Title: Physics as Information: Quantum Theory meets Relativity

Date: Nov 30, 2010 04:00 PM

URL: http://pirsa.org/10110080

Abstract: I will review some recent advances on the line of deriving quantum field theory from pure quantum information processing. The general idea is that there is only Quantum Theory (without quantization rules), and the whole Physics---including space-time and relativity---is emergent from the processing. And, since Quantum Theory itself is made with purely informational principles, the whole Physics must be reformulated in information-theoretical terms. Here's the TOC of the talk: a) Very short review of the informational axiomatization of Quantum Theory; b) How space-time and relativistic covariance emerge from the quantum computation; c) Special relativity without space: other ideas; d) Dirac equation derived as information flow (without the need of Lorentz covariance); e) Information-theoretical meaning of inertial mass and Planck constant; f) Observable consequences (at the Planck scale?); h) What about Gravity? Three alternatives as a start for a brainstorming.

QUIT quantum information theory group

PHYSICS AS INFORMATION: QUANTUM THEORY MEETS RELATIVITY

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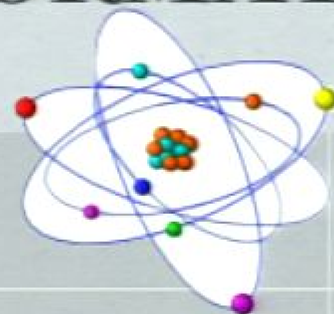
November 30th 2010, Perimeter Institute, Waterloo, Ontario, CA

EXPLORING THE POSSIBILITY THAT PURE INFORMATION MAY UNDERLIE ALL OF PHYSICS

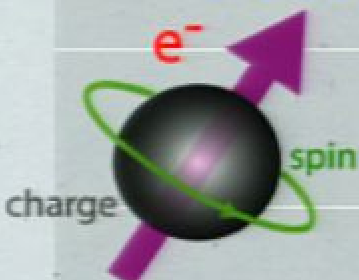
EXPLORING THE POSSIBILITY THAT PURE INFORMATION MAY UNDERLIE ALL OF PHYSICS

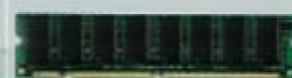
Such information should be made of *qubits!*

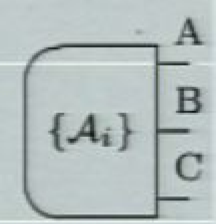
OPERATIONALISM = INFORMATIONALISM

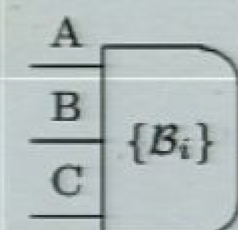


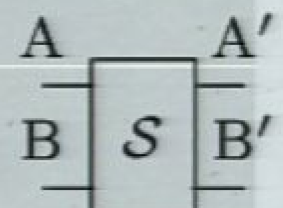
PHYSICS	INFORMATION
system	register
state	initialization
effect	readout
transformation	processing
event	subroutine









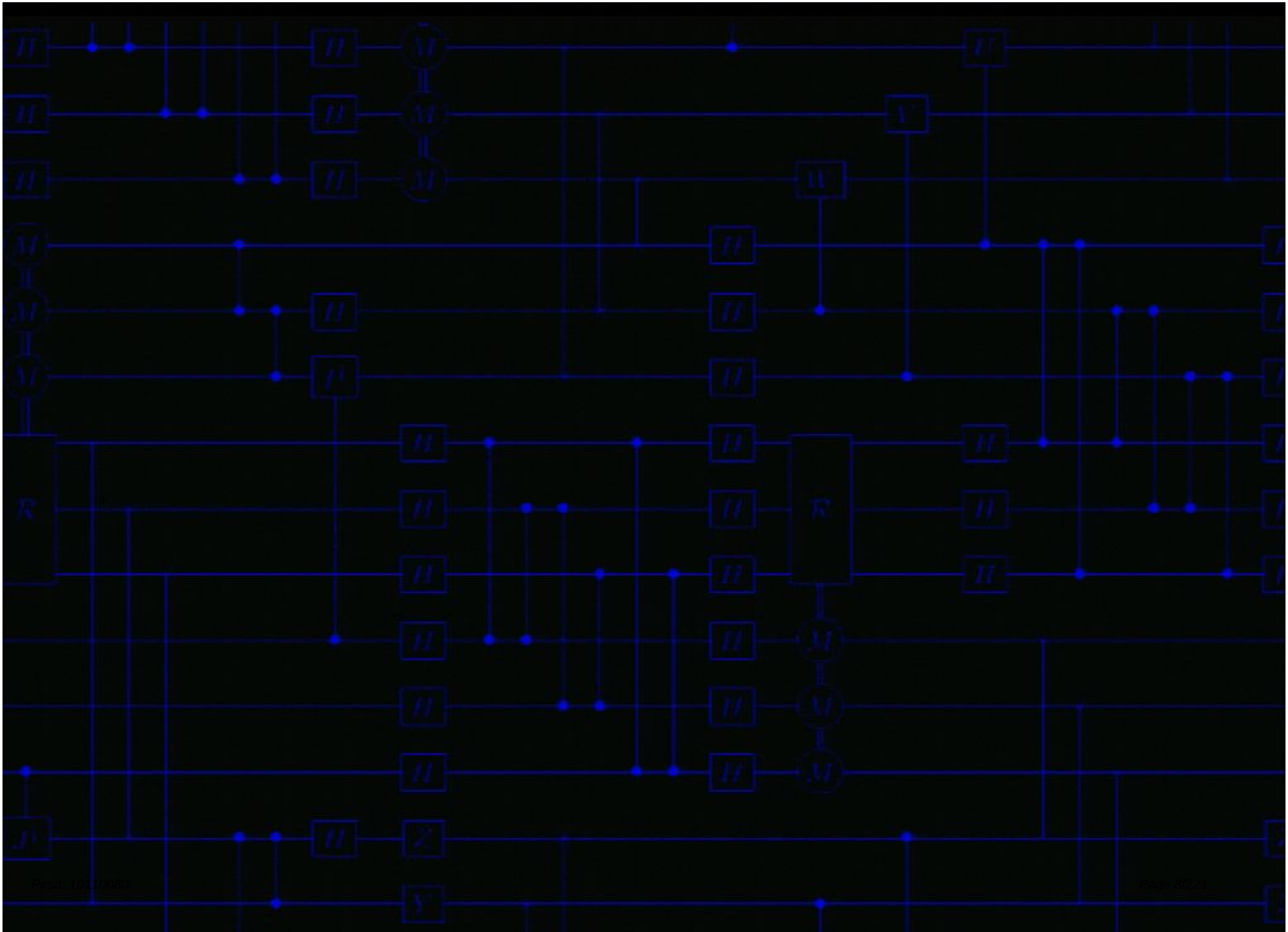


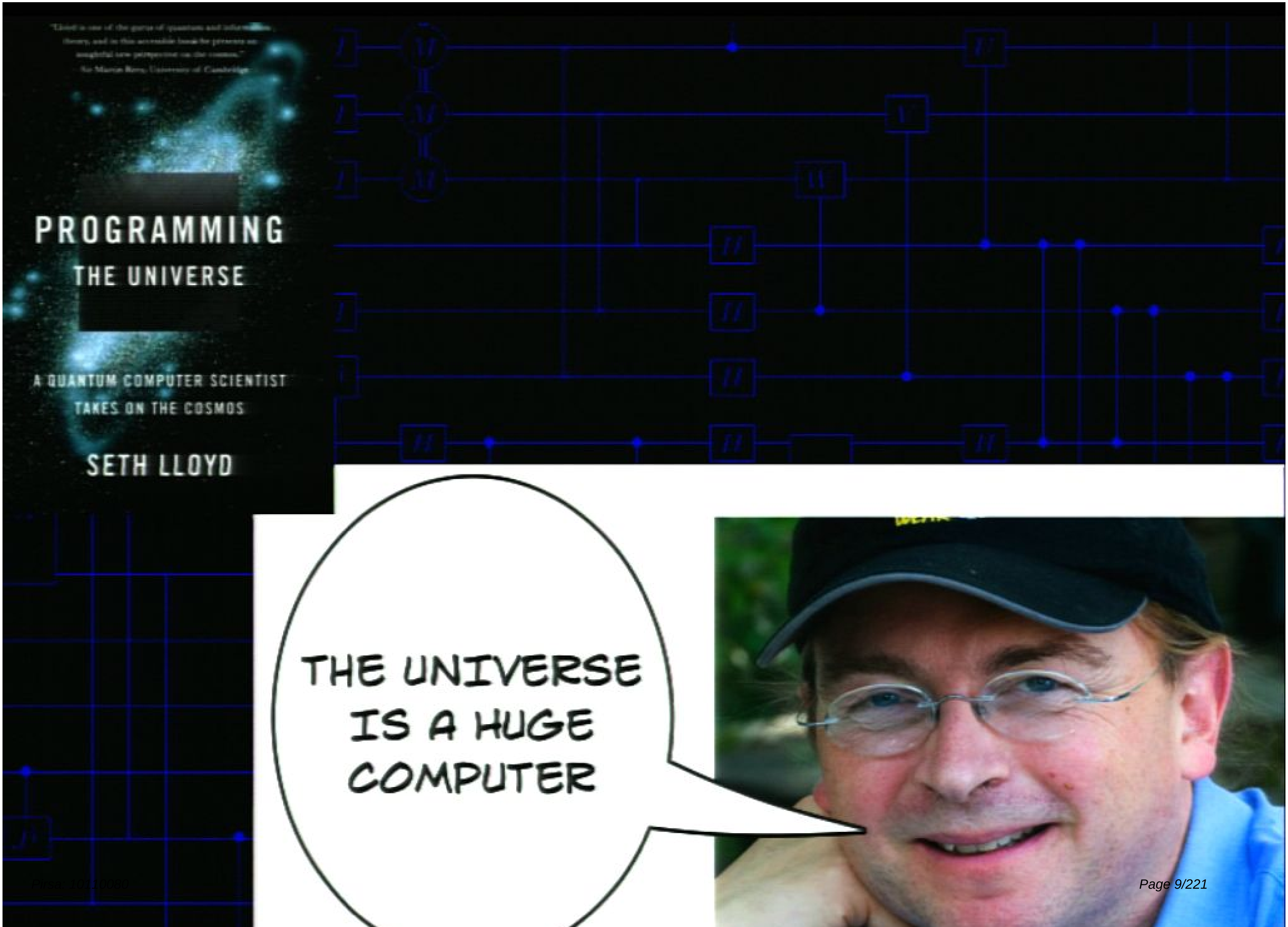
EXPLORING THE POSSIBILITY THAT PURE INFORMATION MAY UNDERLIE ALL OF PHYSICS

Such information should be made of *qubits!*

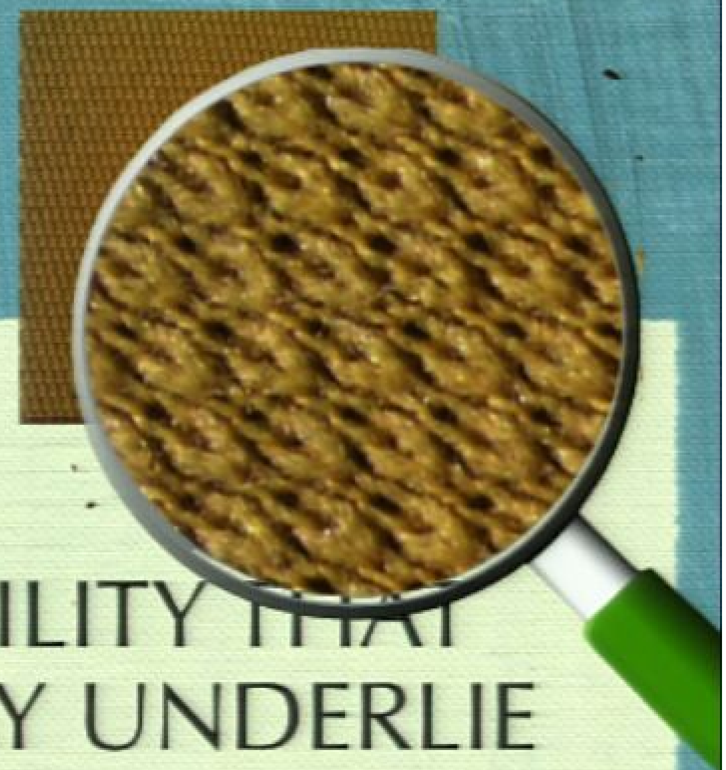
EXPLORING THE POSSIBILITY THAT PURE INFORMATION MAY UNDERLIE ALL OF PHYSICS

Can we say that a quantum field is just a collection of (infinitely many) quantum systems (each at every "space point = Planck cell) unitarily interacting with a bunch of other systems?

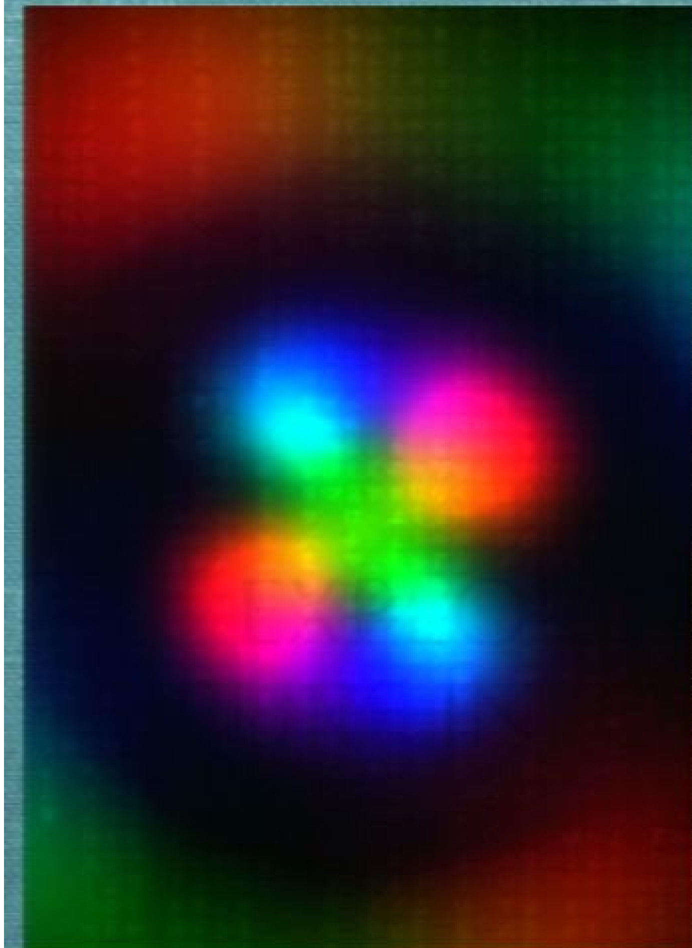


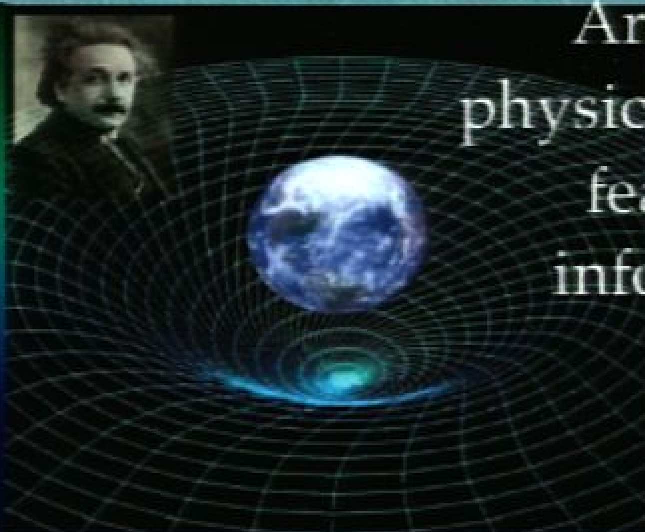

PROGRAMMING
THE UNIVERSE
A QUANTUM COMPUTER SCIENTIST
TAKES ON THE COSMOS
SETH LLOYD
THE UNIVERSE IS A HUGE COMPUTER

Does the continuum play a fundamental role, or it is only a mathematical idealization?



EXPLORING THE POSSIBILITY THAT PURE INFORMATION MAY UNDERLIE ALL OF PHYSICS





Are space, time, and all physical observables emergent features of a quantum information processing?

G THE POSSIBILITY THAT
RMATION MAY UNDERLIE
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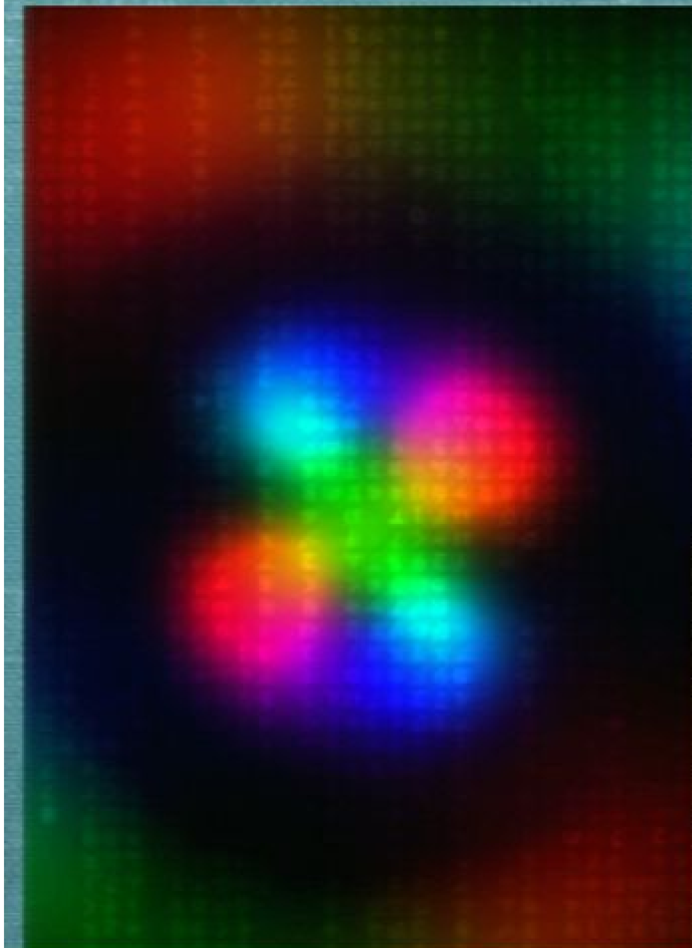
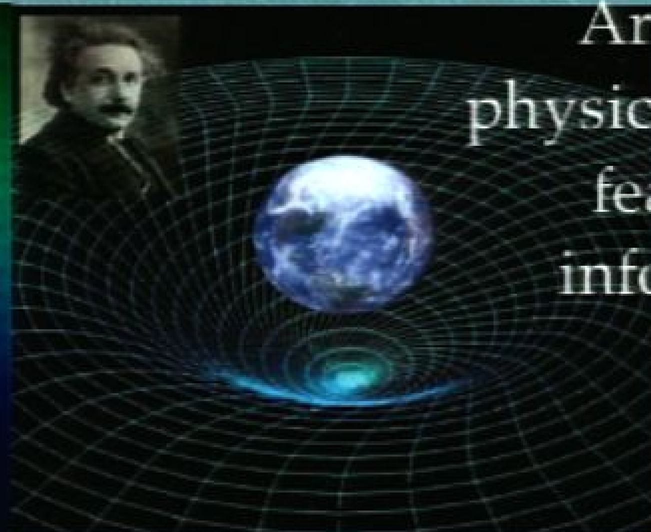




Are space, time, and all physical observables emergent features of a quantum information processing?

G THE POSSIBILITY THAT RMATION MAY UNDERLIE LL OF PHYSICS

Physics is Information

"It from Bit"

"Information is physical"

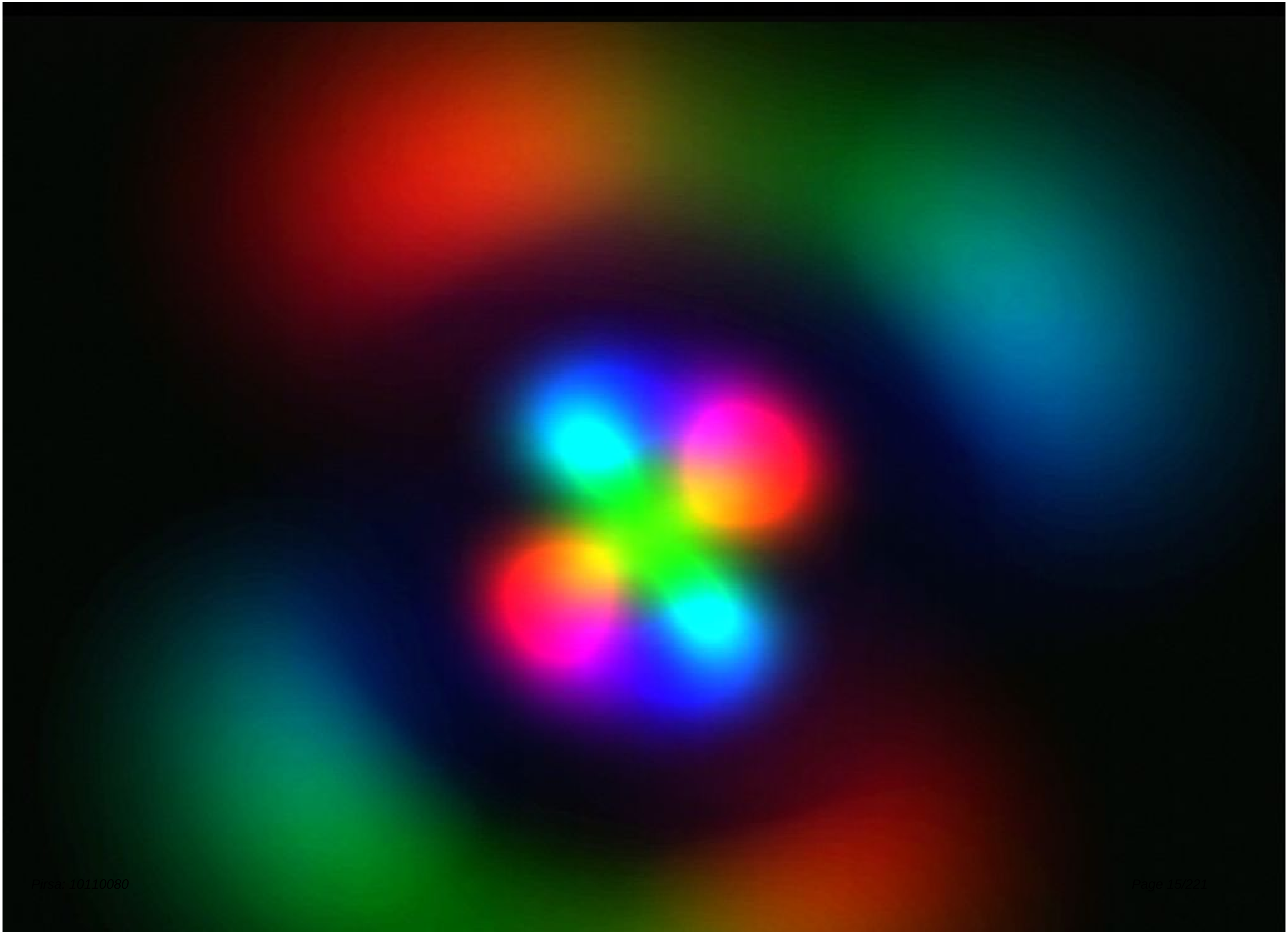
(Bit from It)

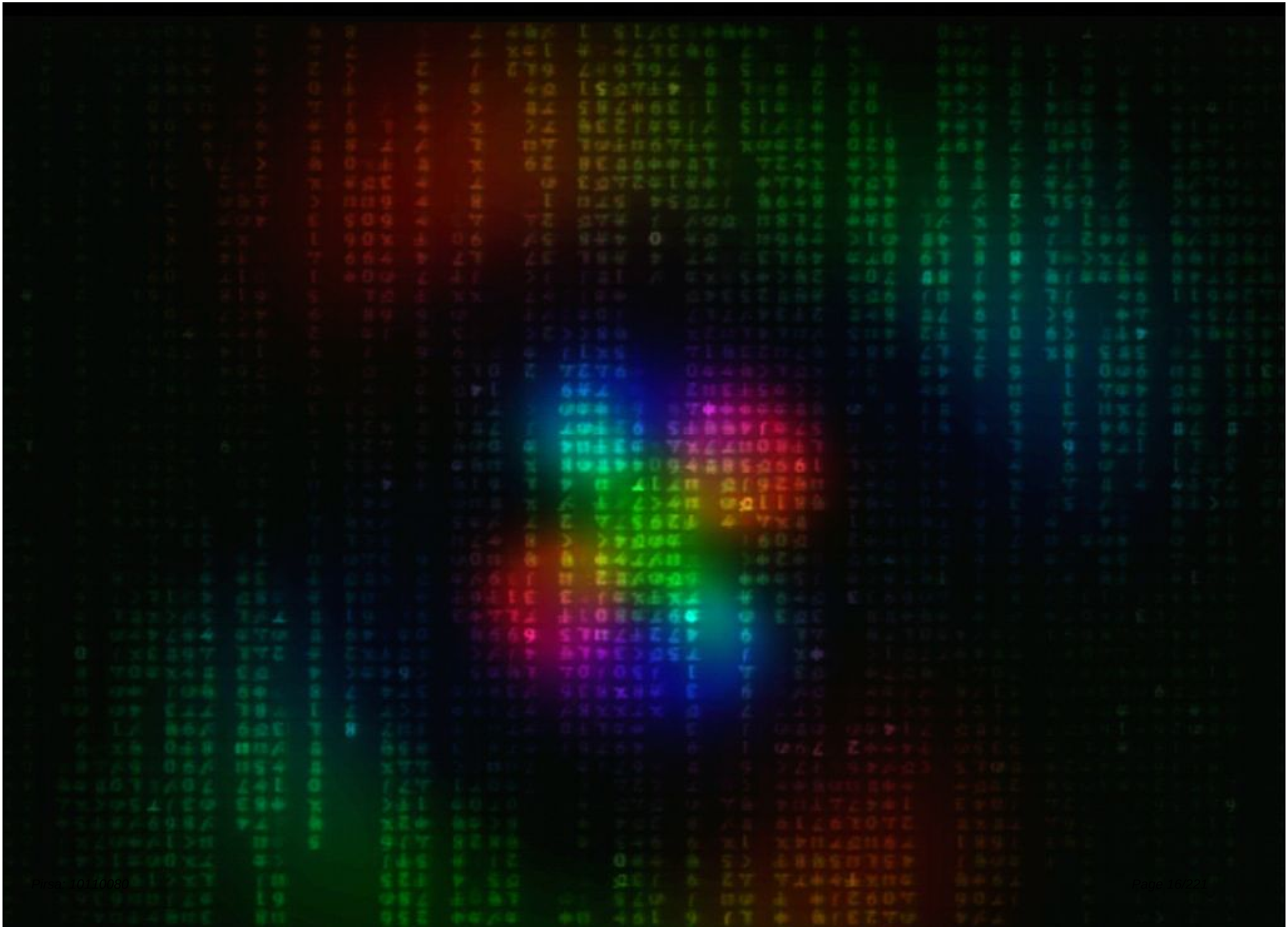
Physics is Information

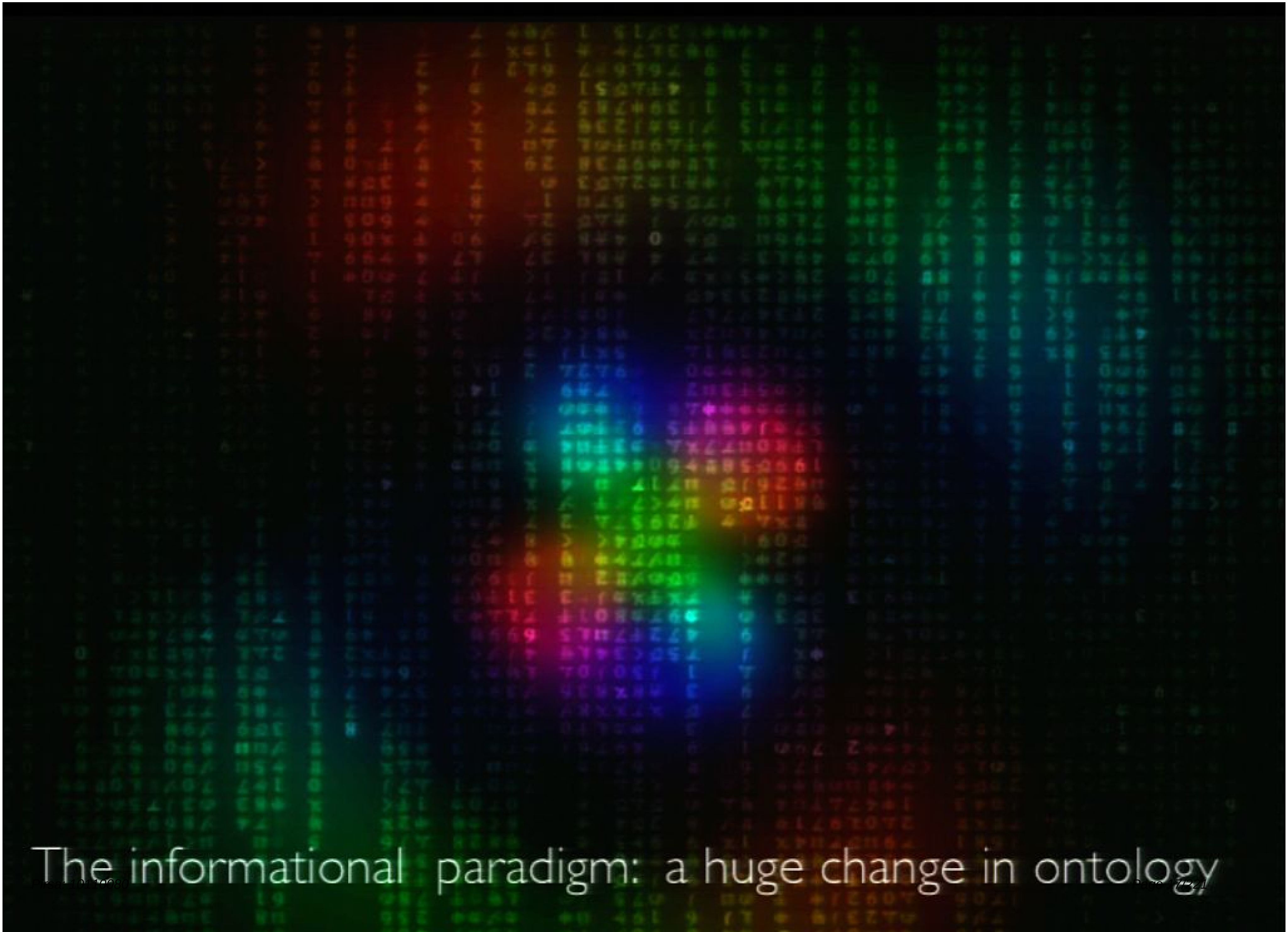
"It from QBit"

