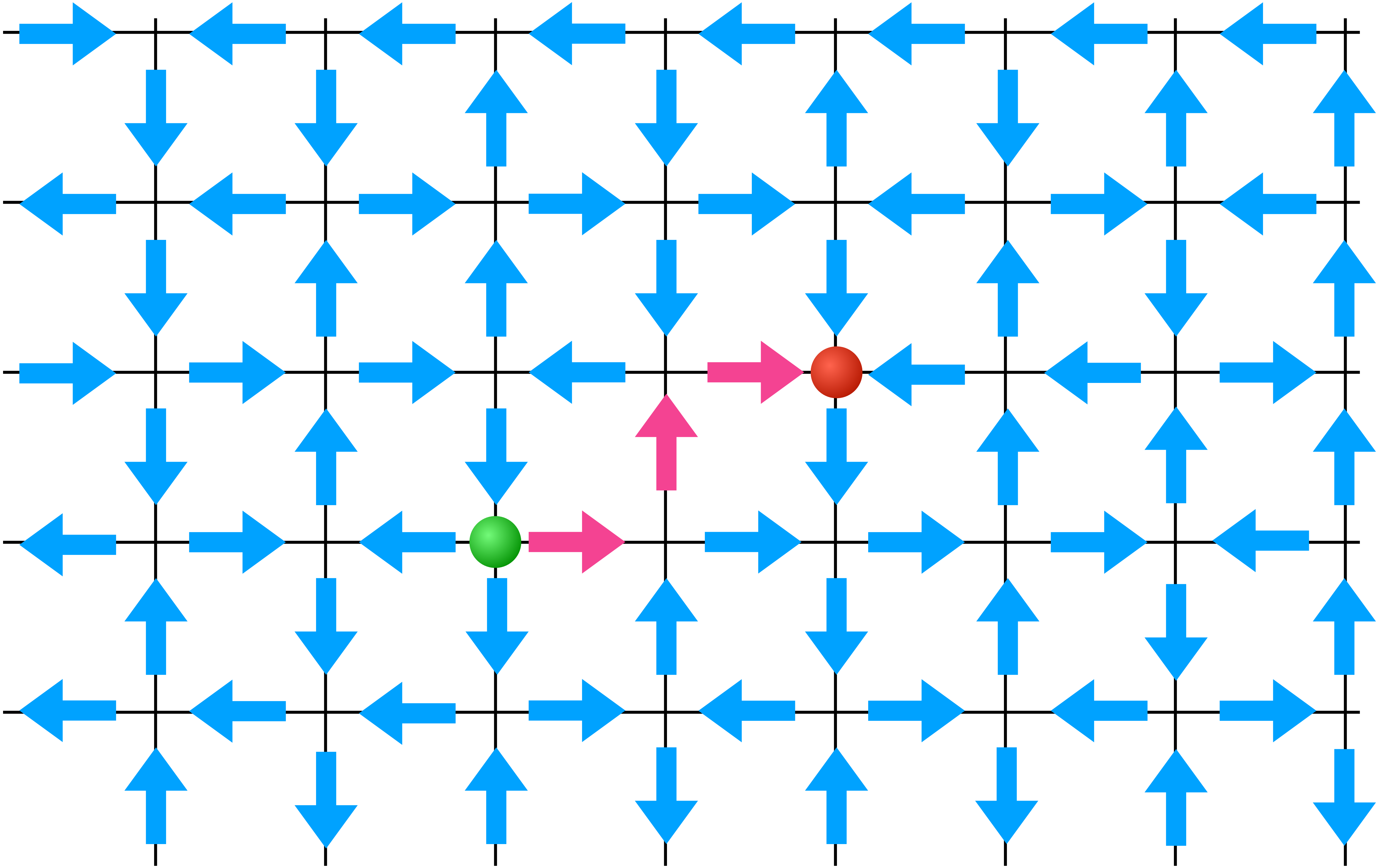

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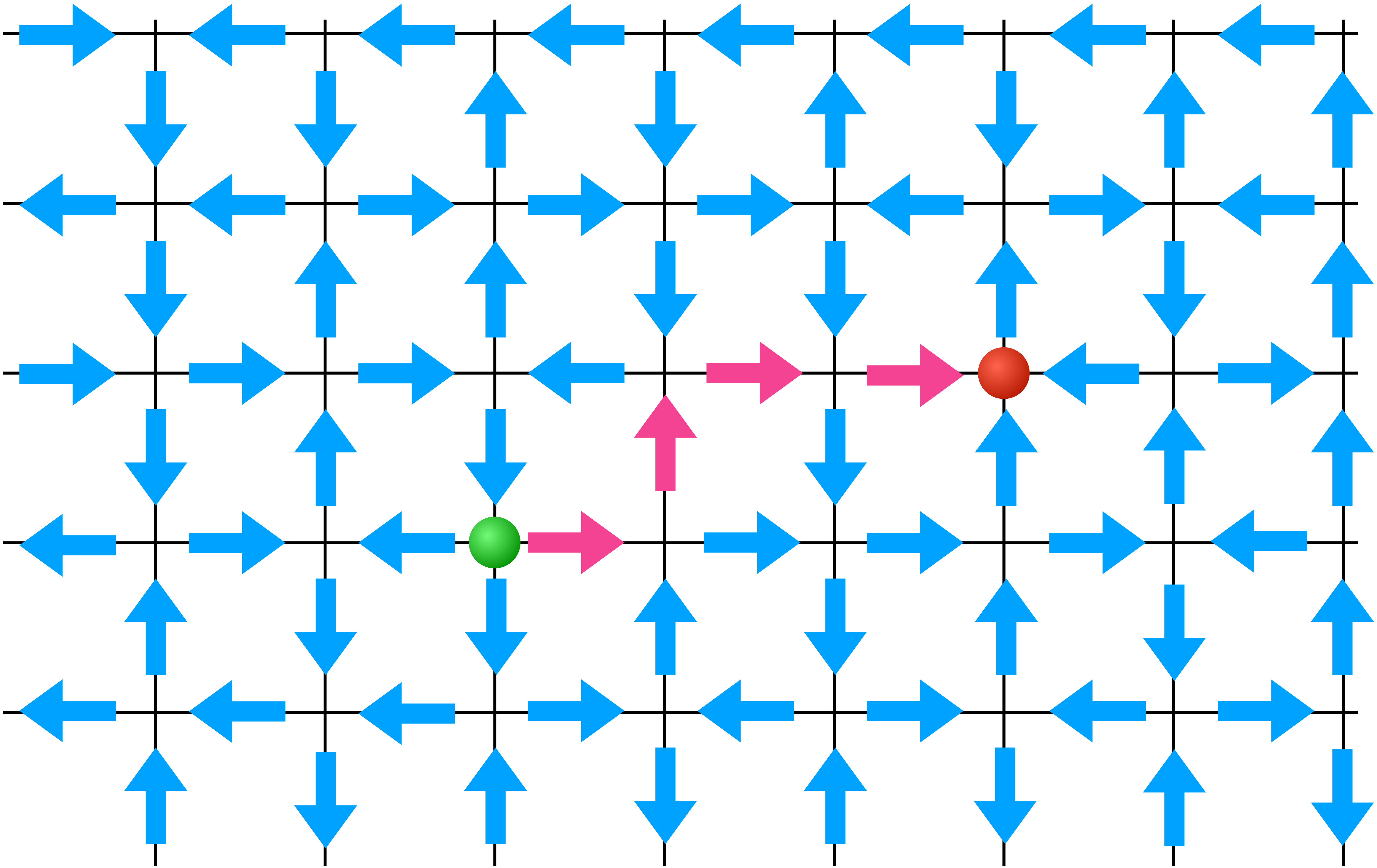

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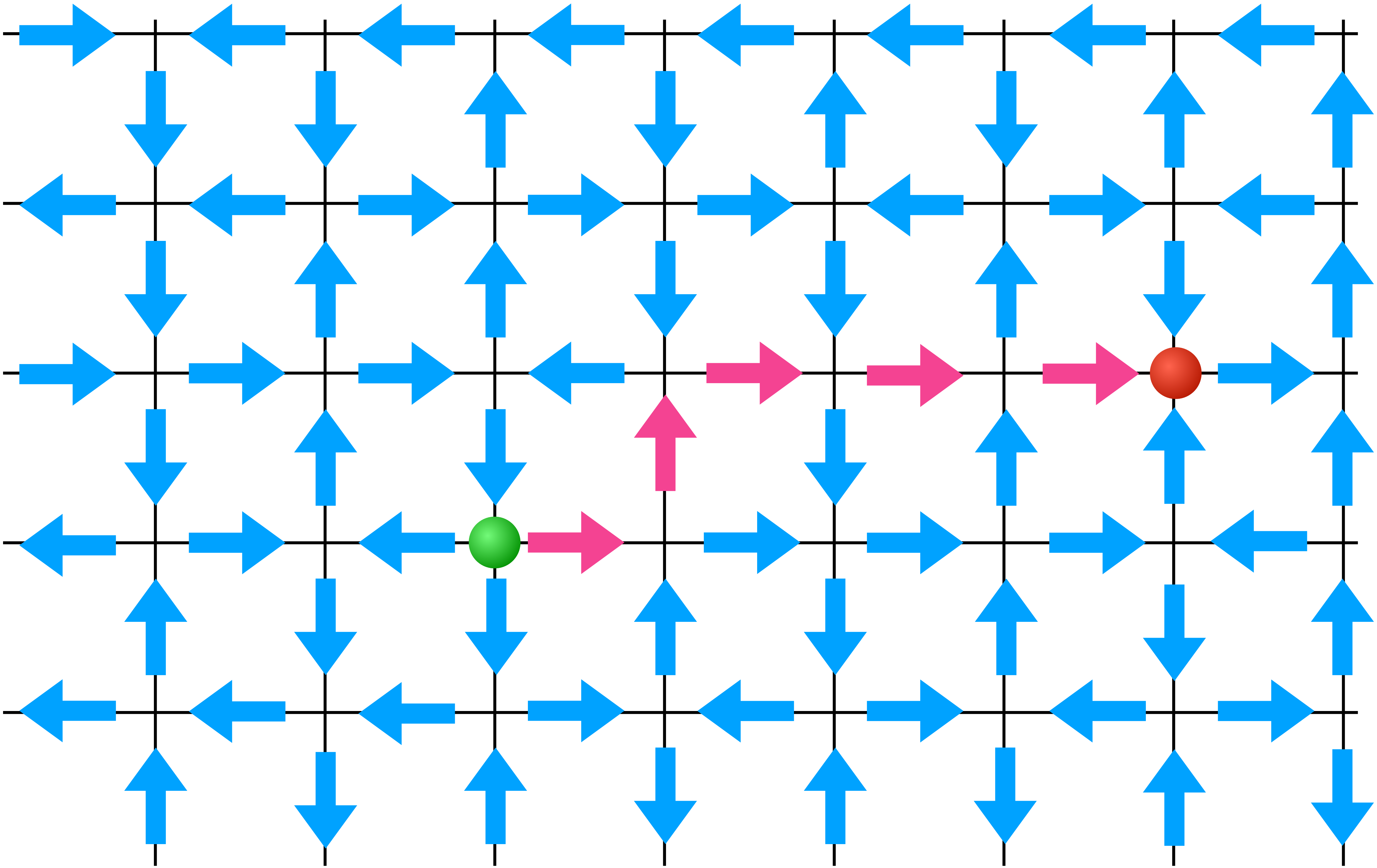

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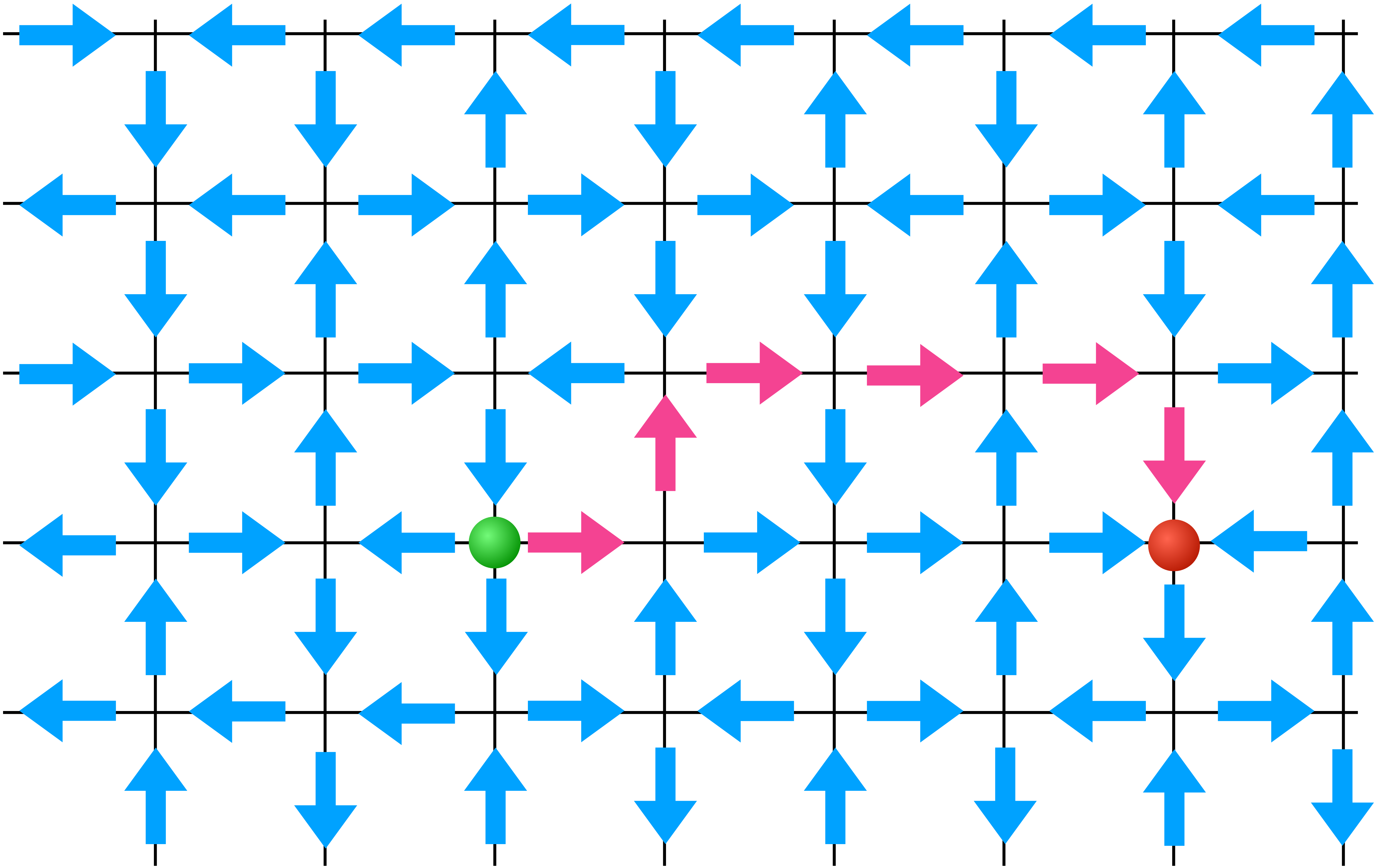

