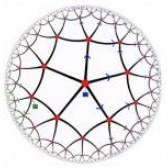
Entangled Butterflies: Chaos in the Quantum World

Brian Swingle (University of Maryland)

January 18, 2020

KITP Teachers Conference



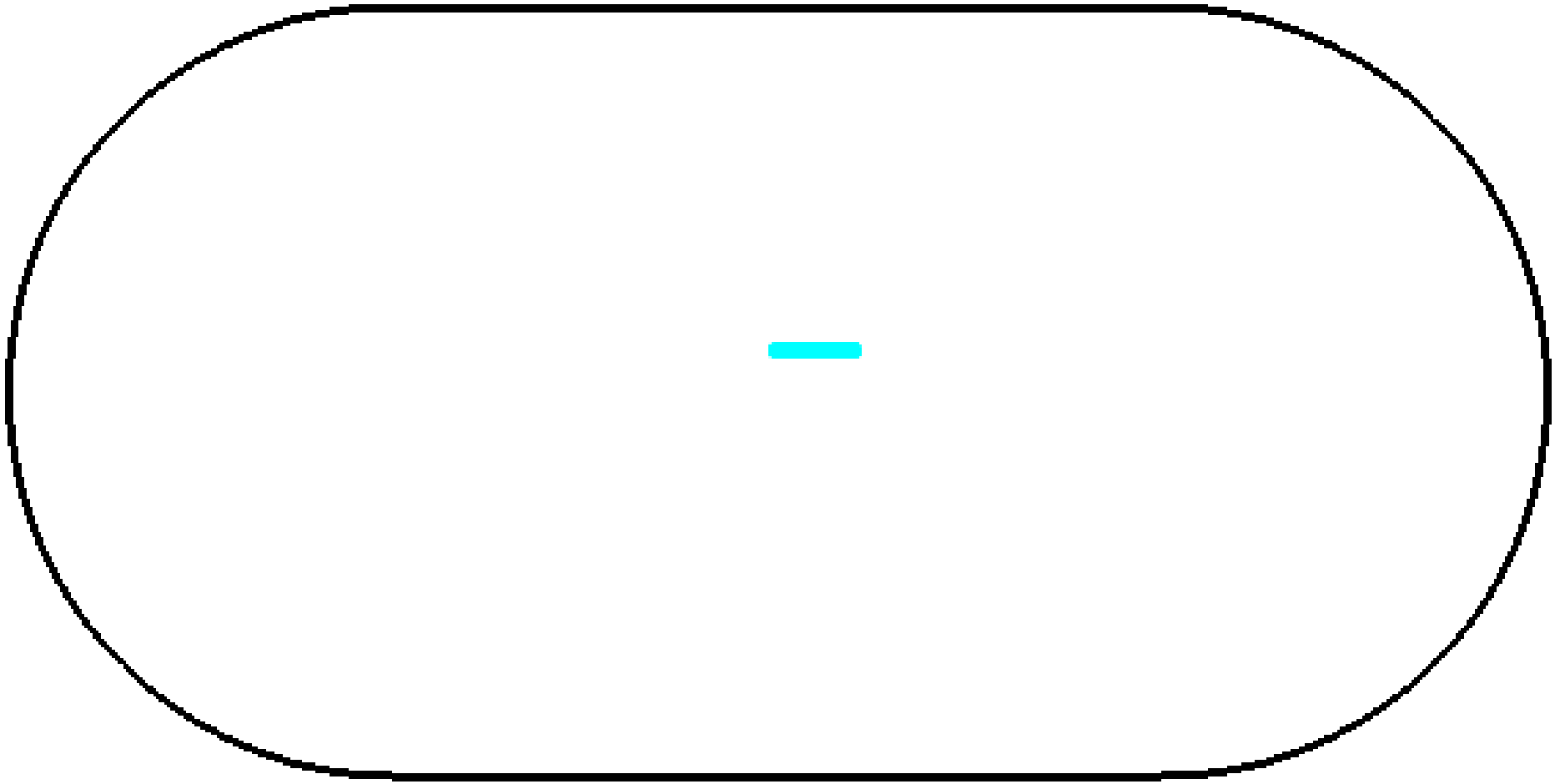
It from Qubit
Simons Collaboration on
Quantum Fields, Gravity and Information

PHYSICS FRONTIER CENTER
JOINT QUANTUM INSTITUTE

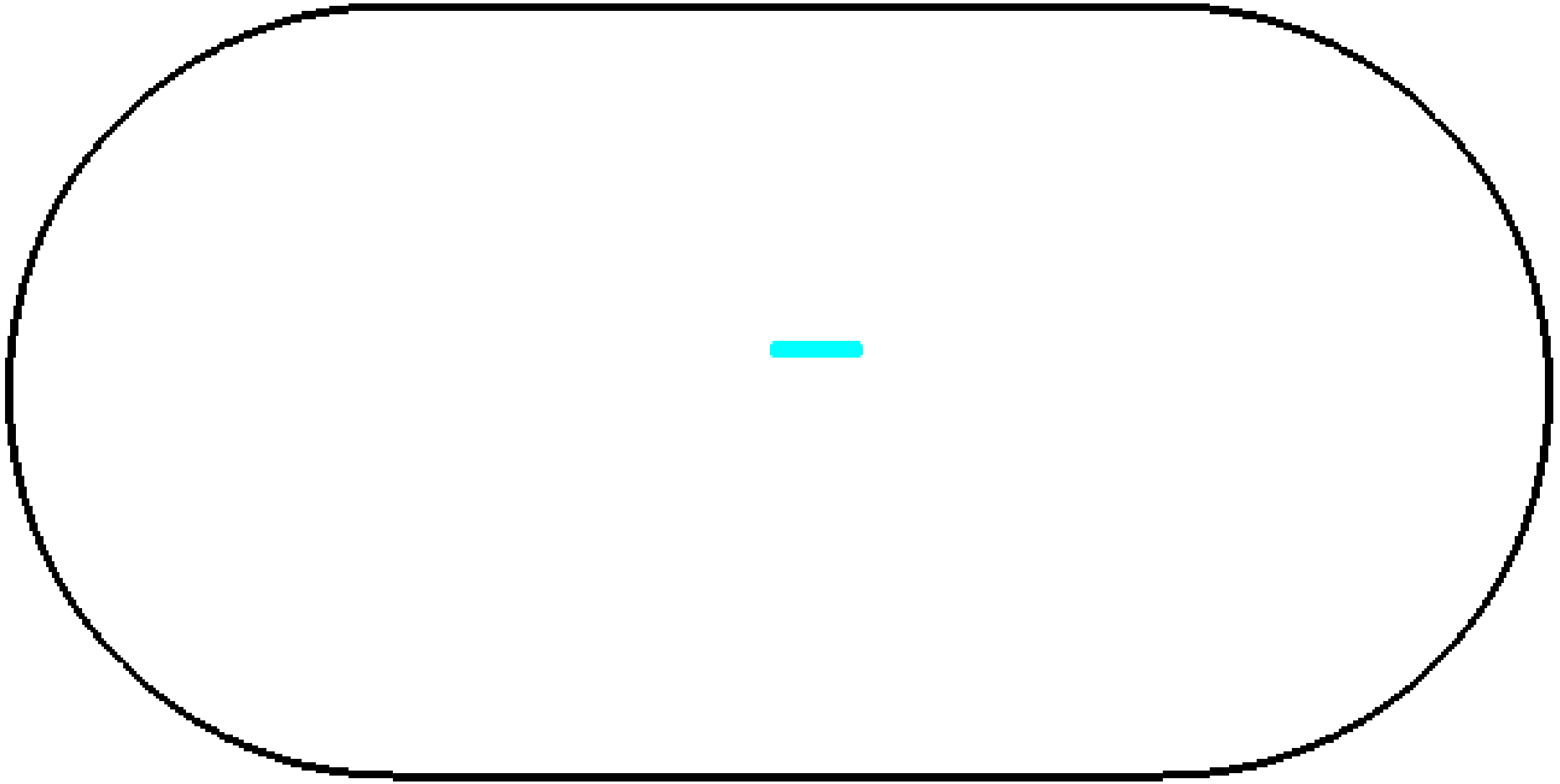
The Butterfly Effect.

by
J. L. Westover

www.mrlovenstein.com

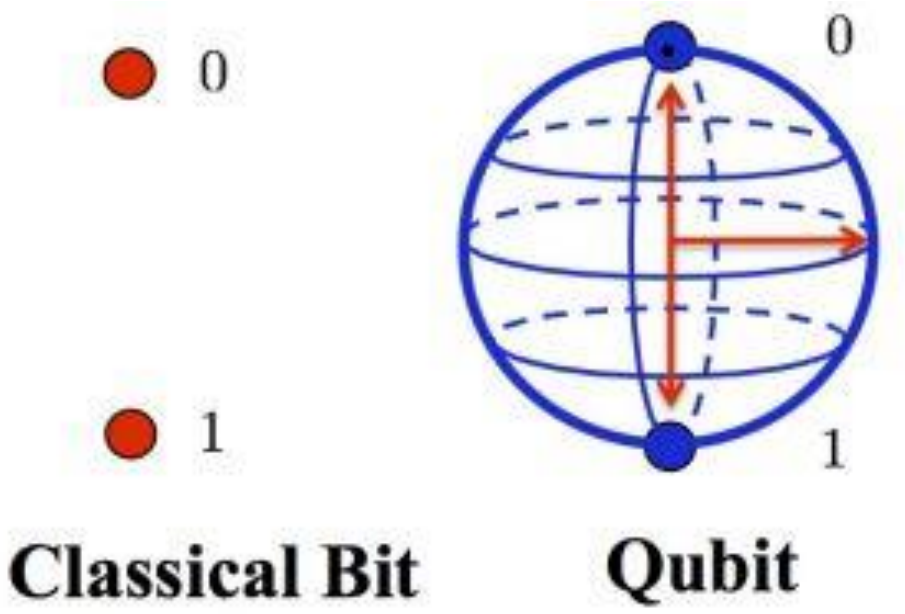


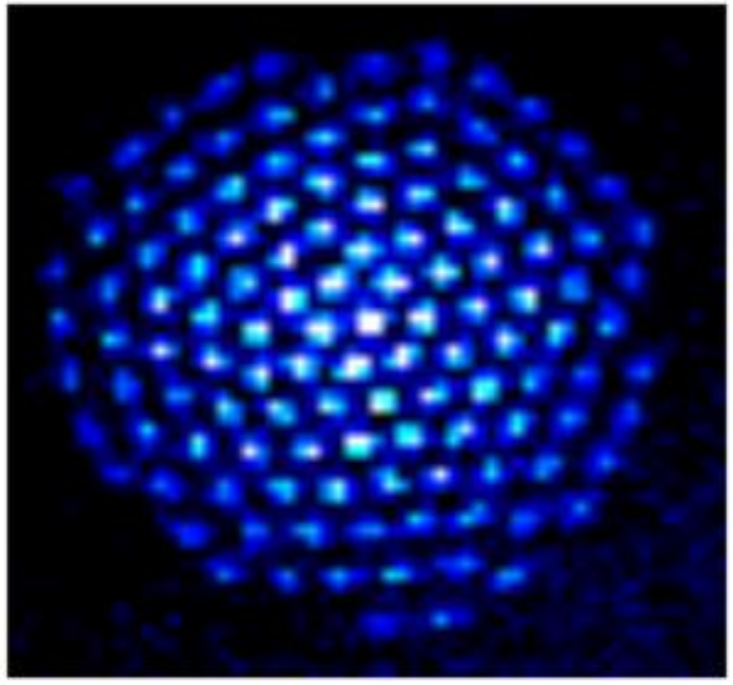
[Bunimovich stadium – simulation by Phillipe Roux, https://blogs.ams.org/visualinsight/2016/11/15/bunimovich-stadium/]



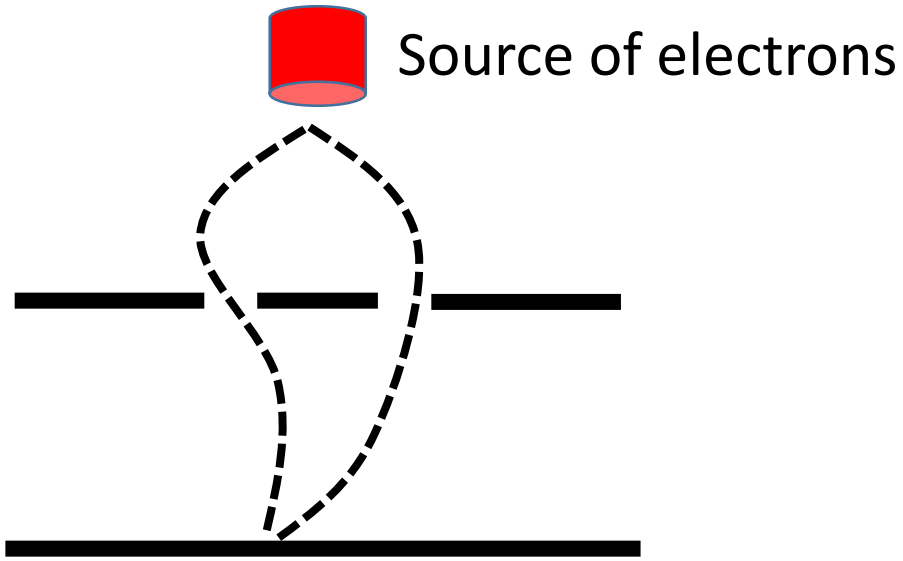
[Bunimovich stadium – simulation by Phillipe Roux, https://blogs.ams.org/visualinsight/2016/11/15/bunimovich-stadium/]

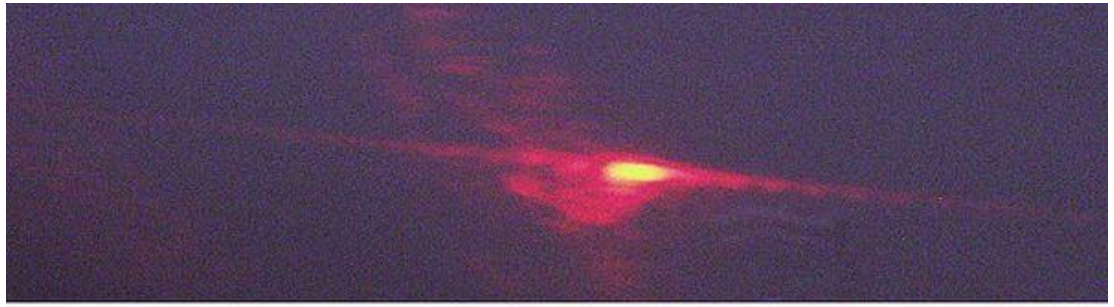
Smallest possible perturbation?