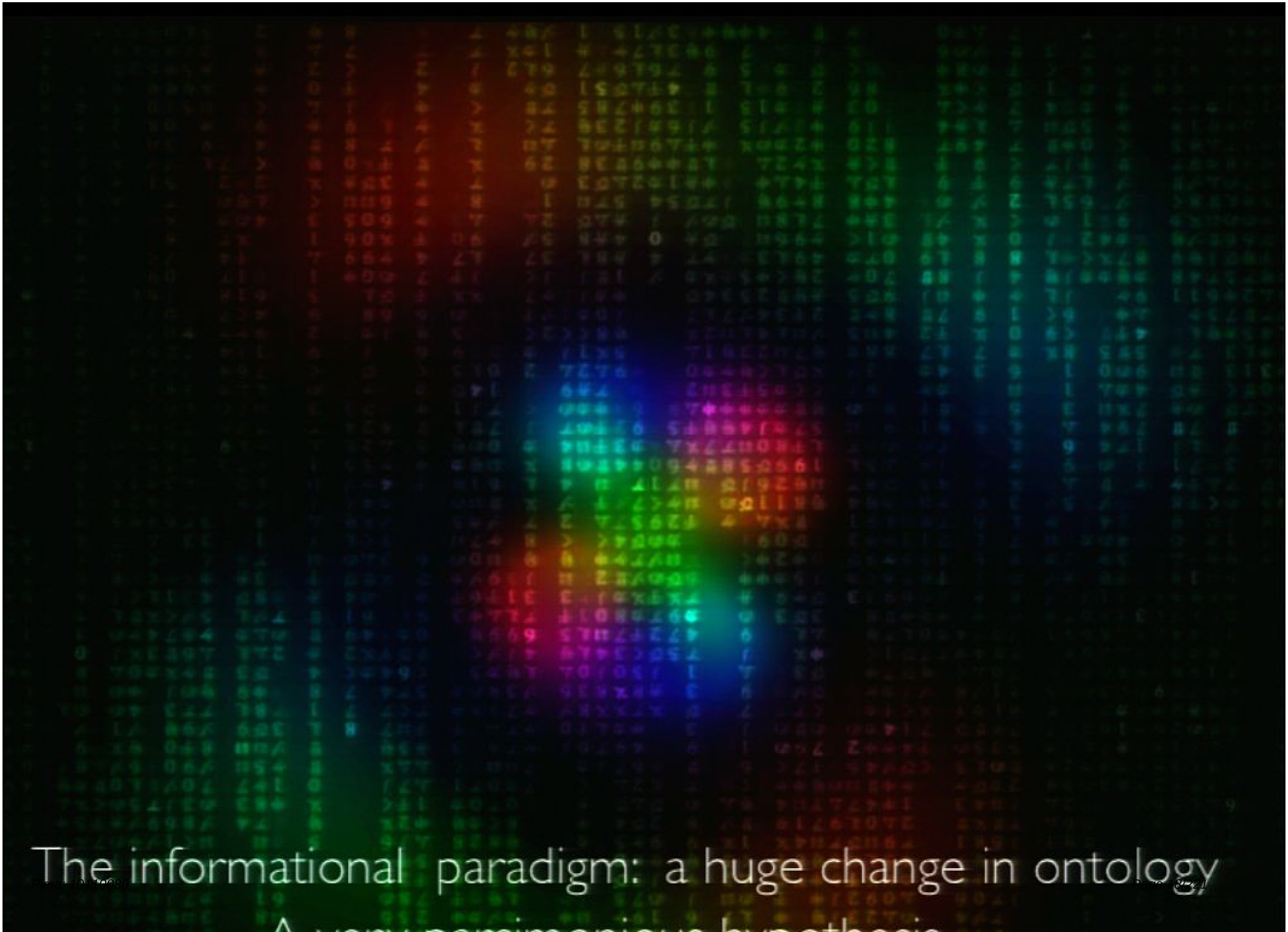
"Information is physical"

(QBit from It)






The informational paradigm: a huge change in ontology


The informational paradigm: a huge change in ontology

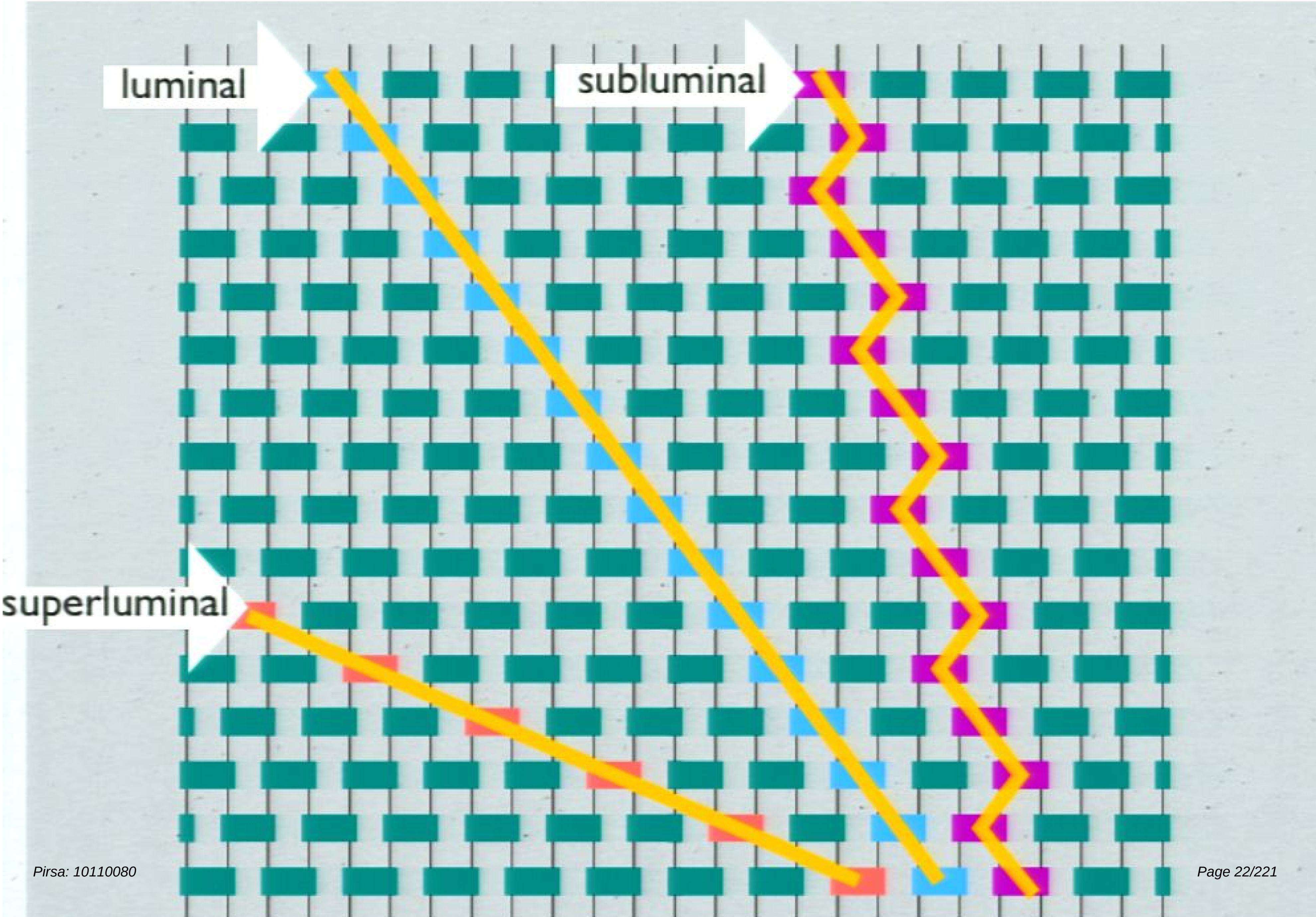
OUTLINE

- Very short review of the informational axiomatization of QT
- How space-time and relativistic covariance emerge from the quantum computation
- Special relativity without space and time: other ideas
- Dirac equation derived as information flow (without the need of Lorentz covariance)
- Information-theoretical meaning of inertial mass and Planck constant
- Observable consequences (at the Planck scale?)
- What about Gravity? Three alternatives as a start for a brainstorming

HOW RELATIVITY EMERGES FROM THE COMPUTATION?

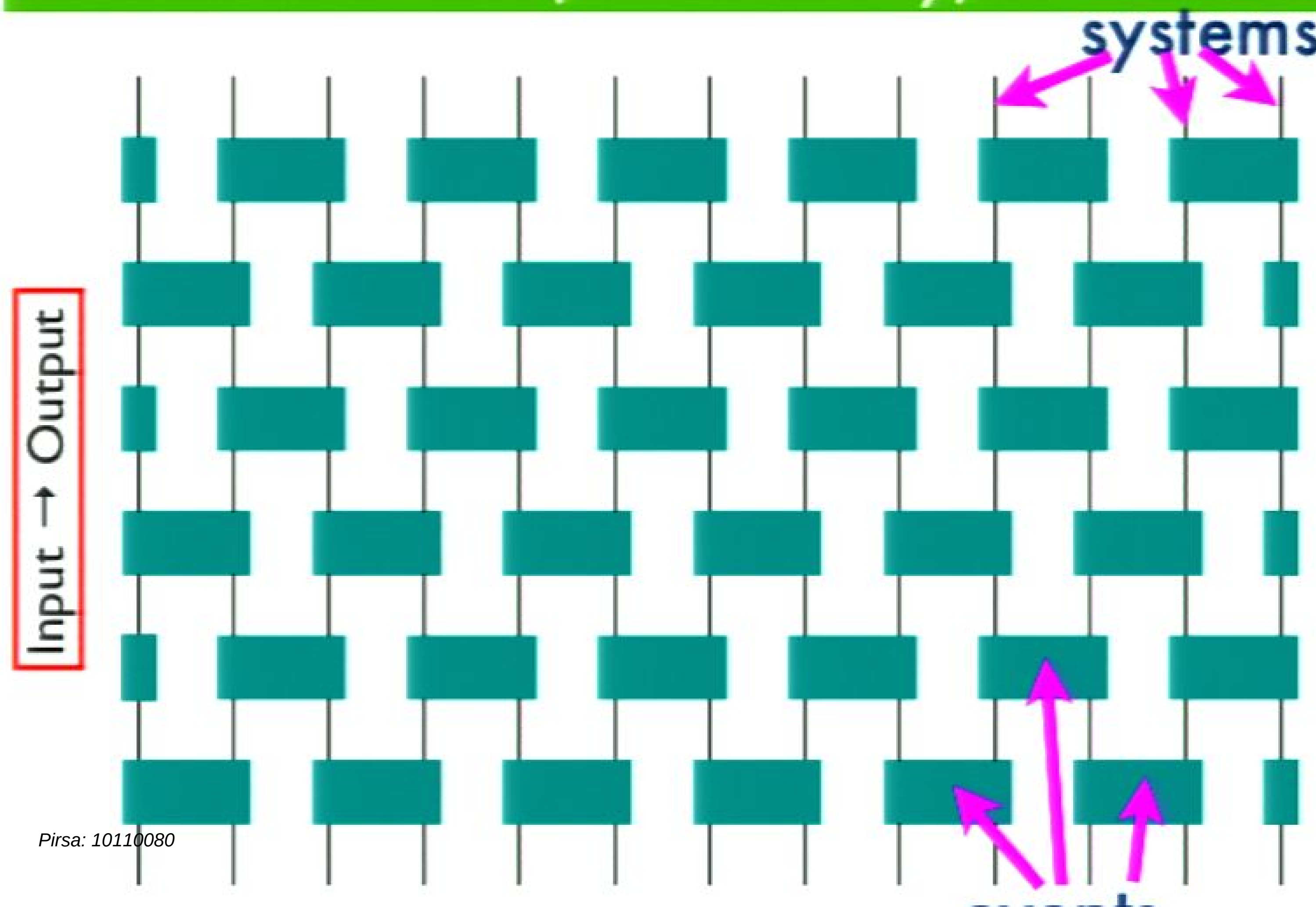
HOW RELATIVITY EMERGES FROM THE COMPUTATION?

Informational description of reality:
a causal network of events.


luminal
subluminal
superluminal

Relativity from QT

(from causality)



Relativity from QT
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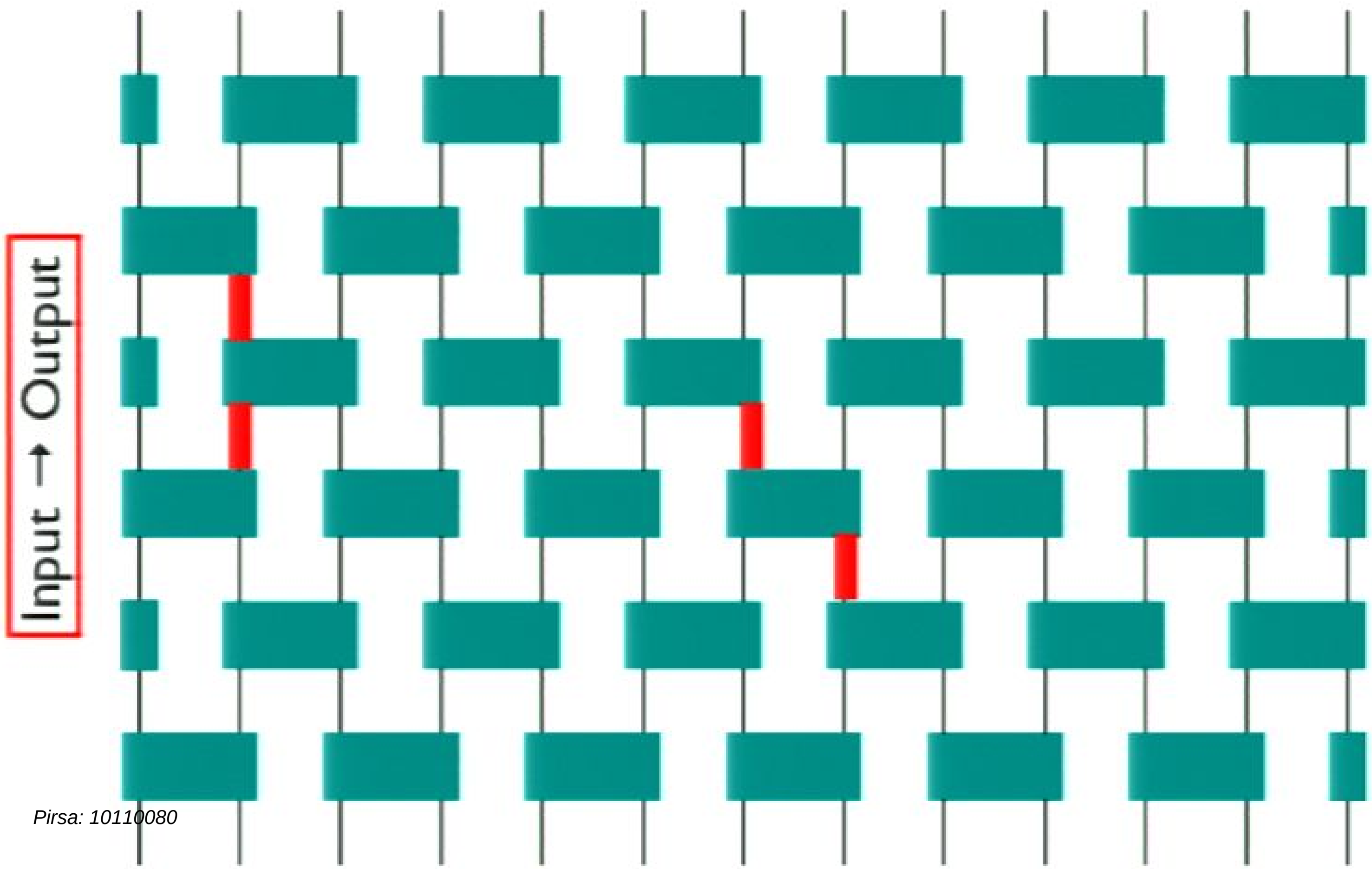
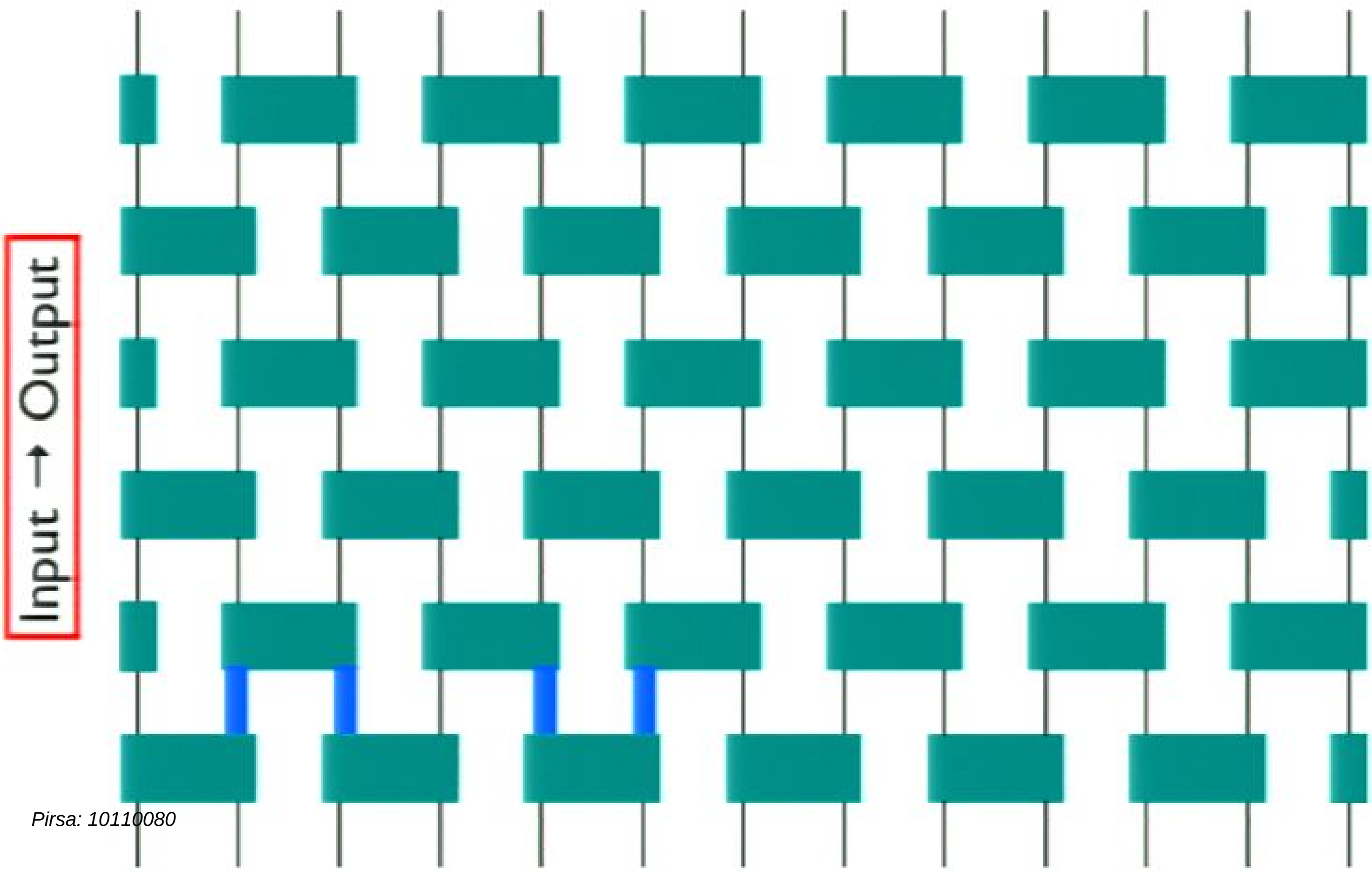


causally connected systems

Relativity from QT
(from causality)



independent systems

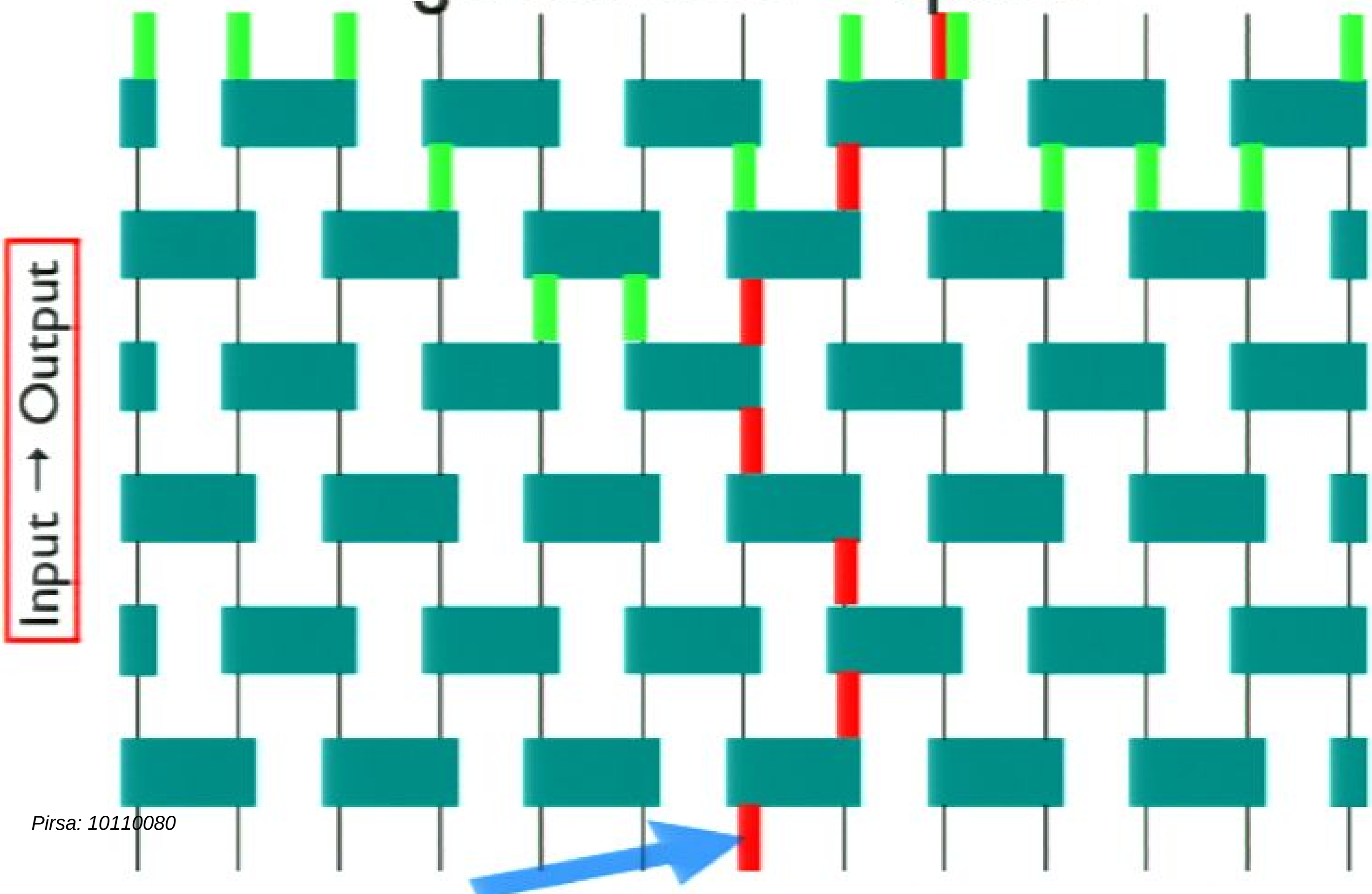
"slice"