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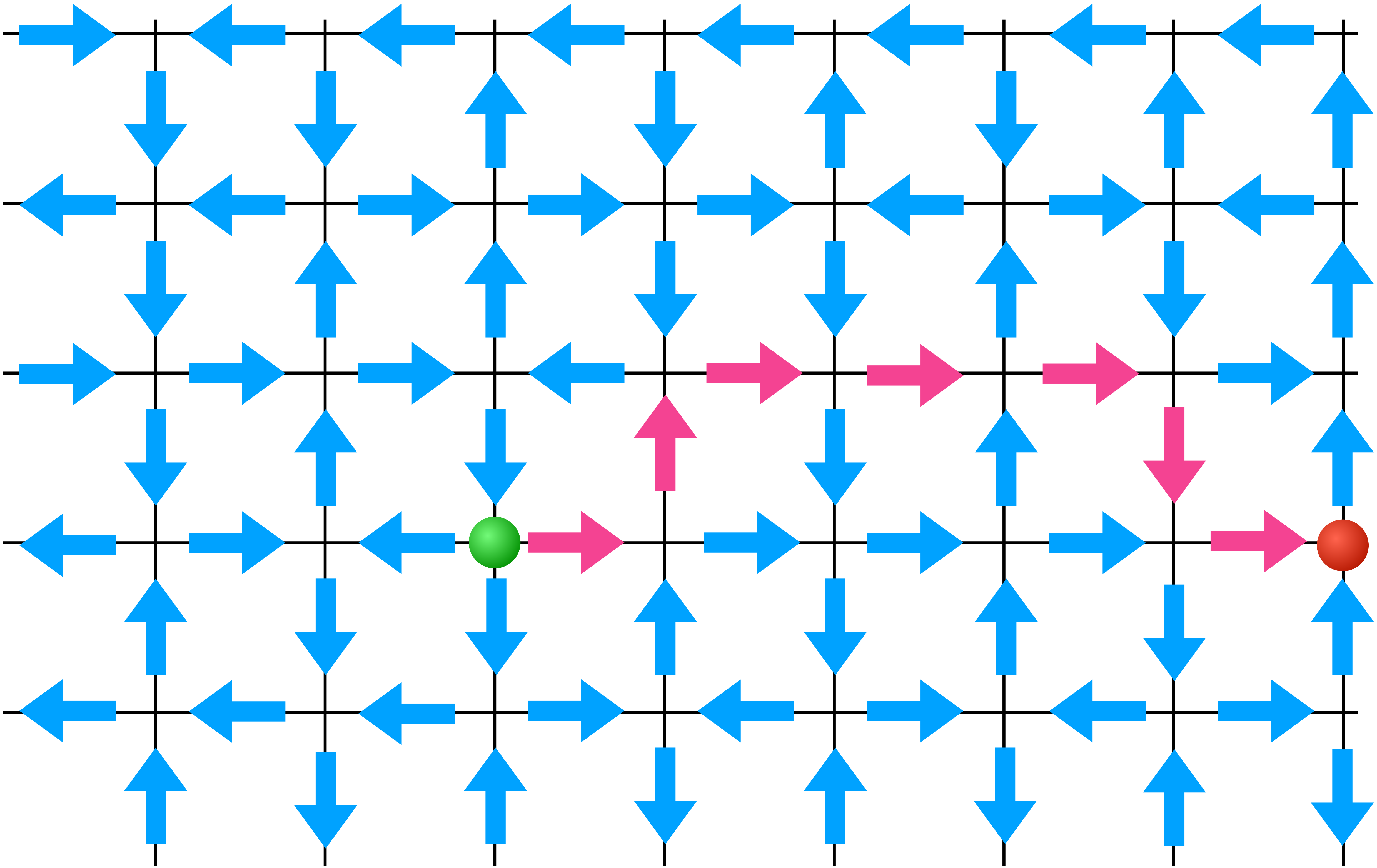

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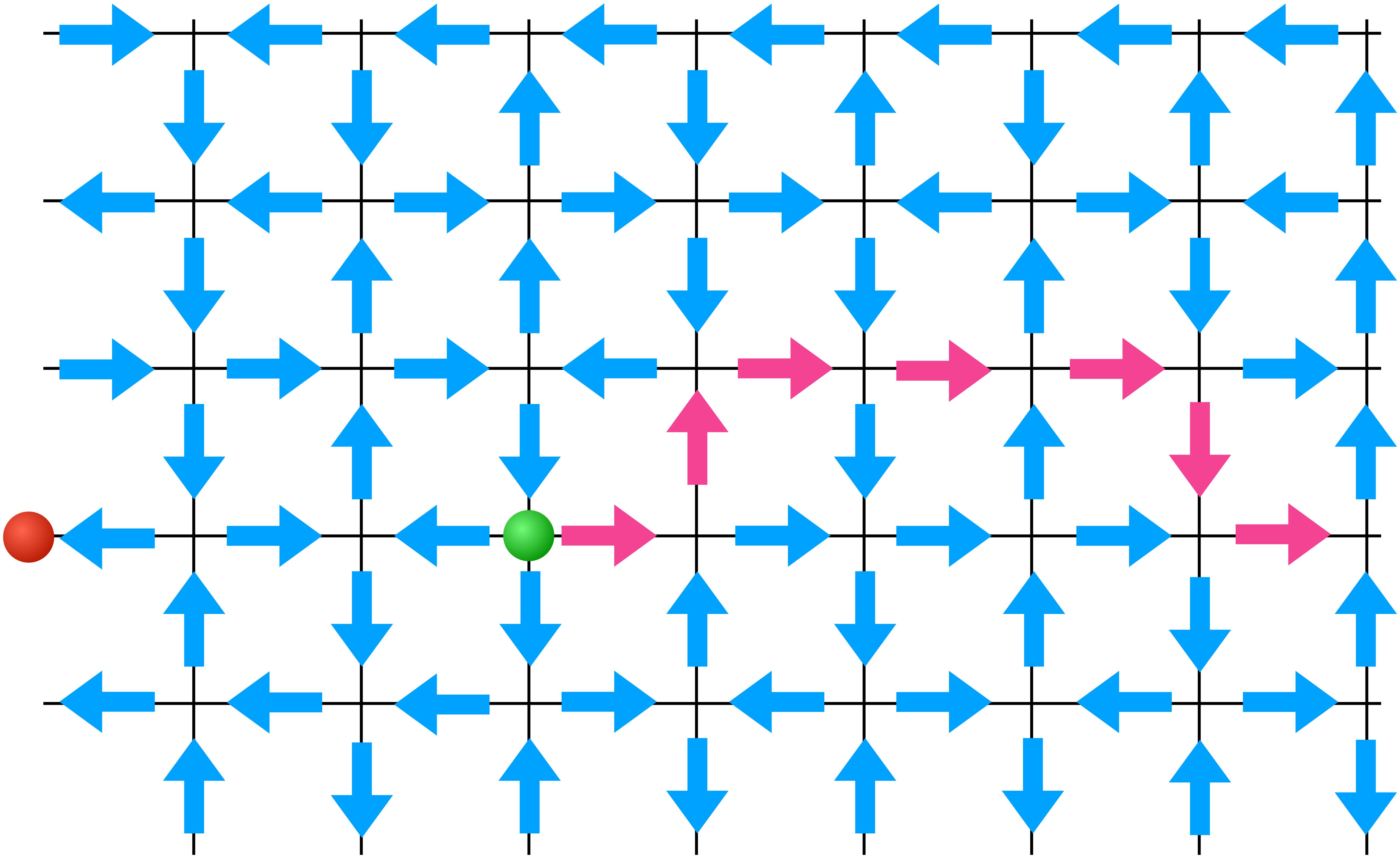

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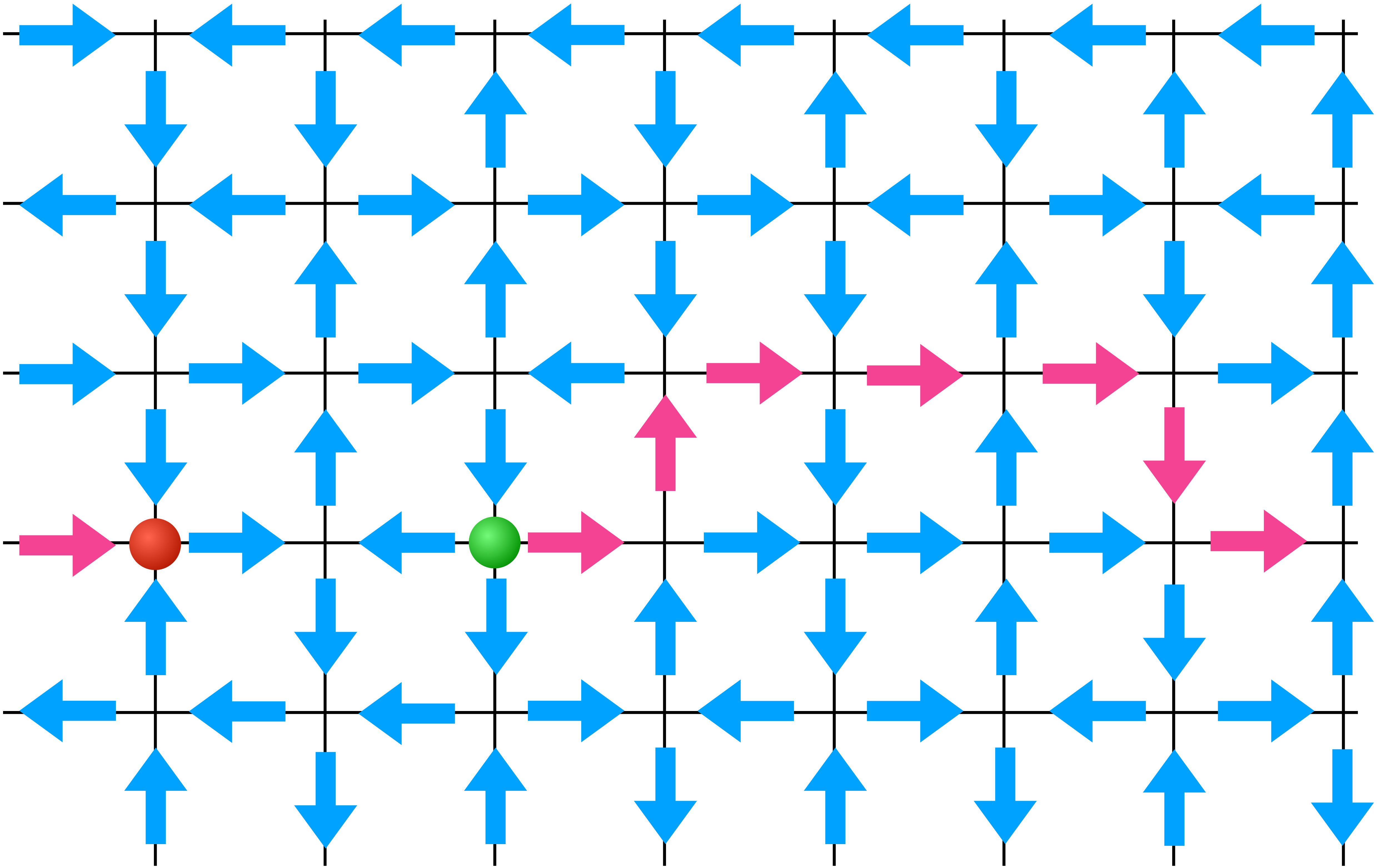

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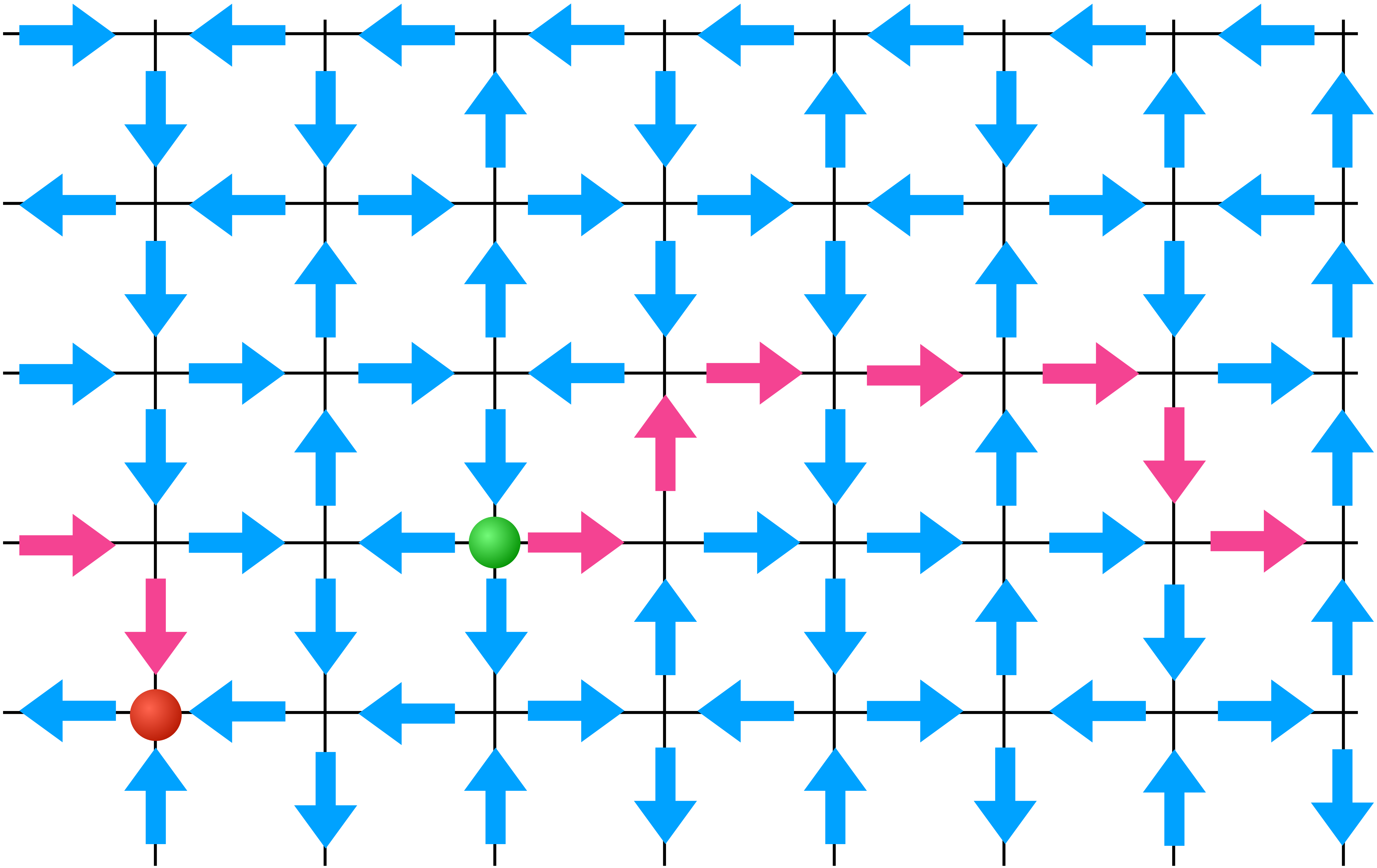