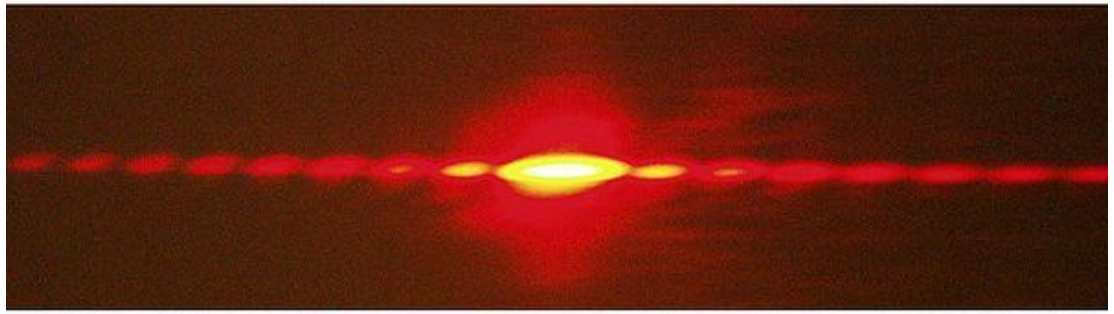


[Courtesy of John Bollinger]



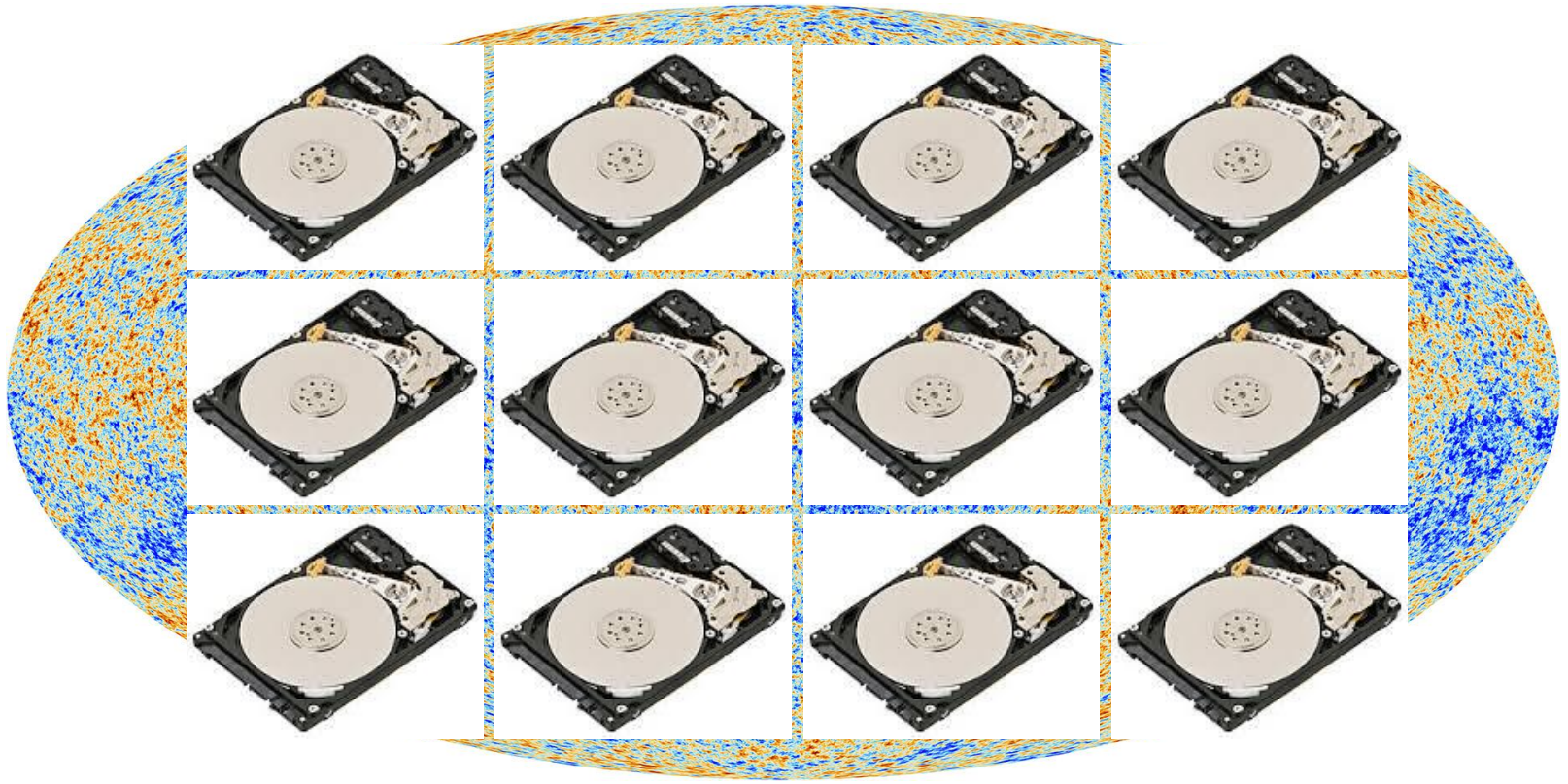


Pattern produced from a single slit.



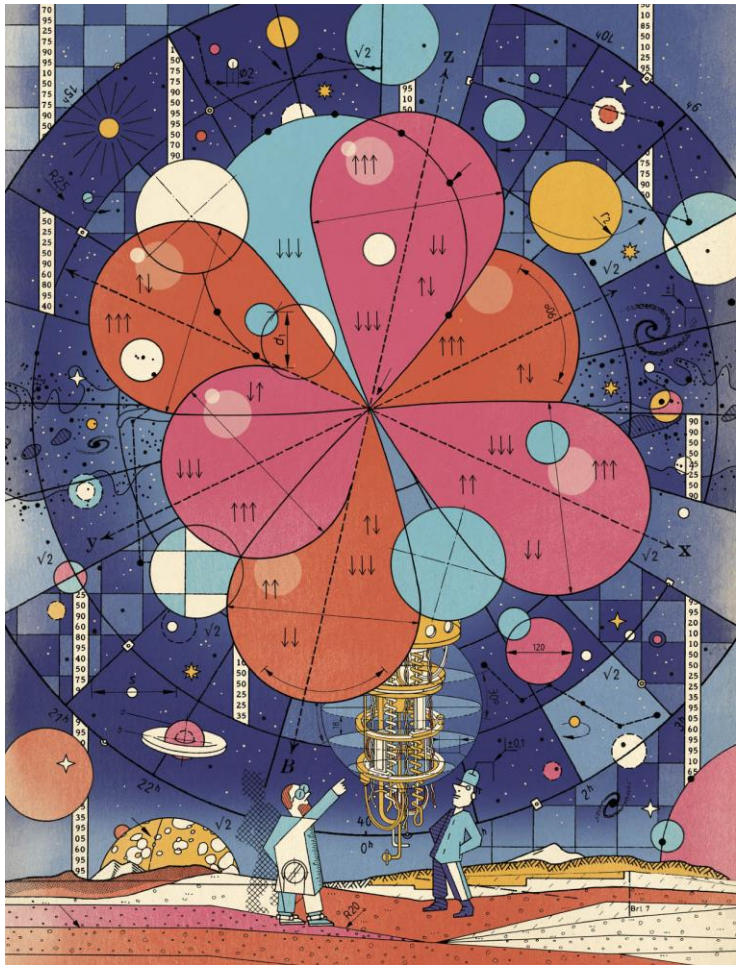
Pattern produced from a double slit.

Context: complexity/entanglement frontier



Fill universe with hard drives $\approx 10^{97}$ bits

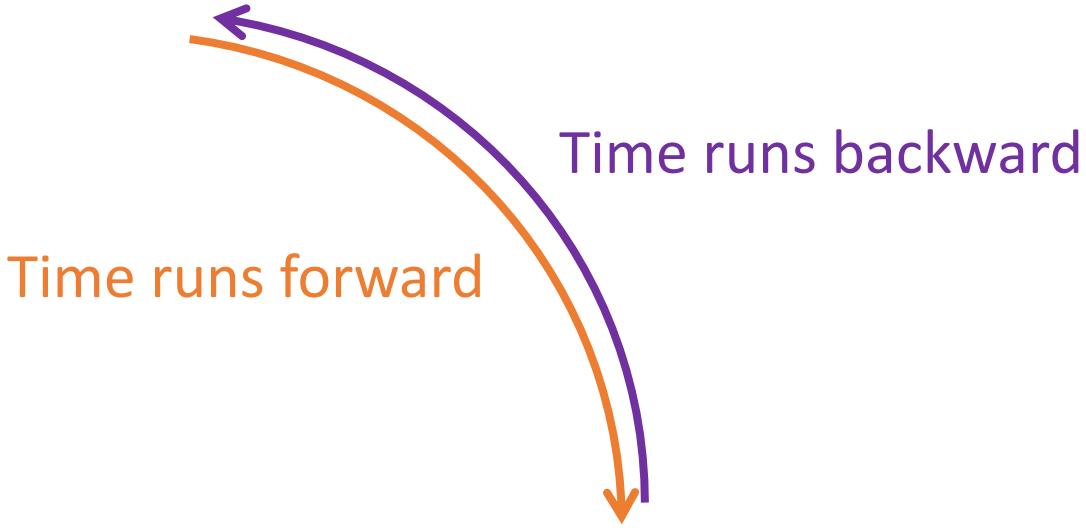
→ Sufficient only for a few hundred spins

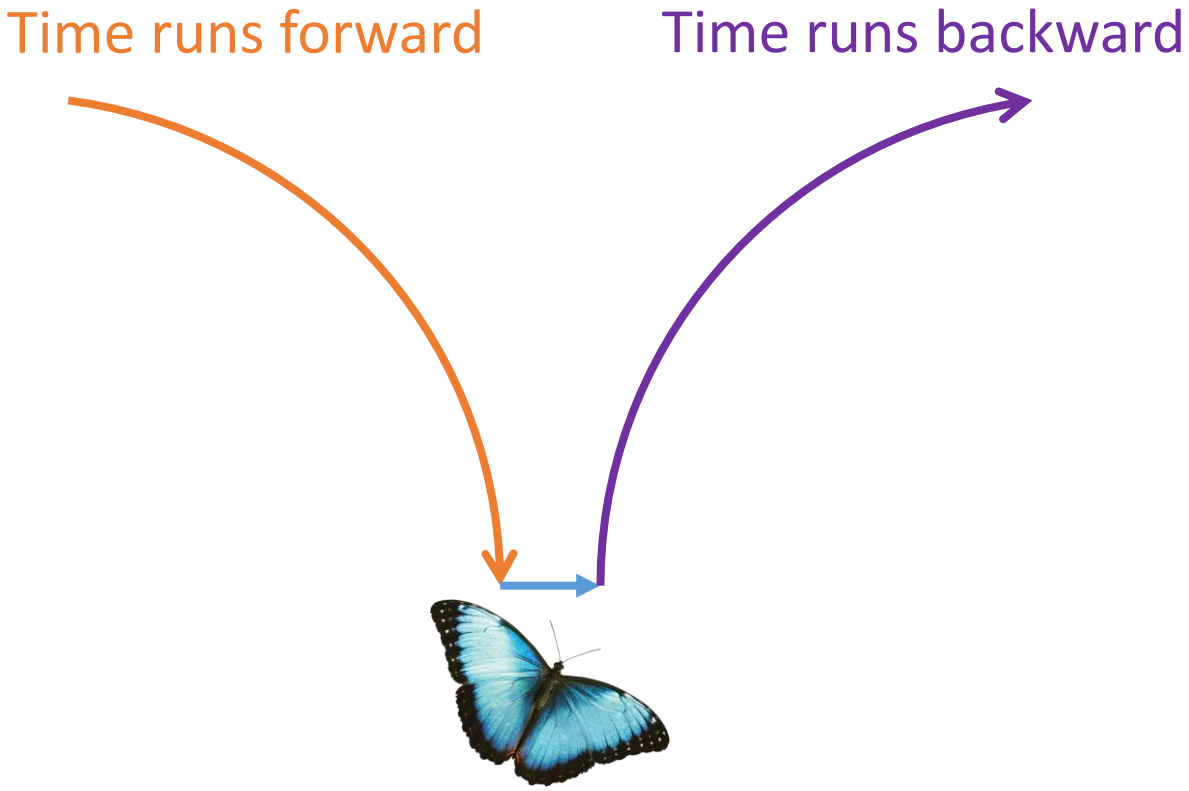


[Art by Christian Gralingen]

The Quantum Butterfly Effect

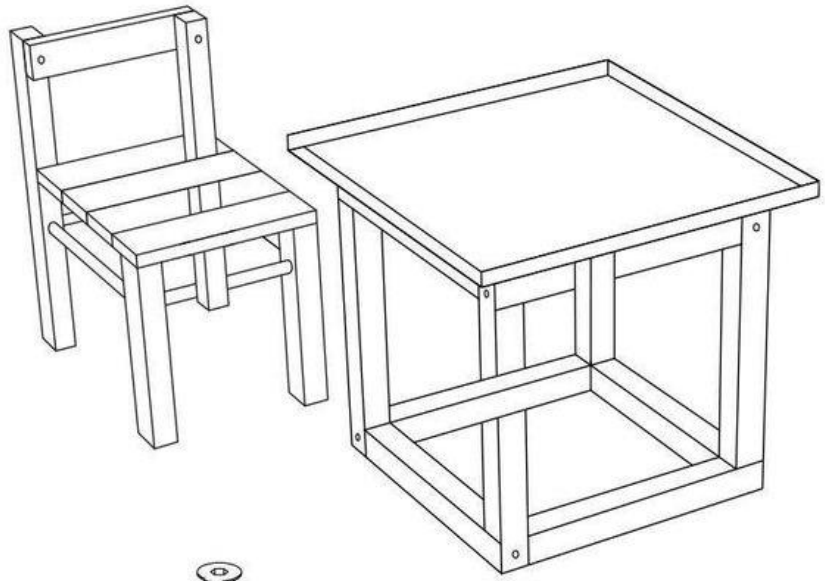
Quantum butterfly effect thought experiment