Relativity from QT

(from causality)

topology (Alexandrov)

global slice = space



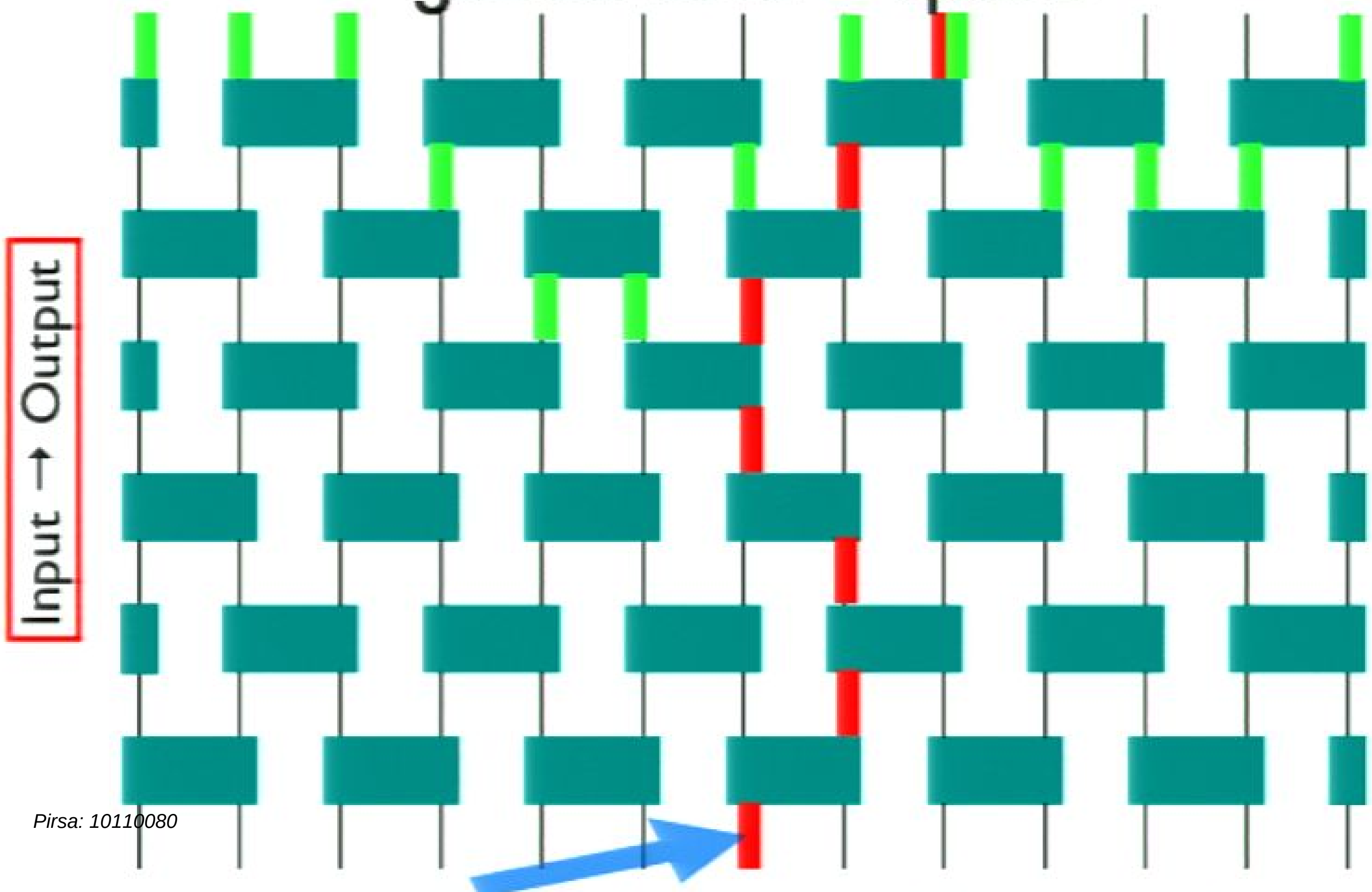
Relativity from QT

(from causality)

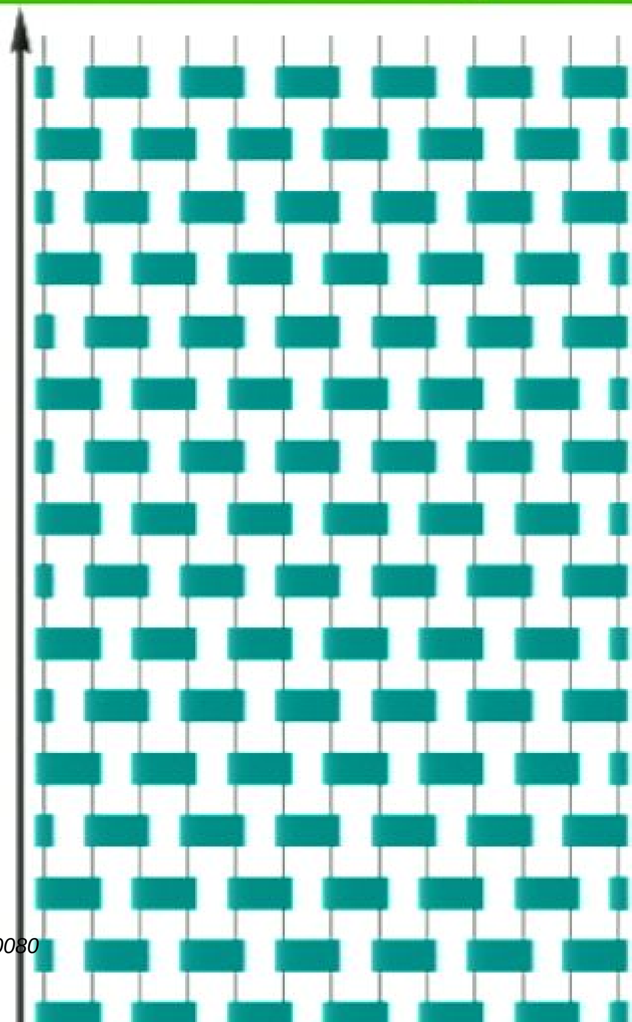
topology (Alexandrov)

metric = event-counting

global slice = space



Relativity from QT
(from causality)



Relativity from QT

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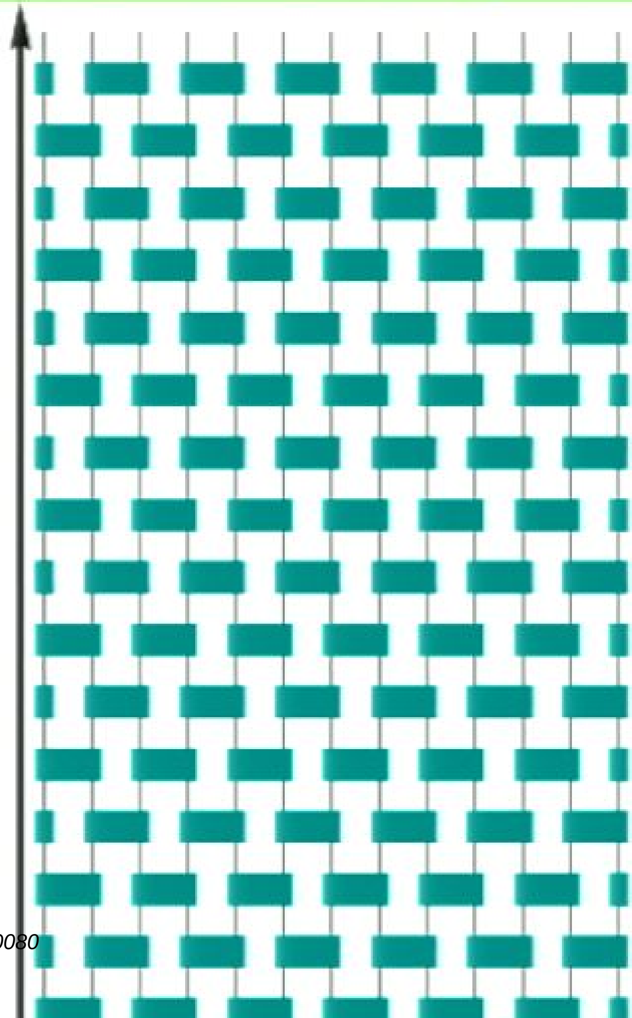
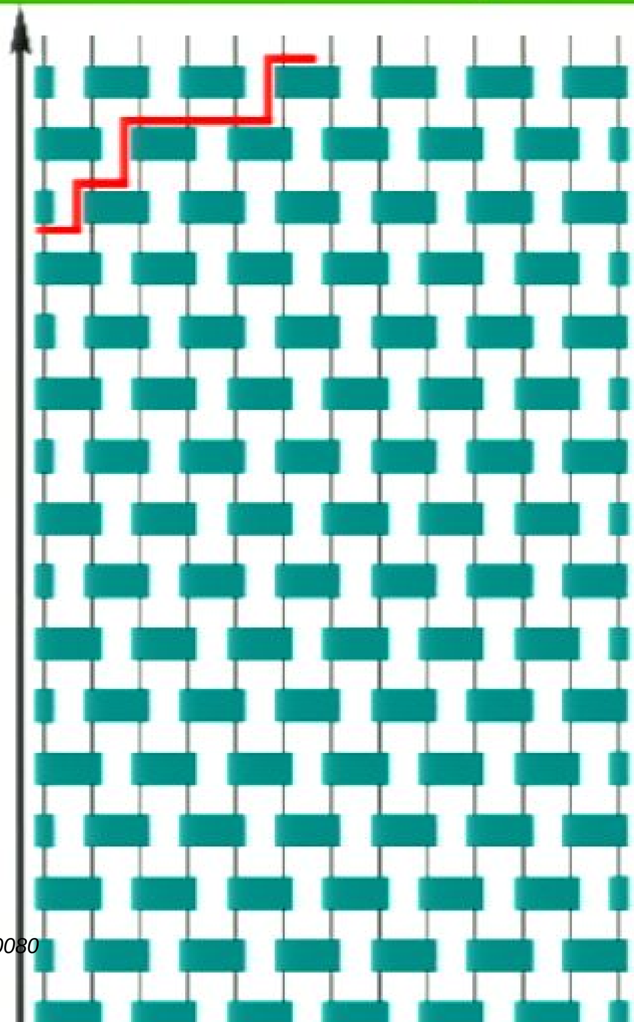


build a uniform foliation

Relativity from QT

(from causality)



build a uniform foliation

Relativity from QT

Operating Systems

R. Stockton Gaines
Editor

Time, Clocks, and the Ordering of Events in a Distributed System

Leslie Lamport
Massachusetts Computer Associates, Inc.

The concept of one event happening before another in a distributed system is examined, and is shown to define a partial ordering of the events. A distributed algorithm is given for synchronizing a system of logical clocks which can be used to totally order the events. The use of the total ordering is illustrated with a method for solving synchronization problems. The algorithm is then specialized for synchronizing physical clocks, and a bound is derived on how far out of synchrony the clocks can become.

Key Words and Phrases: distributed systems, computer networks, clock synchronization, multiprocess

A distributed system consists of a collection of distinct processes which are spatially separated, and which communicate with one another by exchanging messages. A
network of i
net, is a dist
be viewed a
control unit.
channels are
if the messa
pared to the

We will
spatially sep
remarks will
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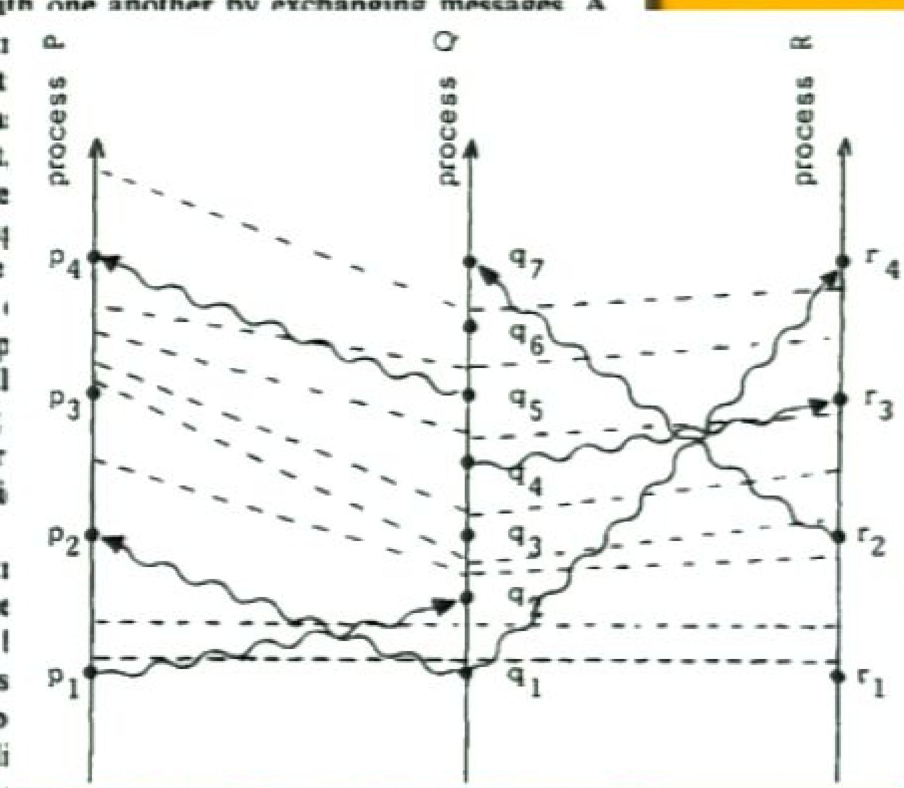
lems similar
the unpredi
occur.

In a distr
say that one
“happened
of the events
often arise b
and its impli

In this pa

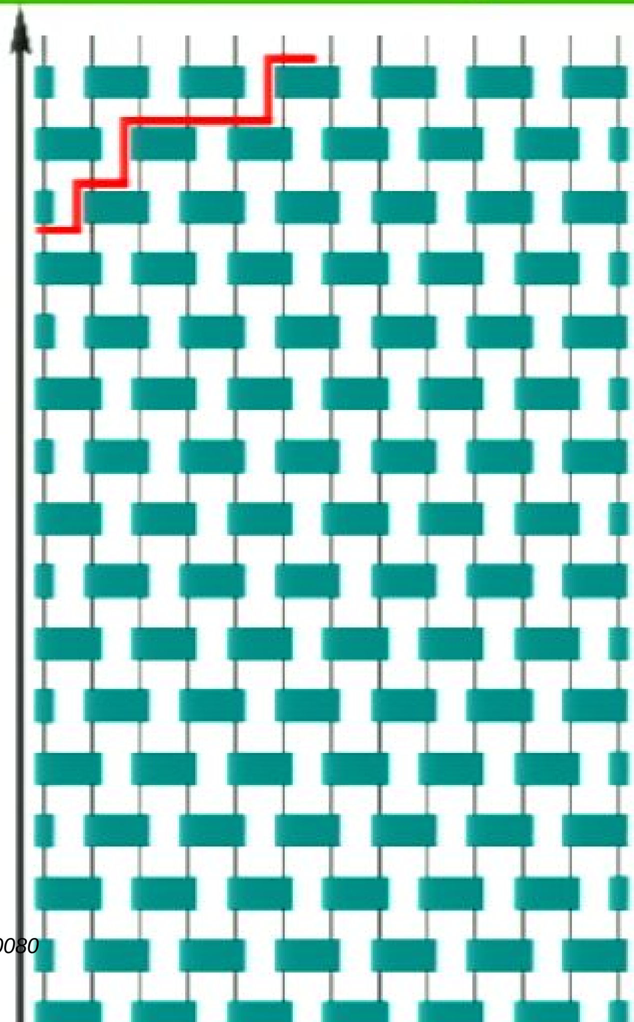
by the “happened before” relation, and give a distributed algorithm for extending it to a consistent total ordering of all the events. This algorithm can provide a useful mechanism for implementing a distr
illustrate its use with a simple meth



Communications of
July 1978
Volume 21

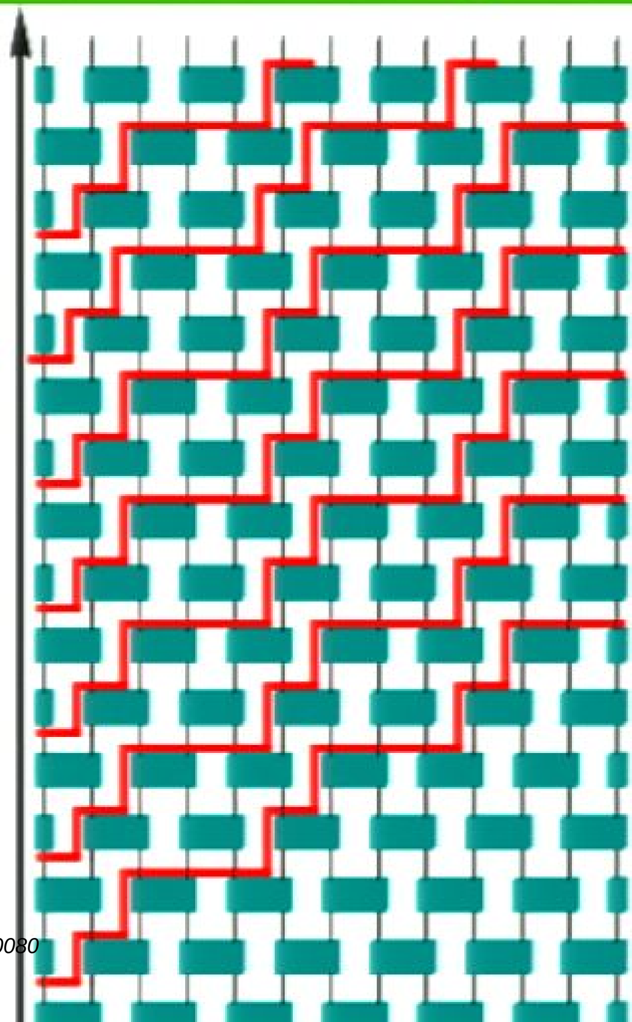
Relativity from QT

(from causality)



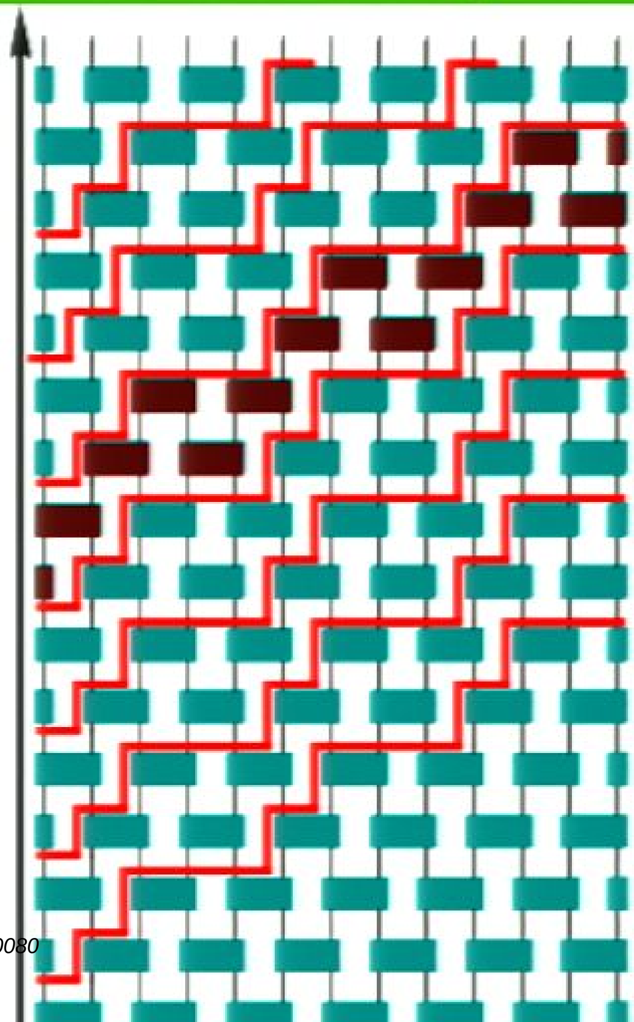
build a uniform foliation

Relativity from QT
(from causality)



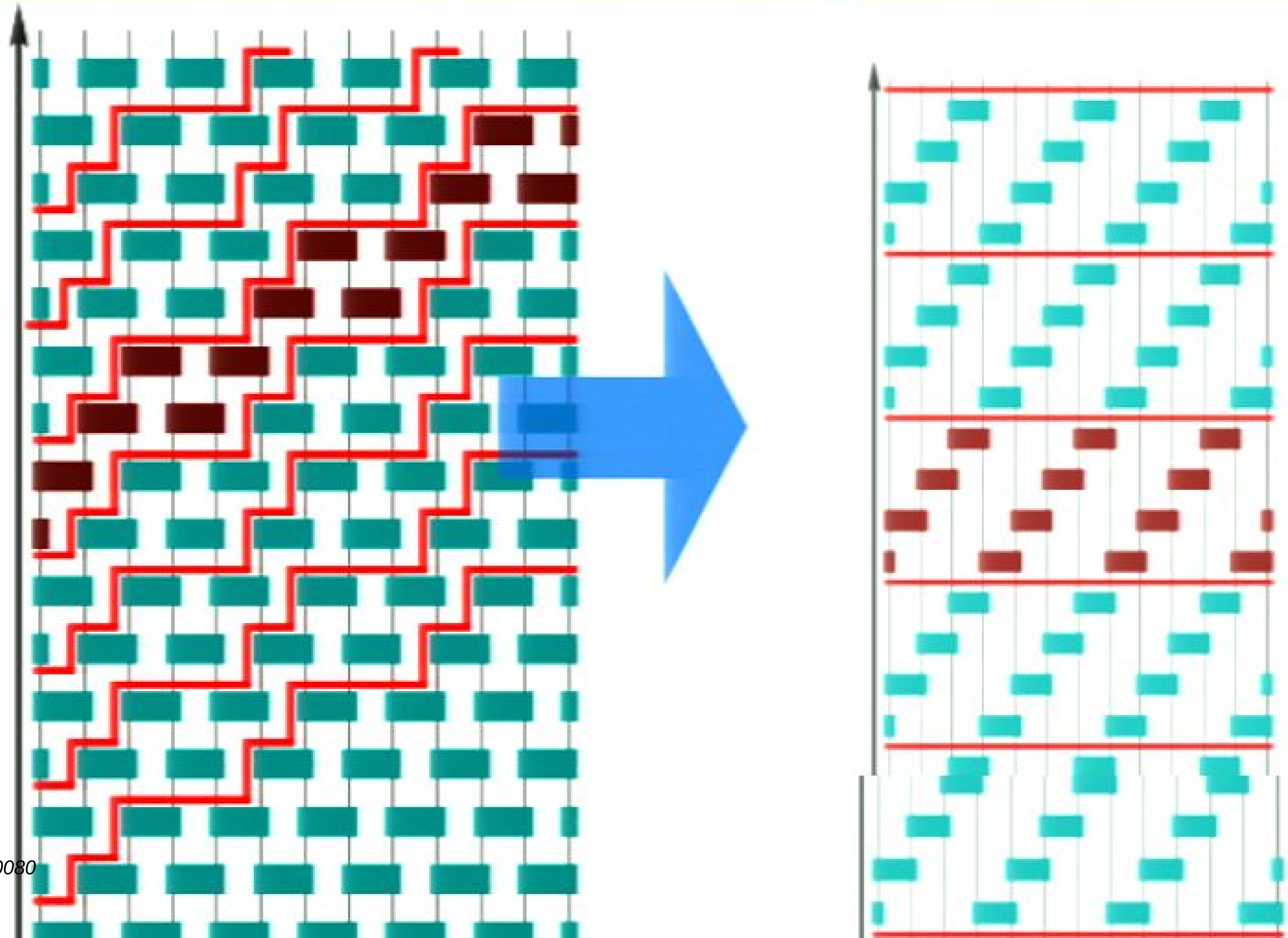
build a uniform foliation

Relativity from QT
(from causality)



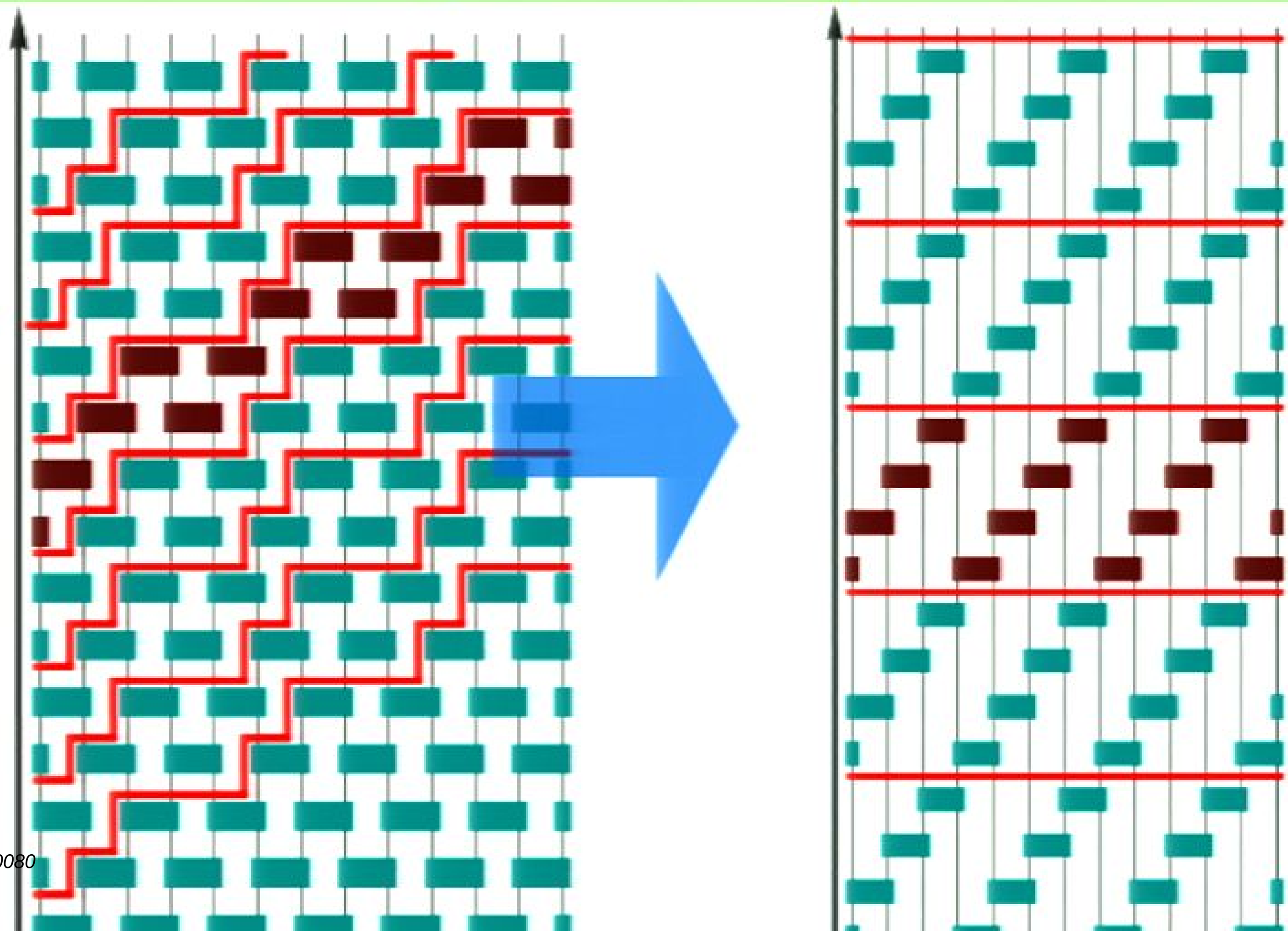
build a uniform foliation

Relativity from QT
(from causality)



change reference

Relativity from QT
(from causality)



change reference

Relativity from QT

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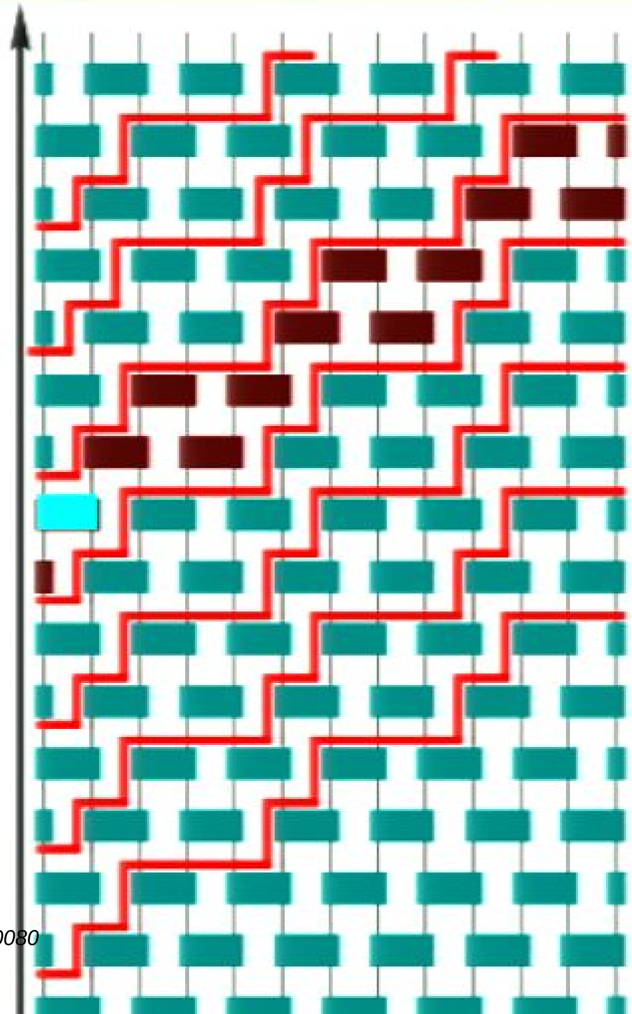
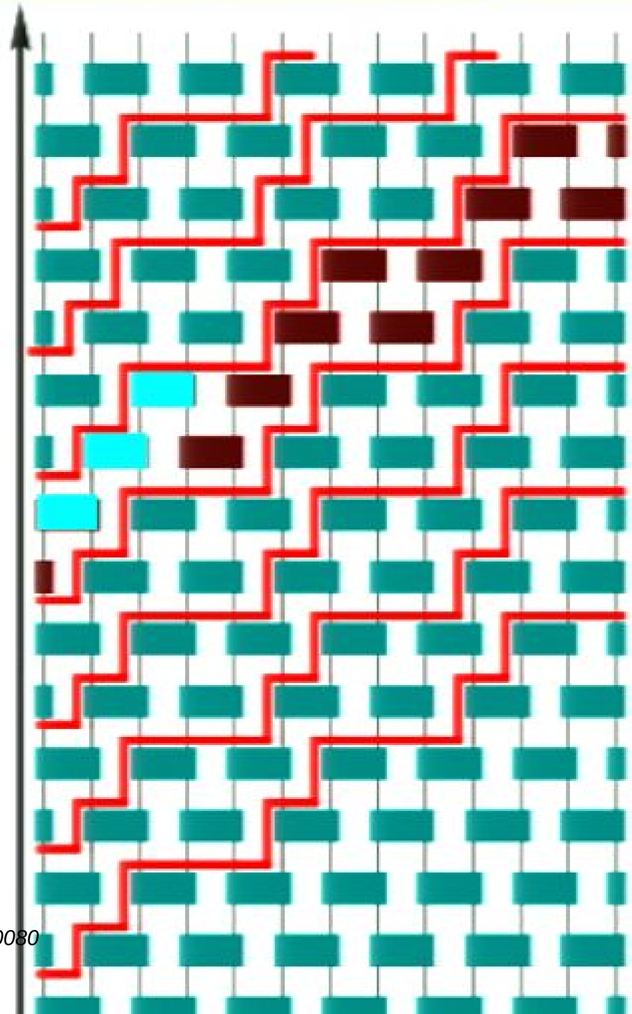


speed of light

Relativity from QT

(from causality)