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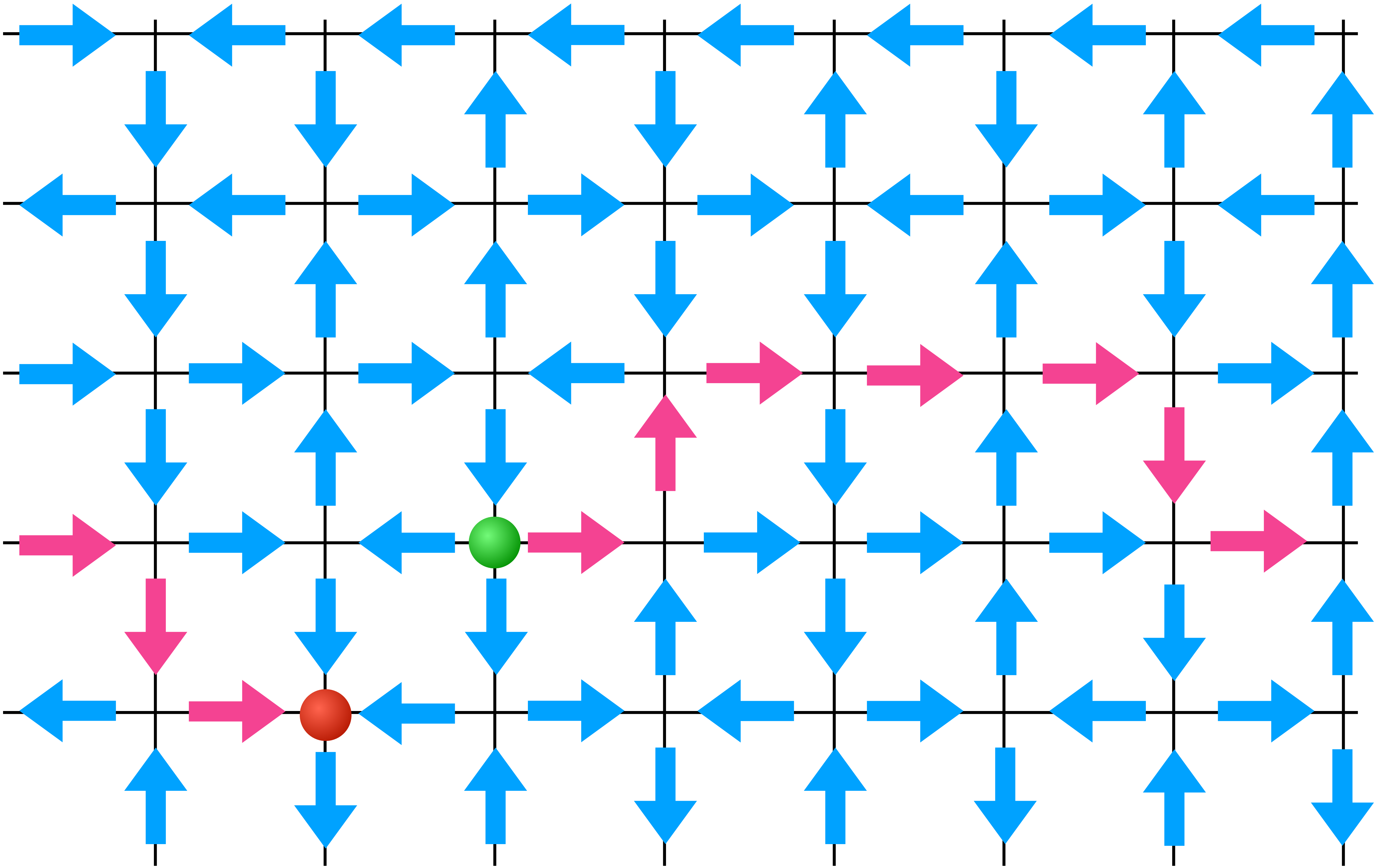

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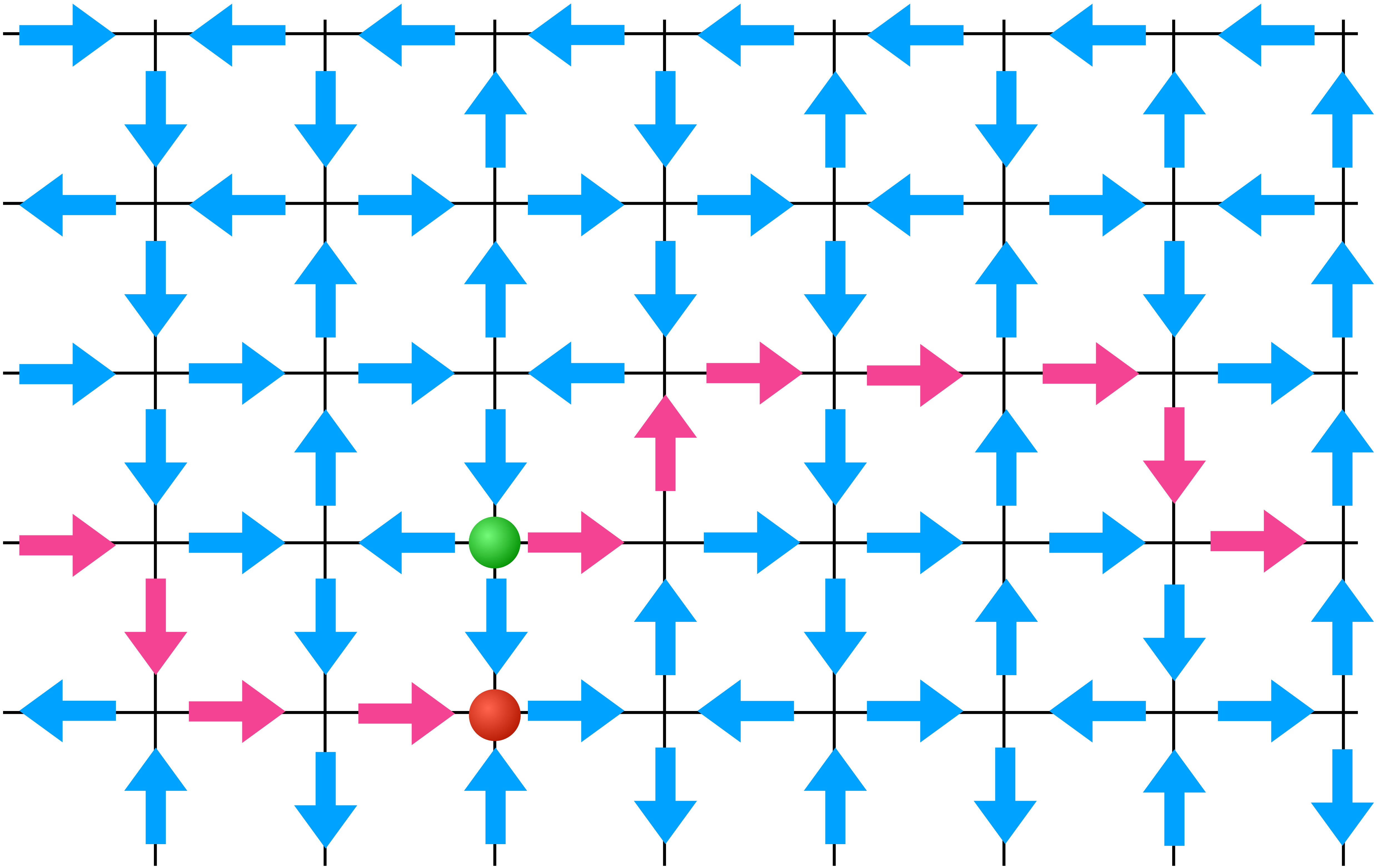

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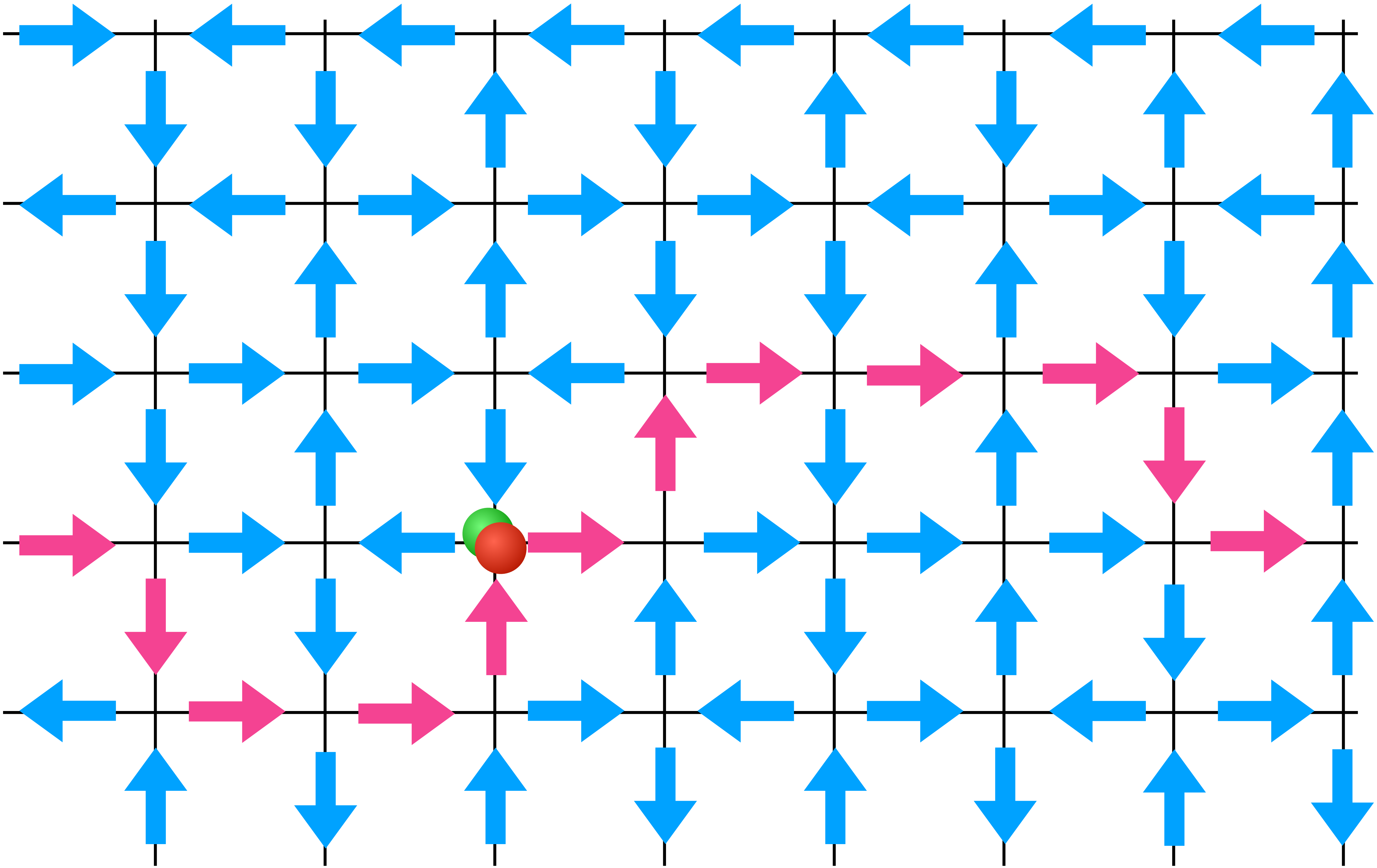
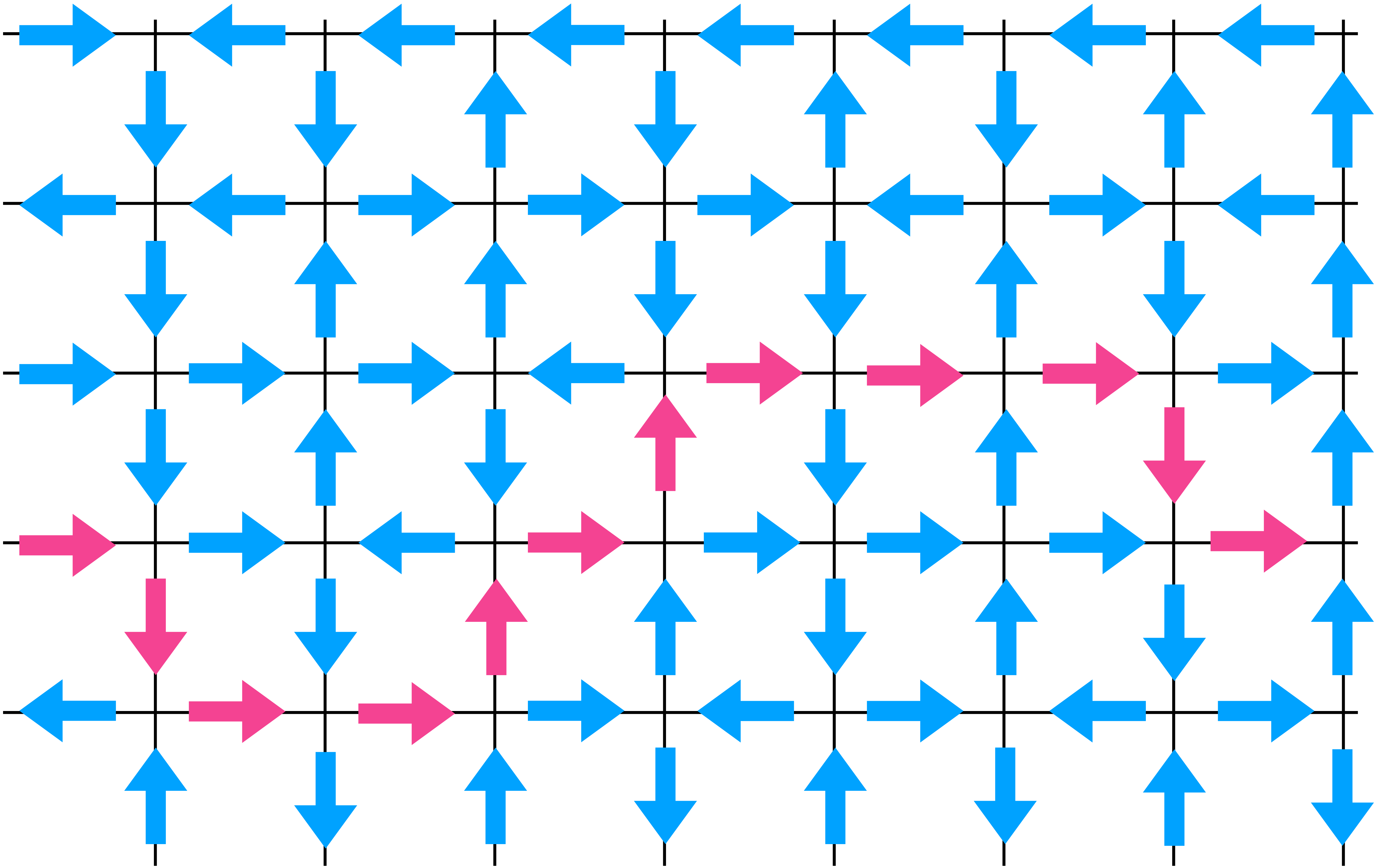
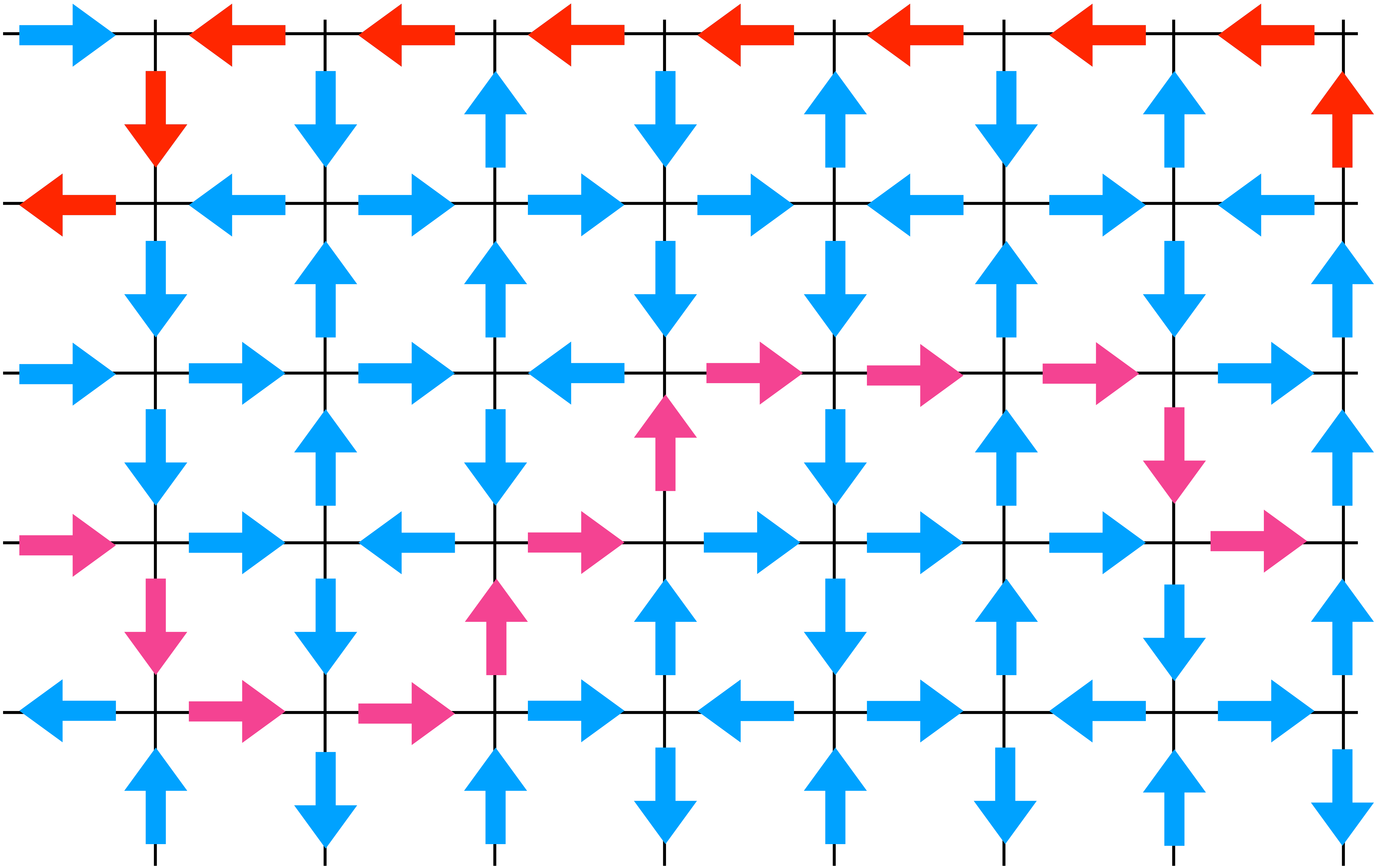