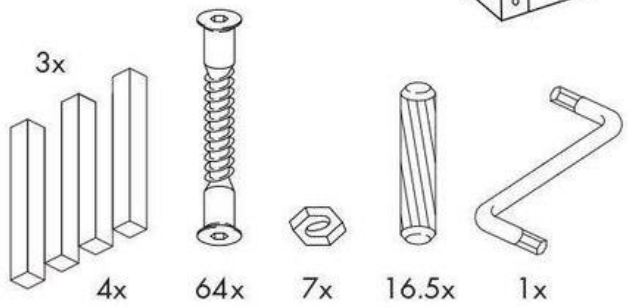




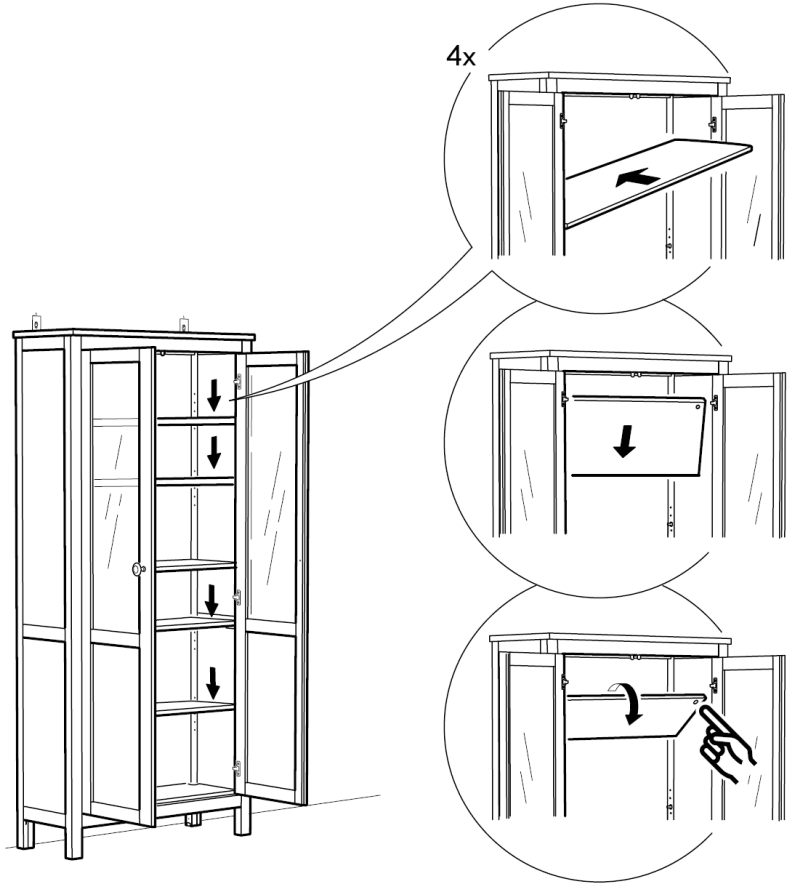
PARADÖX

play table and chair





34

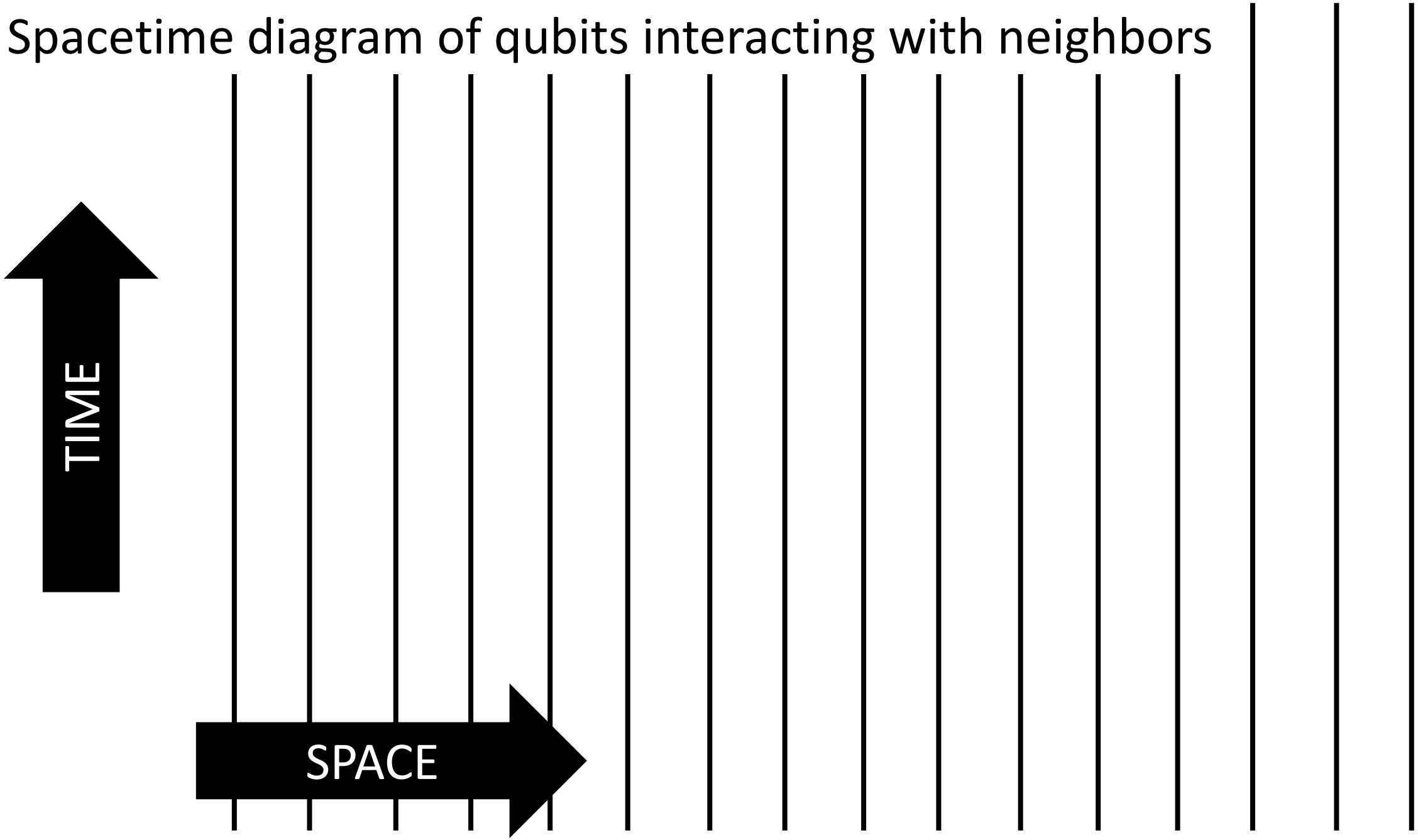


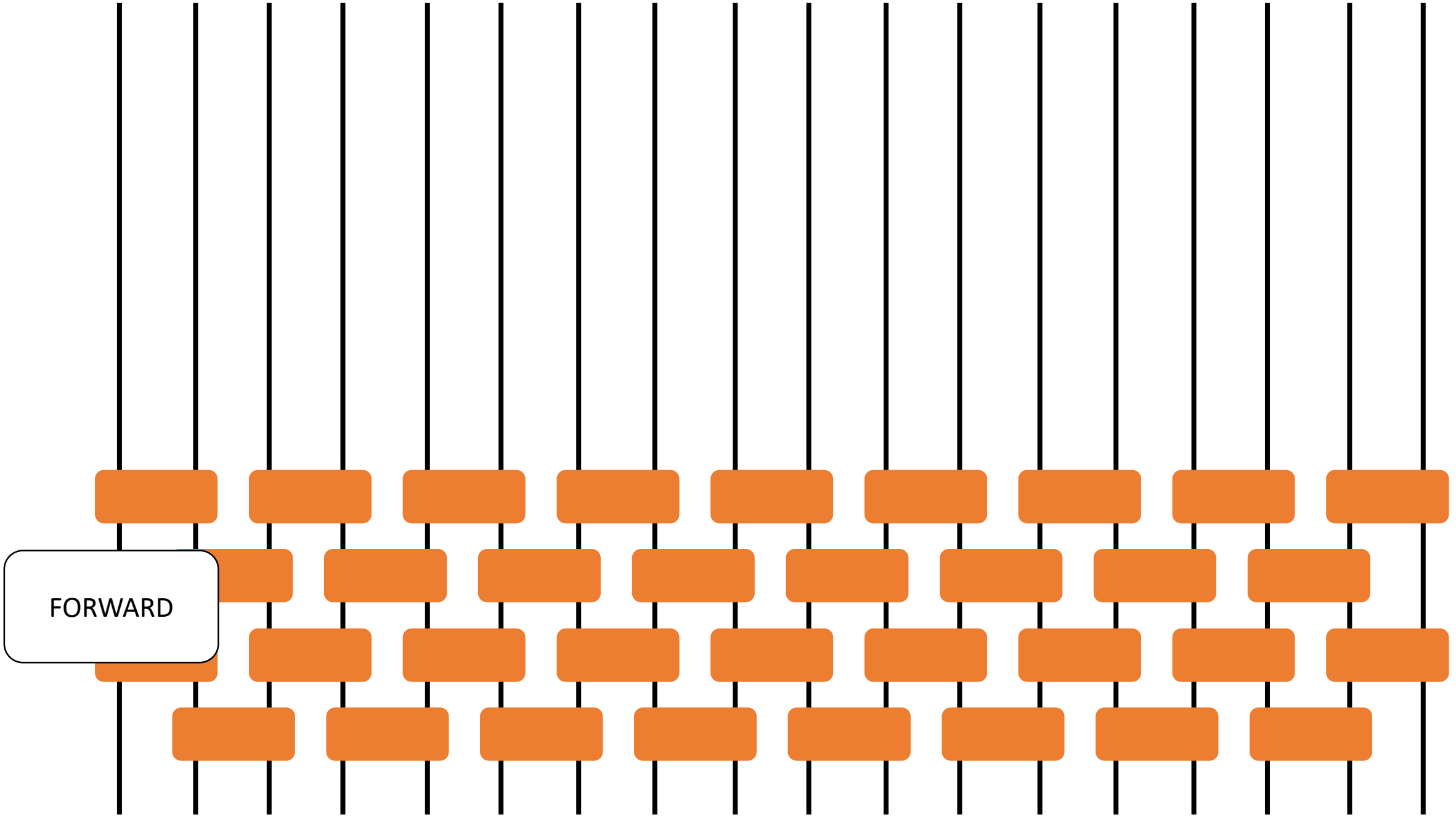
???

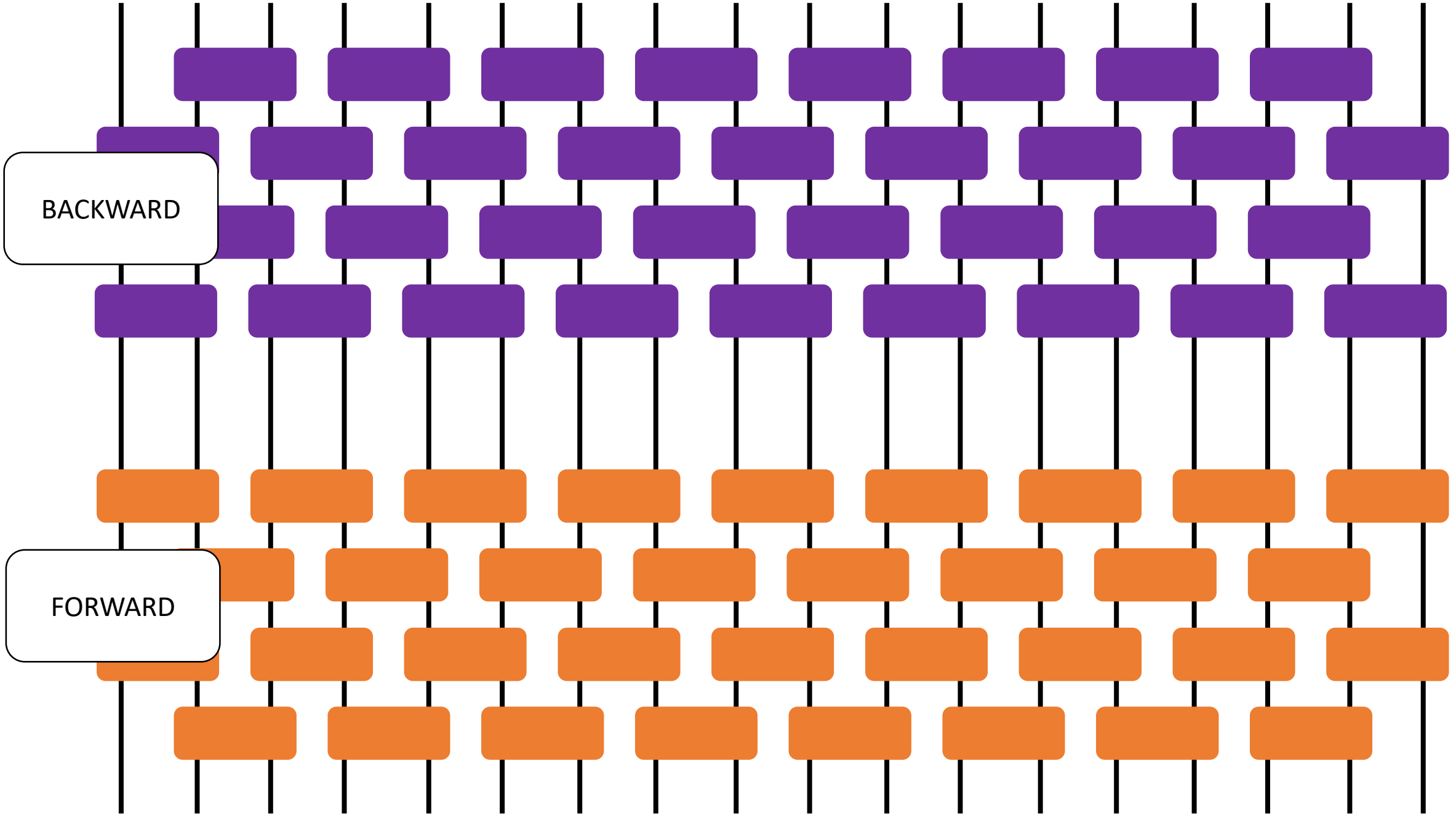
Missed a screw in step 2!

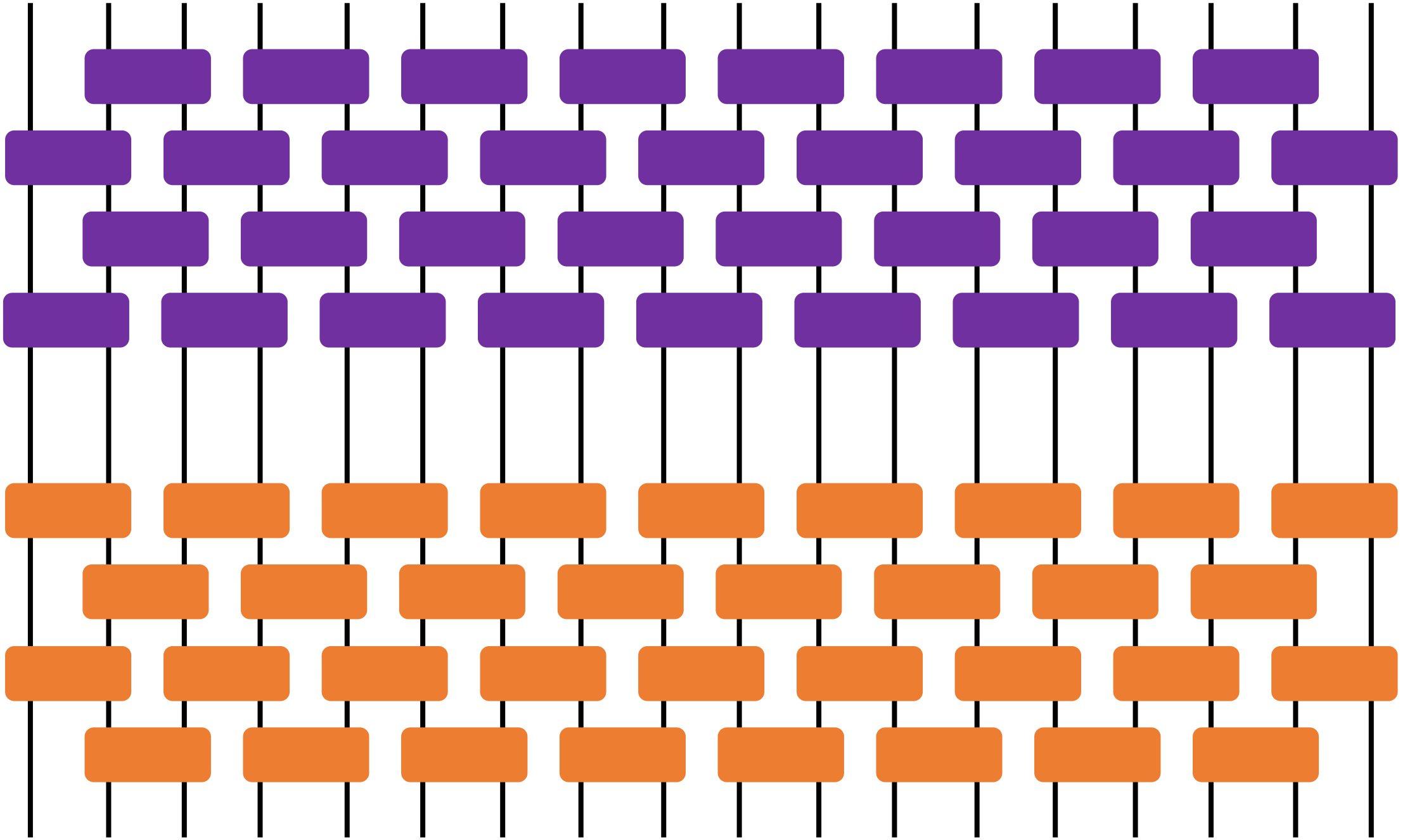
Fix: deconstruct back to step 2, add screw, rebuild

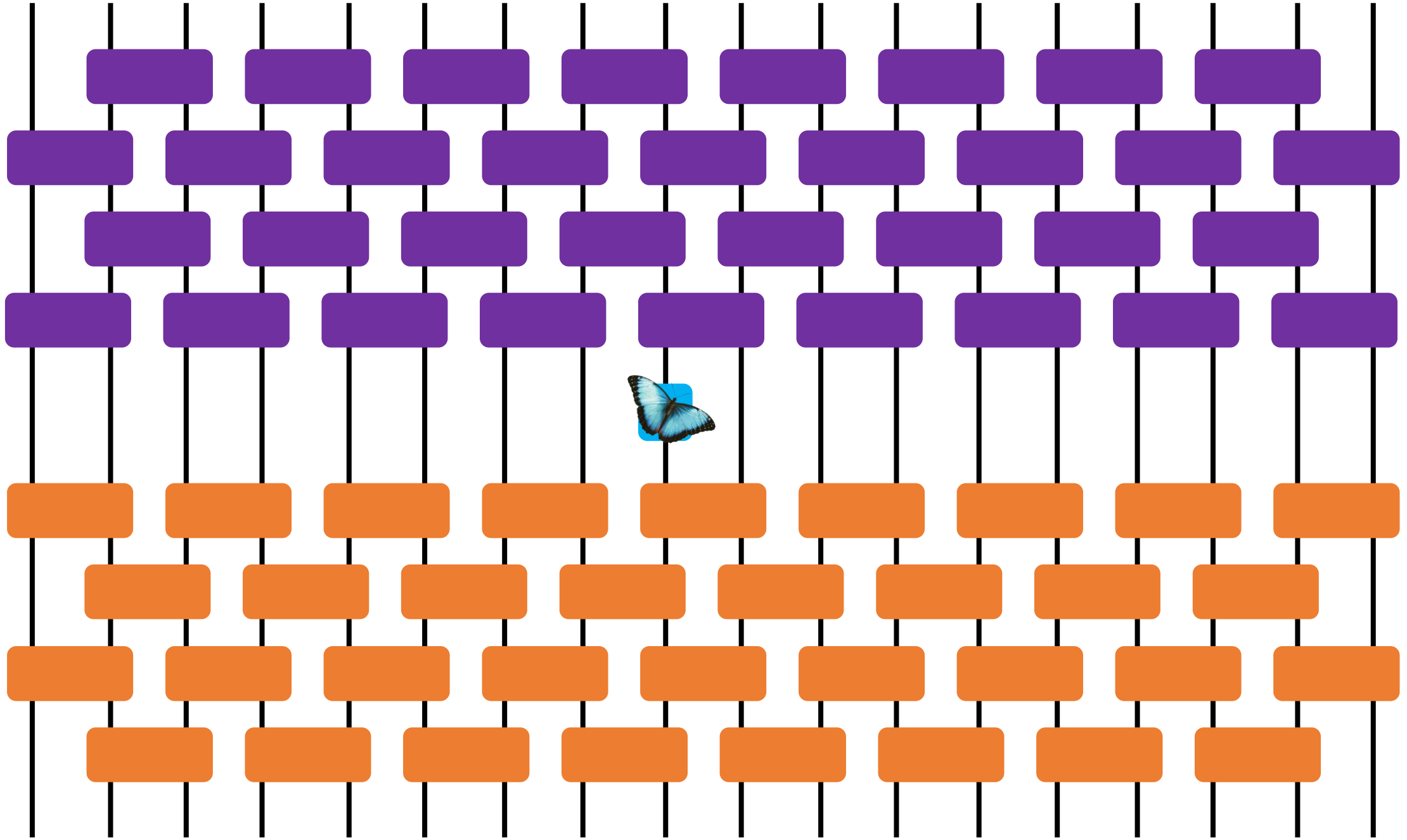
Spacetime diagram of qubits interacting with neighbors