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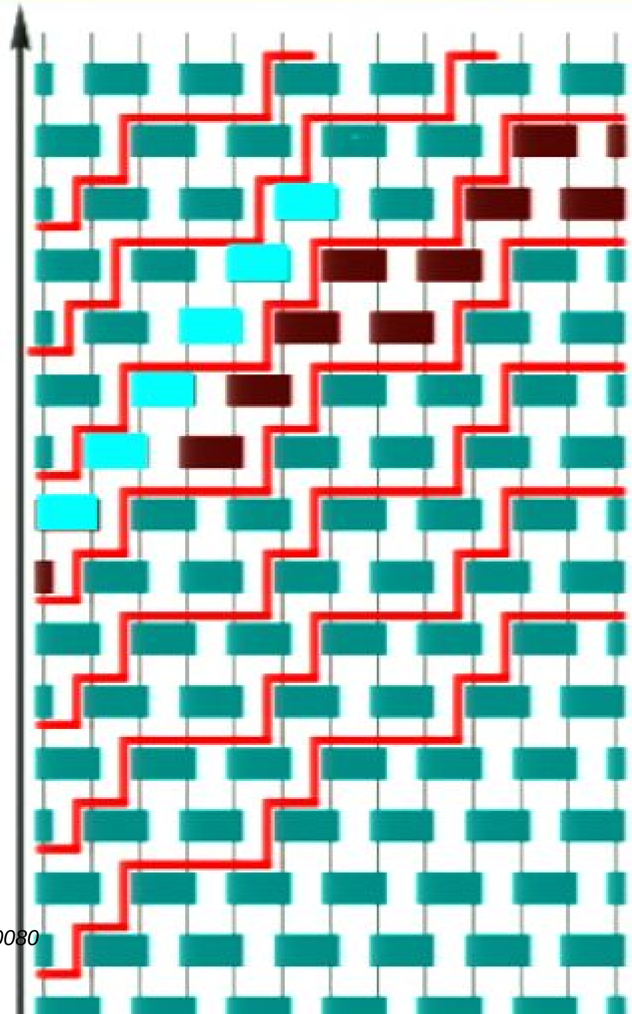

speed of light

Relativity from QT
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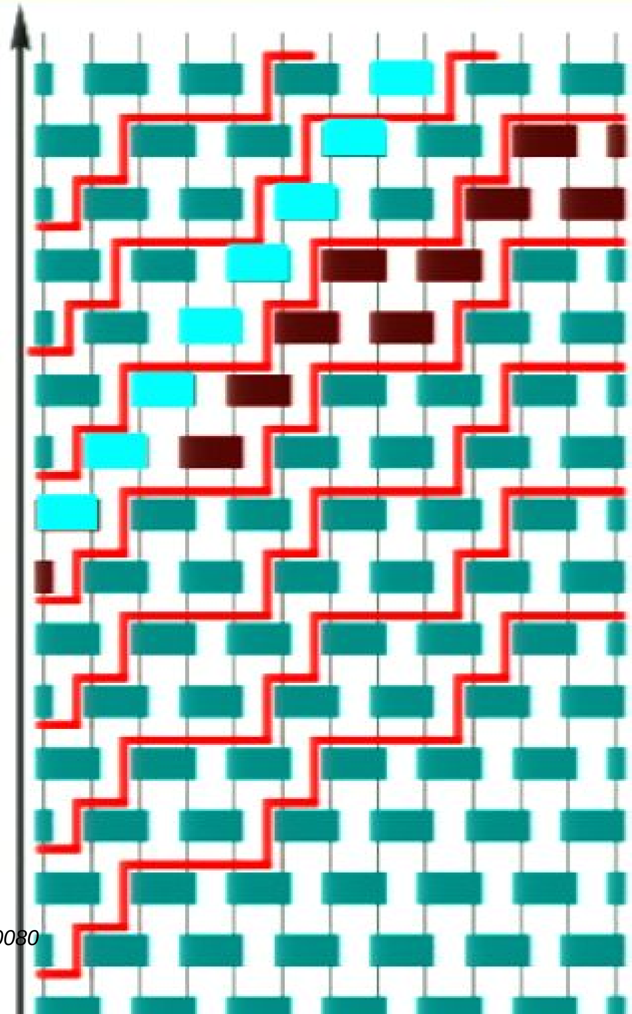
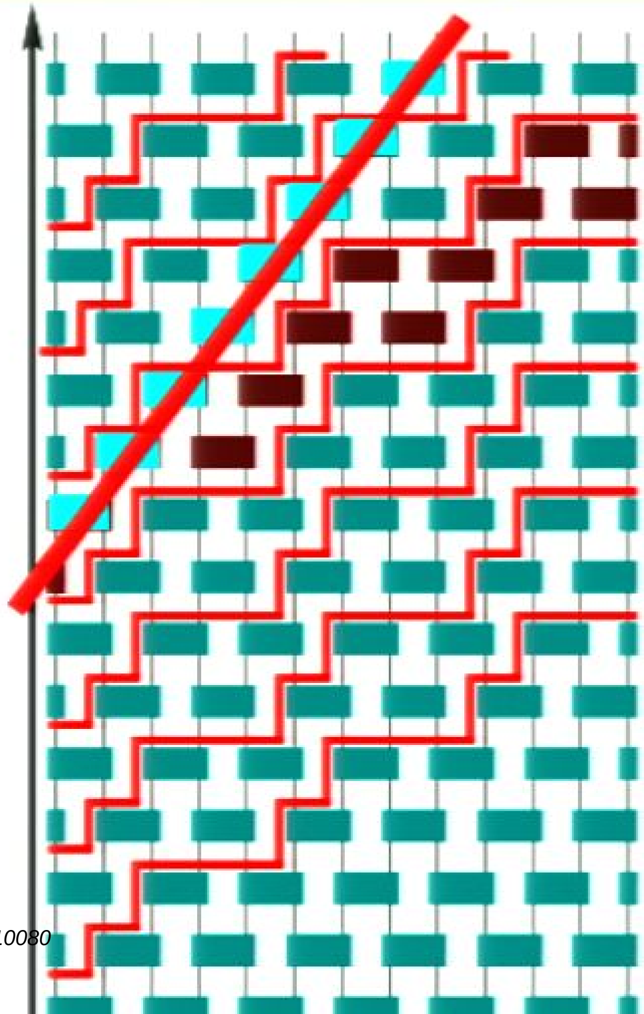


speed of light

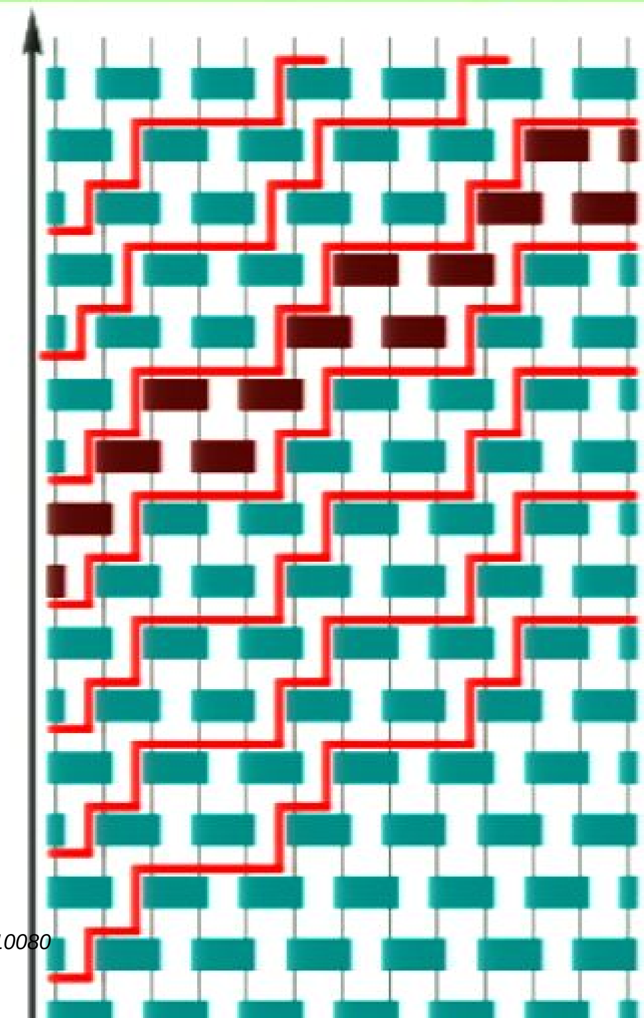
Relativity from QT

(from causality)

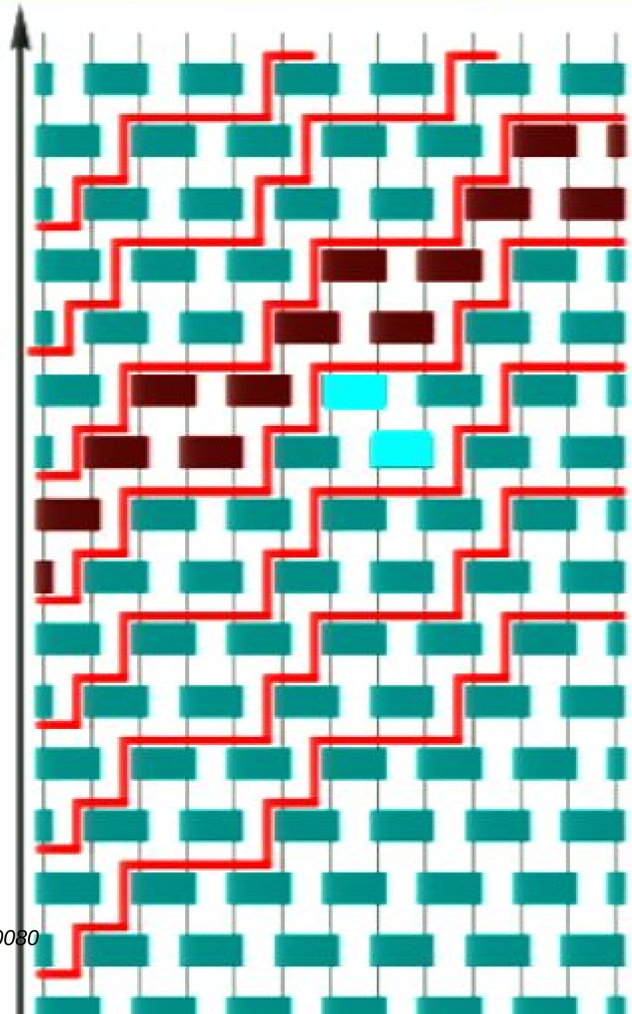


speed of light

Relativity from QT
(from causality)

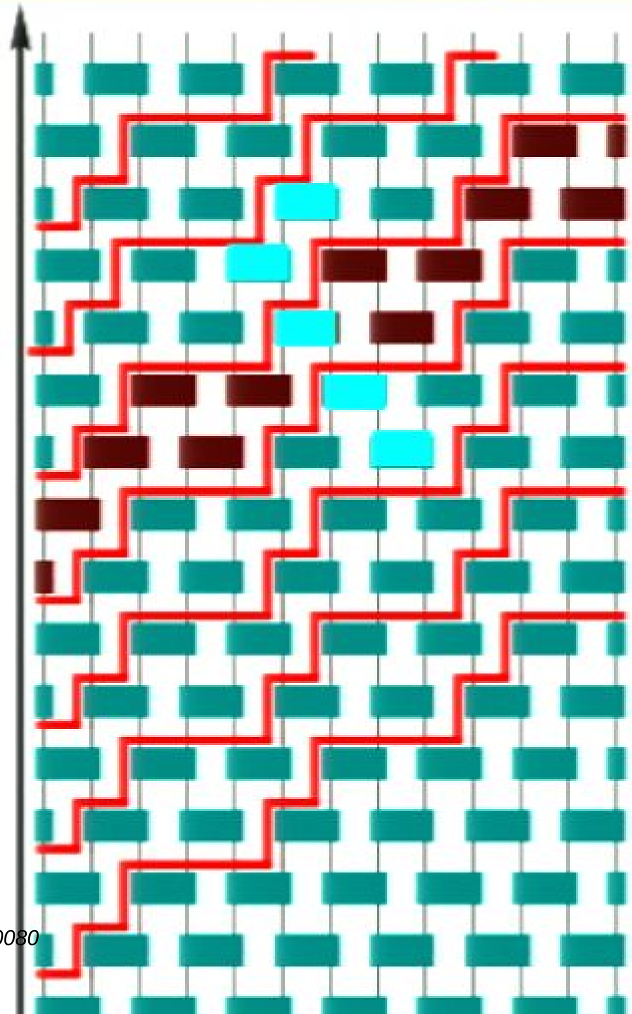


Relativity from QT
(from causality)



clock tic-tac

Relativity from QT
(from causality)



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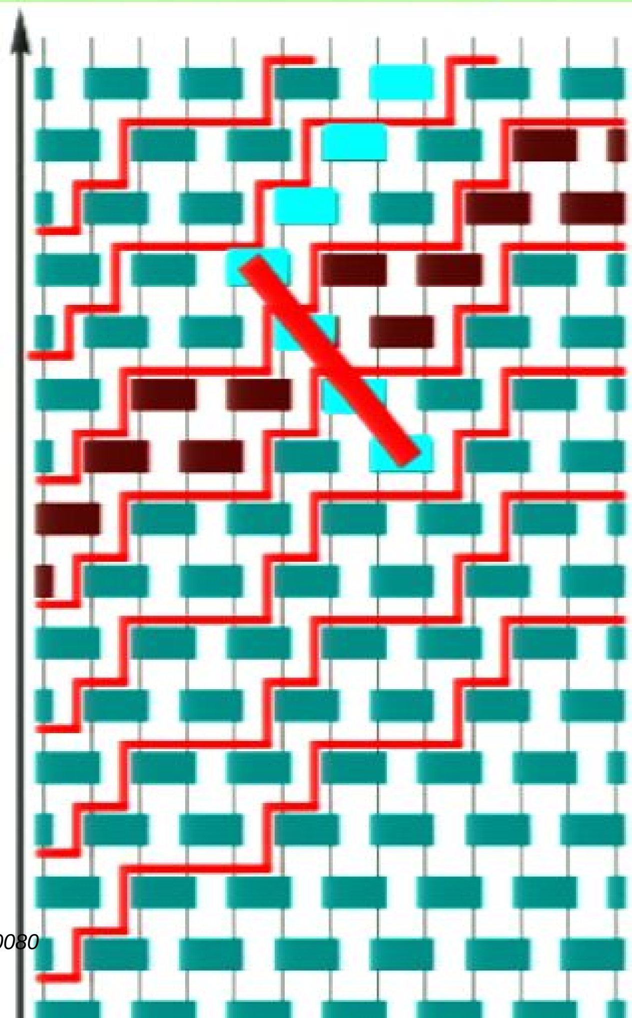
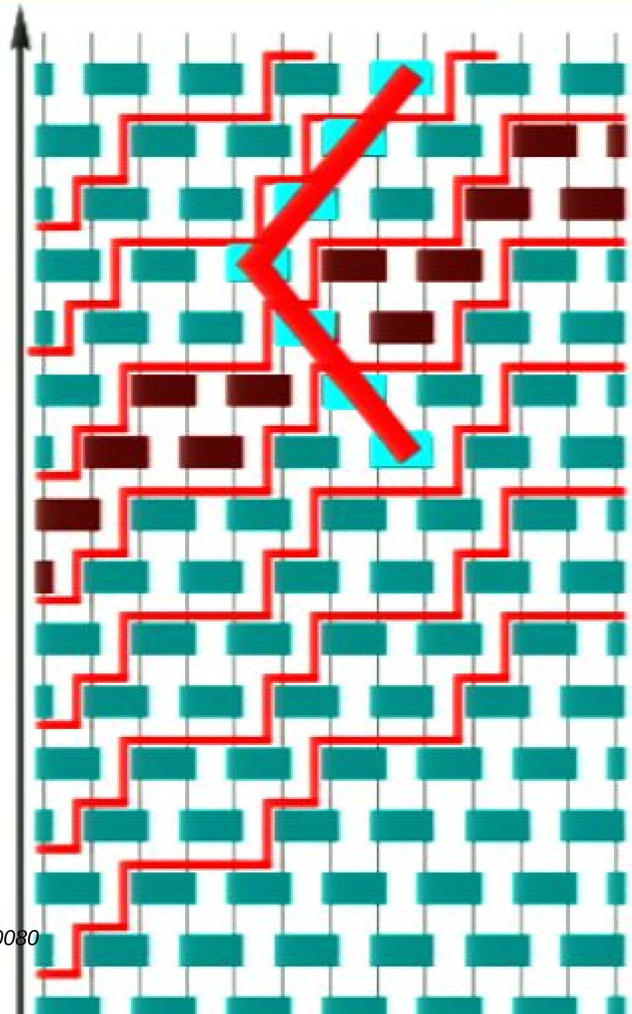
Relativity from QT
(from causality)



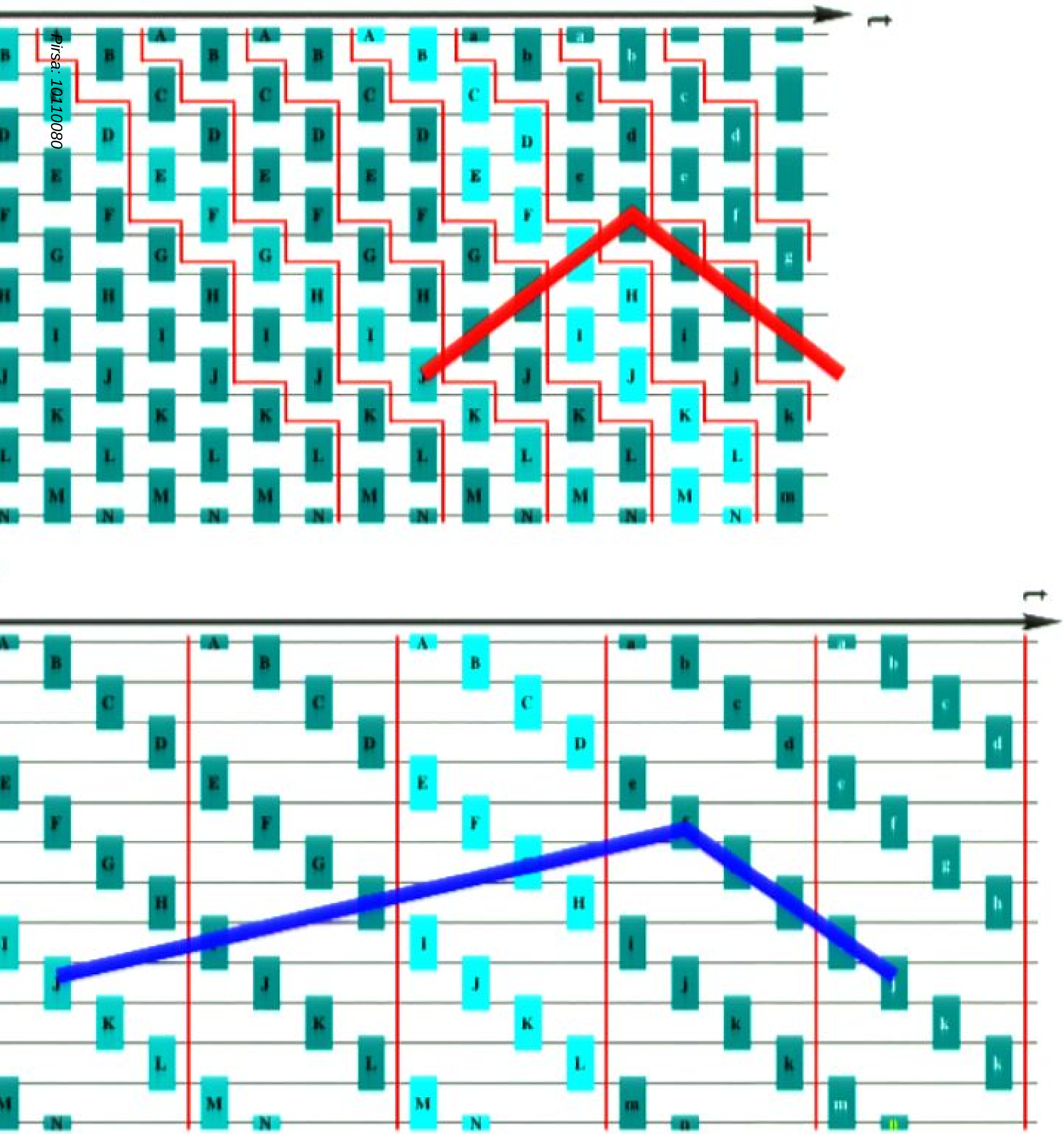
clock tic-tac

Relativity from QT

(from causality)



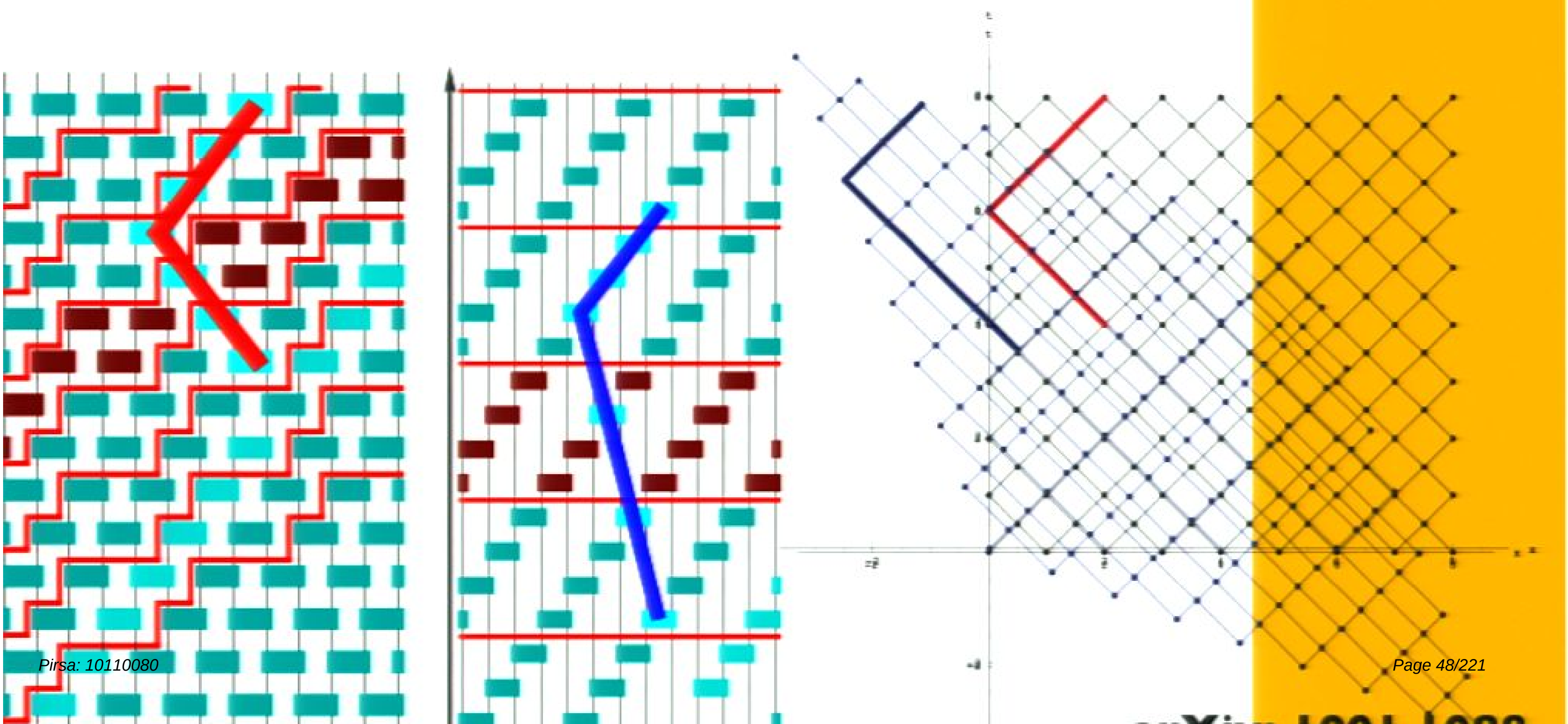
clock tic-tac



Time dilation and space contraction

Relativity from QT

(from causality)