ELECTRIC TOPOLOGICAL SECTORS



ELECTRIC TOPOLOGICAL SECTORS



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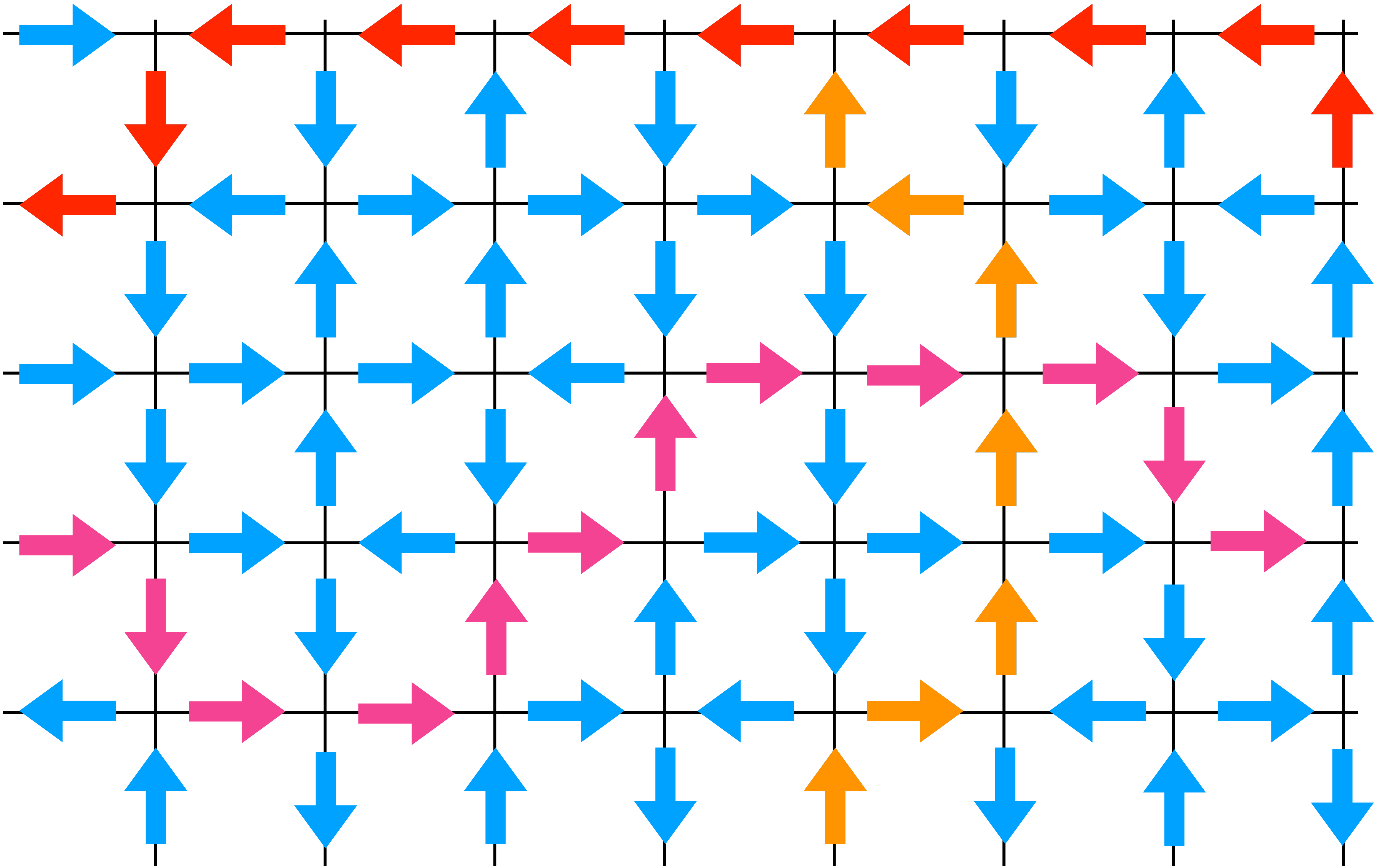

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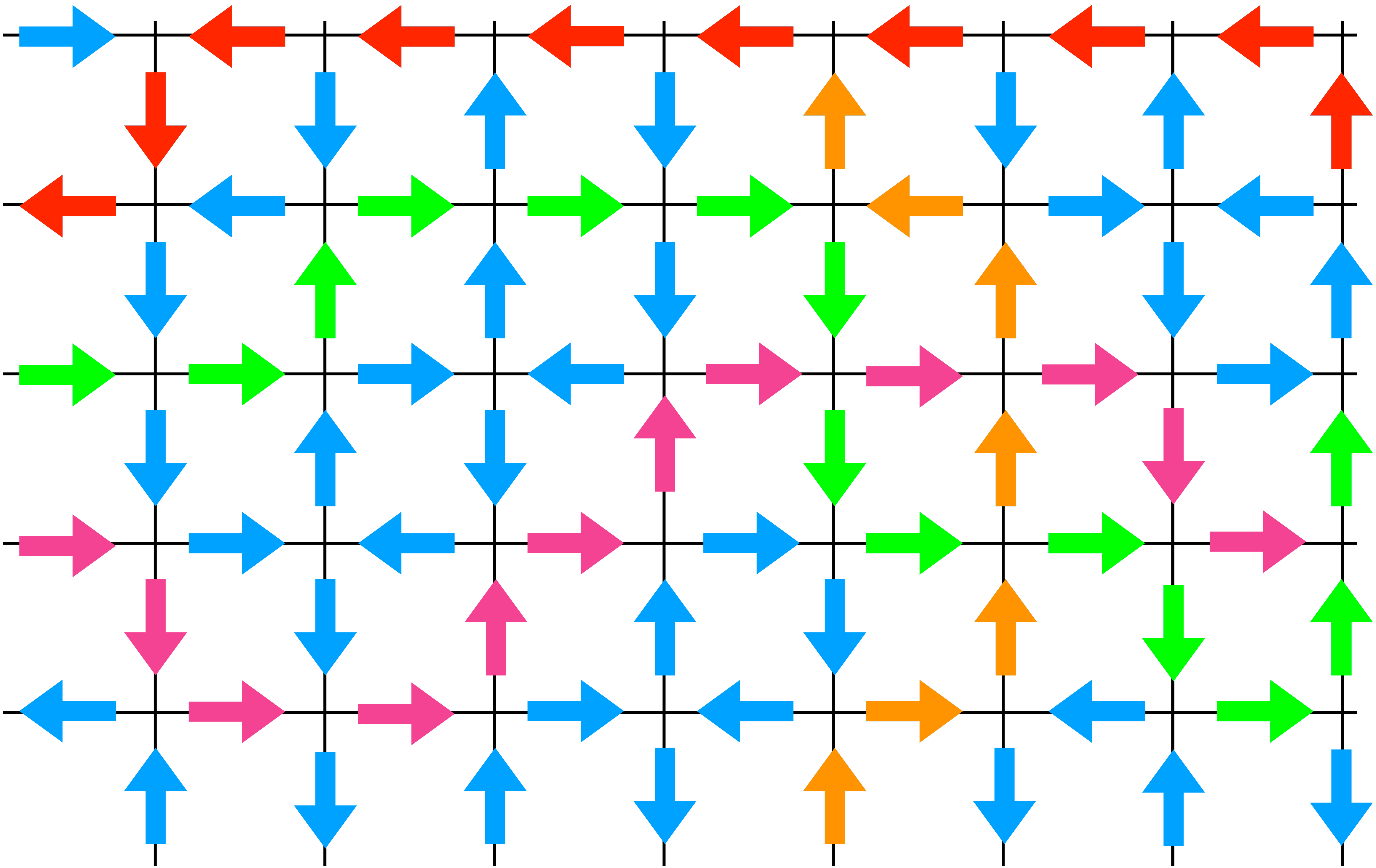

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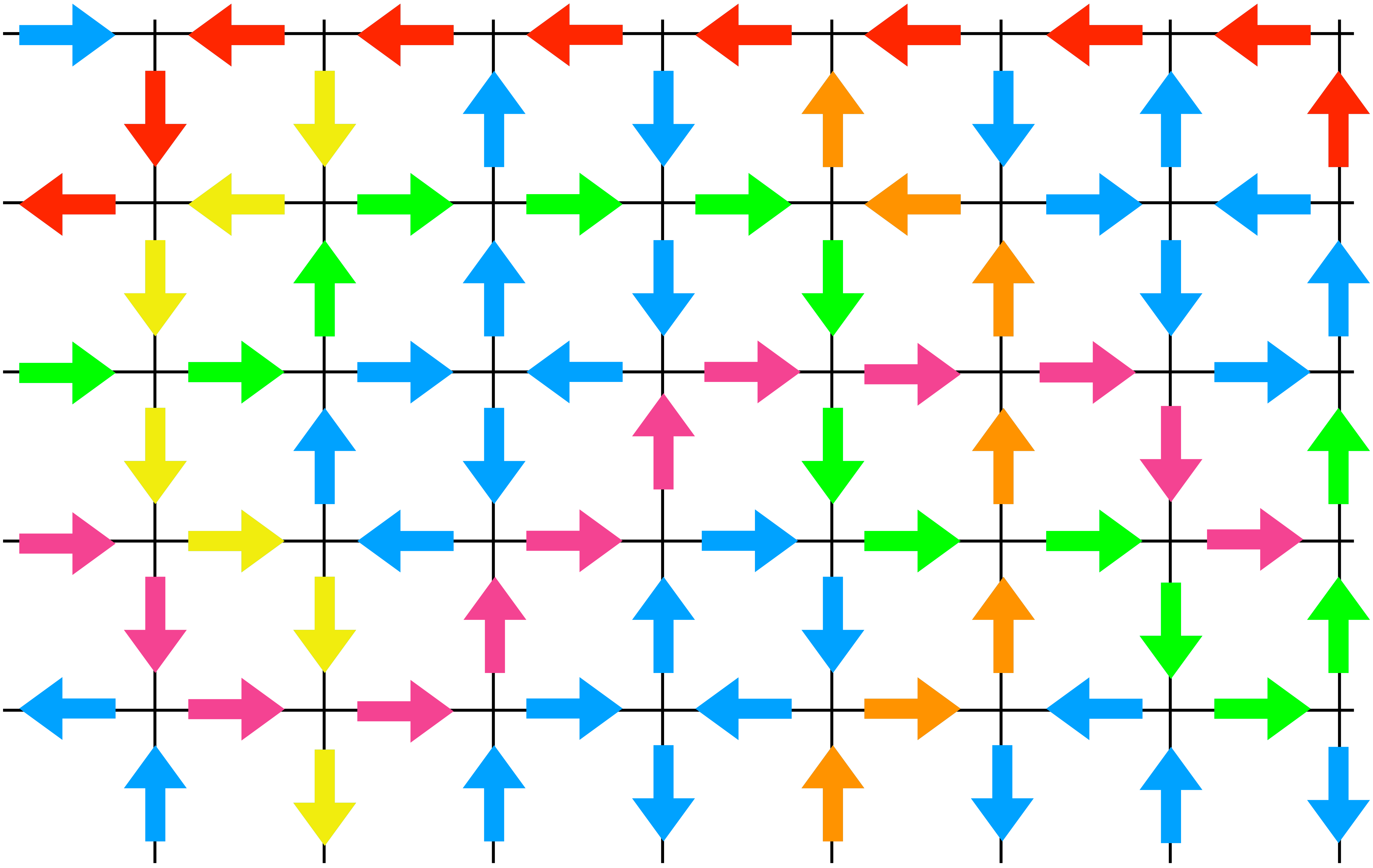
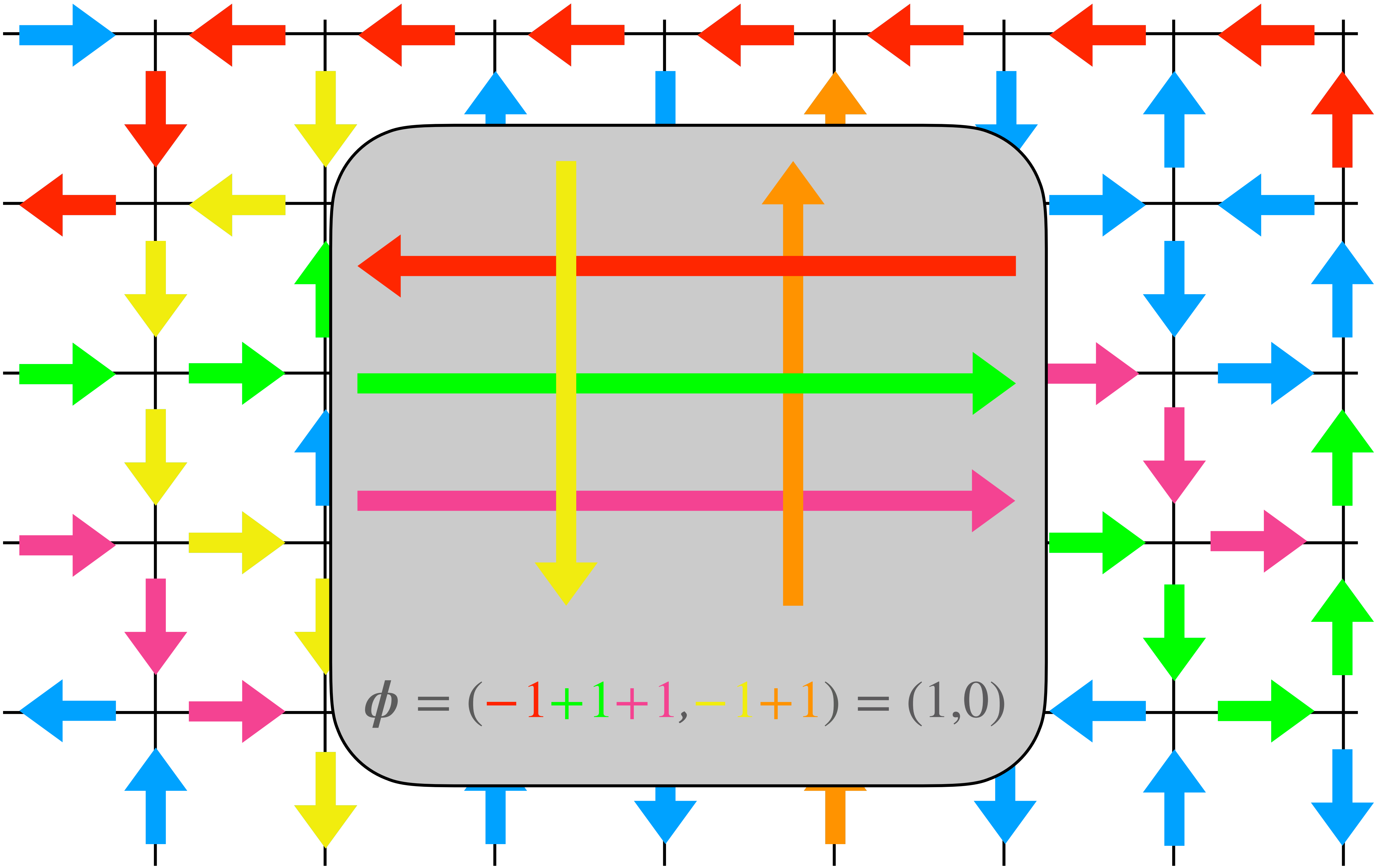