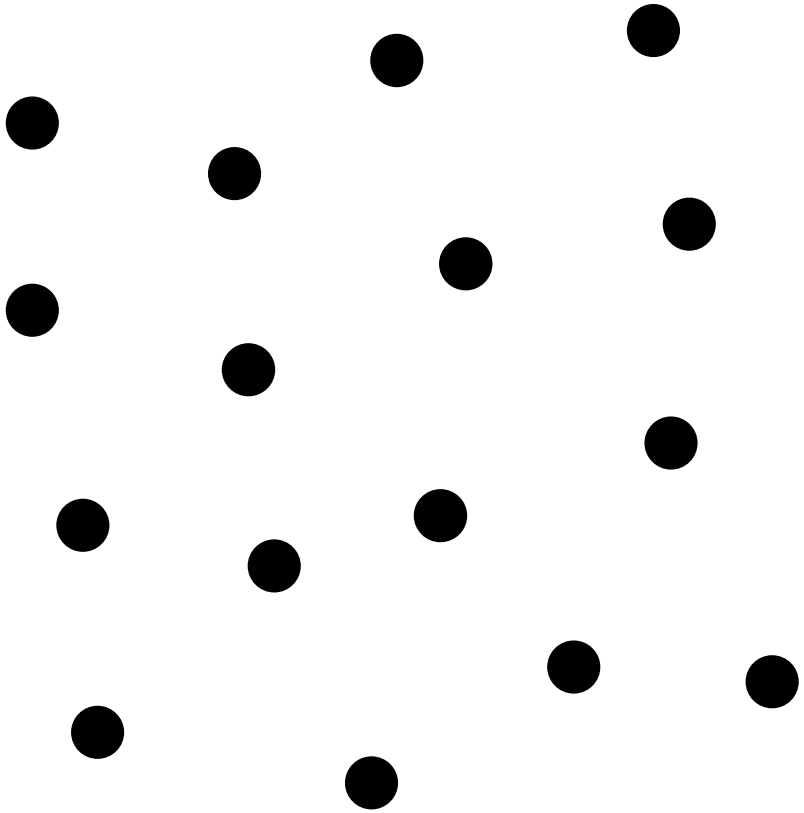

FORWARD

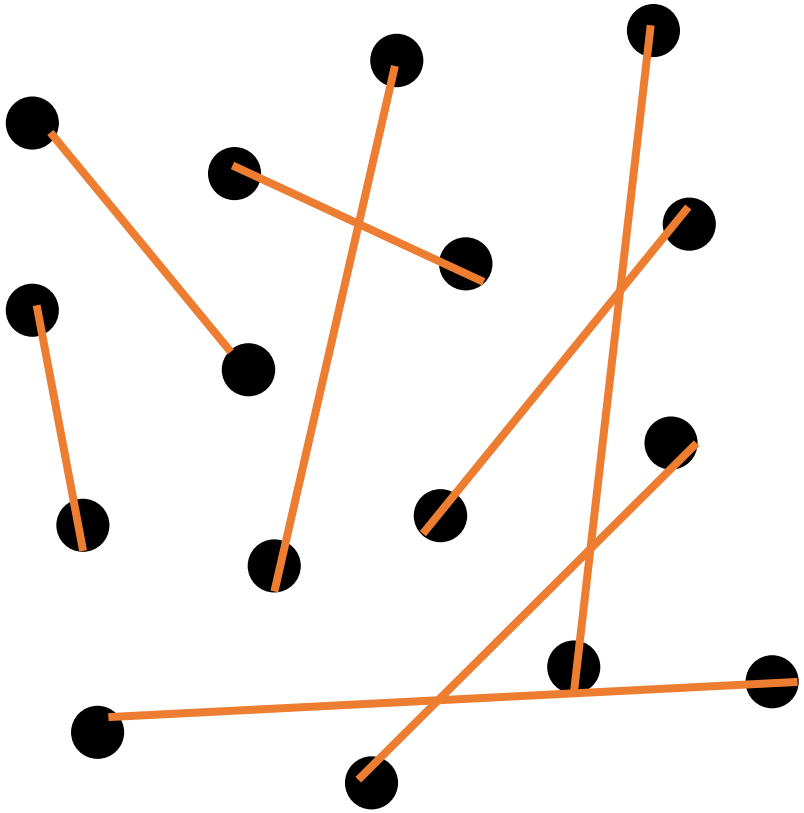

BACKWARD
FORWARD

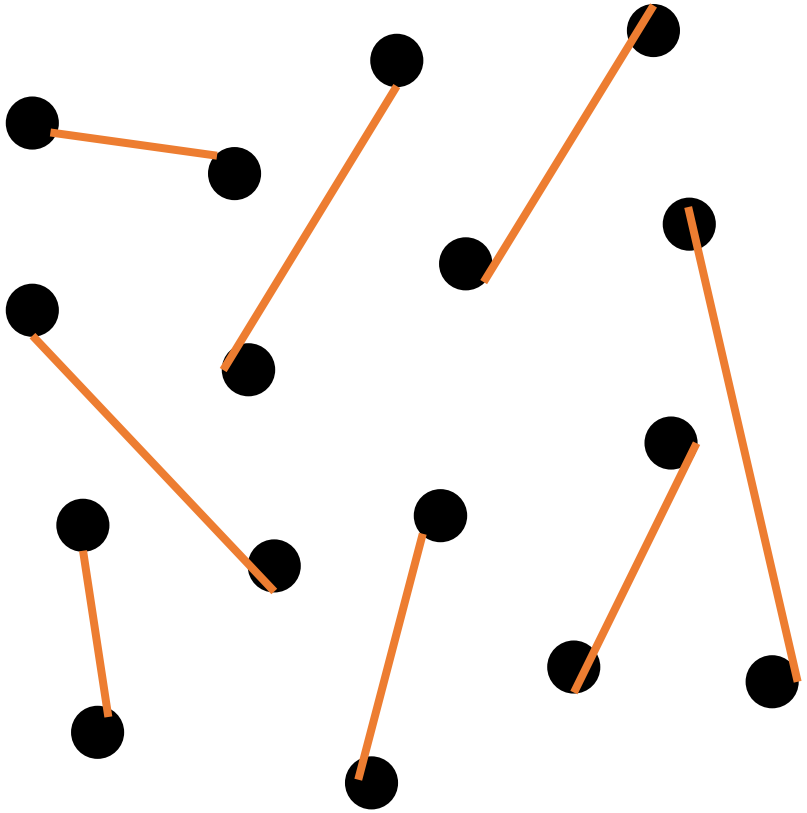


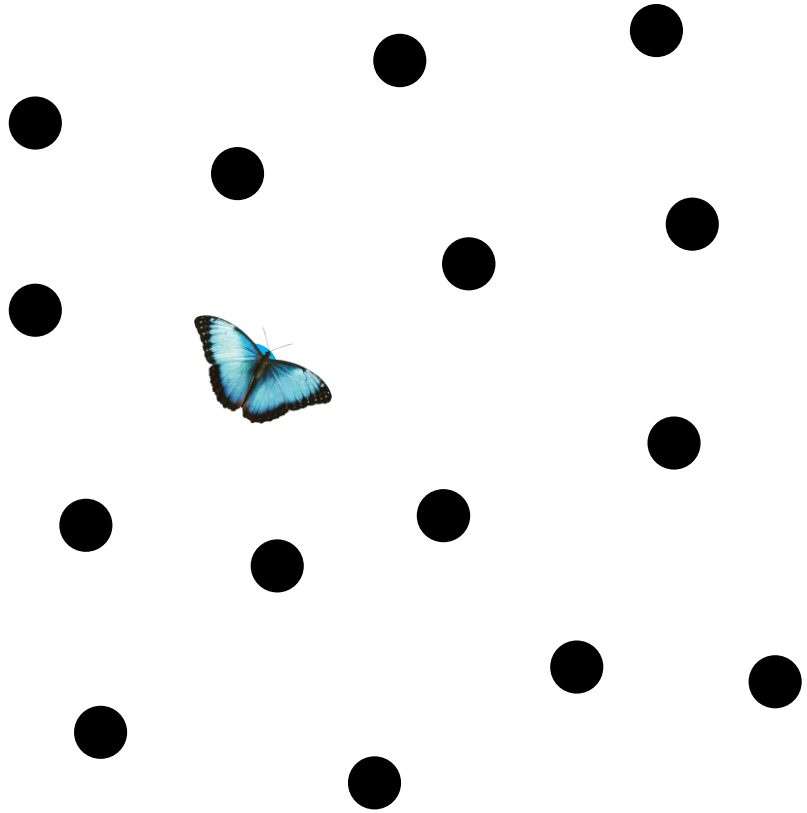


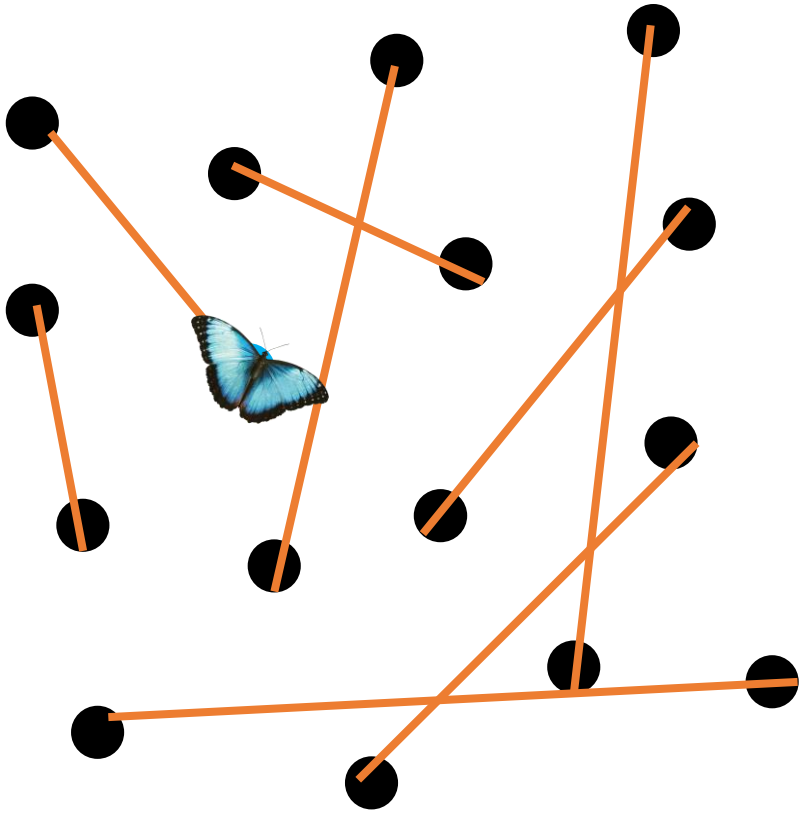
Snapshots of qubits with all-to-all interactions