FROM CAUSALITY WE GOT SPACE-TIME ENDOWED WITH RELATIVITY

Relativity from QT

A theory of quantum gravity based on quantum computation

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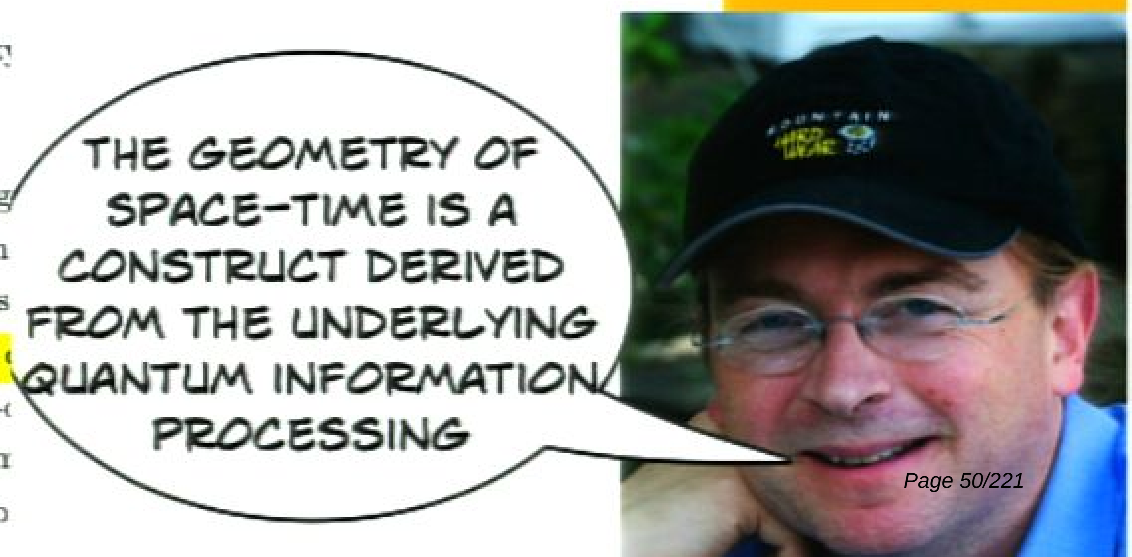
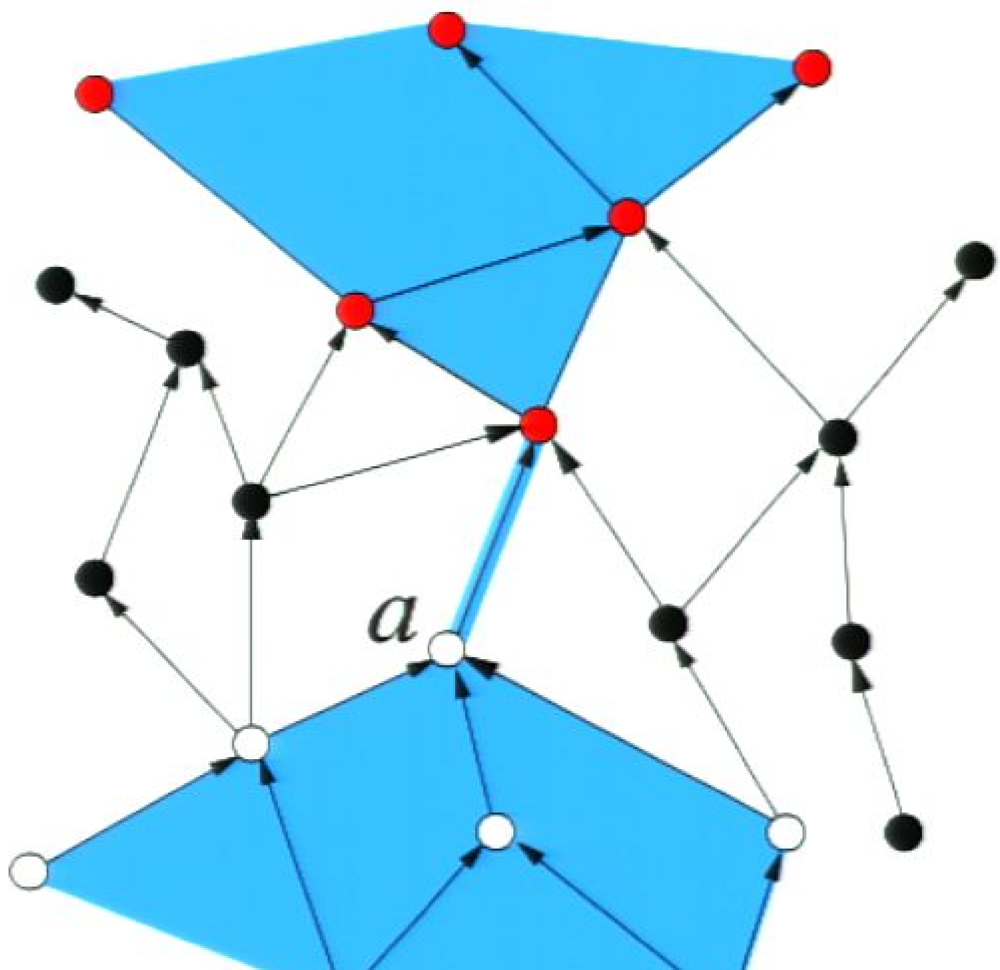
Keywords: quantum computation, quantum gravit

Abstract: This paper proposes a method of unifying
on quantum computation. In this theory, fundam
of pairwise interactions between quantum degrees
time is a construct, derived from the underlying
computation gives rise to a superposition of four-
obeys the Einstein-Regge equations. The theory m
reaction of the metric to computational 'matter,' b



Lorentz transformations from causality and topological homogeneity

GMD and
A. Tosini
1008.4805



"Light" cones

Lorentz transformations from causality and topological homogeneity

GMD and
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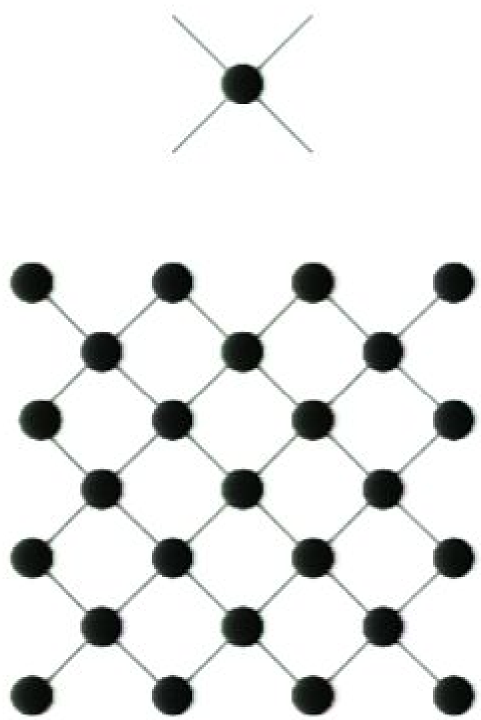

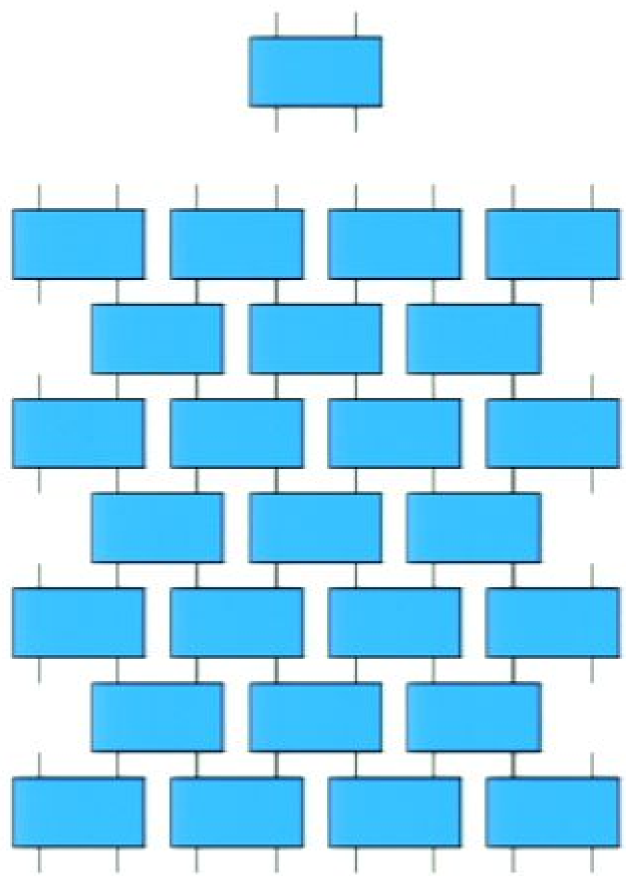

topological homogeneity

Lorentz transformations from causality and topological homogeneity

GMD and
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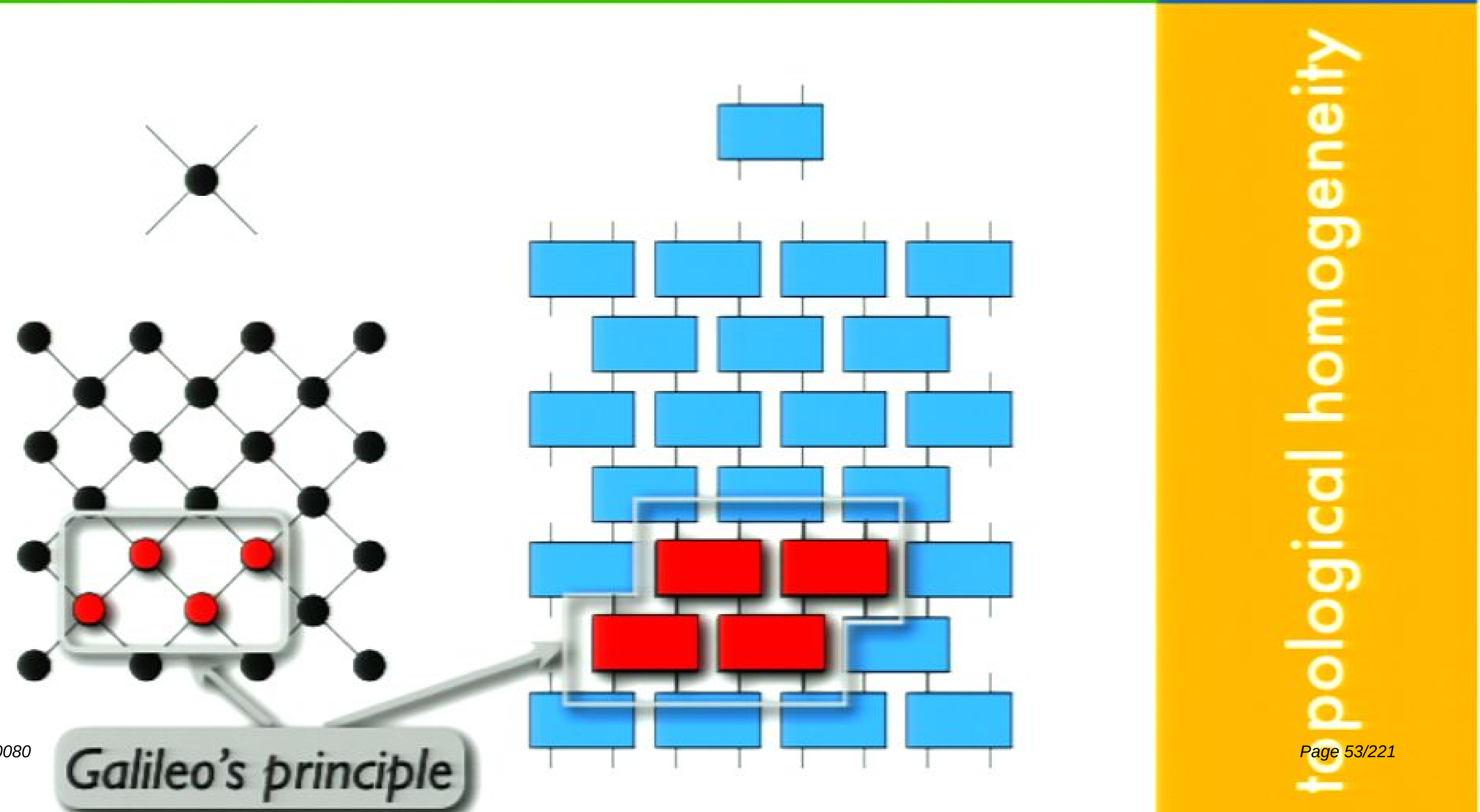
1008.4805



Lorentz transformations from causality and topological homogeneity

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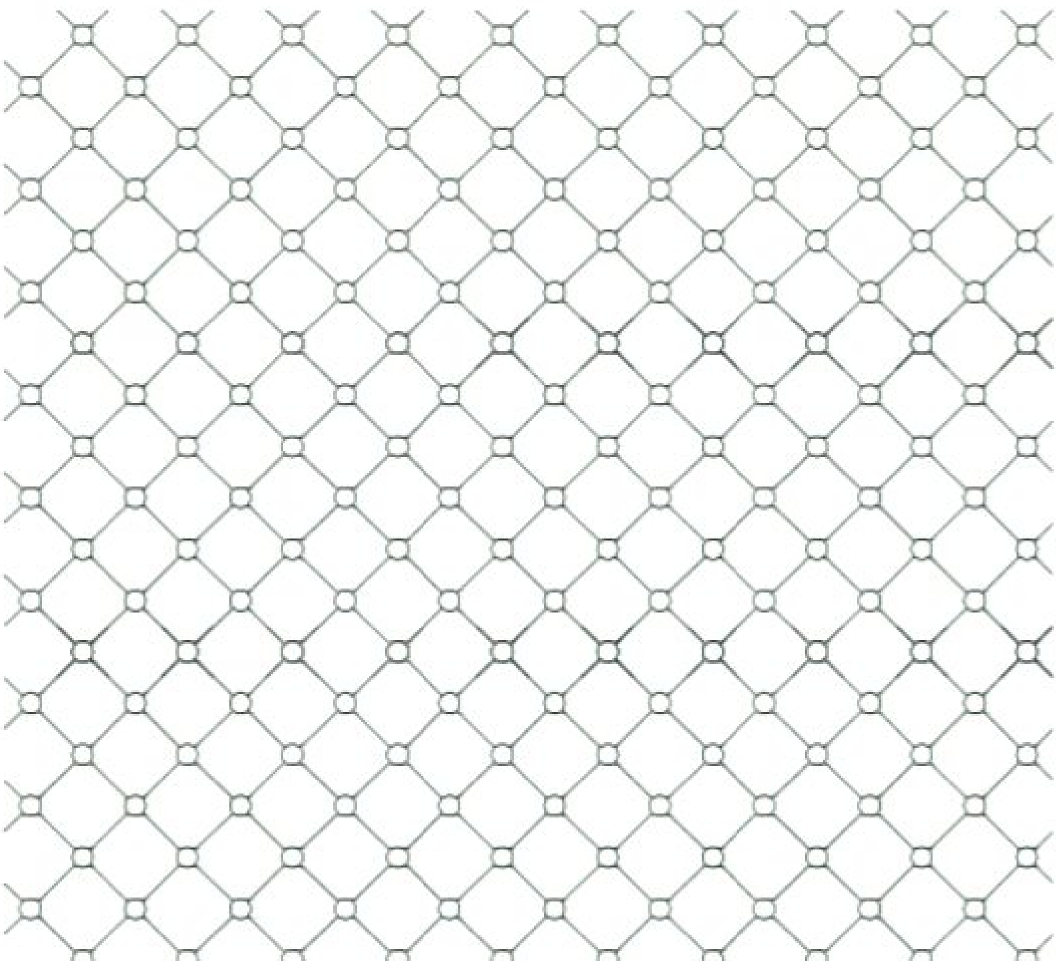

observer

Lorentz transformations from causality and topological homogeneity

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A. Tosini
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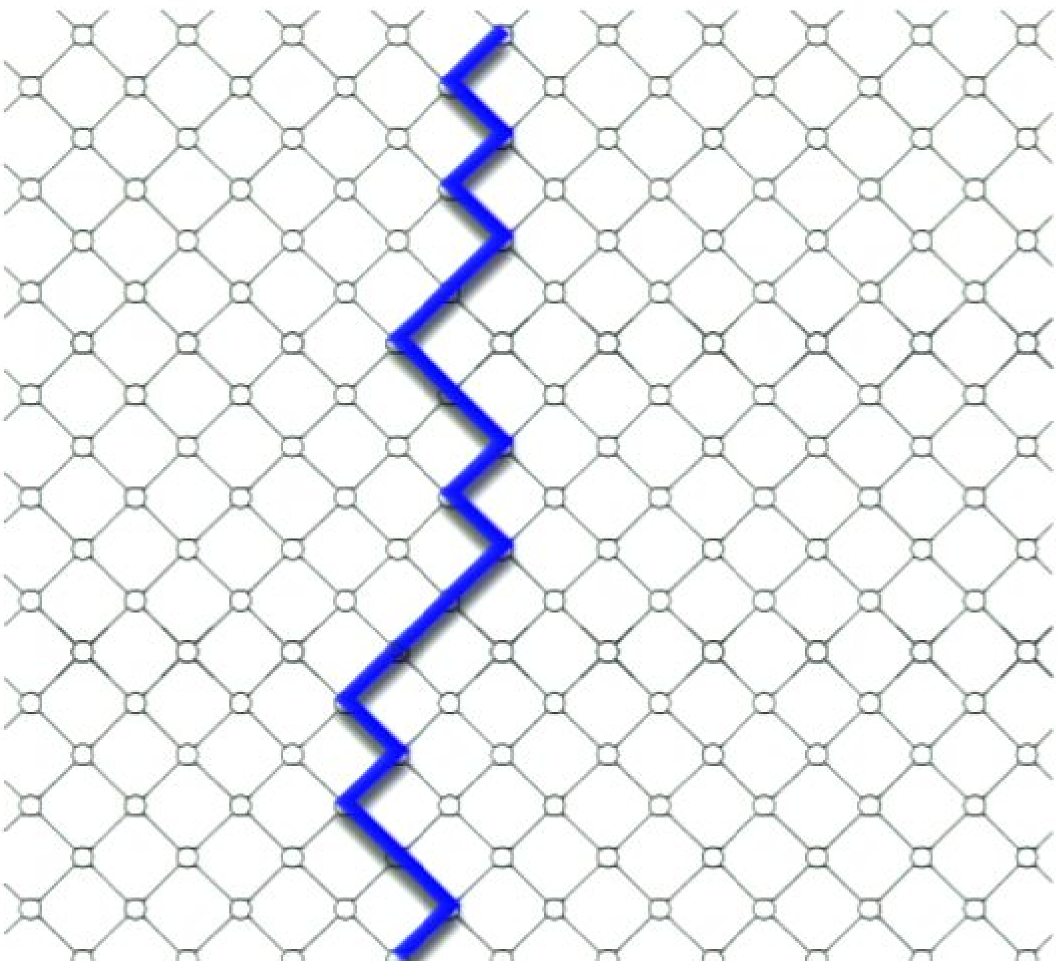

observer

Lorentz transformations from causality and topological homogeneity

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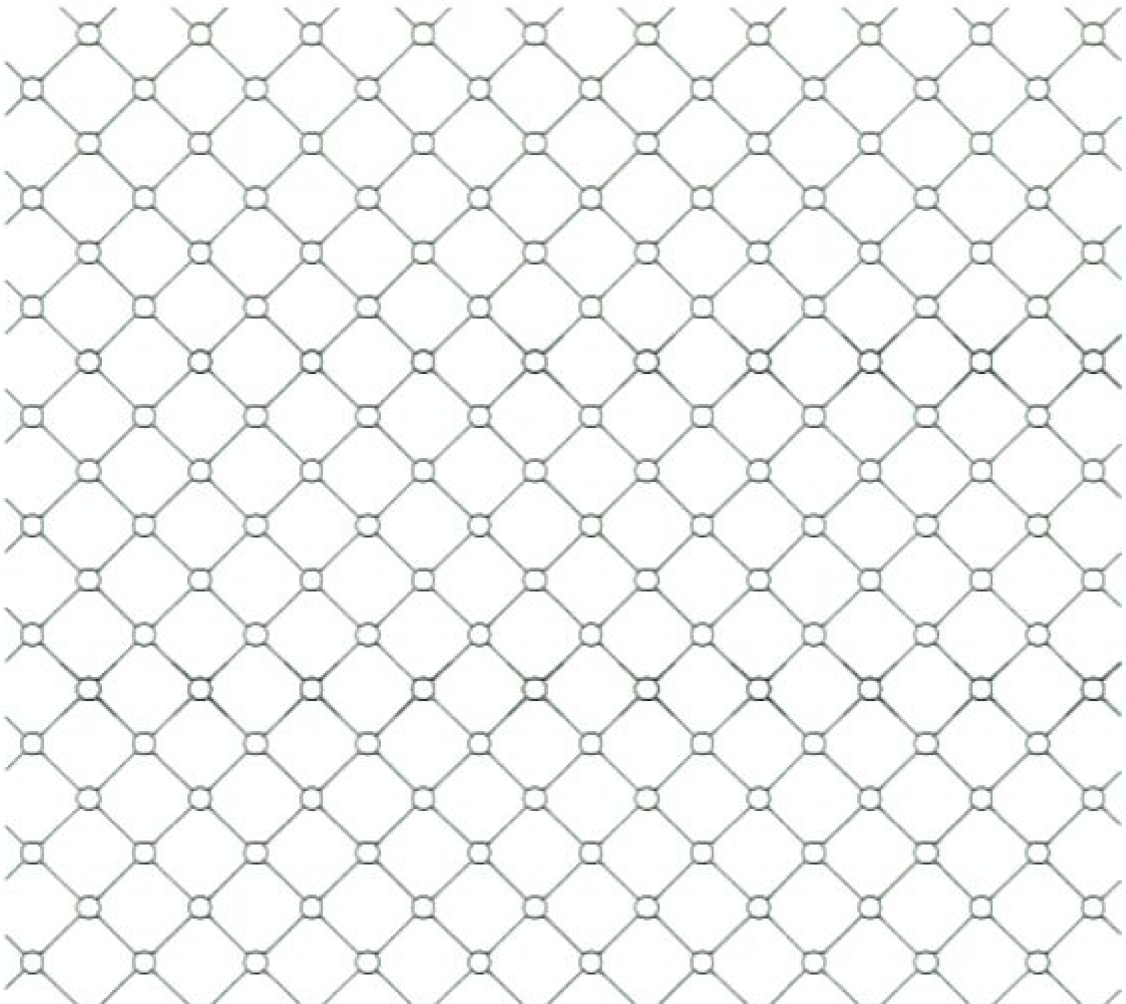
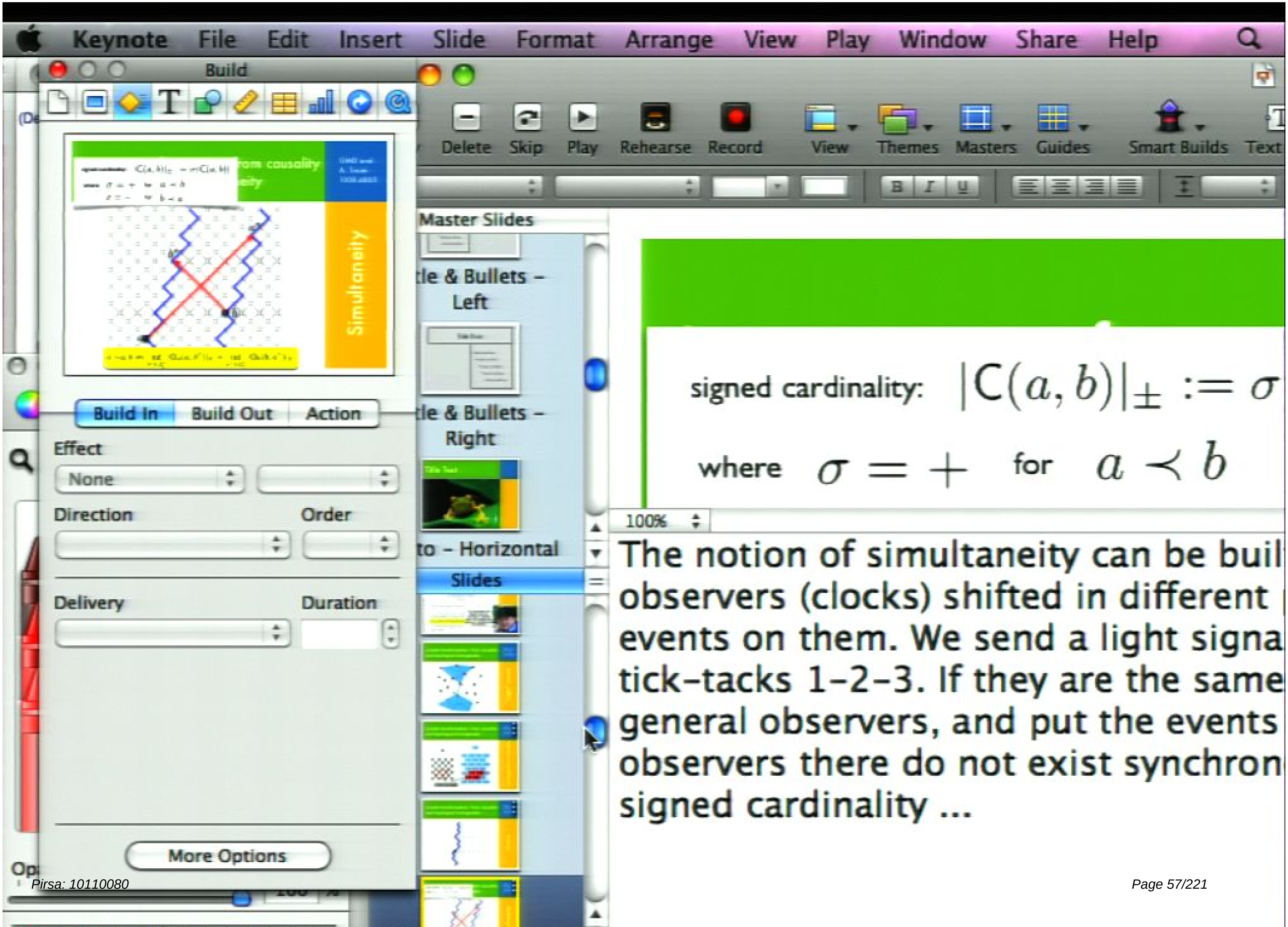
Simultaneity




Keynote File Edit Insert Slide Format Arrange View Play Window Share Help
Build
Build In Build Out Action
Effect
None
Direction
Order
Delivery
Duration
More Options
Delete Skip Play Rehearse Record View Themes Masters Guides Smart Builds Text
Master Slides
tle & Bullets – Left
tle & Bullets – Right
to – Horizontal
Slides
Simultaneity
signed cardinality: $|\mathrm{C}(a,b)|_{\pm} := \sigma$
where $\sigma = +$ for $a \prec b$
100%
The notion of simultaneity can be buil
observers (clocks) shifted in different
events on them. We send a light signa
tick-tacks 1-2-3. If they are the same
general observers, and put the events
observers there do not exist synchron
signed cardinality ...