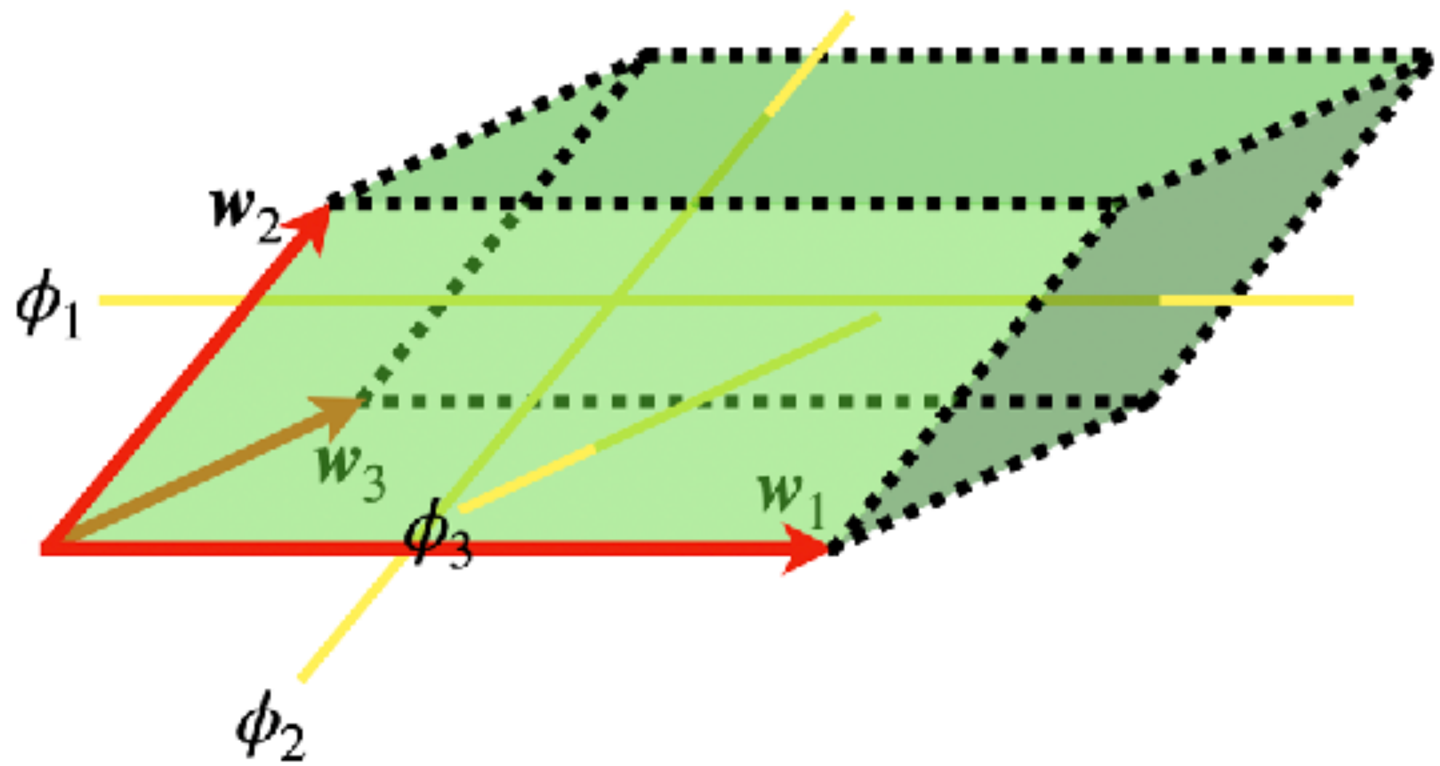
ELECTRIC TOPOLOGICAL SECTORS



$$\phi = (-1+1+1, -1+1) = (1,0)$$

MAXWELL ENERGY DENSITY

Electric Topological Sectors: $\boldsymbol{\phi} = (\phi_1, \phi_2, \phi_3)$



ELECTRIC FIELD CALCULATION

- Gauss's Law:

$$\boldsymbol{E} \cdot (\boldsymbol{w_1} \times \boldsymbol{w_2}) = \phi_3 e_{\mathrm{QSI}}/\epsilon_{\mathrm{QSI}}$$
$$\boldsymbol{E} \cdot (\boldsymbol{w_2} \times \boldsymbol{w_3}) = \phi_1 e_{\mathrm{QSI}}/\epsilon_{\mathrm{QSI}}$$
$$\boldsymbol{E} \cdot (\boldsymbol{w_3} \times \boldsymbol{w_1}) = \phi_2 e_{\mathrm{QSI}}/\epsilon_{\mathrm{QSI}}$$

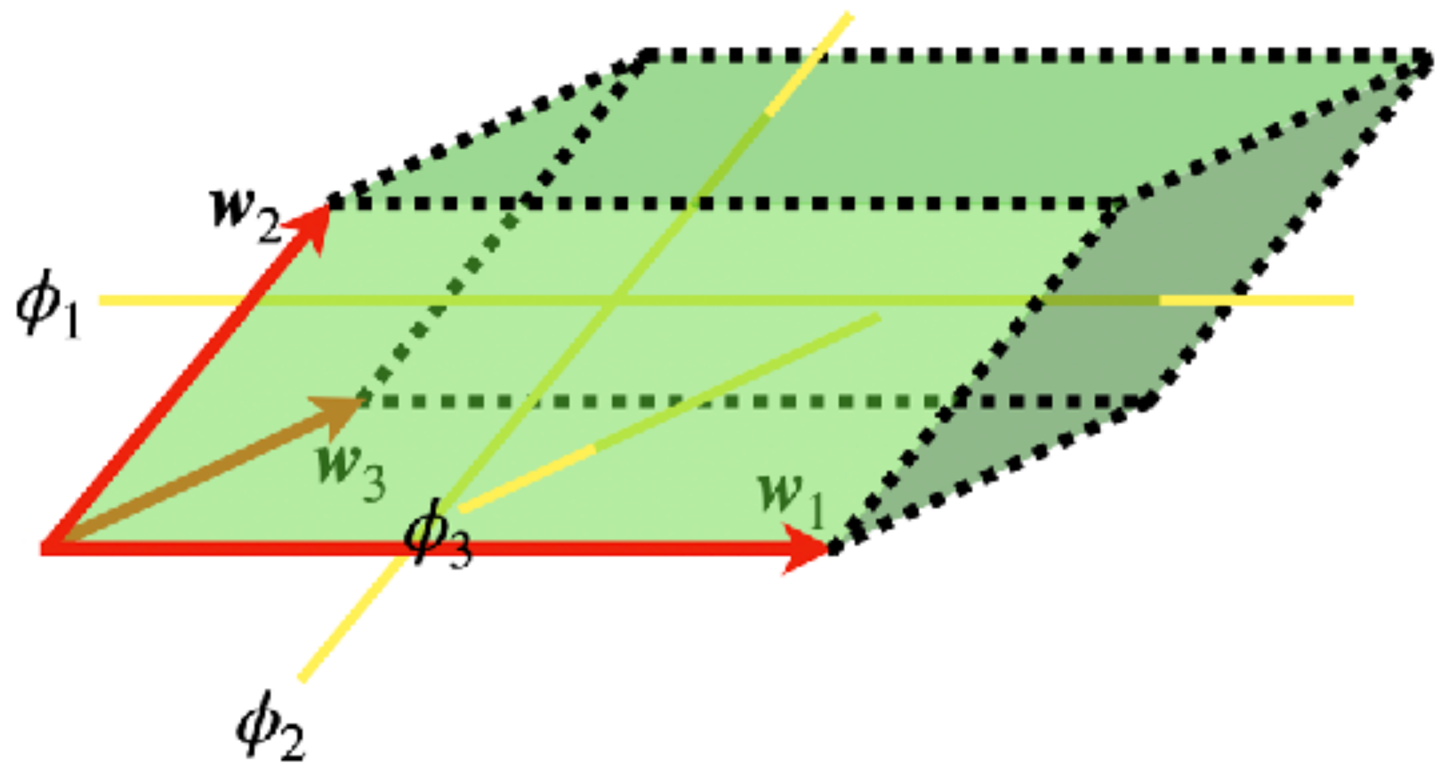
$$\longrightarrow \quad \boldsymbol{E} = \frac{\phi_1 \boldsymbol{w_1} + \phi_2 \boldsymbol{w_2} + \phi_3 \boldsymbol{w_3}}{V} \frac{e_{\mathrm{QSI}}}{\epsilon_{\mathrm{QSI}}}$$

- Q Matrix

$$Q \equiv \frac{a^2}{V} \begin{pmatrix} | & | & | \\ \boldsymbol{w_1} & \boldsymbol{w_2} & \boldsymbol{w_3} \\ | & | & | \end{pmatrix} \quad \longrightarrow \quad \boldsymbol{E} = \frac{Q\boldsymbol{\phi}}{a^2} \frac{e_{\mathrm{QSI}}}{\epsilon_{\mathrm{QSI}}}$$