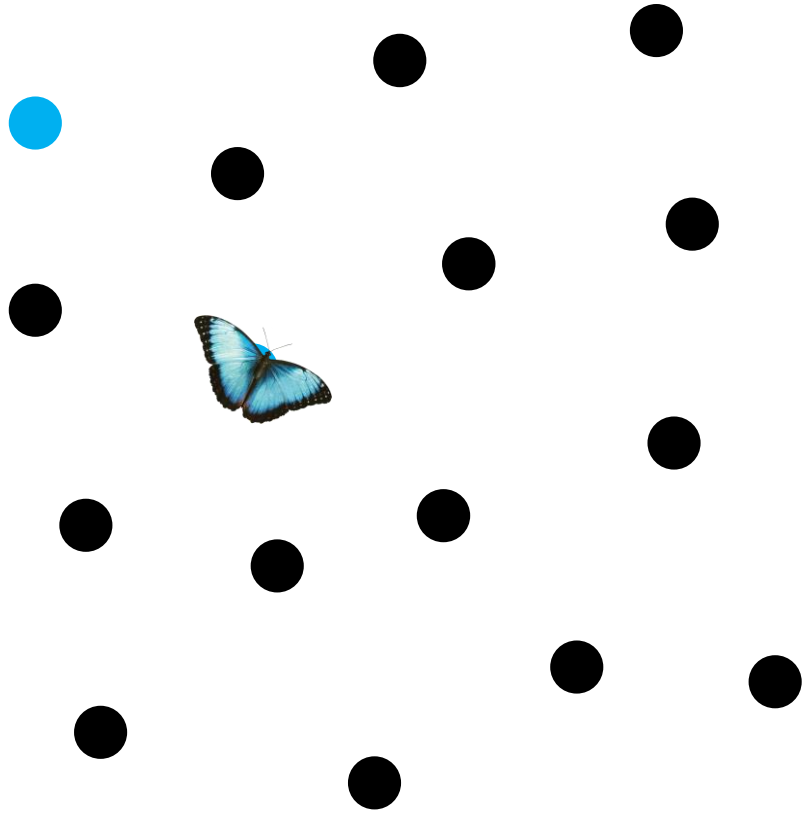


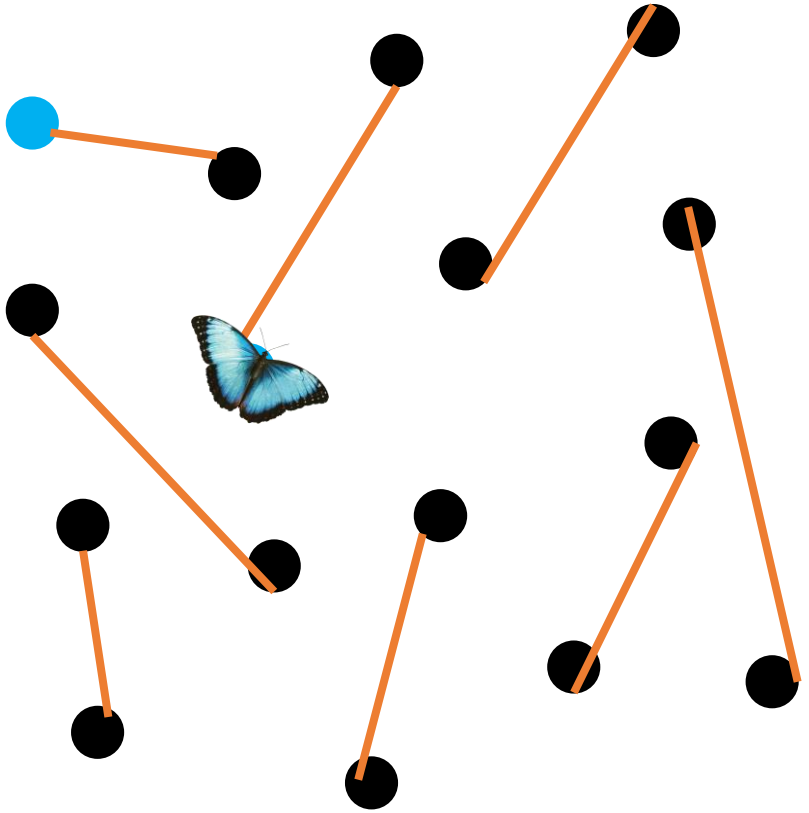


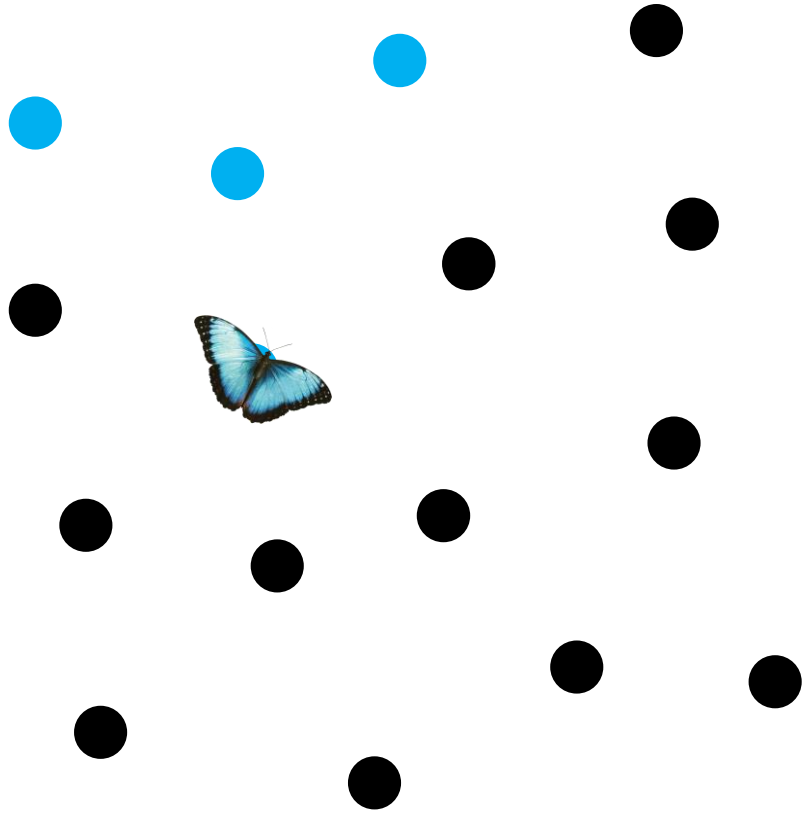


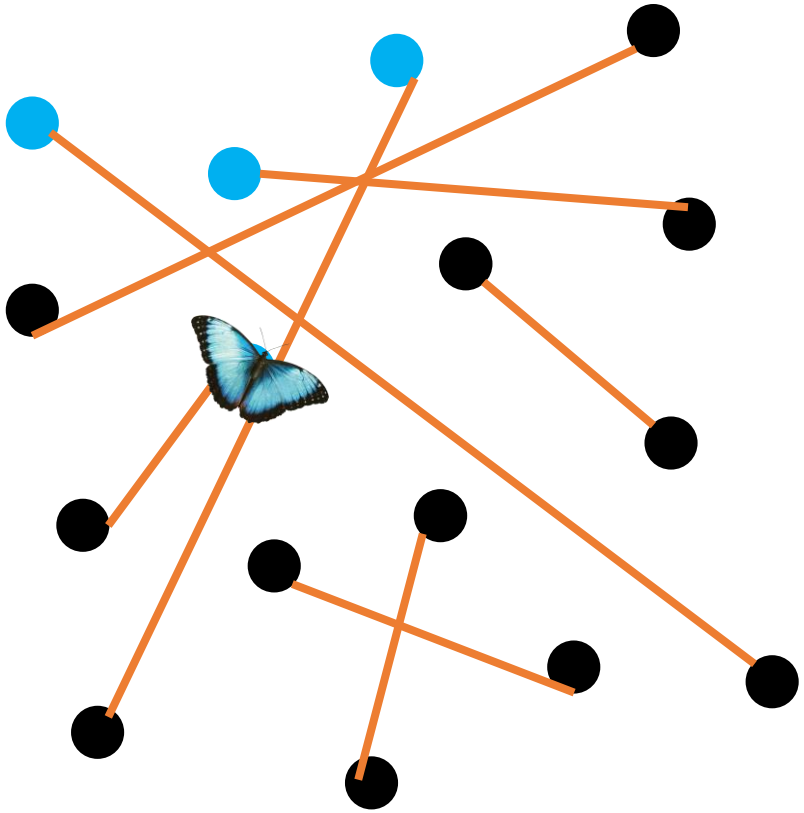


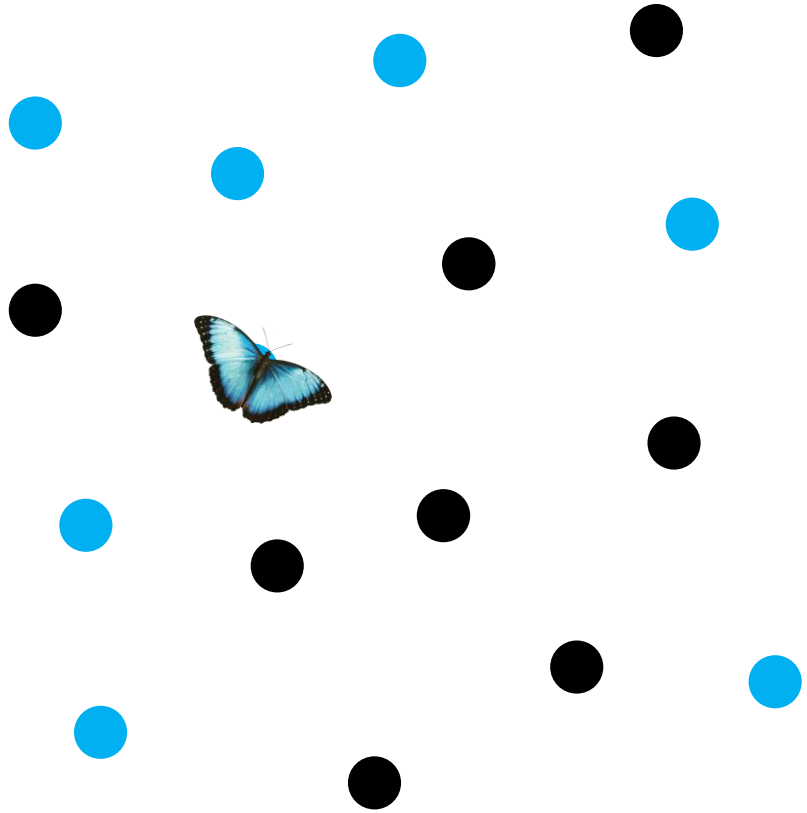




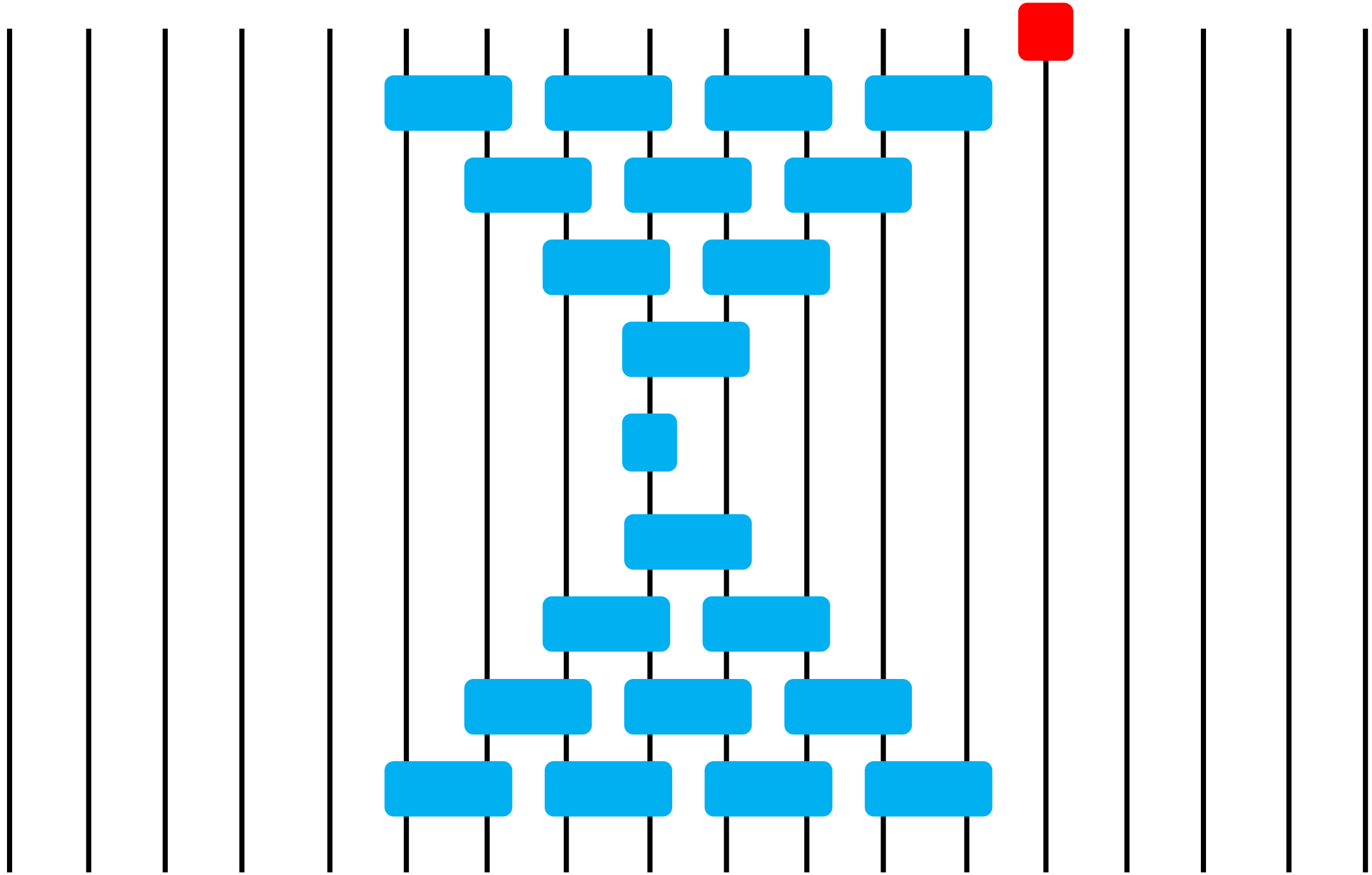








Affected region doubles every time step …

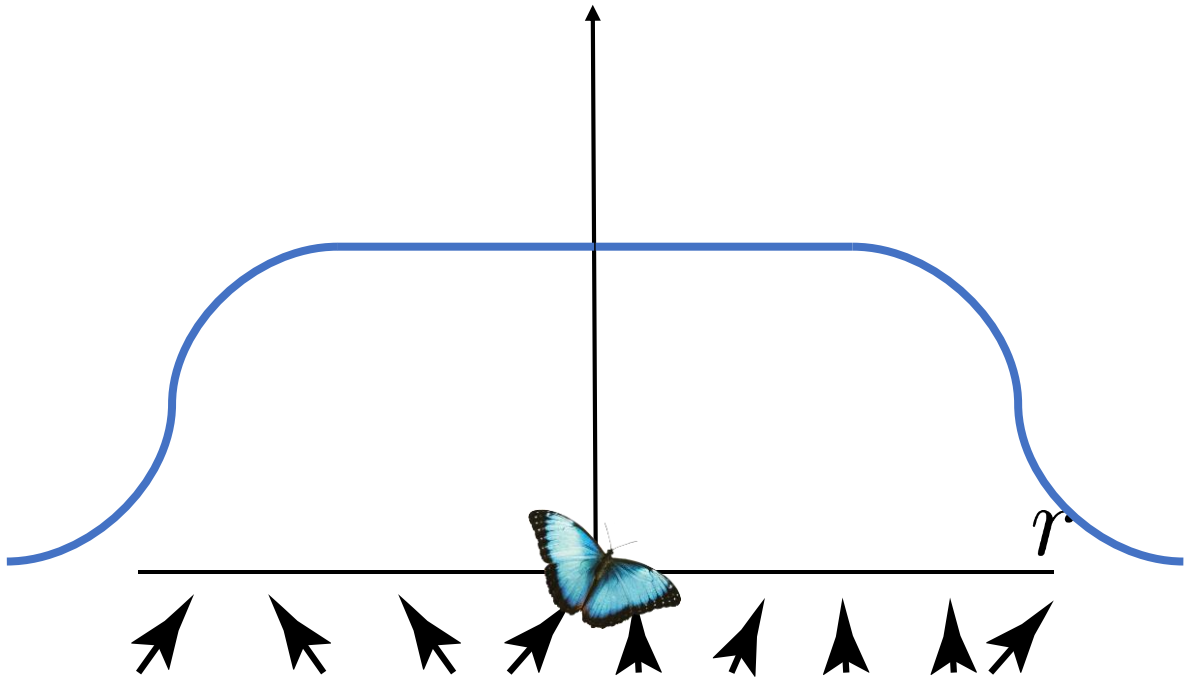


$$
\begin{aligned}
\partial_t \tilde{h} = \sum_r \Big[-\gamma_r^+(w)\tilde{h}(\mathbf{w}) + \gamma_r^+(w+1)\tilde{h}(\mathbf{w}+\mathbf{e}_r) \Big] + \\
\Big[-\gamma_r^-(w)\tilde{h}(\mathbf{w}) + \gamma_r^-(w-1)\tilde{h}(\mathbf{w}-\mathbf{e}_r) \Big] \\
+ \sum_{\langle rr' \rangle} \Big[-\gamma_b^+(w_r, w_{r'})\tilde{h}(\mathbf{w}) + \gamma_b^+(w_r+1, w_{r'})\tilde{h}(\mathbf{w}+\mathbf{e}_r) \Big] \\
+ \Big[-\gamma_b^-(w_r, w_{r'})\tilde{h}(\mathbf{w}) + \gamma_b^-(w_r-1, w_{r'})\tilde{h}(\mathbf{w}-\mathbf{e}_r) \Big] \\
+ [r \longleftrightarrow r']
\end{aligned}
$$

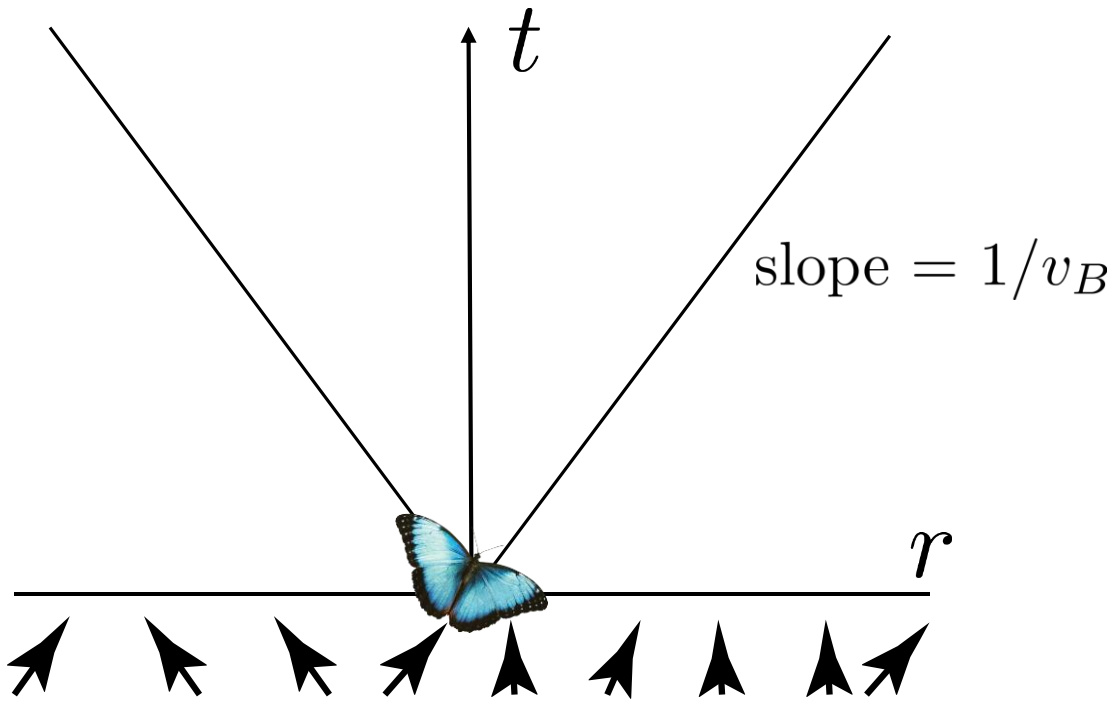
$$
\gamma_r^+(w) = \frac{1}{N-1} w(w-1), \;\; \gamma_r^-(w) = \frac{1}{N-1} 3(N-w)w
$$

$$
\gamma_b^+(w_1, w_2) = \frac{g^2}{2N} w_1 w_2, \;\; \gamma_b^-(w_1, w_2) = \frac{g^2}{2N} 3(N-w_1)w_2.
$$