Lorentz transformations from causality and topological homogeneity

GMD and
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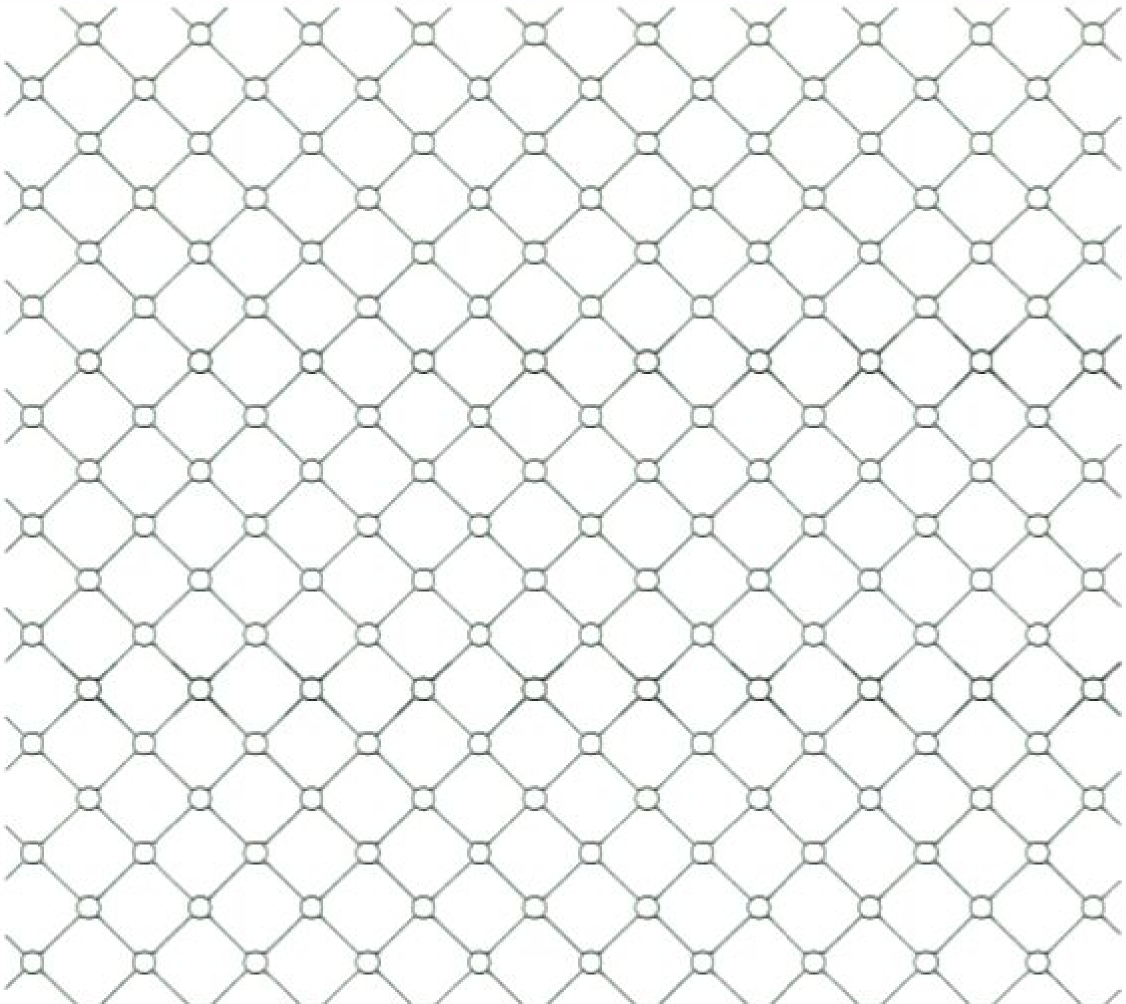
1008.4805



Simultaneity

Lorentz transformations from causality and topological homogeneity

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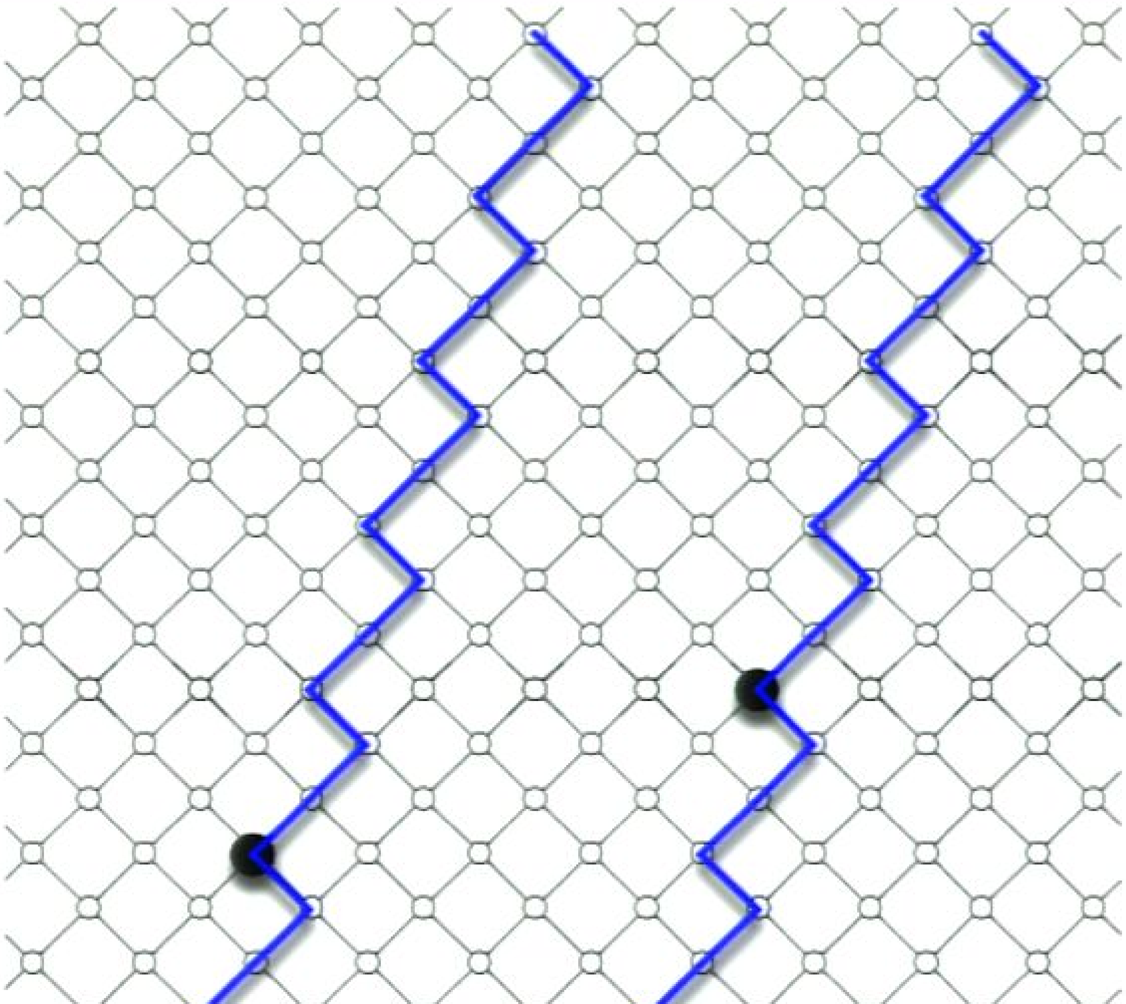
Simultaneity



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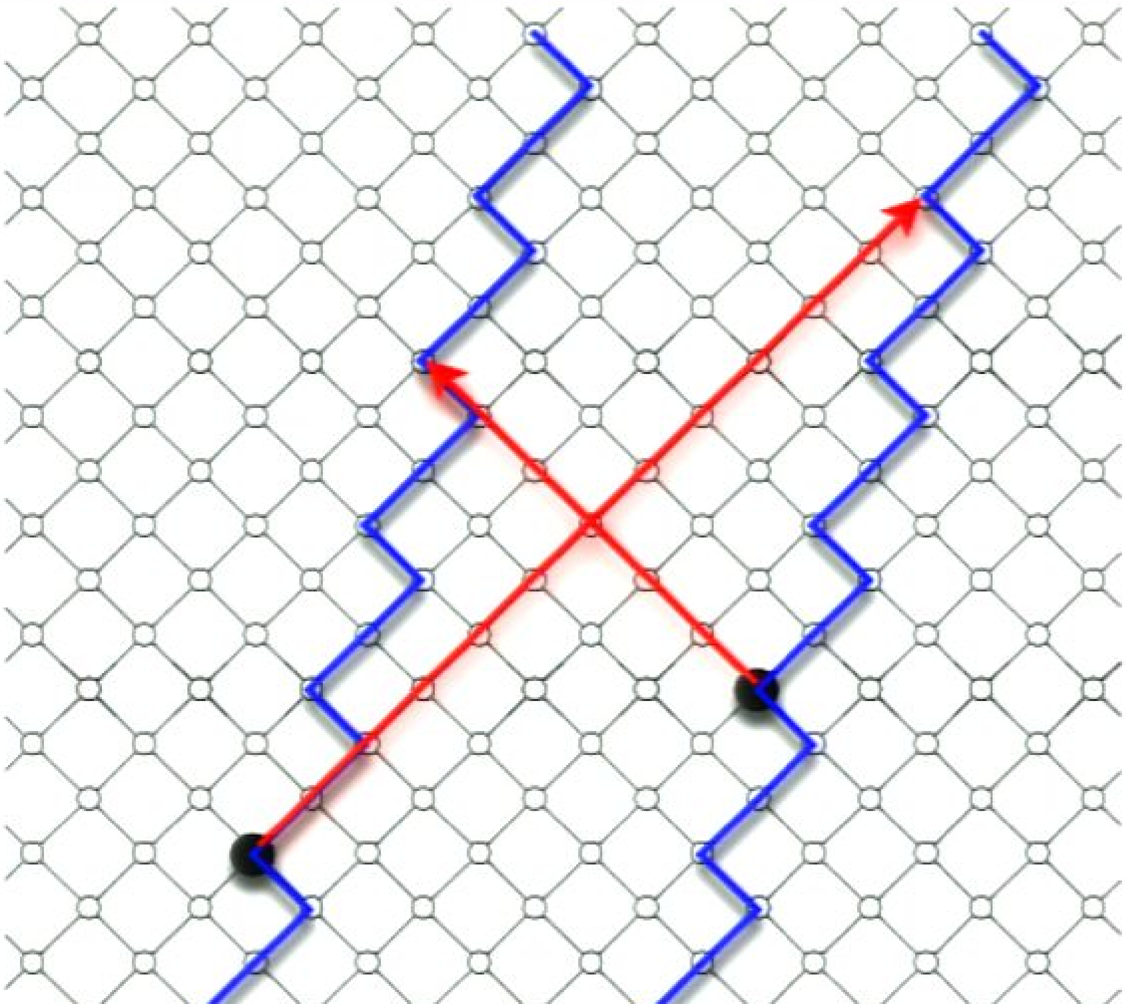
A. Tosini
1008.4805



Simultaneity

rom causality
eity

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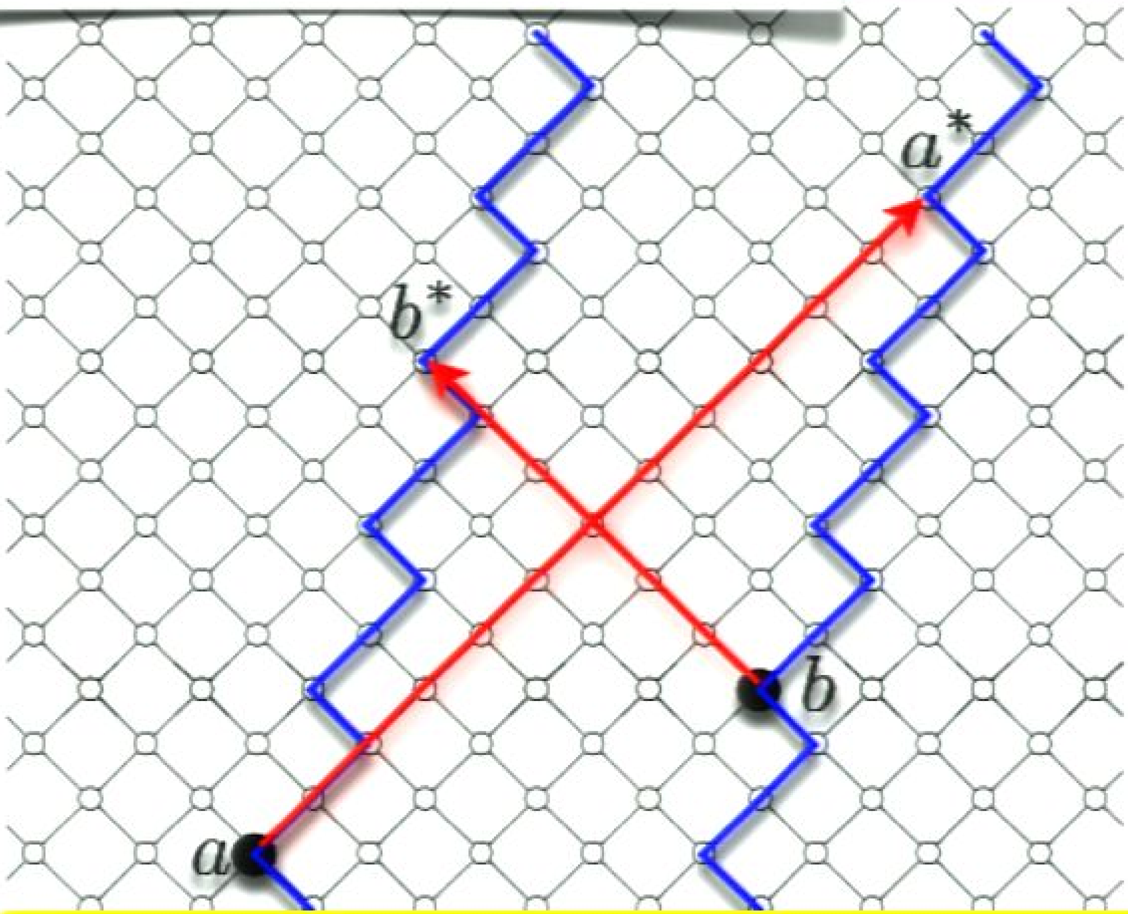
signed cardinality: $|\mathsf{C}(a,b)|_{\pm} := \sigma|\mathsf{C}(a,b)|$

where $\sigma = +$ for $a \prec b$

$\sigma = -$ for $b \prec a$



Simultaneity

$a \sim_{\mathsf{O}} b \Leftarrow \inf |\mathsf{O}_a(a,b^*)|_{\pm} = \inf |\mathsf{O}_b(b,a^*)|_{\pm}.$

Lorentz transformations from causality and topological homogeneity

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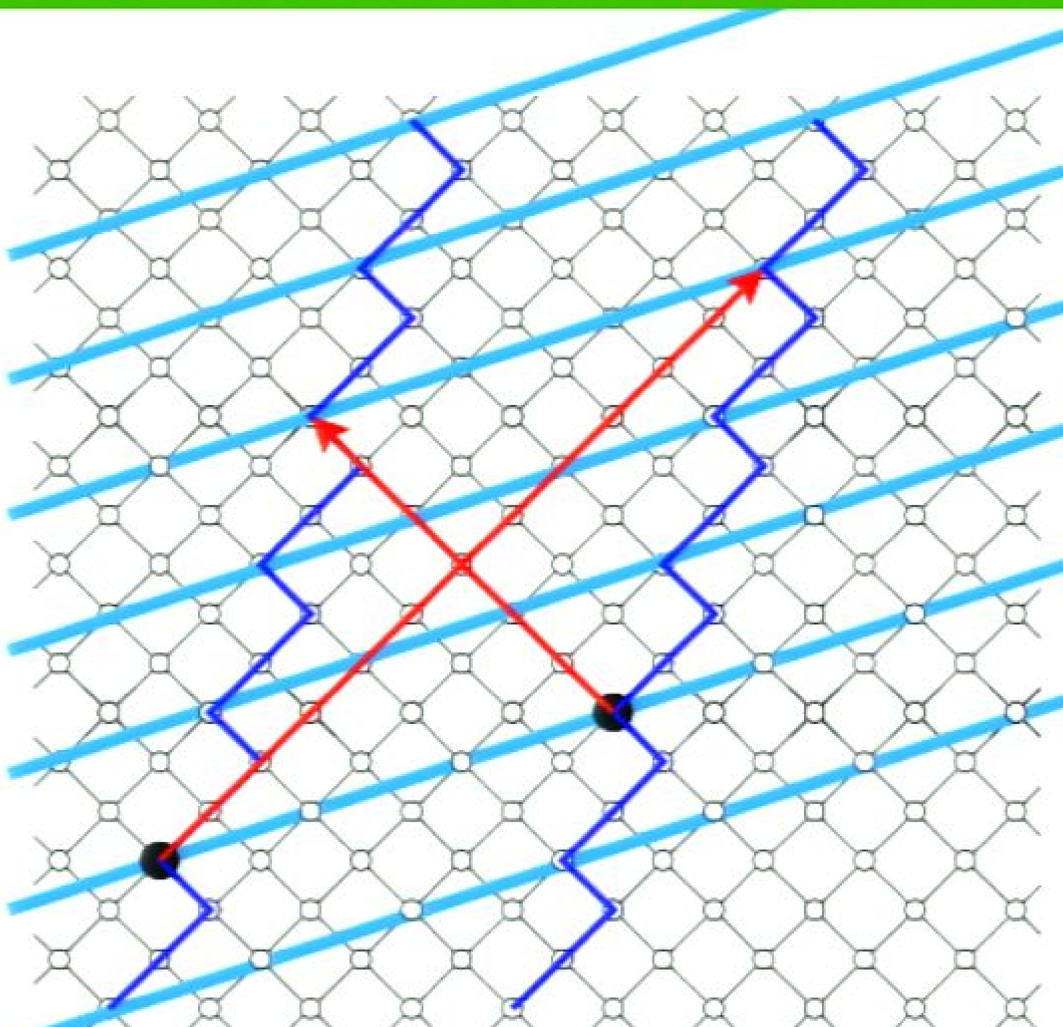

Foliation

Lorentz transformations from causality and topological homogeneity

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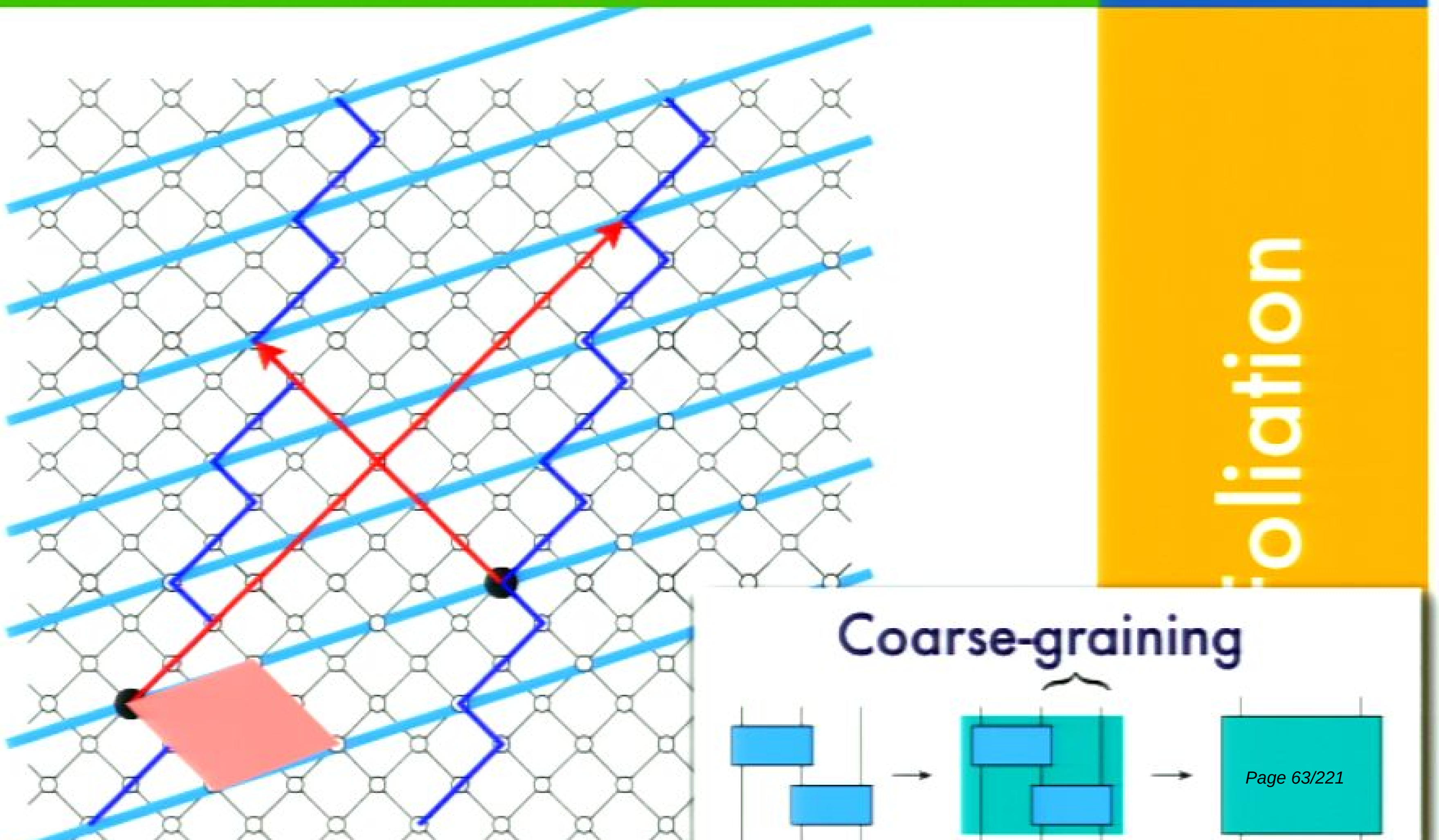

Lorentz transformations from causality and topological homogeneity

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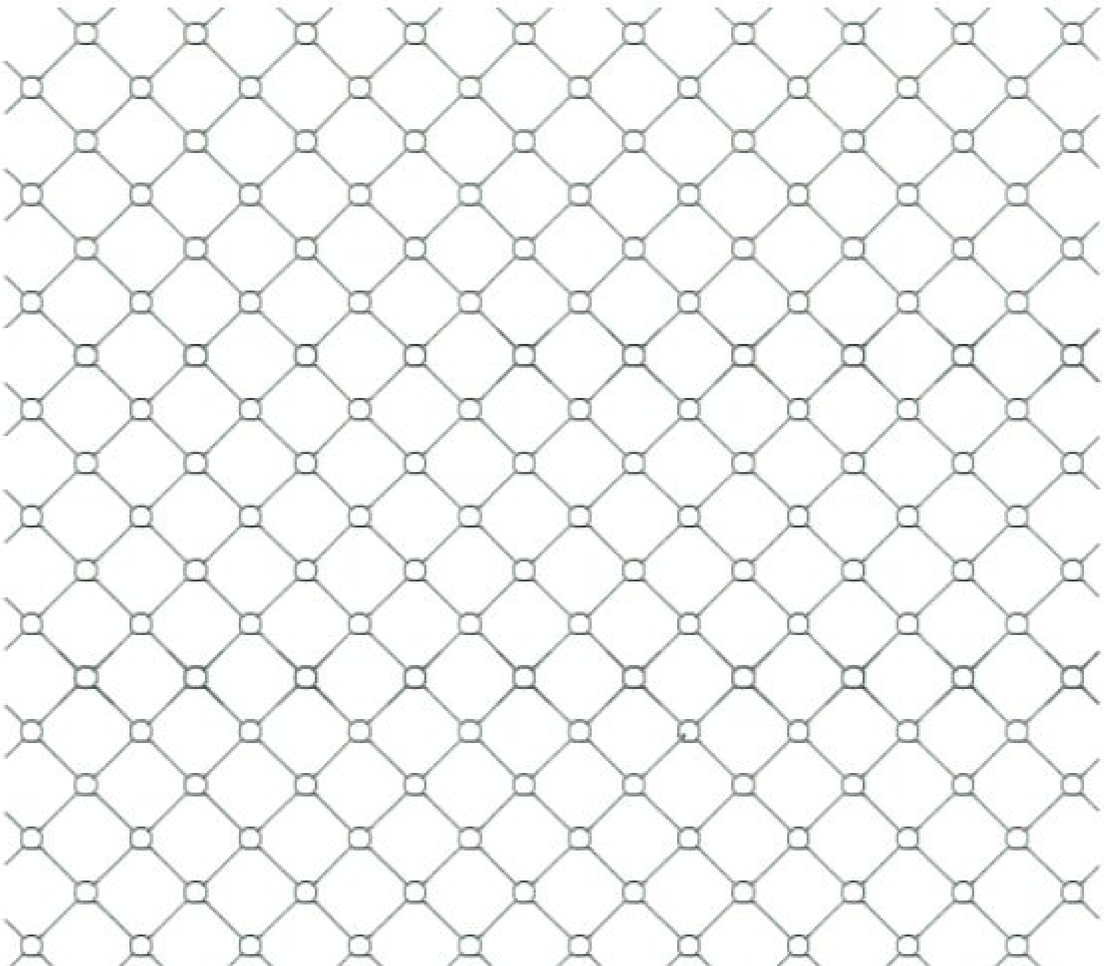

Coordinates

Lorentz transformations from causality and topological homogeneity

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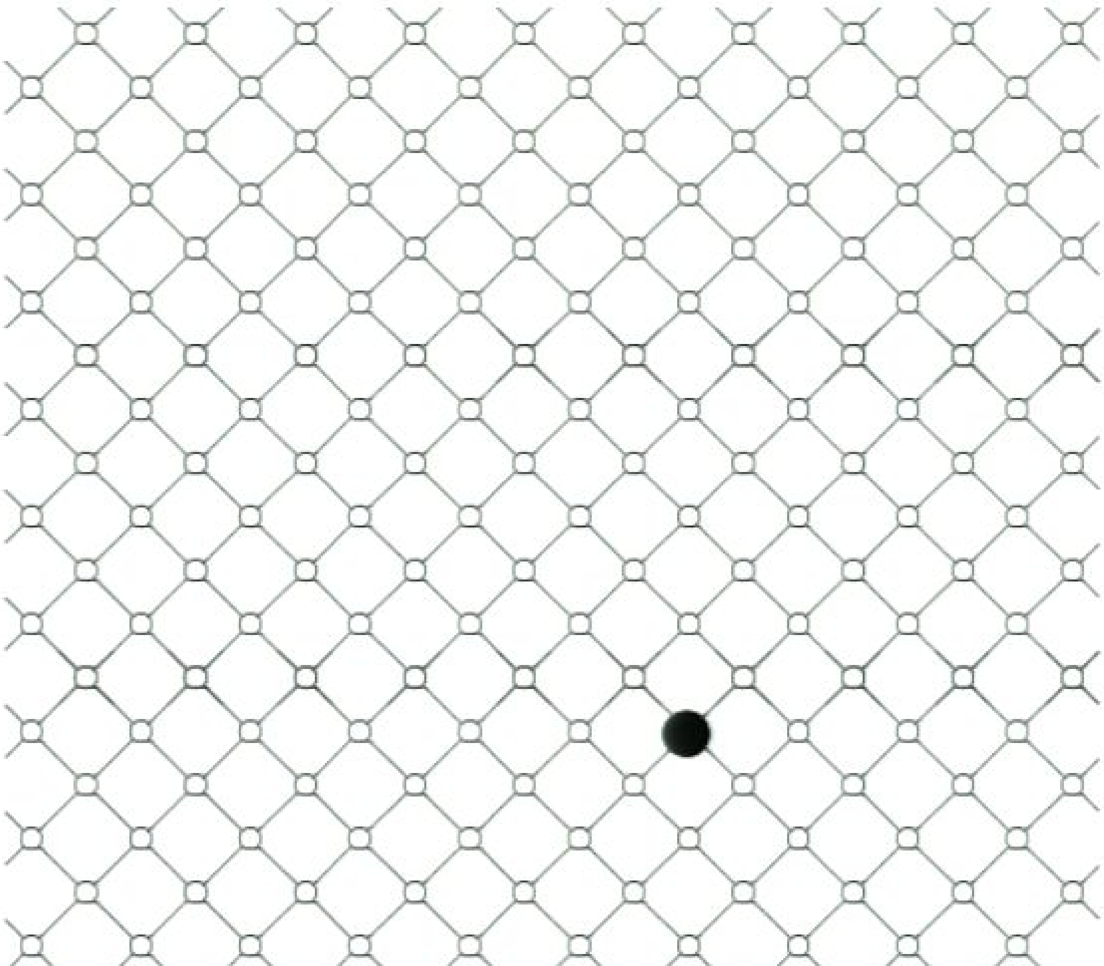