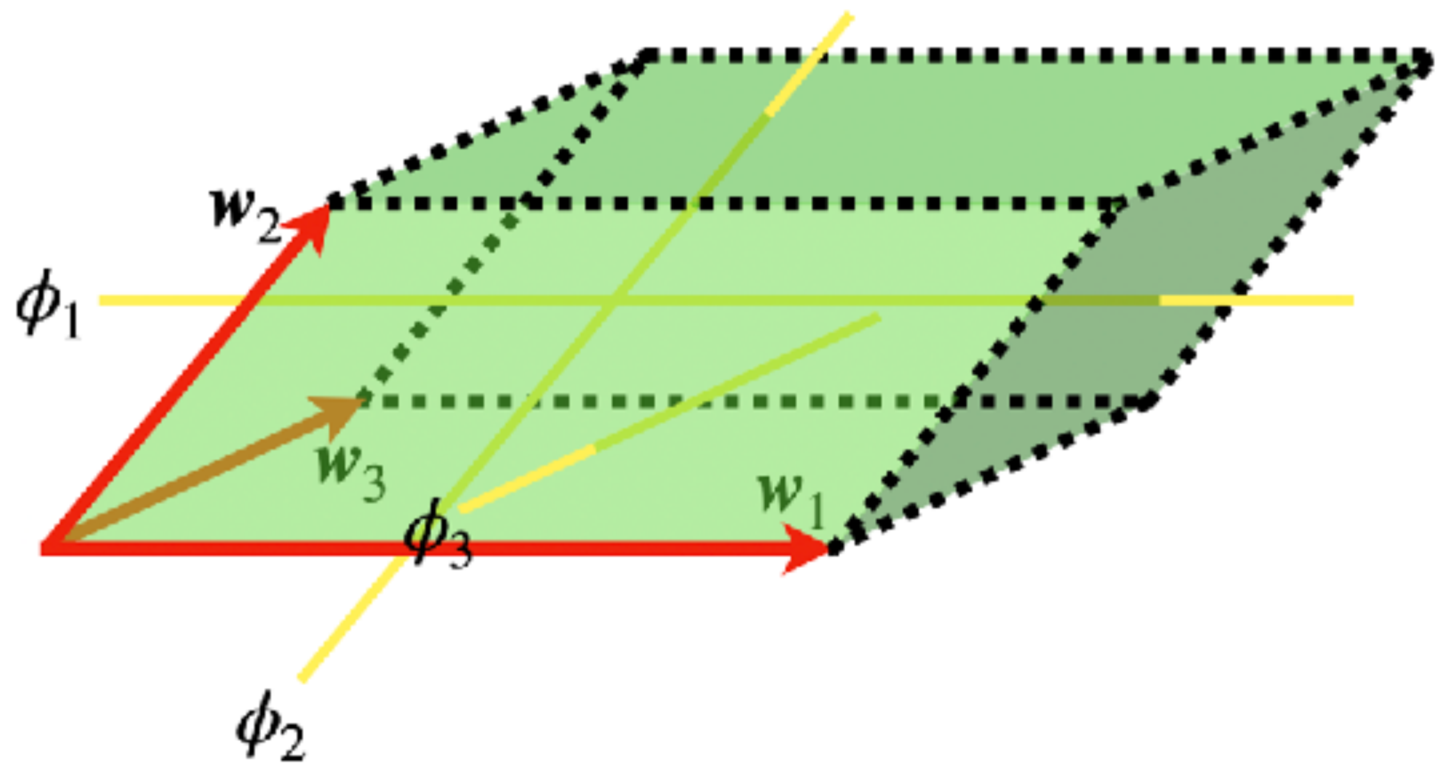
MAXWELL ENERGY DENSITY

Electric Topological Sectors: $\boldsymbol{\phi} = (\phi_1, \phi_2, \phi_3)$



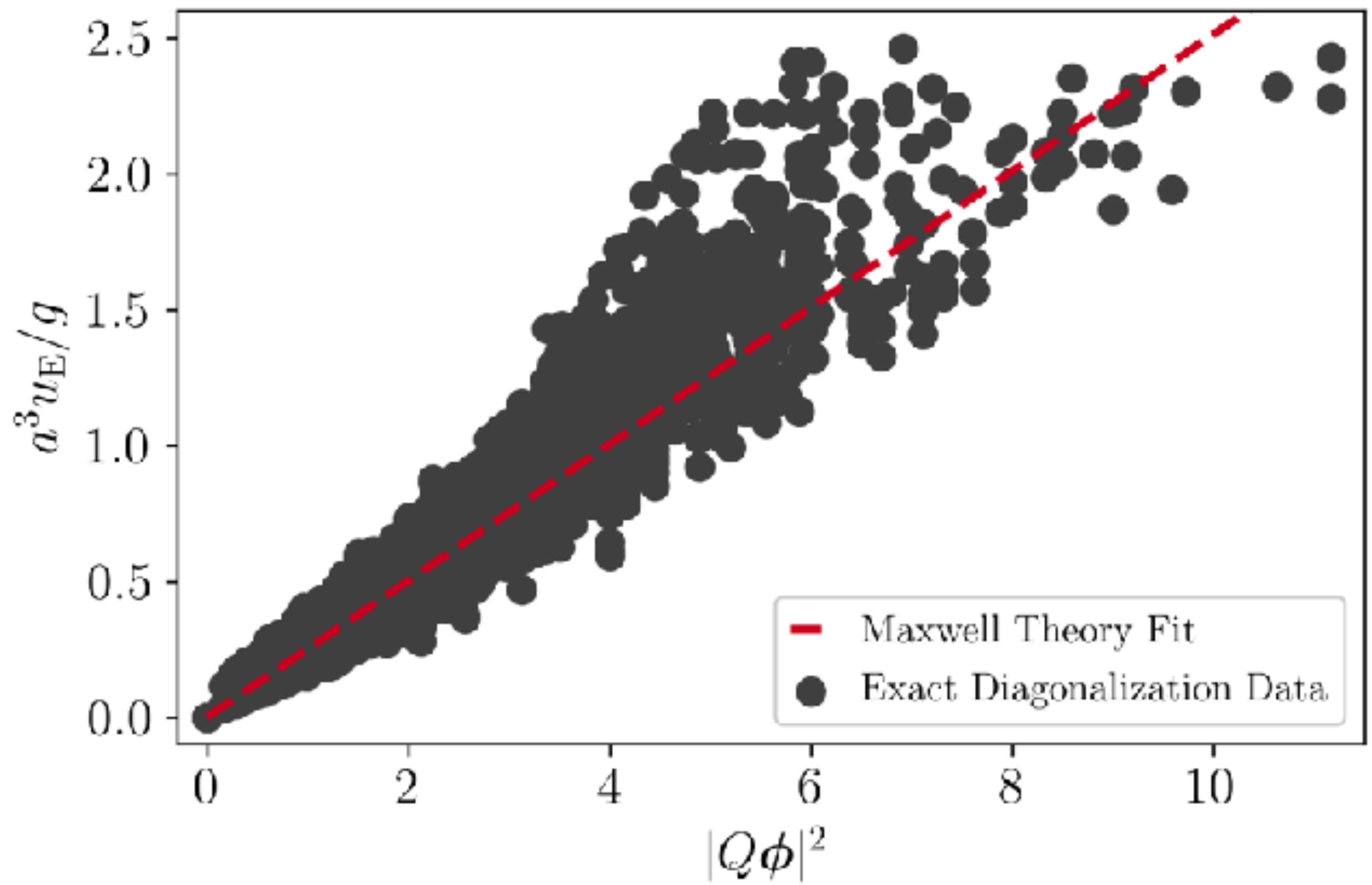
MAXWELL ENERGY DENSITY

Electric Topological Sectors: $\boldsymbol{\phi} = (\phi_1, \phi_2, \phi_3)$



$$\boldsymbol{E} = \frac{Q\boldsymbol{\phi}}{a^2}\frac{e_{\mathrm{QSI}}}{\epsilon_{\mathrm{QSI}}} \longrightarrow \boxed{u_E = \frac{1}{2}\frac{|Q\boldsymbol{\phi}|^2}{a^4}\frac{e_{\mathrm{QSI}}^2}{\epsilon_{\mathrm{QSI}}}}$$

FITTING $e_{\mathrm{QSI}}^2/\epsilon_{\mathrm{QSI}}$



$$\frac{e_{\mathrm{QSI}}^2}{\epsilon_{\mathrm{QSI}}} = (0.50 \pm 0.07)ag$$

GAUSSIAN PHOTON DISPERSION

- Start from Gaussian Theory: $H = \frac{U}{2}\sum_{\langle \mathbf{rr}' \rangle} E^2_{\mathbf{rr}'} + \frac{K}{2}\sum_h \left(\nabla \times A_{\mathbf{rr}'}\right)$
- Write:

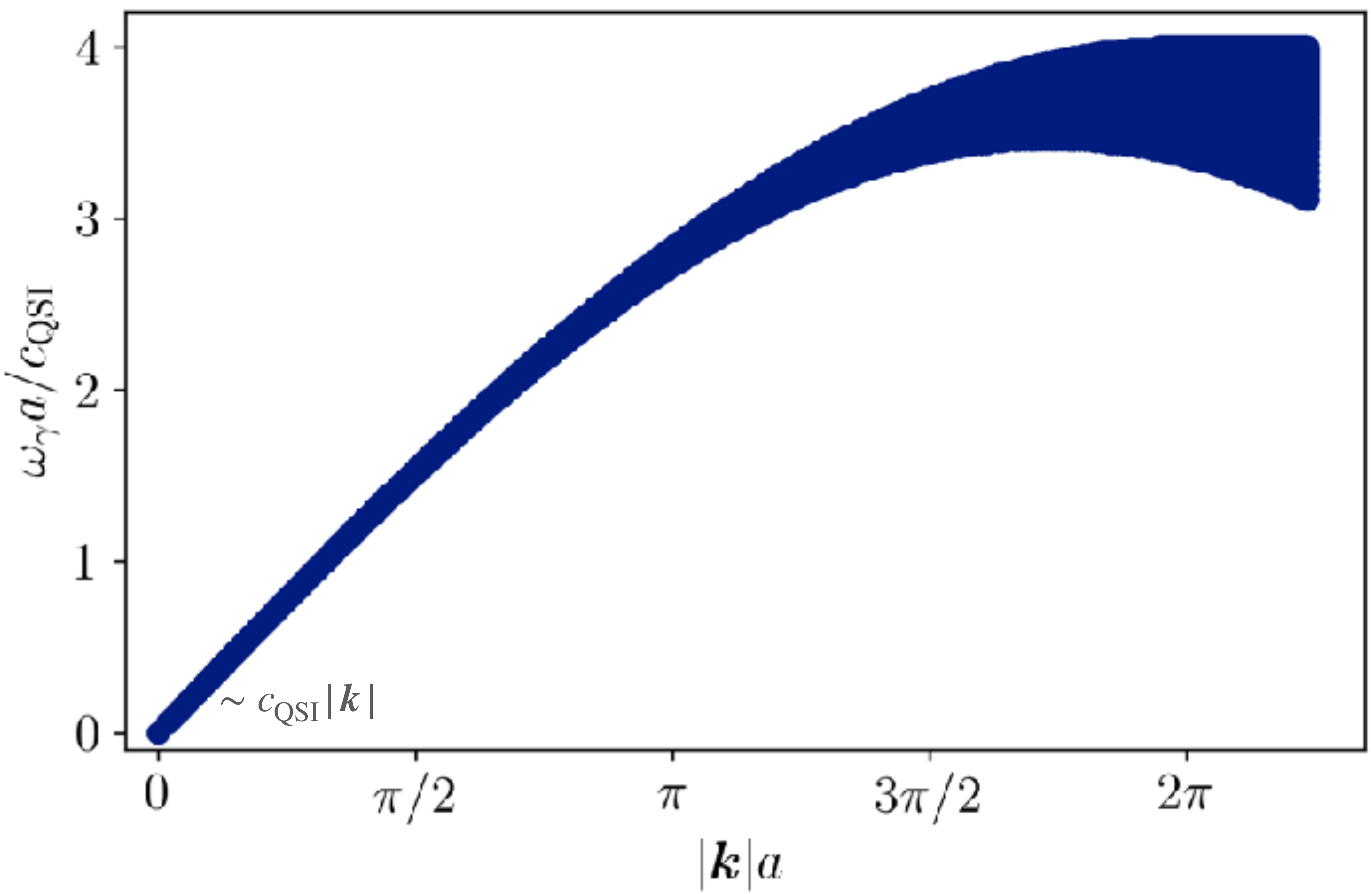
$$A_{(r,n)} = \frac{1}{\sqrt{N}} \sum_{\boldsymbol{k},\alpha} \sqrt{\frac{U}{2\omega_\alpha(\boldsymbol{k})}} \left[e^{-i\boldsymbol{k}\cdot\left(\boldsymbol{r} + \boldsymbol{e}_n/2\right)} \xi_{n\alpha}(\boldsymbol{k}) a_\alpha(\boldsymbol{k}) + e^{i\boldsymbol{k}\cdot\left(\boldsymbol{r} + \boldsymbol{e}_n/2\right)} \xi^*_{\alpha n}(\boldsymbol{k}) a^\dagger_\alpha(\boldsymbol{k})\right]$$

$$E_{(\boldsymbol{r},n)} = i\frac{1}{\sqrt{N}} \sum_{\boldsymbol{k},\alpha} \sqrt{\frac{\omega_\alpha(\boldsymbol{k})}{2U}} \left[e^{-i\boldsymbol{k}\cdot\left(\boldsymbol{r} + e_n/2\right)} \xi_{n\alpha}(\boldsymbol{k}) a_\alpha(\boldsymbol{k}) - e^{i\boldsymbol{k}\cdot\left(\boldsymbol{r} + e_n/2\right)} \xi^*_{\alpha n}(\boldsymbol{k}) a^\dagger_\alpha(\boldsymbol{k})\right]$$

  - ξ is spin-1 polarization tensor
  - $a_\alpha(k)$ destroys photon of momentum k
  - ω is the photon dispersion

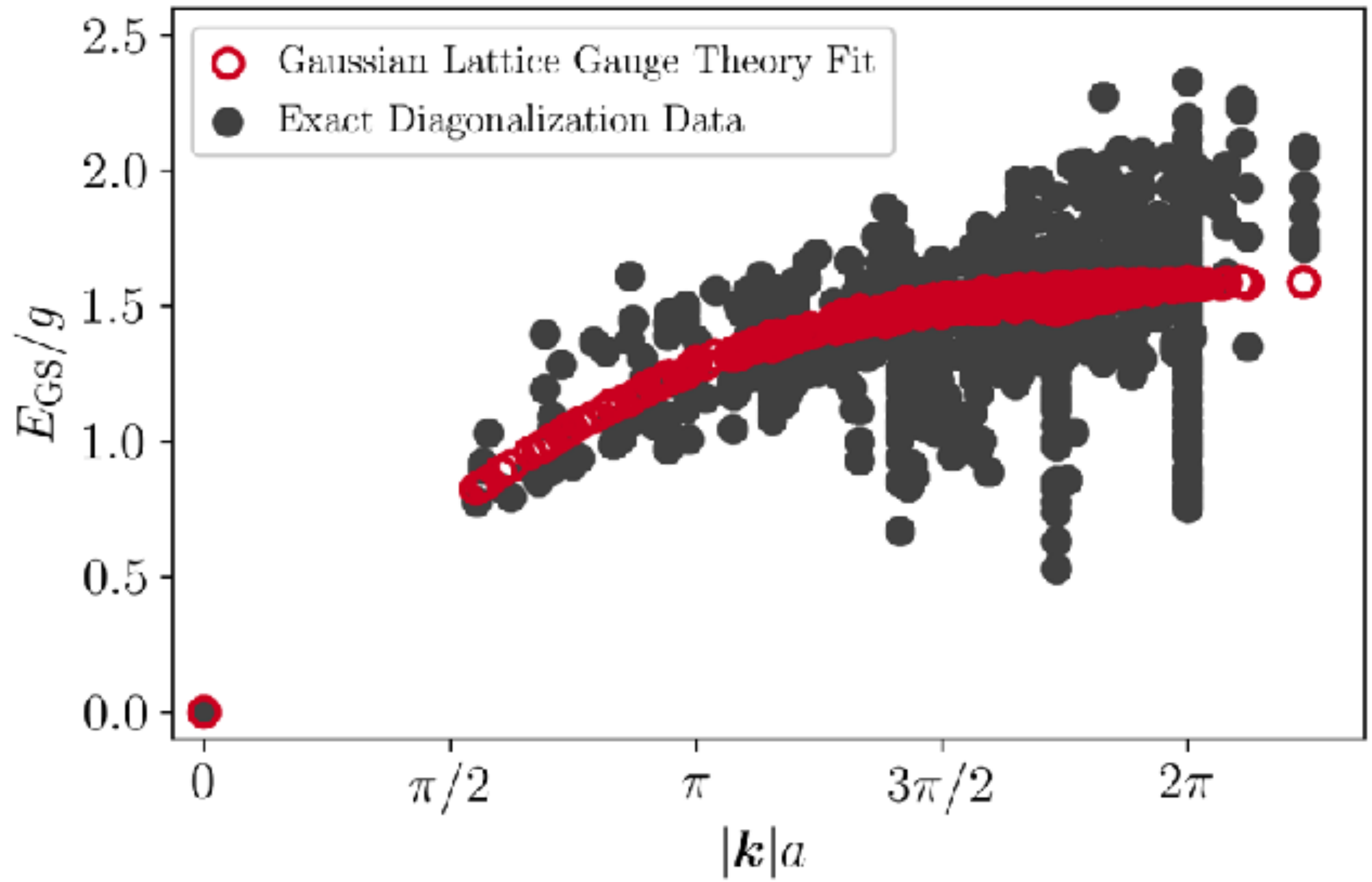
QSI GAUSSIAN PHOTON DISPERSION

$$\omega(k) = \frac{2c_{\text{QSI}}}{a}\sqrt{3 - \cos\left(\frac{k_1 a}{2}\right)\cos\left(\frac{k_2 a}{2}\right) - \cos\left(\frac{k_1 a}{2}\right)\cos\left(\frac{k_3 a}{2}\right) - \cos\left(\frac{k_2 a}{2}\right)\cos\left(\frac{k_3 a}{2}\right)}$$



Benton, Owen, Olga Sikora, and Nic Shannon. *Physical Review B* 86.7 (2012): 075154.