strength of perturbation at a fixed time



spacetime contours of constant strength



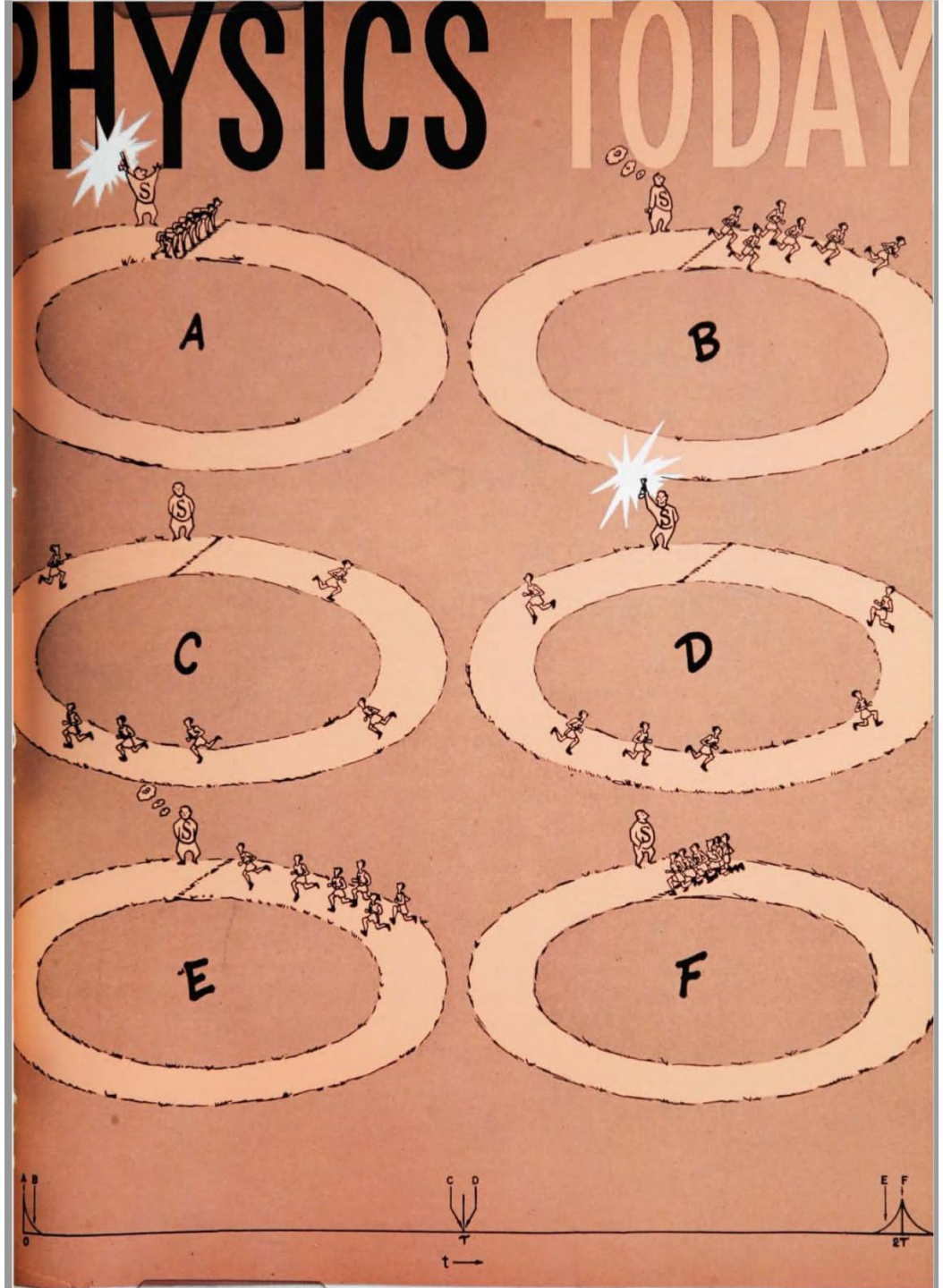
Two related questions:

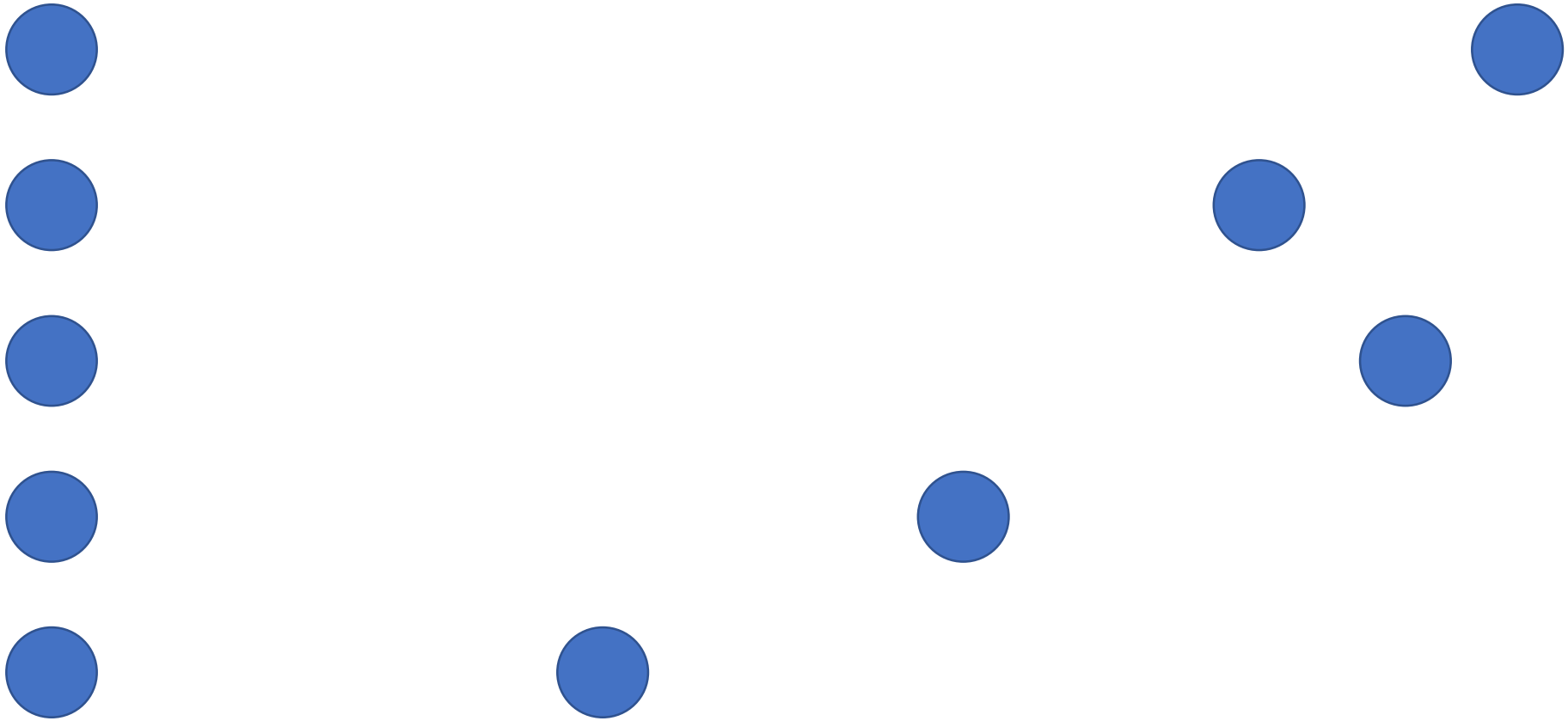
(1) How do we measure this effect?

(2) How does it manifest in physical properties?

Measuring Quantum Chaos

PHYSICS TODAY





Reverse!

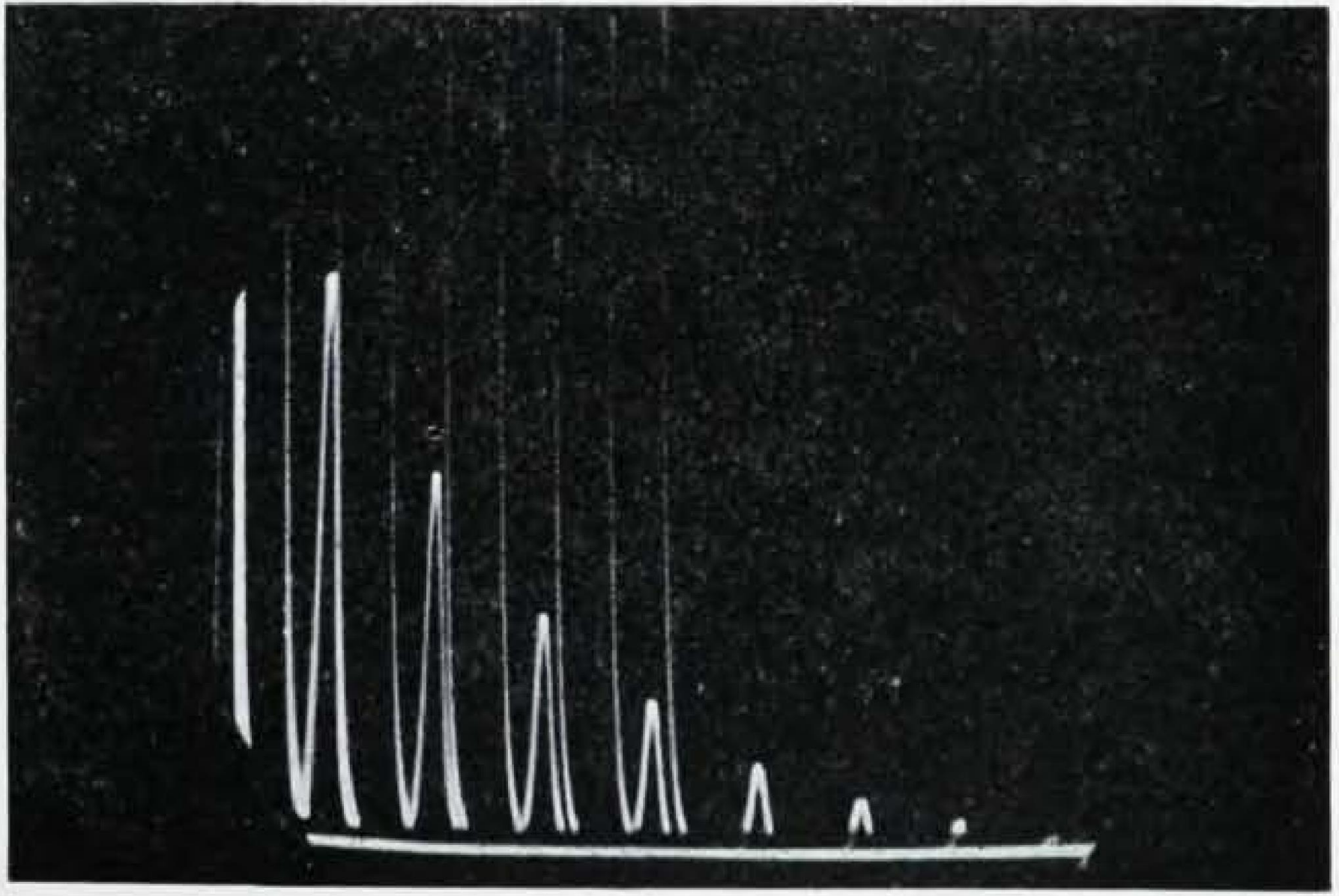
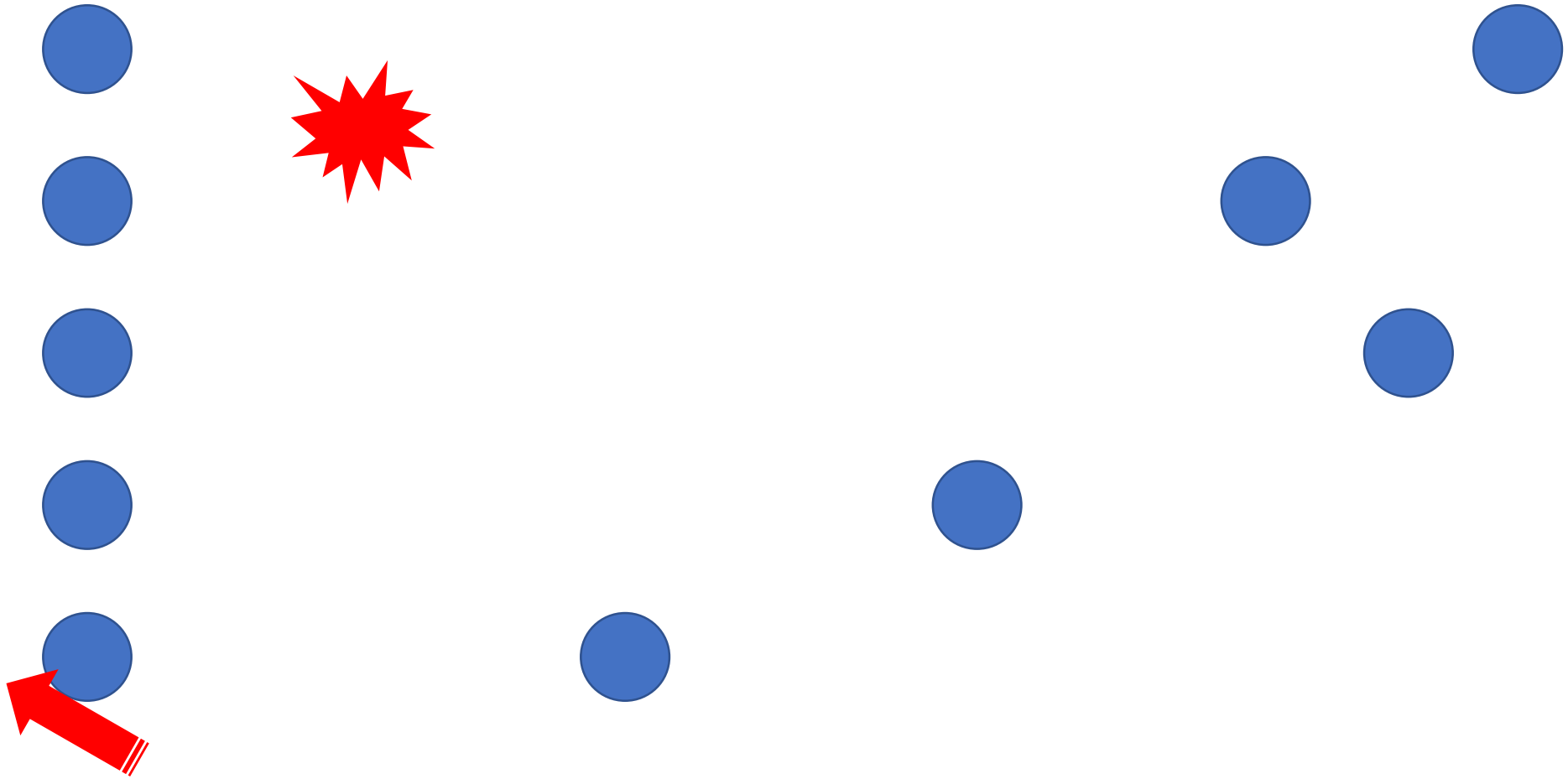


Fig. 6. Multiple exposures of single proton echoes. The first rf pulse occurs at the beginning of the trace and the second pulse is spaced from the origin at equal intervals for each exposure with the sample at thermal equilibrium. The echo envelope provides a measure of the phase coherence parameter T_2.