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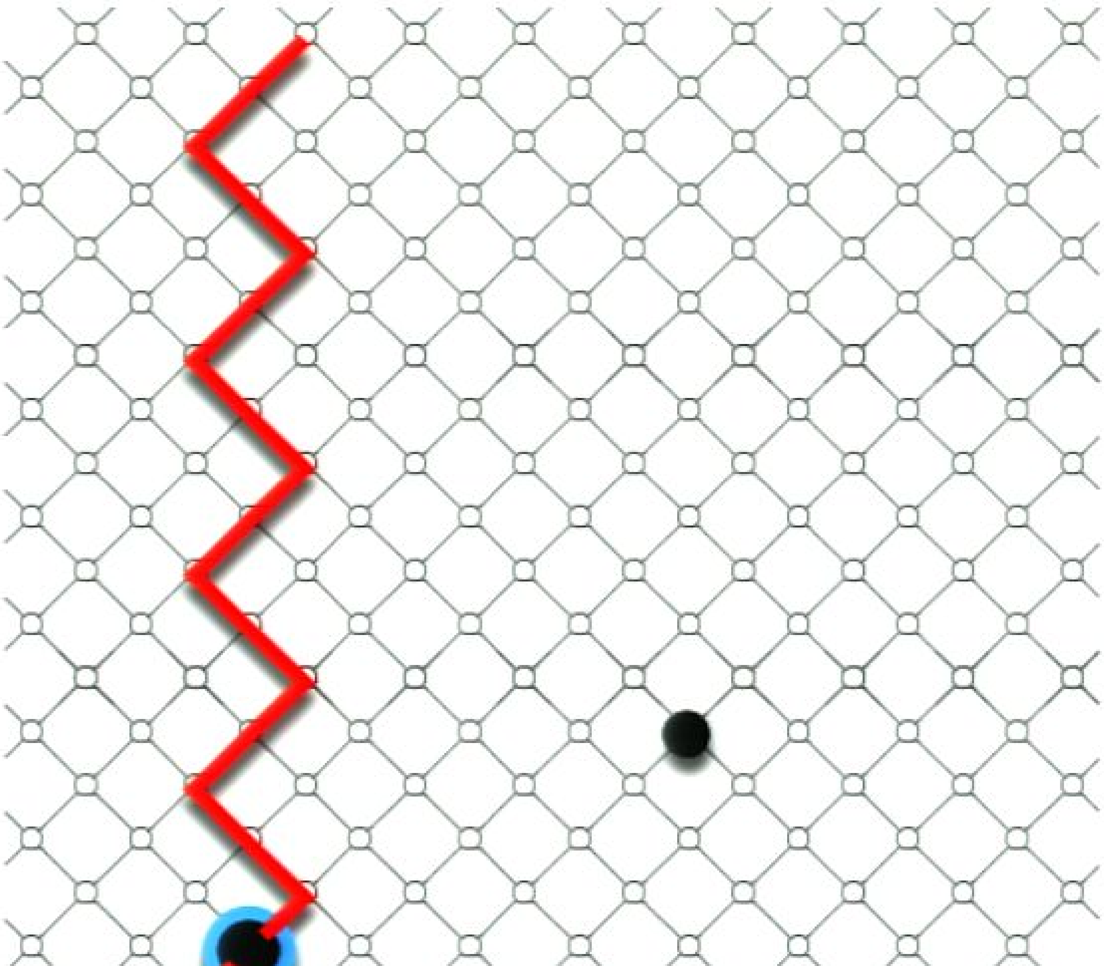

Coordinates

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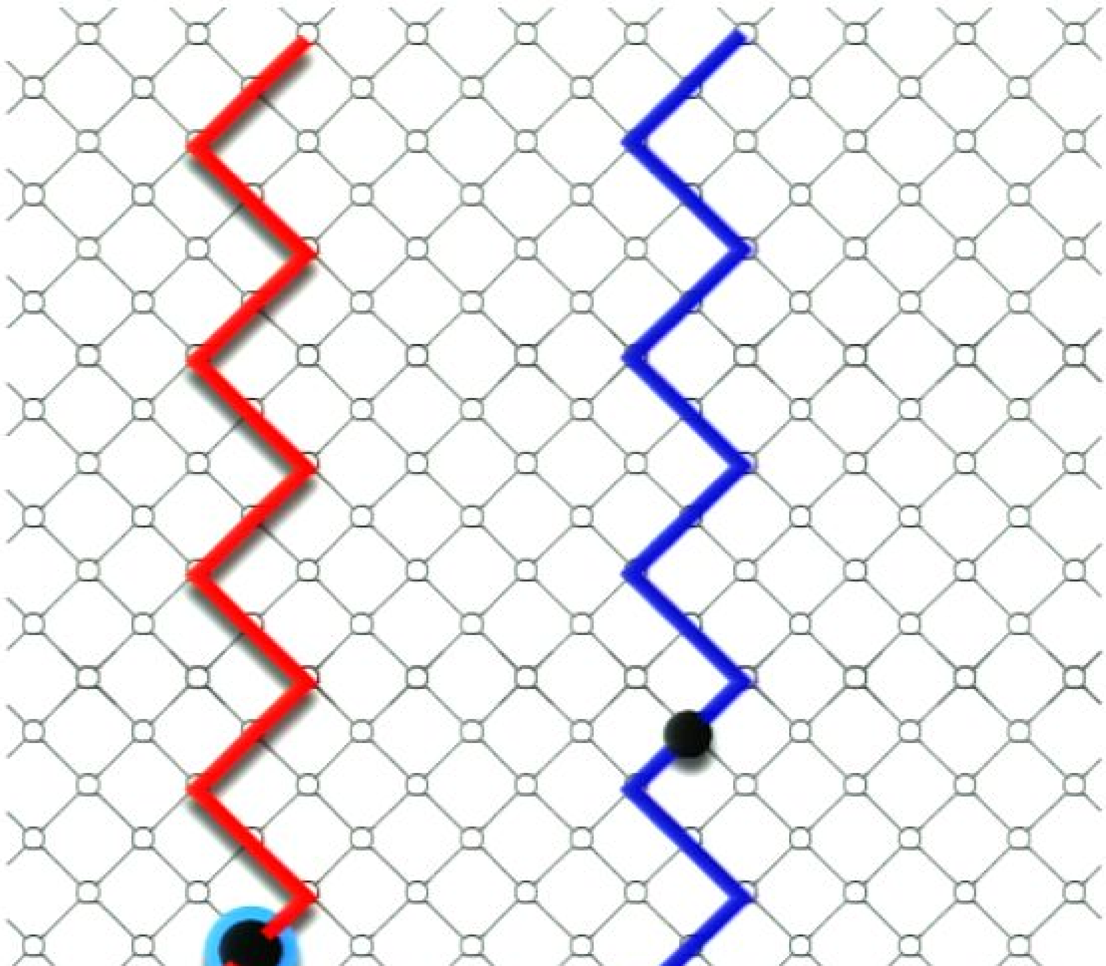
Coordinates



Lorentz transformations from causality and topological homogeneity

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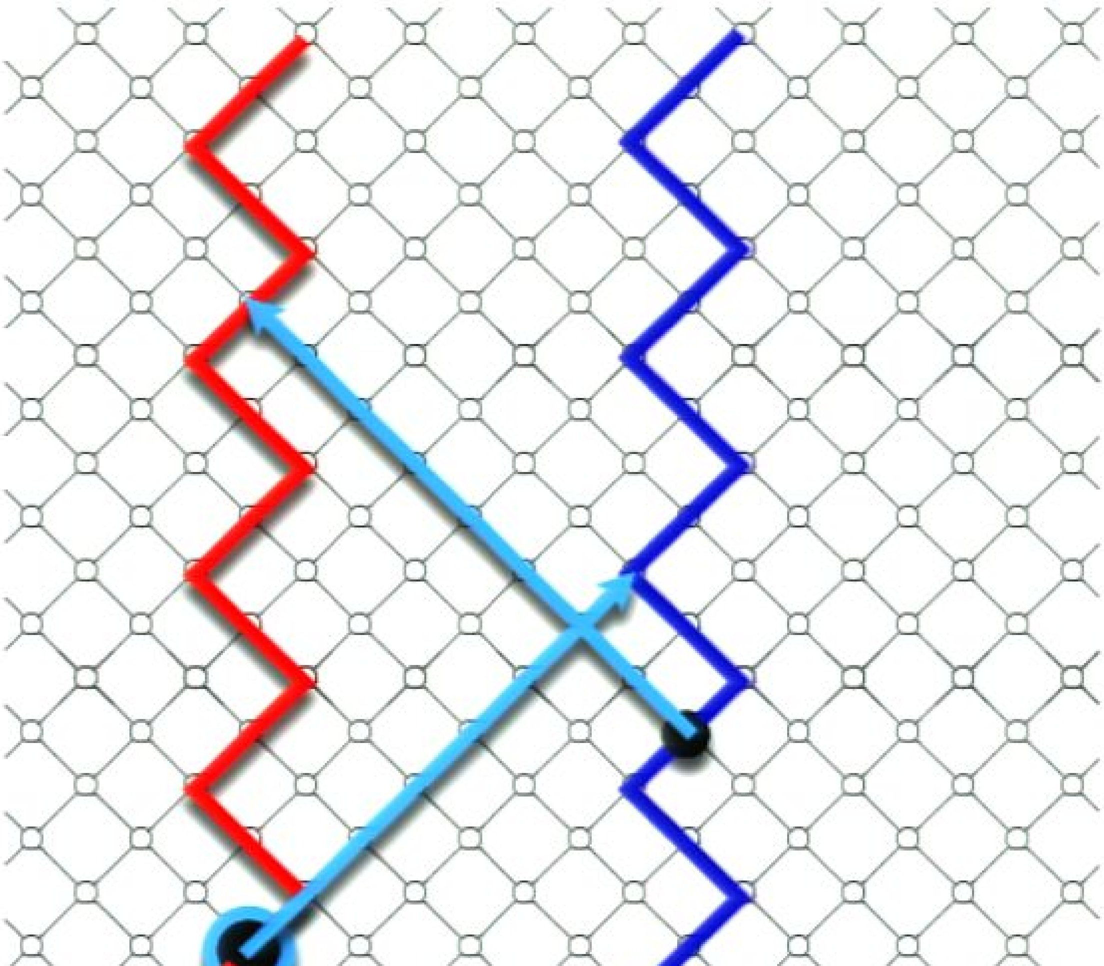
Coordinates



Lorentz transformations from causality and topological homogeneity

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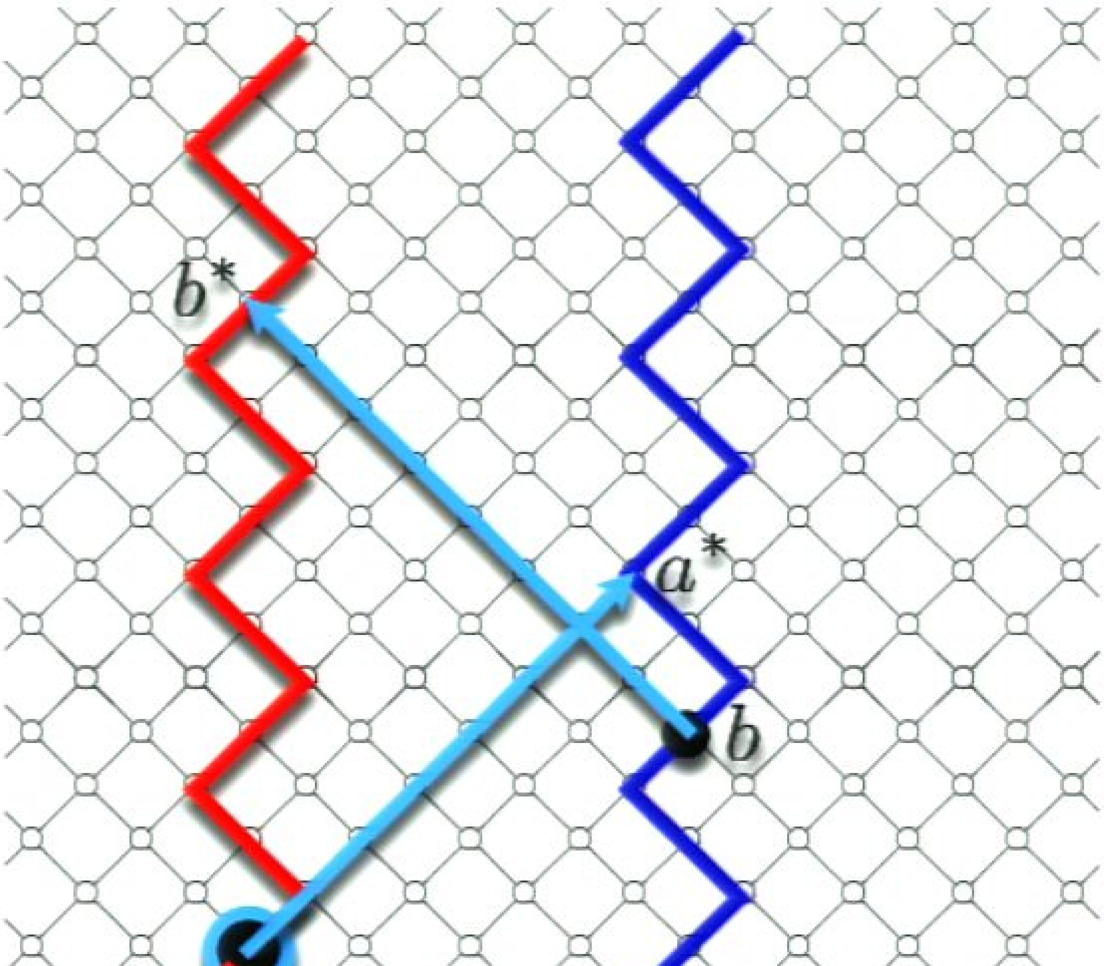

Coordinates

Lorentz transformations from causality and topological homogeneity

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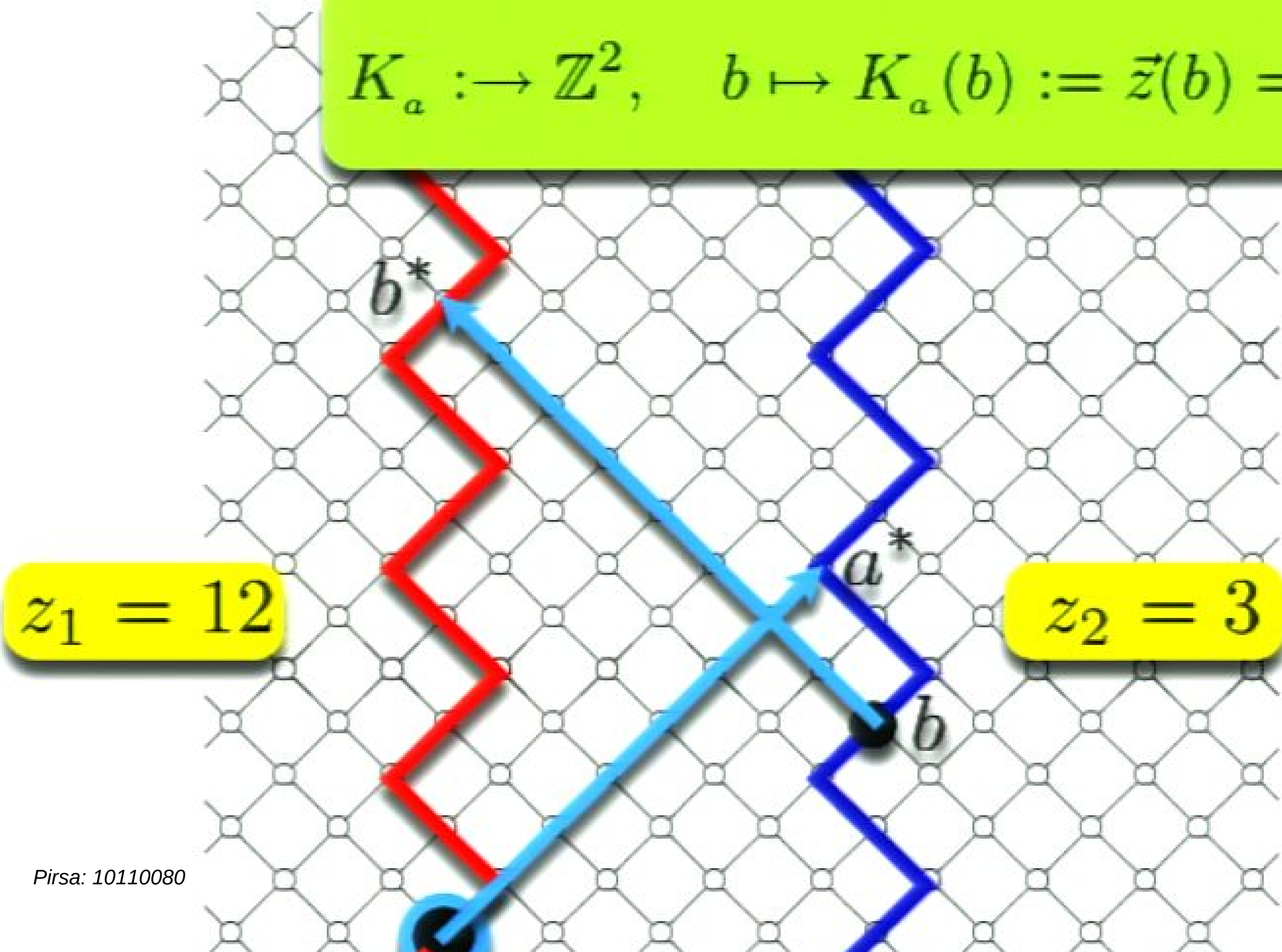
Coordinates

$$K_a :\to \mathbb{Z}^2, \quad b \mapsto K_a(b) := \vec{z}(b) = \begin{bmatrix} z_1(b) \\ z_2(b) \end{bmatrix}$$



Lorentz transformations from causality and topological homogeneity

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Coordinates

Lemma 1 *An event* $b \in \mathsf{L}(\mathsf{O}_a)$ *belongs to the* t*-th leaf* $\mathsf{L}_t(\mathsf{O}_a)$ *for* $t = (z_1 - z_2)/2$*, and the number of events on such leaf between* b *and* O_a *is given by* $s = (z_1 + z_2)/2$.

According to the last Lemma the coordinates

$$\begin{bmatrix} t(b) \\ s(b) \end{bmatrix} := 2^{\frac{1}{2}}\mathbf{U}(\pi/4)\begin{bmatrix} z(b) \\ z(b) \end{bmatrix}, \qquad (10)$$

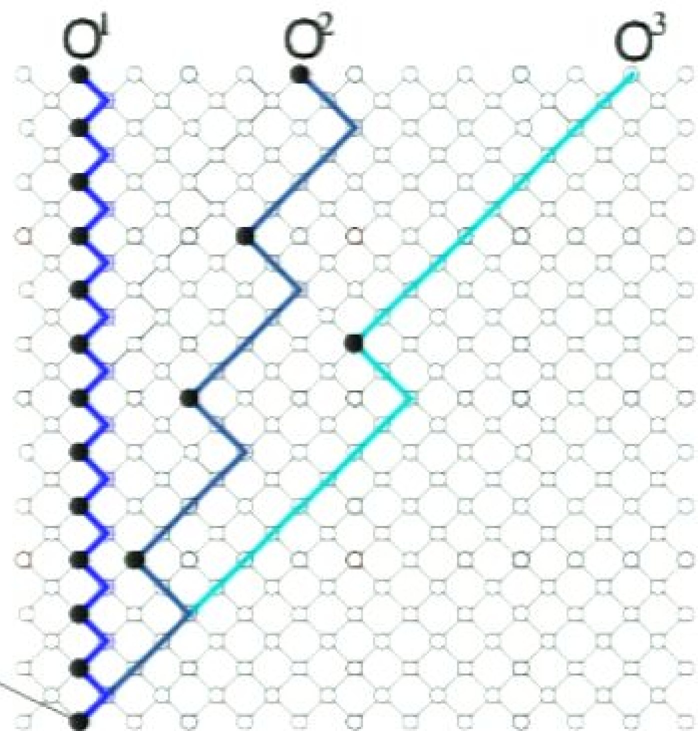
where $\mathbf{U}(\theta)$ is the matrix performing a θ-rotation, can be interpreted as the space-time coordinates of the event b in the frame $\mathsf{L}(\mathsf{O}_a)$.

Frames in standard configuration (boosted). Consider now two observers $\mathsf{O}^1_a = \{o^1_i\}$ and $\mathsf{O}^2_a = \{o^2_j\}$ sharing the same origin (homogeneity guarantees the existence of observers sharing the origin). We will shortly denote the two frames as $\mathfrak{R}^1$ and $\mathfrak{R}^2$, and the corresponding coordinate maps as K^1 and K^2. We will say that the two frames $\mathfrak{R}^1$ and $\mathfrak{R}^2$ are in *standard configuration* if there exist positive α^{12}, β^{12}, such that $\forall i \in \mathbb{Z}$

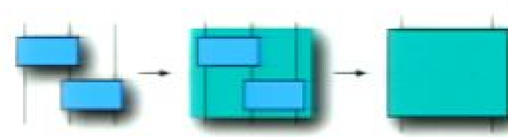
$$K^1(o^2_i) = \mathbf{D}^{12} K^2(o^2_i), \; \mathbf{D}^{12} := \mathrm{diag}(\alpha^{12}, \beta^{12}). \qquad (11)$$

$\alpha^1=1$	$\beta^1=1$
$\alpha^2=4$	$\beta^2=2$
$\alpha^3=12$	$\beta^3=2$

$\alpha^{12}=4$	$\beta^{12}=2$
$\alpha^{23}=3$	$\beta^{23}=1$
$\alpha^{13}=12$	$\beta^{13}=2$



$o^1_0 = o^2_0 = o^3_0 = a$



$$v^{12} = \frac{\alpha^{12} - \beta^{12}}{\alpha^{12} + \beta^{12}}$$

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Boosts

Lorentz transformations from causality and topological homogeneity

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$$v^{13} = \frac{\alpha^{12}\alpha^{23} - \beta^{12}\beta^{23}}{\alpha^{12}\alpha^{23} + \beta^{12}\beta^{23}} = \frac{v_{12} + v_{23}}{1 + v_{12}v_{23}}$$

Coordinates

Lorentz transformations from causality and topological homogeneity

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Coordinates

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$$t^1 = \chi_{12}\frac{t^2 + v^{12}s^2}{\sqrt{1-(v^{12})^2}}, \qquad s^1 = \chi_{12}\frac{s^2 + v^{12}t^2}{\sqrt{1-(v^{12})^2}},$$

$$\chi_{12} := \sqrt{\alpha^{12}\beta^{12}}$$

which differ from the Lorentz transformations only by the multiplicative factor χ_{12}. The factor χ_{12} can be removed by rescaling the coordinate map in Eq. (10) using the

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Boosts

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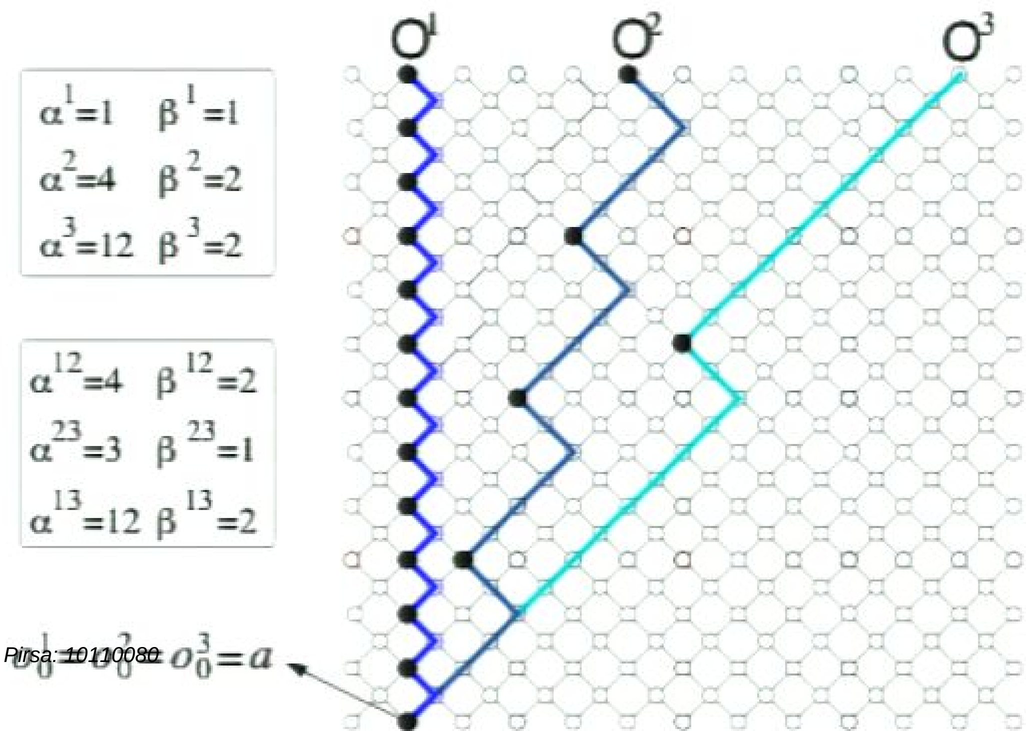

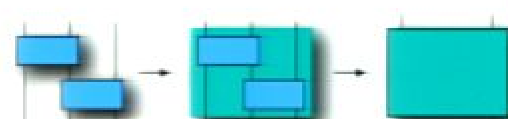

$$v^{12} = \frac{\alpha^{12} - \beta^{12}}{\alpha^{12} + \beta^{12}}$$

Lorentz transformations from causality and topological homogeneity

Conventionality of simultaneity, homogeneity, ...

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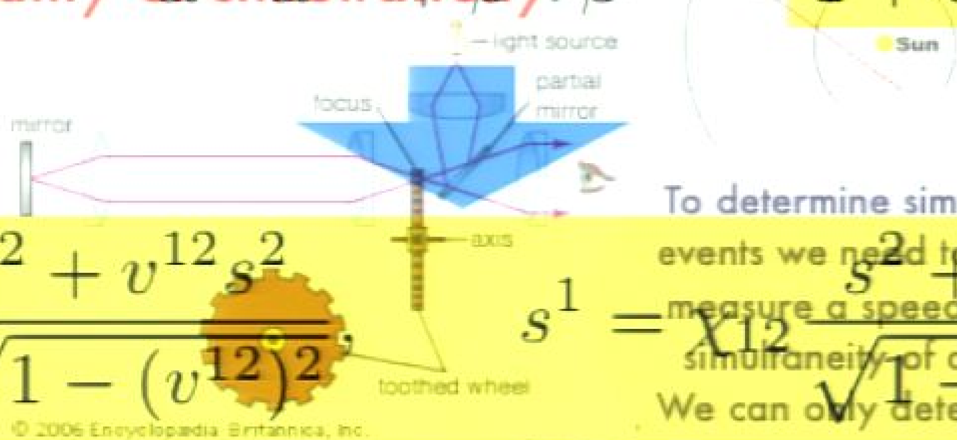
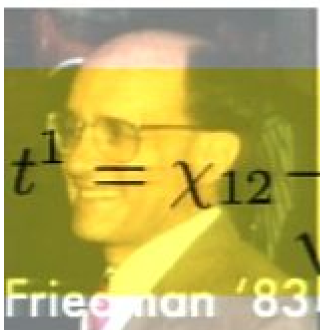
The causal network manifests the conventionality of simultaneity.

$$v^{13} = \frac{\alpha^{12}\alpha^{23} - \beta^{12}\beta^{23}}{\alpha^{12}\alpha^{23} + \beta^{12}\beta^{23}} = \frac{v_{12} + v_{23}}{1 + v_{12}v_{23}}$$



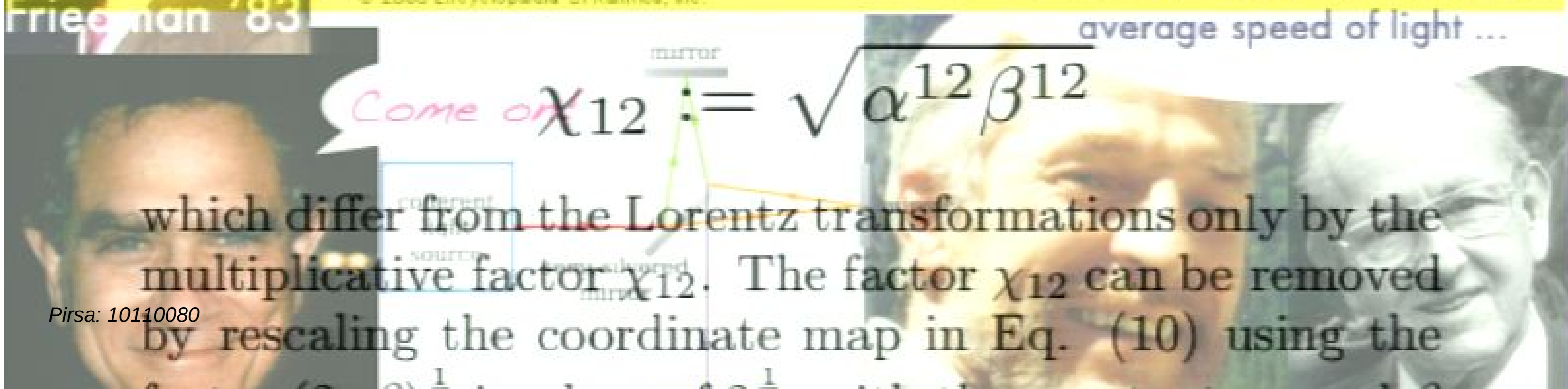
To determine simultaneity of distant events we need to know a speed, to measure a speed we need to know simultaneity of different events'... We can only determine the two-way average speed of light ...

$$t^1 = \chi_{12}\frac{t^2 + v^{12}s^2}{\sqrt{1-(v^{12})^2}}, \qquad s^1 = \chi_{12}\frac{s^2 + v^{12}t^2}{\sqrt{1-(v^{12})^2}},$$



Come on

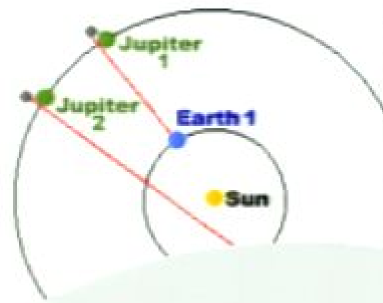
$$\chi_{12} := \sqrt{\alpha^{12}\beta^{12}}$$

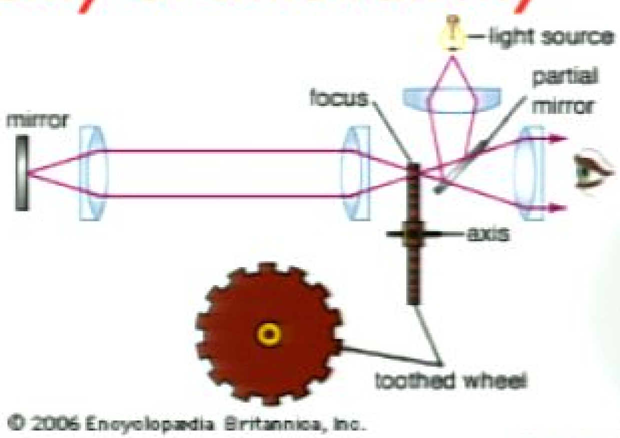


which differ from the Lorentz transformations only by the multiplicative factor χ_{12}. The factor χ_{12} can be removed by rescaling the coordinate map in Eq. (10) using the

Conventionality of simultaneity, homogeneity, ...