FITTING c_{QSI}



$$c_{\mathrm{QSI}} = (0.51 \pm 0.06)ag/\hbar$$

EMERGENT FINE STRUCTURE CONSTANT

$$\frac{e_{\mathrm{QSI}}^2}{\epsilon_{\mathrm{QSI}}}$$

$$c_{\mathrm{QSI}}$$

$$\boxed{\alpha_{\mathrm{QSI}} = \frac{e_{\mathrm{QSI}}^2}{4\pi\epsilon_{\mathrm{QSI}}\hbar c_{\mathrm{QSI}}}}$$

EMERGENT FINE STRUCTURE CONSTANT

$$\frac{e_{\mathrm{QSI}}^2}{\epsilon_{\mathrm{QSI}}} = 0.5ag$$

$$c_{\mathrm{QSI}}$$

$$\alpha_{\mathrm{QSI}} = \frac{e_{\mathrm{QSI}}^2}{4\pi\epsilon_{\mathrm{QSI}}\hbar c_{\mathrm{QSI}}}$$

EMERGENT FINE STRUCTURE CONSTANT

$$\frac{e^2_{\mathrm{QSI}}}{\epsilon_{\mathrm{QSI}}} = 0.5ag$$

$$c_{\mathrm{QSI}} = 0.51ag/\hbar$$

$$\alpha_{\mathrm{QSI}} = \frac{e^2_{\mathrm{QSI}}}{4\pi\epsilon_{\mathrm{QSI}}\hbar c_{\mathrm{QSI}}}$$

EMERGENT FINE STRUCTURE CONSTANT

$$\frac{e_{\mathrm{QSI}}^2}{\epsilon_{\mathrm{QSI}}} = 0.5ag$$

$$c_{\mathrm{QSI}} = 0.51ag/\hbar$$

$$\alpha_{\mathrm{QSI}} = 0.08$$

QSI BALLPARK NUMBERS

- Lattice spacing: $a \sim 10$ Å
- Ring exchange energy: $g \sim 10\ \mu$eV

Parameters	QSI	QED
c	10 m/s	3×10^8 m/s
e^2/ϵ	10^{-33} J m	2.9×10^{-27} J m
α	1/10	1/137

Gardner, Jason S., Michel JP Gingras, and John E. Greedan. *Reviews of Modern Physics* 82.1 (2010): 53.
Savary, Lucile, and Leon Balents. *Physical review letters* 108.3 (2012): 037202.

PERTURBING THE MODEL

$$\hat{H}_{\mathrm{QSI}} = J_{zz} \sum_{\langle i,j \rangle} \hat{S}_i^z \hat{S}_j^z - g \sum_{\mathrm{h}} \left(\hat{W}_{\mathrm{h}} + \hat{W}_{\mathrm{h}}^{\dagger} \right)$$

PERTURBING THE MODEL

$$\hat{H}_{\mathrm{QSI}} = J_{zz} \sum_{\langle i,j \rangle} \hat{S}_i^z \hat{S}_j^z - g \sum_{\mathrm{h}} \left(\hat{W}_{\mathrm{h}} + \hat{W}_{\mathrm{h}}^\dagger \right) + \hat{H}_{\mathrm{p}}$$

PERTURBING THE MODEL

$$\hat{H}_{\mathrm{QSI}} = J_{zz} \sum_{\langle i,j \rangle} \hat{S}_i^z \hat{S}_j^z - g \sum_{\mathrm{h}} \left(\hat{W}_{\mathrm{h}} + \hat{W}_{\mathrm{h}}^\dagger \right) + \hat{H}_{\mathrm{p}}$$

- $$\hat{H}_{\mathrm{p}} = \mu g \sum_{\mathrm{h}} \left(\hat{W}_{\mathrm{h}}^\dagger \hat{W}_{\mathrm{h}} + \hat{W}_{\mathrm{h}} \hat{W}_{\mathrm{h}}^\dagger \right)$$

- Counts flippable hexagons
- QED phase: $-0.5 \lesssim \mu \leq 1$
- Rokhsar-Kivelson point: $\mu = 1$

Shannon, Nic, et al. *Physical review letters* 108.6 (2012): 067204.

PERTURBING THE MODEL

$$\hat{H}_{\mathrm{QSI}} = J_{zz} \sum_{\langle i,j \rangle} \hat{S}_i^z \hat{S}_j^z - g \sum_{\mathrm{h}} \left(\hat{W}_{\mathrm{h}} + \hat{W}_{\mathrm{h}}^\dagger \right) + \hat{H}_{\mathrm{p}}$$

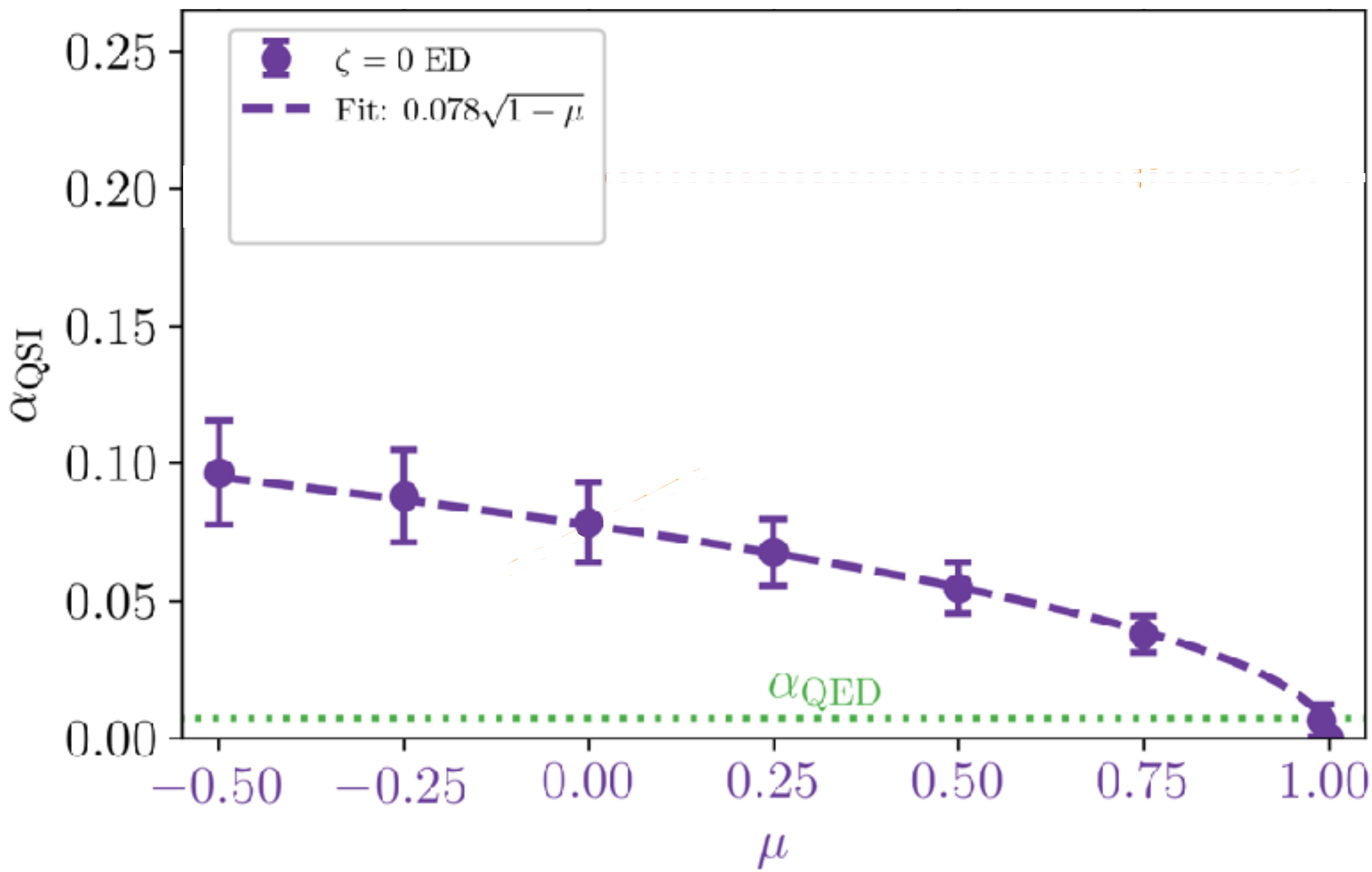
- $$\hat{H}_{\mathrm{p}} = \mu g \sum_{\mathrm{h}} \left(\hat{W}_{\mathrm{h}}^\dagger \hat{W}_{\mathrm{h}} + \hat{W}_{\mathrm{h}} \hat{W}_{\mathrm{h}}^\dagger \right) + \zeta g \sum_{\langle\langle\langle i,j \rangle\rangle\rangle} \hat{S}_i^z \hat{S}_j^z$$

- Counts flippable hexagons
- QED phase: $-0.5 \lesssim \mu \leq 1$
- Rokhsar-Kivelson point: $\mu = 1$

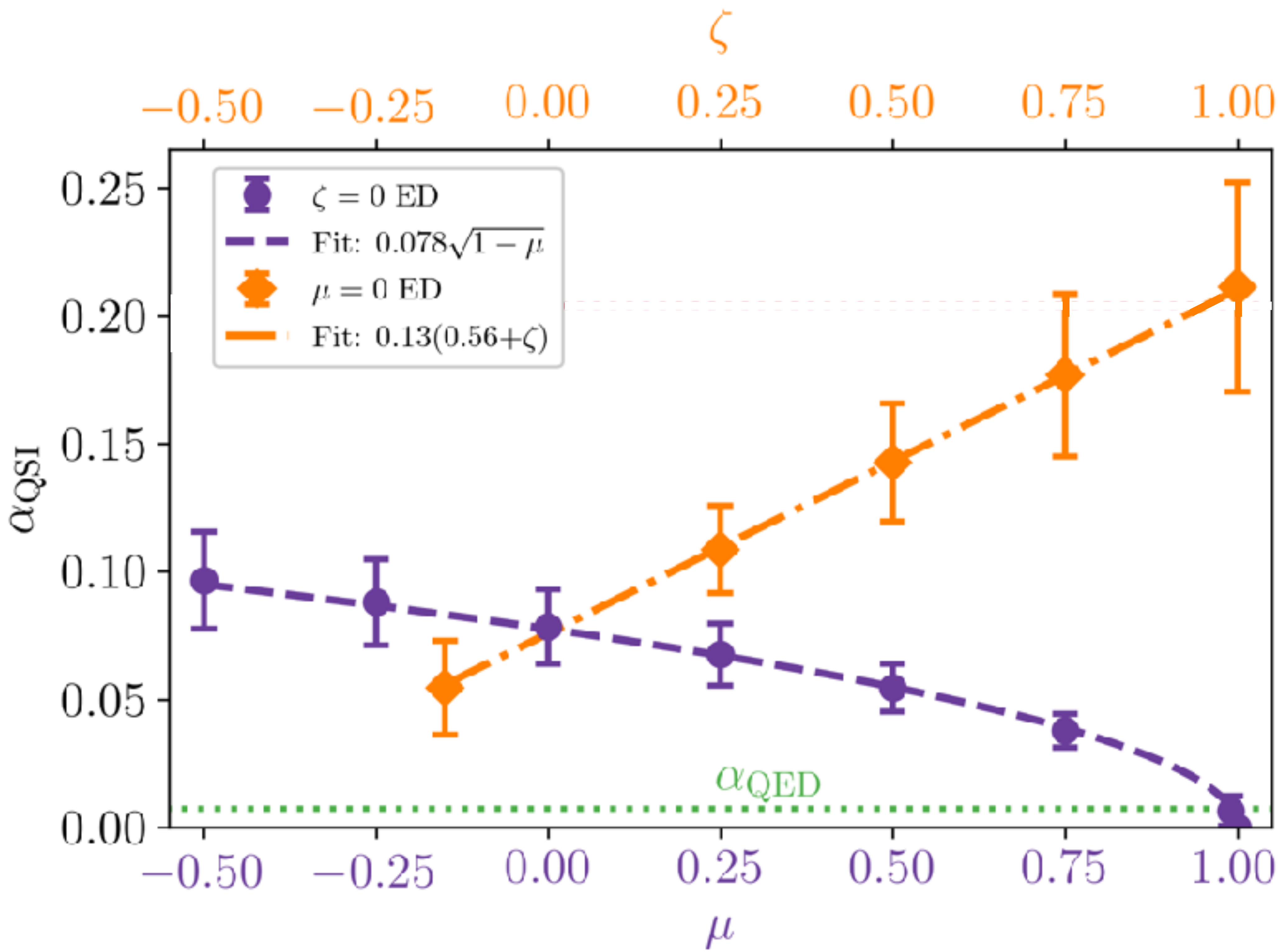
- $\langle\langle\langle i, j \rangle\rangle\rangle$: Spins across hexagons
- Realistic two body term
- QED phase: $-0.2 \lesssim \zeta \lesssim 1$

Shannon, Nic, et al. *Physical review letters* 108.6 (2012): 067204.