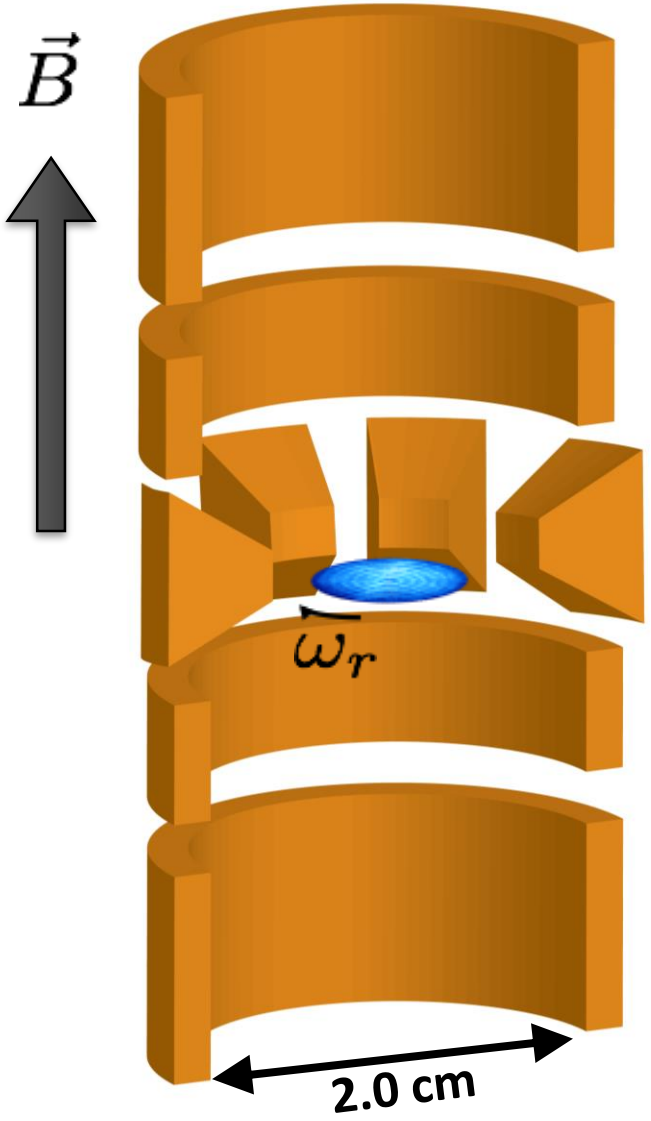
[Spin Echoes: Hahn 1950]

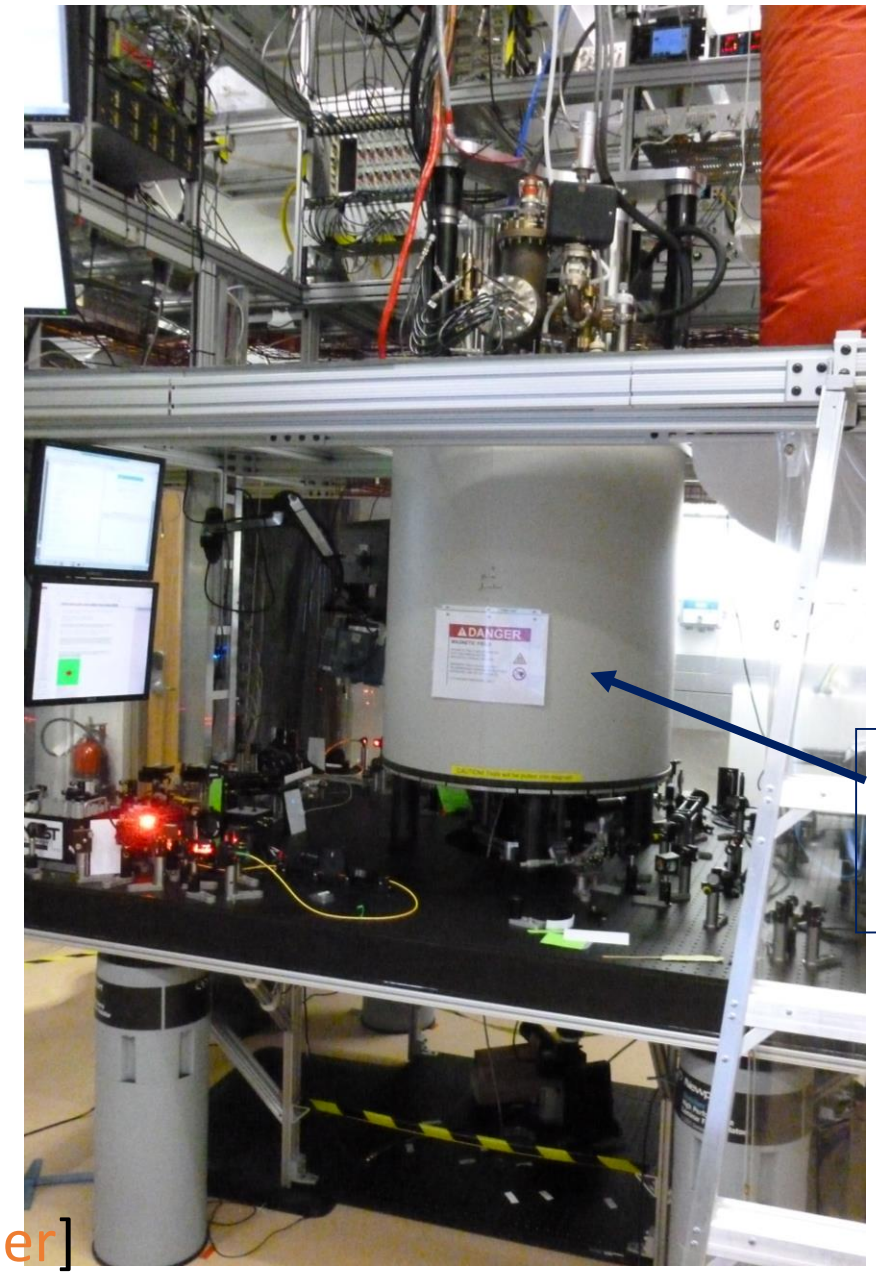

Reverse!

Needed: inverse DeLorean

-1

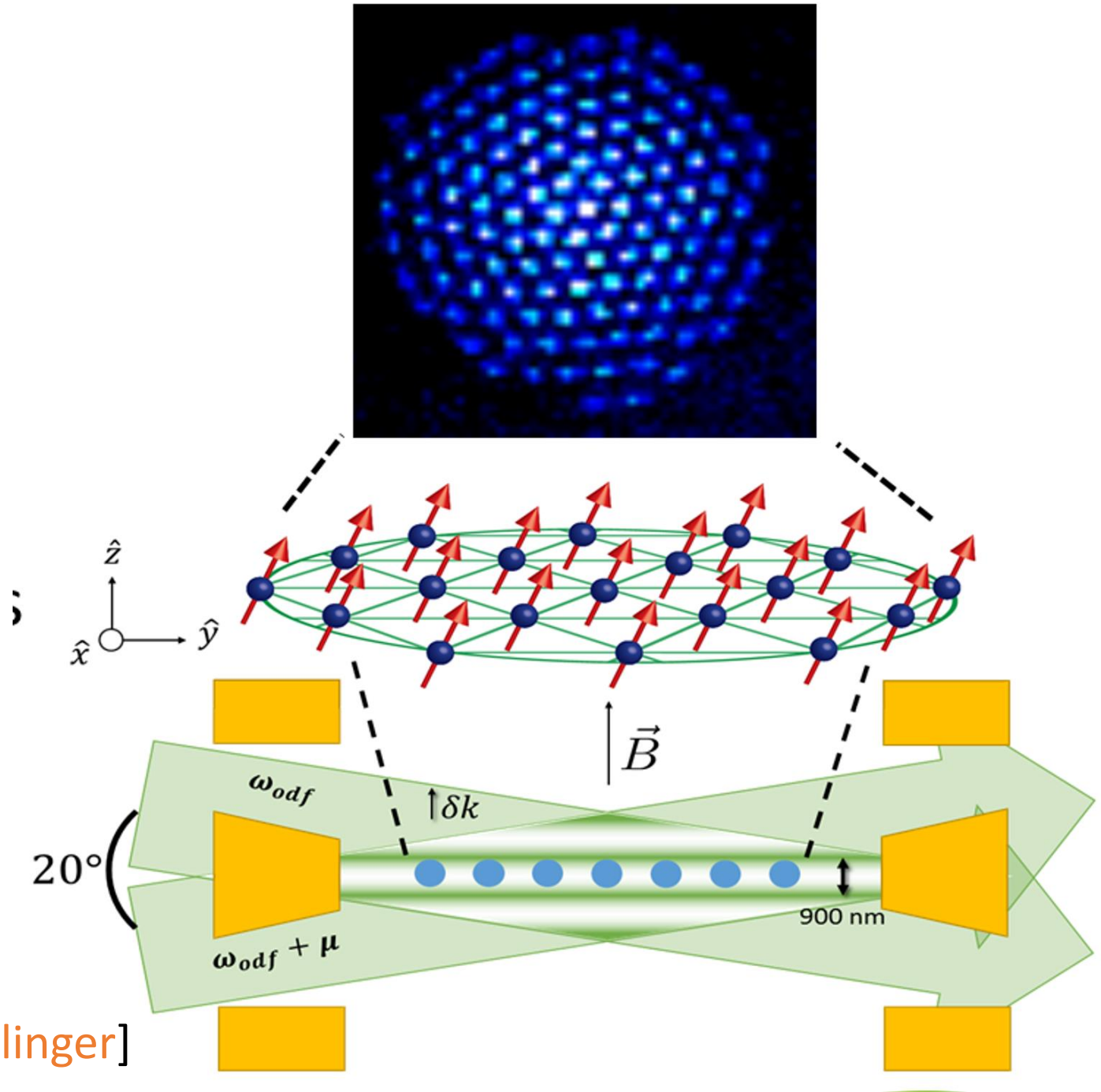
NIST Penning trap





4.5 Tesla superconducting solenoid

[Courtesy of John Bollinger, NIST Boulder]

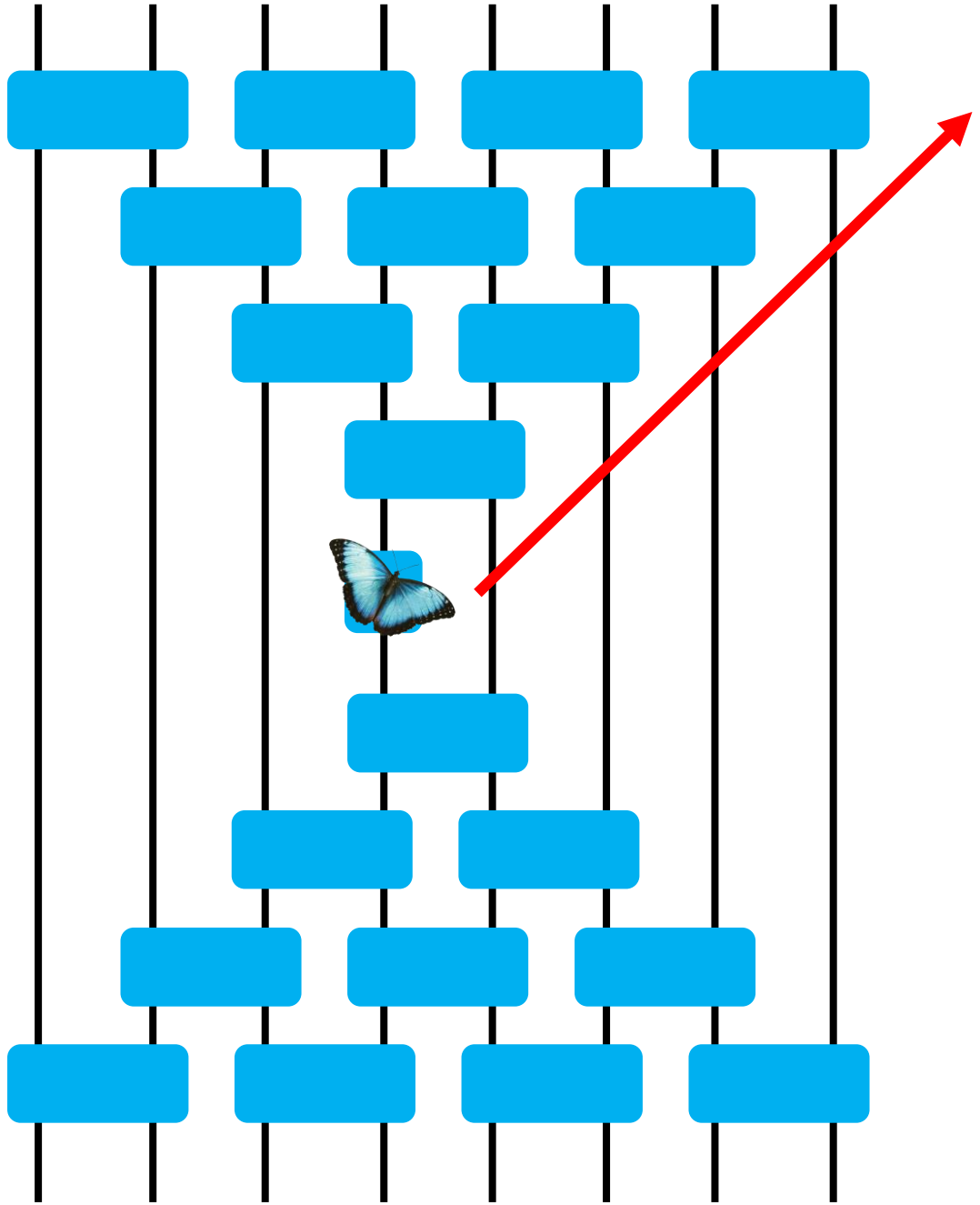


[Courtesy of John Bollinger]