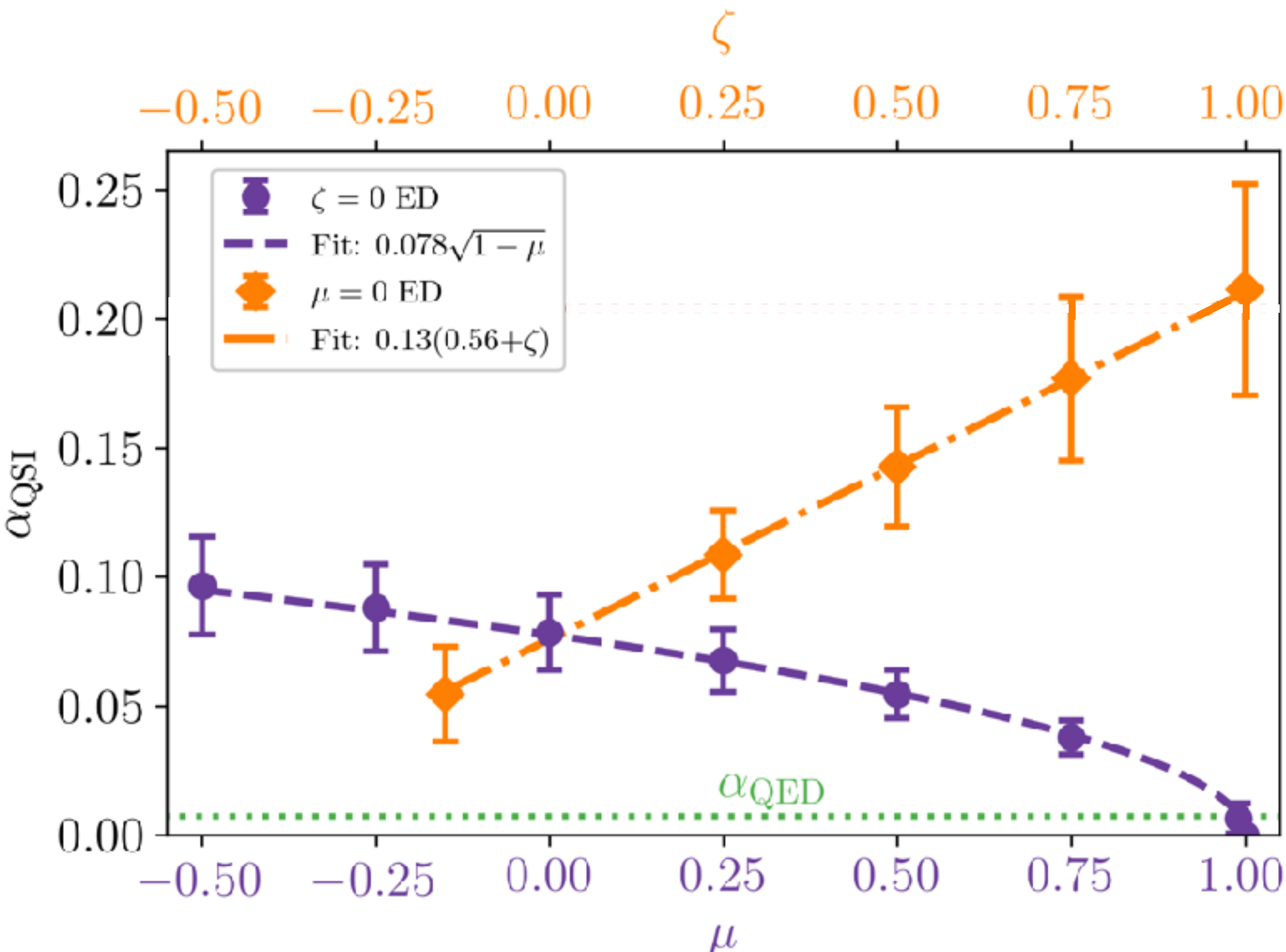
TUNING α_{QSI}



TUNING α_{QSI}

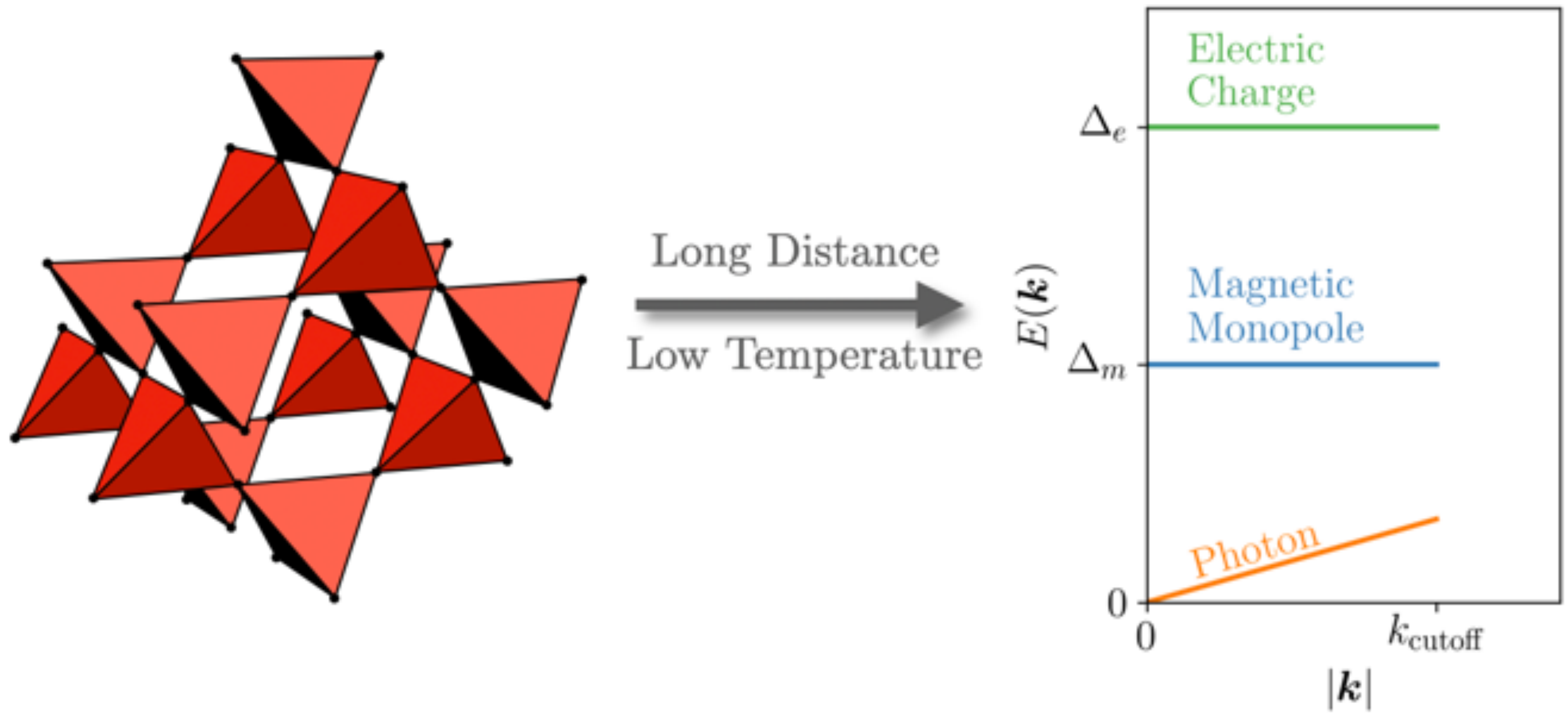


TUNING α_{QSI}

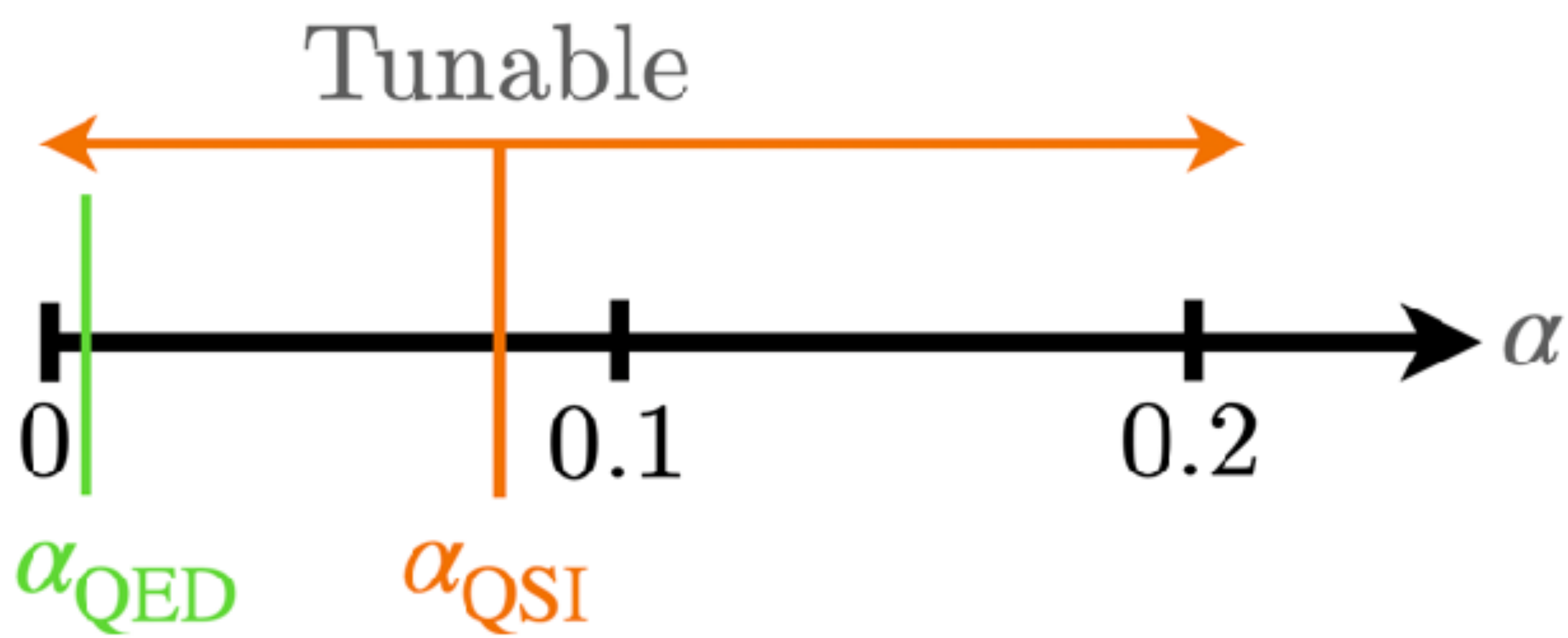


Cardy, John L. *Nuclear Physics B* 170.3 (1980): 369-387.
Cella, G., et al. *Physical Review D* 56.7 (1997): 3896.
Luck, J. M. *Nuclear Physics B* 210.1 (1982): 111-124.

RECAP



Long Distance
Low Temperature
Electric
Charge
Magnetic
Monopole
Photon
Δ_e
Δ_m
0
$E(\boldsymbol{k})$
k_{cutoff}
$|\boldsymbol{k}|$



Tunable
0
0.1
0.2
α
α_{QED}
α_{QSI}

THANK YOU! QUESTIONS?

arXiv:2009.04499

Roderich Moessner	Chris Laumann	Sid Morampudi
		
Max Planck Institute for the Physics of Complex Systems	*Boston University*	*MIT*

QUANTUM SPIN ICE

- Most general quantum Hamiltonian:

$$H = \sum_{\langle i,j\rangle} [J_{zz} S_i^z S_j^z - J_{\pm}\left(S_i^+ S_j^- + S_i^- S_j^+\right)$$

$$+J_{\pm\pm}\left[\gamma_{ij} S_i^+ S_j^+ + \gamma_{ij}^* S_i^- S_j^-\right]$$

$$+J_{z\pm}\left[S_i^z\left(\left(\zeta_{ij} S_j^+ + \zeta_{ij}^* S_j^-\right) + i \leftrightarrow j\right)\right]\Big]$$

- Experiments on $Yb_2Ti_2O_7$ found that in meV:

$$J_{zz} = 0.17 \pm 0.04, \quad J_{\pm} = 0.05 \pm 0.01$$

$$J_{\pm\pm} = 0.05 \pm 0.01 \quad J_{z\pm} = -0.14 \pm 0.01$$

EXPERIMENTAL CONSEQUENCES

1. Cherenkov Radiation
   - Theoretical study whose results where in terms of the fine structure constant
   - Since the speed of light is being tuned too, the threshold for Cherenkov radiation is also moved
2. Dynamical Structure Factor
   - Shows sharp lines from excitonic bound states and a continuum.
   - We now have all the information to know the spacing between bound states in numerics and neutron scattering experiment.

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Morampudi, Siddhardh C., Frank Wilczek, and Chris R. Laumann. *Physical Review Letters* 124.9 (2020): 097204.

XXZ MODEL TO QSI

- Setting $J_{\pm\pm} = J_{z\pm} = 0$, XXZ model:
  - $H = J_{zz} \sum_{\langle i,j \rangle} S_i^z S_j^z + J_{\pm} \sum_{\langle i,j \rangle} \left(S_i^+ S_j^- + \mathrm{h.c.} \right)$
- Study quantum fluctuations within spin ice manifold (Set spinon gap to infinity)
  - For $J_{zz} \gg J_{\pm\pm}$, third order perturbation
  - $H_{eff} = P \left[H_{zz} + H_{\pm} - H_{\pm} \frac{1-P}{H_{zz}} H_{\pm} + H_{\pm} \frac{1-P}{H_{zz}} H_{\pm} \frac{1-P}{H_{zz}} H_{\pm} \right] P$

    $$H_{eff} = -\frac{3J_{\pm}^3}{2J_{zz}^2} \sum_h \left(S_{h,1}^+ S_{h,2}^- S_{h,3}^+ S_{h,4}^- S_{h,5}^+ S_{h,6}^- + \mathrm{h.c.} \right)$$

  - $$\equiv -g \sum_h \left(S_{h,1}^+ S_{h,2}^- S_{h,3}^+ S_{h,4}^- S_{h,5}^+ S_{h,6}^- + \mathrm{h.c.} \right)$$

EMERGENT COMPACT QED

- Introduce quantum rotor variables: $S_i^{\pm} = e^{\pm i\phi_i}$
- Introduce oriented link variables
  - $A_i = \pm\,\phi_i$
- Hamiltonian becomes $H = -2g \sum_h \cos(\mathrm{curl} A)$
- Consider Hamiltonian
  - $H = \dfrac{U}{2} \sum_r E_r^2 - K \sum_h \cos(\mathrm{curl} A)$
  - When $U \gg K$, gives same low-energy physics as above.

EMERGENT COMPACT QED: COMMENTS

- $H = \dfrac{U}{2}\sum_r E_r^2 - K\sum_h \cos(\mathrm{curl}A)$ is a compact $U(1)$ LGT.
- H is invariant under gauge transformation $A_{ij} \to A_{ij} + g_j - g_i$
- Canonically conjugate $[A, E] = i$
- magnetic monopoles
- Because $E_{ij} = \pm 1/2$, LGT is frustrated an non-trivial in $U \gg K$ limit

RECALL FINE STRUCTURE CONSTANT

- $\mathscr{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \partial_\mu\phi^\dagger\partial^\mu\phi - m^2\phi^\dagger\phi - 2i\sqrt{\pi\alpha}\phi^\dagger\overleftrightarrow{\partial_\mu}\phi A^\mu - 4\pi\alpha A_\mu A^\mu\phi^\dagger\phi$
  - Scalar QED Lagrangian
- α gives coupling strength between photon field and scalar boson field.
- Electron-positron to electron positron scatter leading order term is proportional to α
  - In the QED of our universe, $\alpha = 1/137$

FULL DISPERSION

- Effective theory near the RK point, with $U = 1 - \mu$

$$H_{RK} = \frac{U}{2}\sum_{\langle ij\rangle} E_{ij}^2 + \frac{K}{2}\sum_h (\nabla_h \times A)^2 + \frac{W}{2}\sum_h (\nabla_h \times E)^2$$

- Diagonalize to find the dispersion

$$\omega_{1,2}(\boldsymbol{k}) = \frac{2}{a}\sqrt{c^2\zeta(\boldsymbol{k}) + V\zeta^2(\boldsymbol{k})}$$

$$\zeta(\boldsymbol{k}) = 3 - \cos\left(\frac{k_1 a}{2}\right)\cos\left(\frac{k_2 a}{2}\right) - \cos\left(\frac{k_1 a}{2}\right)\cos\left(\frac{k_3 a}{2}\right) - \cos\left(\frac{k_2 a}{2}\right)\cos\left(\frac{k_3 a}{2}\right)$$

$$c = \sqrt{UK}a \quad \textit{and} \quad V = UW$$