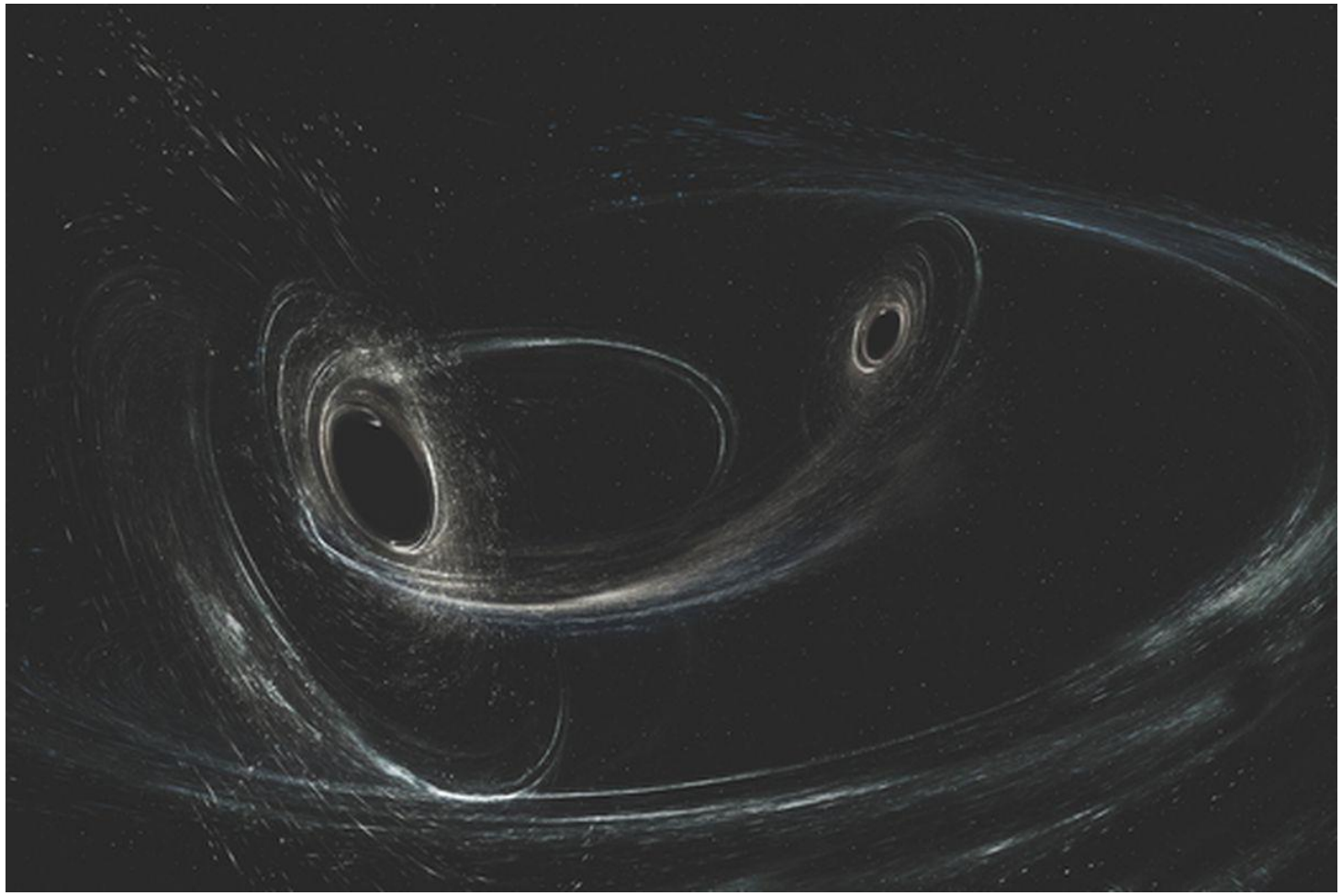
Speed Limits

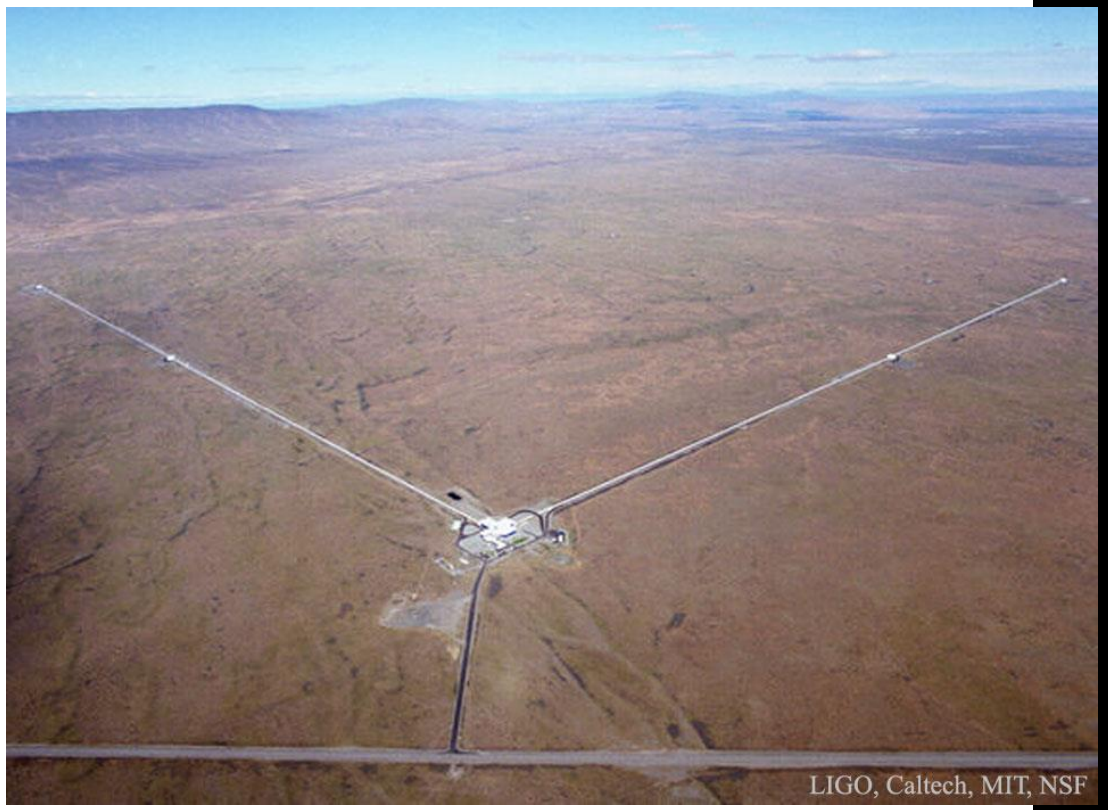
SPEED
LIMIT
670616629

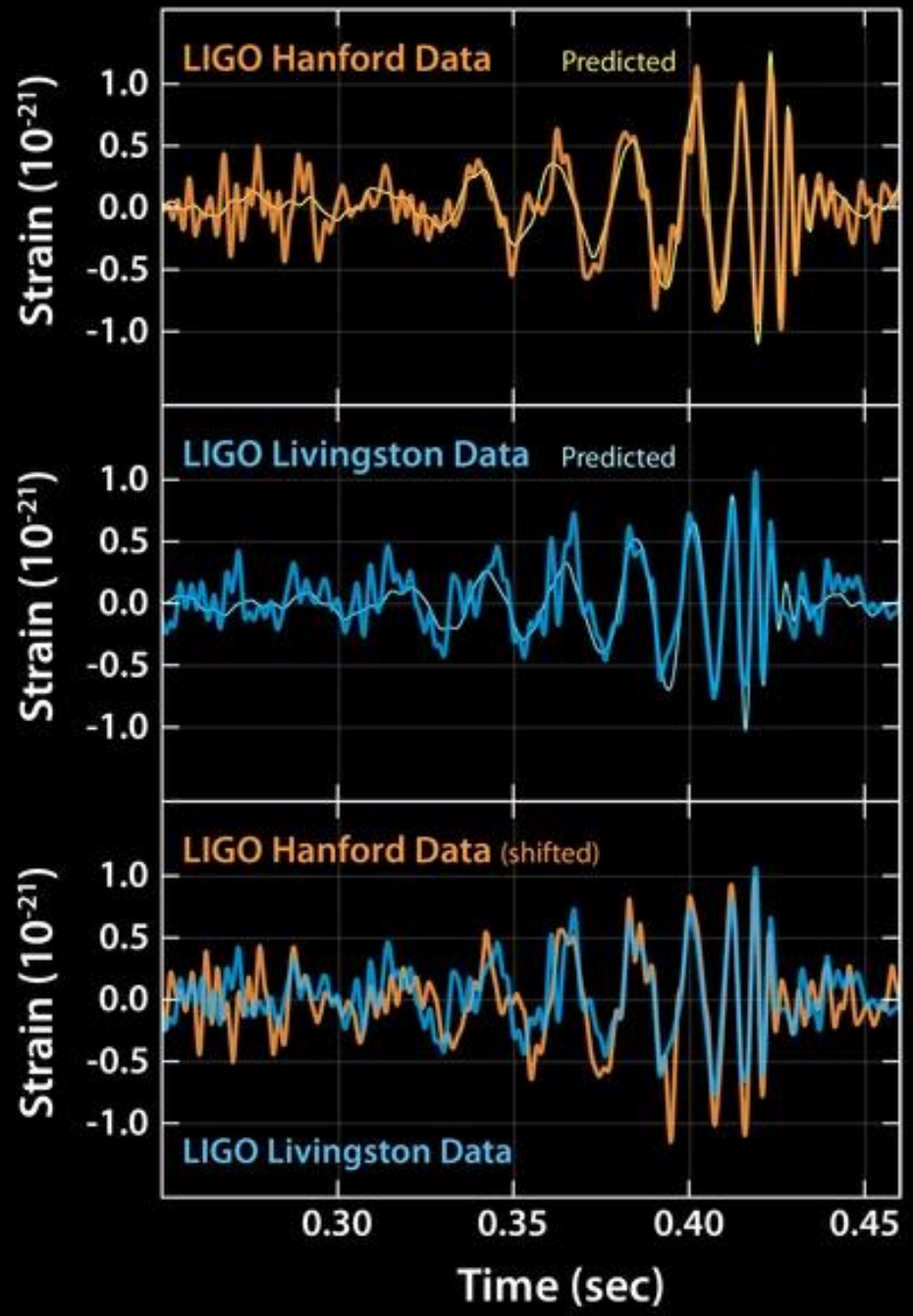
SPEED
LIMIT
50



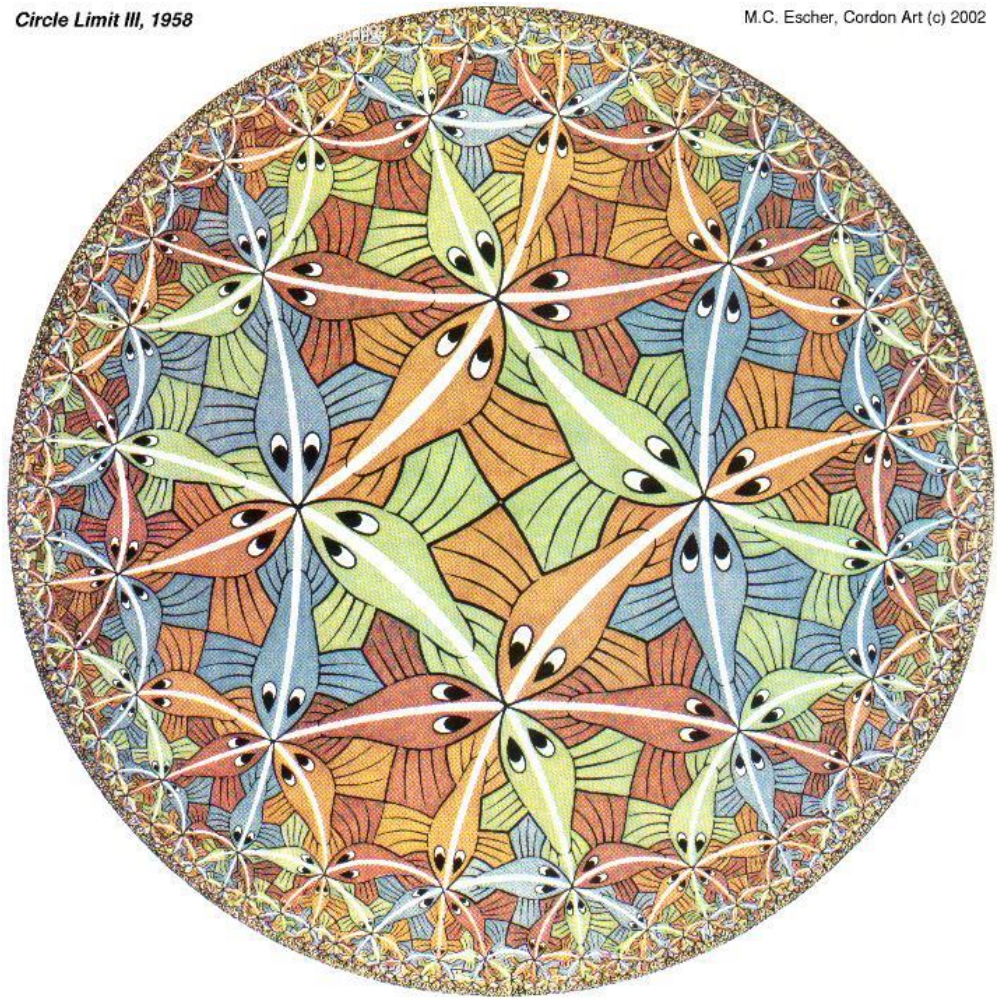
Black Holes



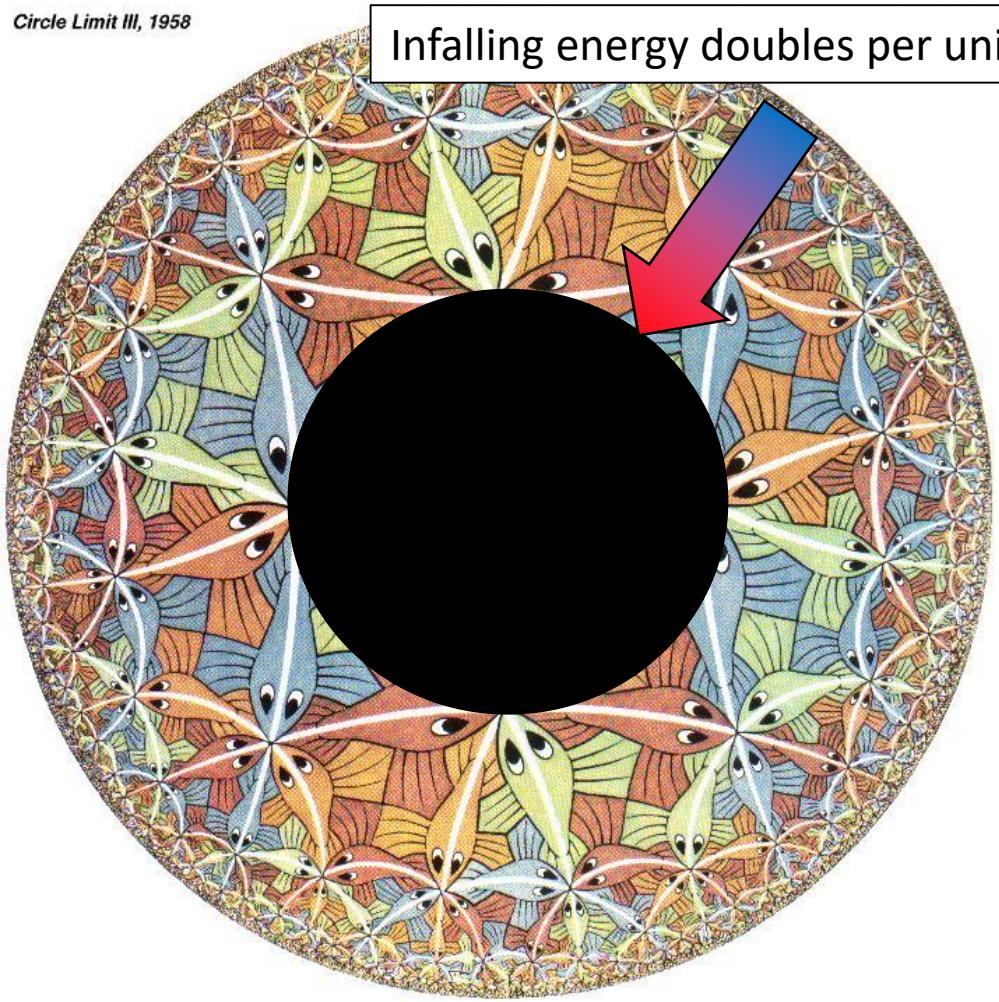




[LIGO and VIRGO collaborations, 2016]

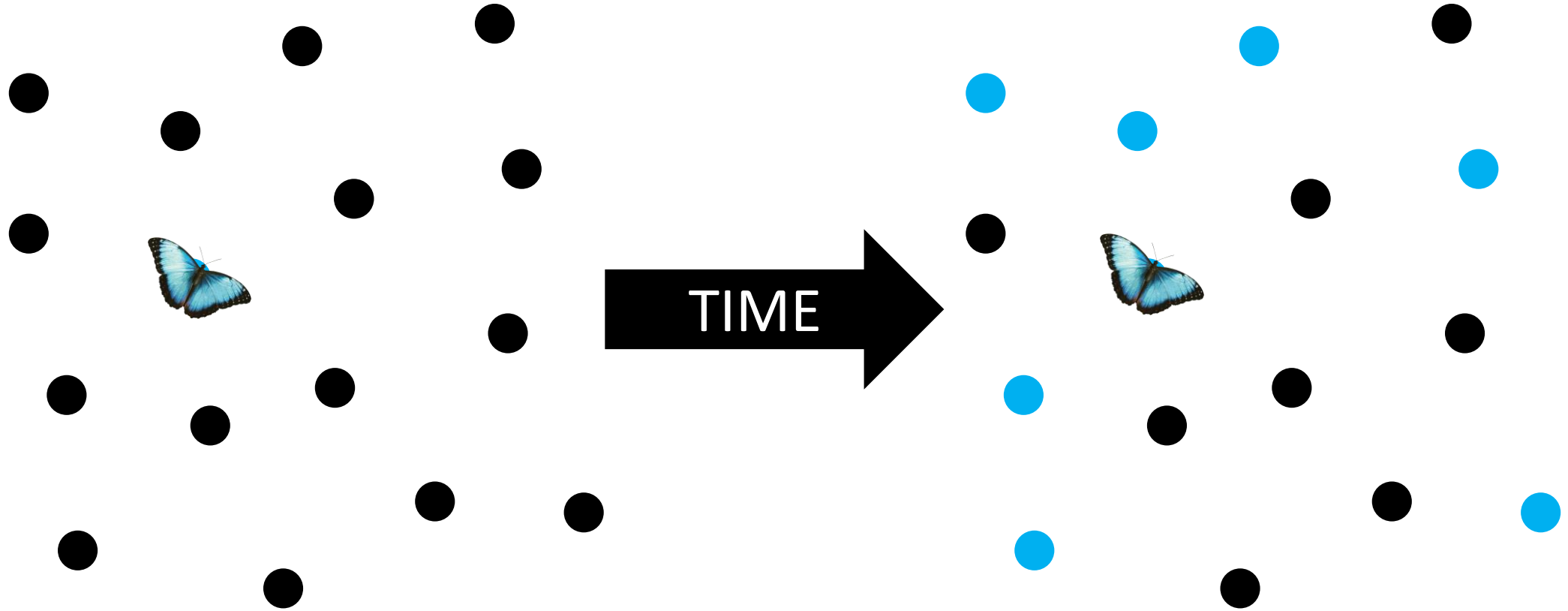


Anti-de-Sitter spacetime



Anti-de-Sitter spacetime + black hole

[Maldacena]



Affected region doubles every time step …

[Shenker-Stanford, Kitaev, Sachdev-Ye, …]

Outlook

- Today we discussed the quantum butterfly effect and its various manifestations in different physical systems
- This is just the tip of the iceberg: quantum chaos has a long history, and there are many new ideas and experiments to explore
- Thank you to my collaborators: Greg Bentsen, Monika Schleier-Smith, Patrick Hayden, Shenglong Xu, Nicole Yunger-Halpern, Subhayan Sahu, Masaki Tezuka, Masanori Hanada, Hrant Gharibyan, Debanjan Chowdhury, Aavishkar Patel, Subir Sachdev, Gong Cheng, Julia Steinberg, Andrew Guo, Dan Roberts, Norm Yao, Fabian Grusdt, Misha Lukin, Dan Stamper-Kurn, Joel Moore, Eugene Demler, Xiao Li, Yi-Ting Hsu, Sankar Das Sarma, …

THANK YOU!