The causal network manifests the ***conventionality of simultaneity***.





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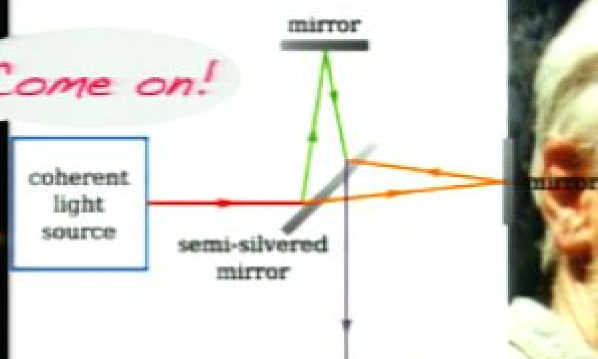
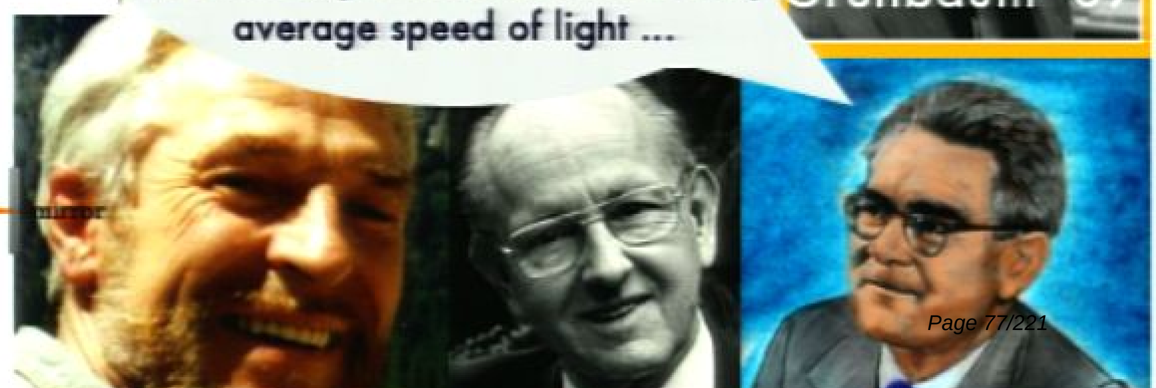
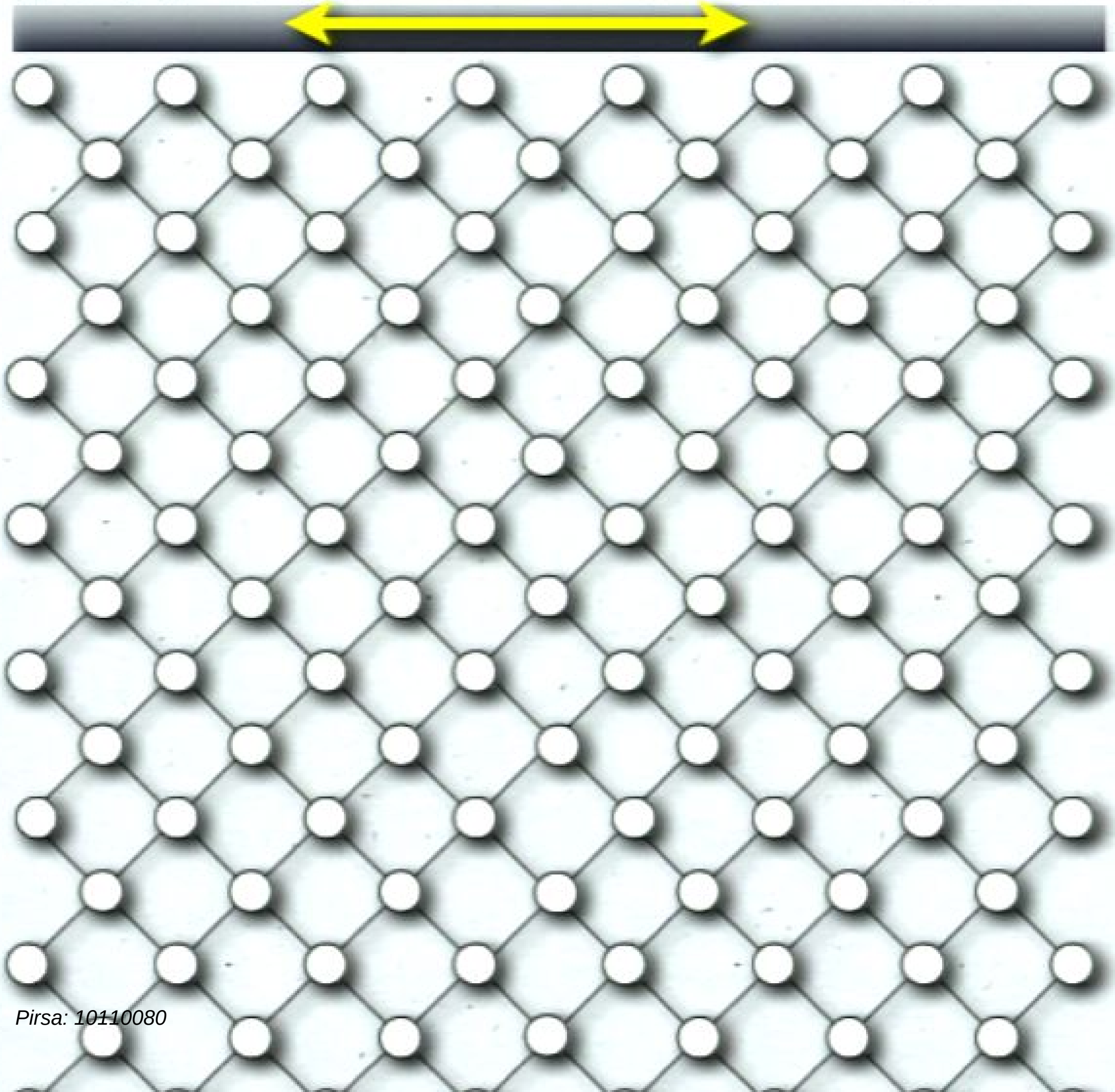




SPECIAL RELATIVITY WITHOUT SPACE: OTHER IDEAS

SPECIAL RELATIVITY FROM RANDOMNESS

(from Irving Stein, SLAC)



I. Stein, *The concept of object as the*

SPECIAL RELATIVITY FROM RANDOMNESS

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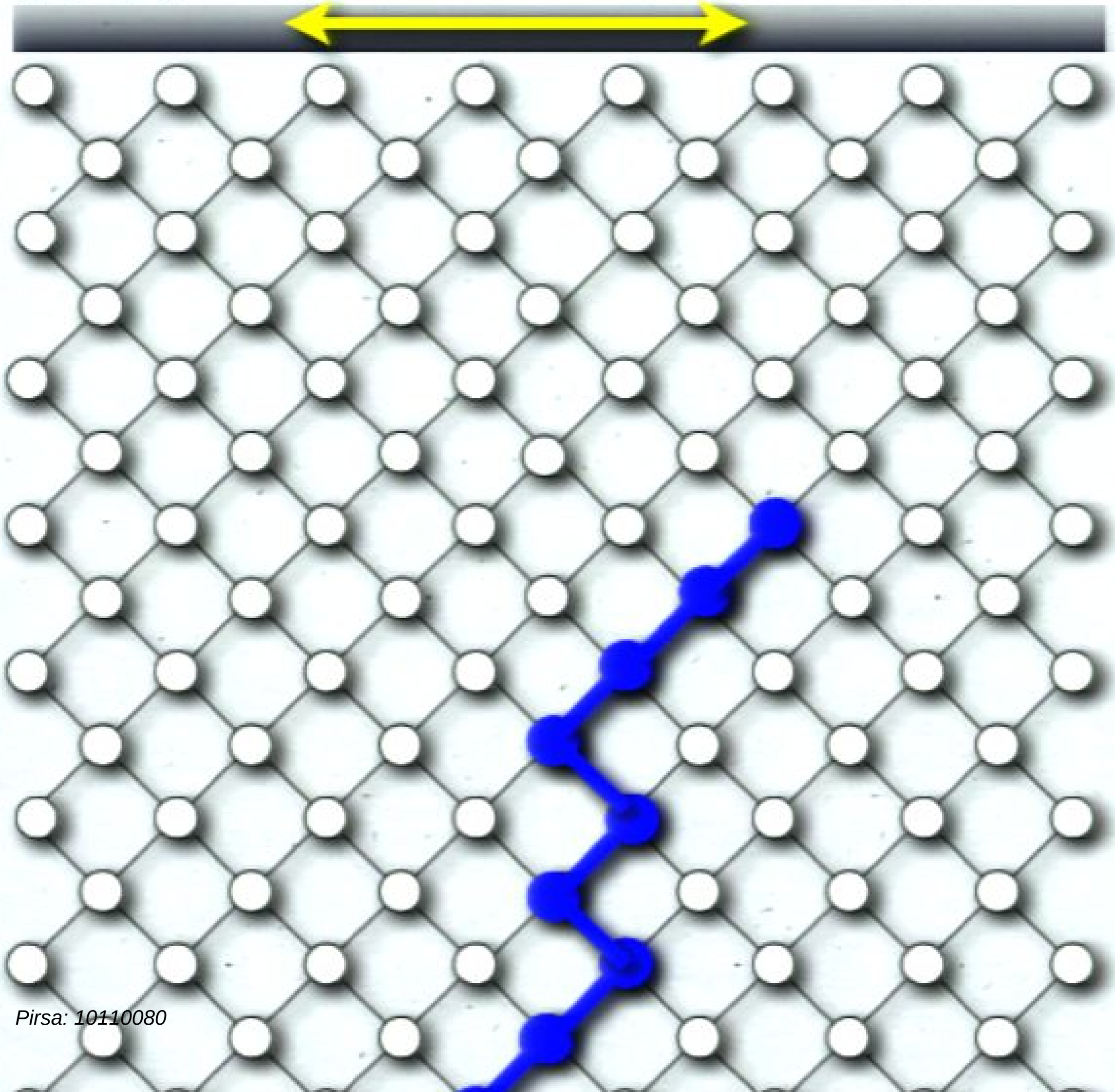

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I. Stein, *The concept of object as the*

SPECIAL RELATIVITY FROM RANDOMNESS

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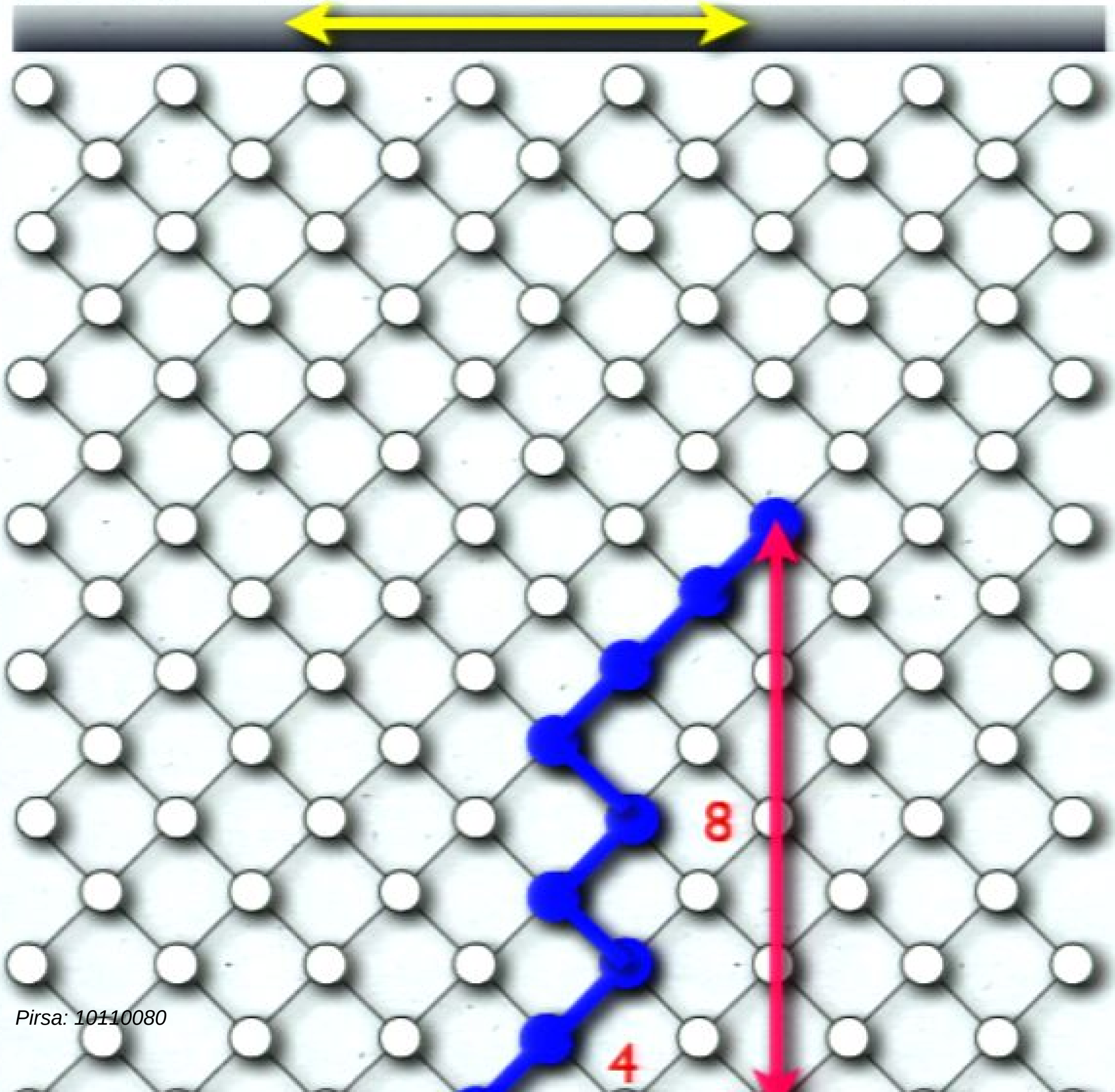

++-+-+++

$$p = \frac{3}{4} \quad q = \frac{1}{4}$$

Average velocity:

$$v = p - q = \frac{1}{2}$$

I. Stein, *The concept of object as the*

SPECIAL RELATIVITY FROM RANDOMNESS

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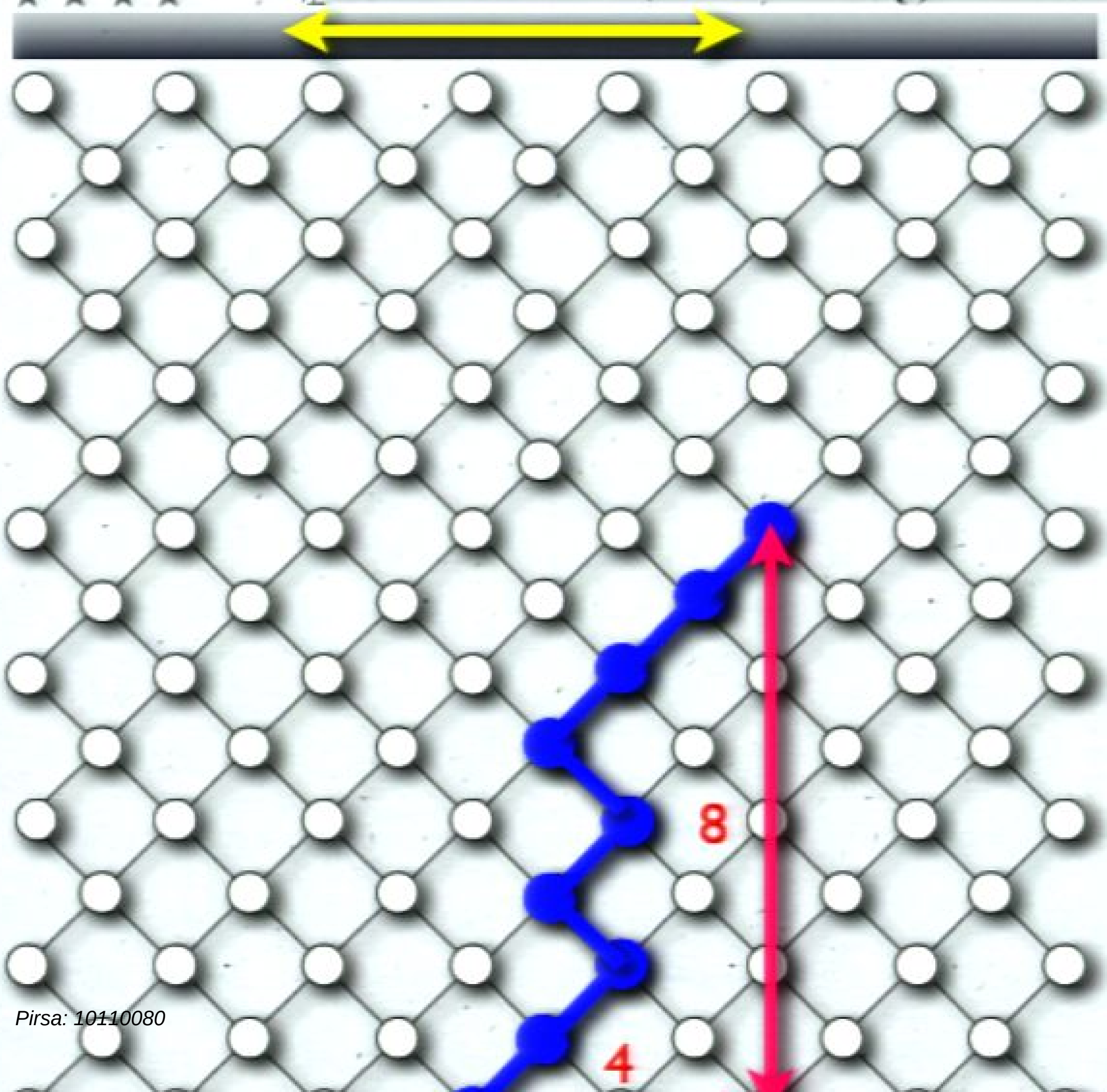

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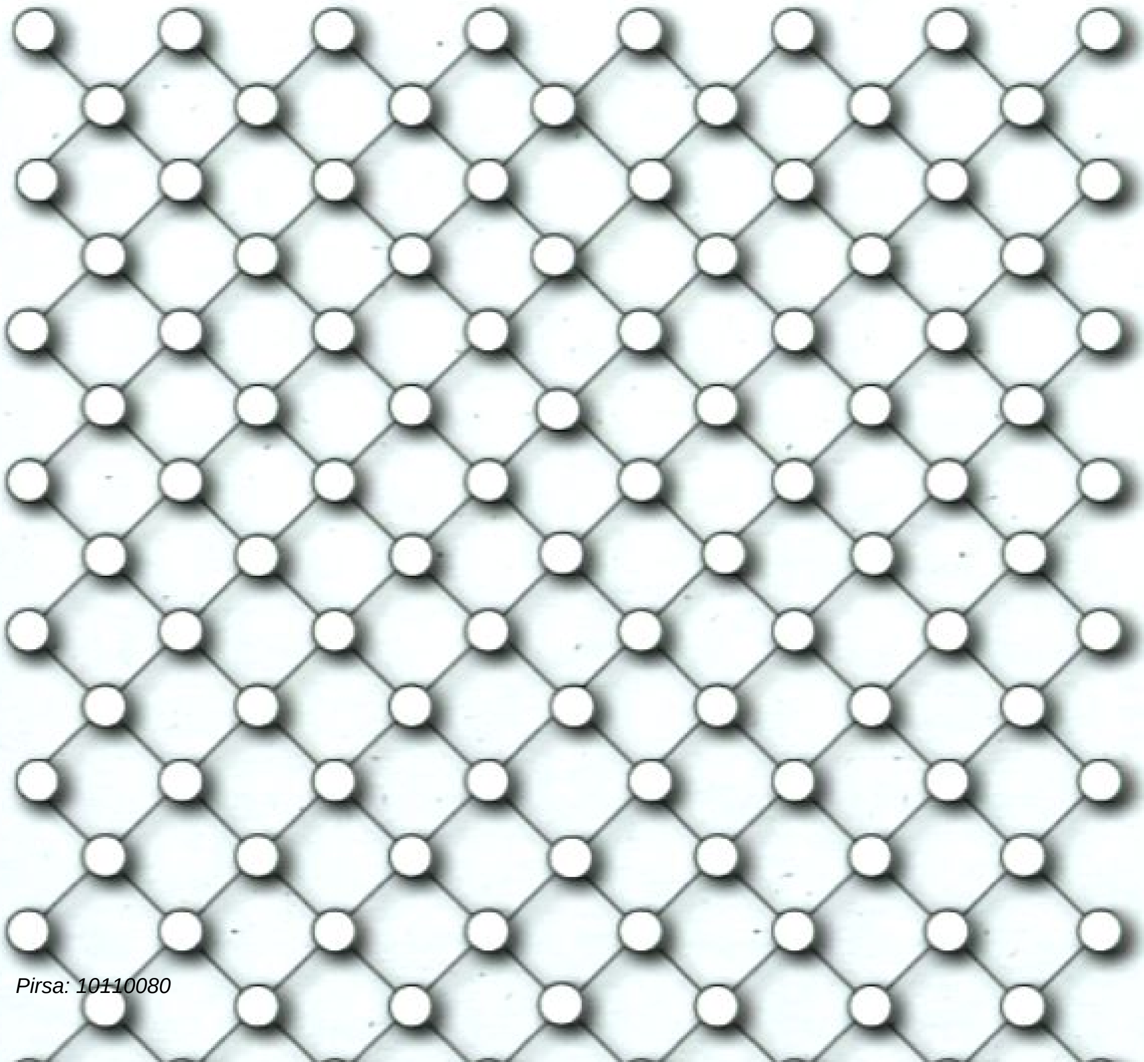

SPECIAL RELATIVITY FROM RANDOMNESS

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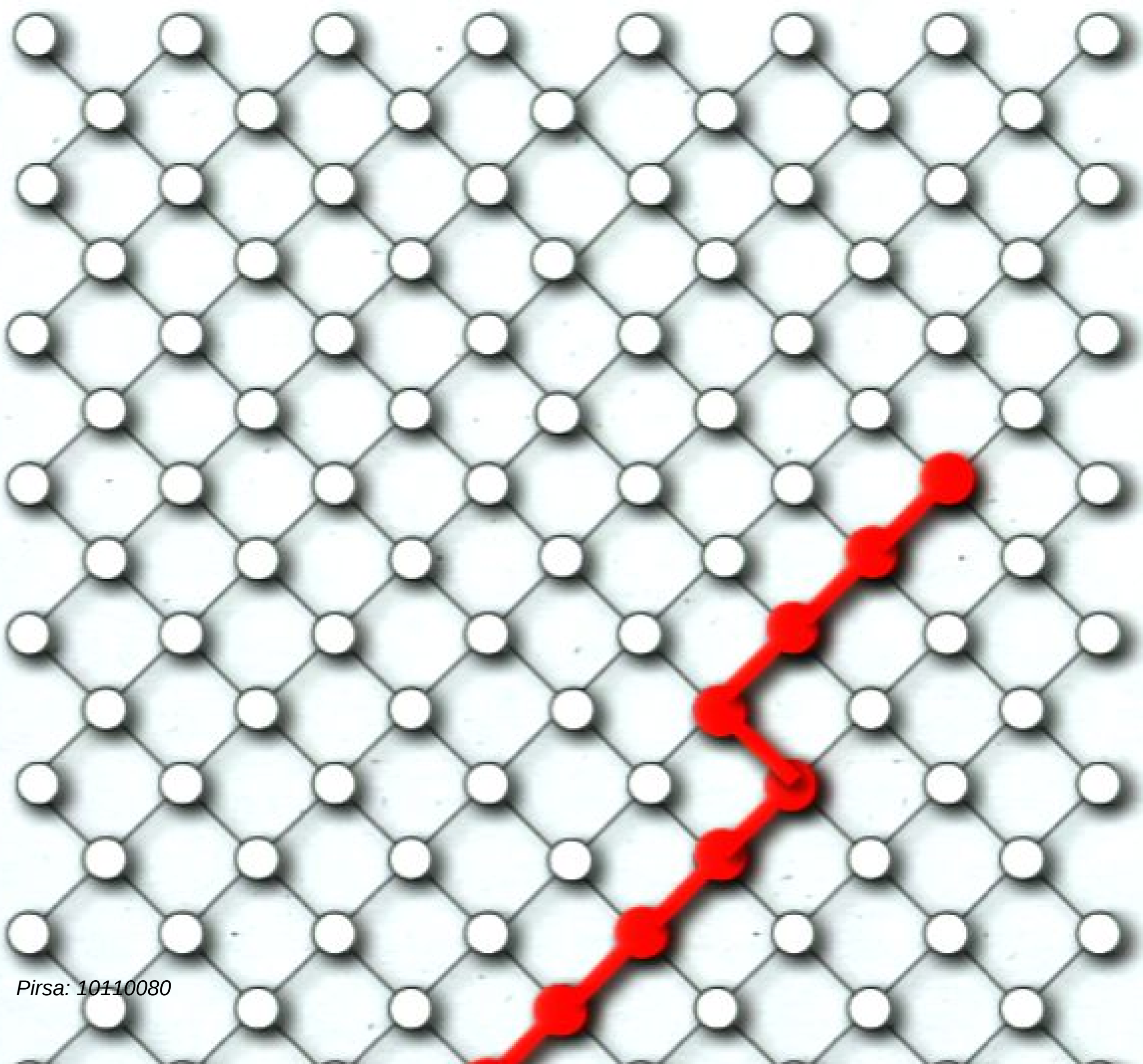

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SPECIAL RELATIVITY FROM RANDOMNESS

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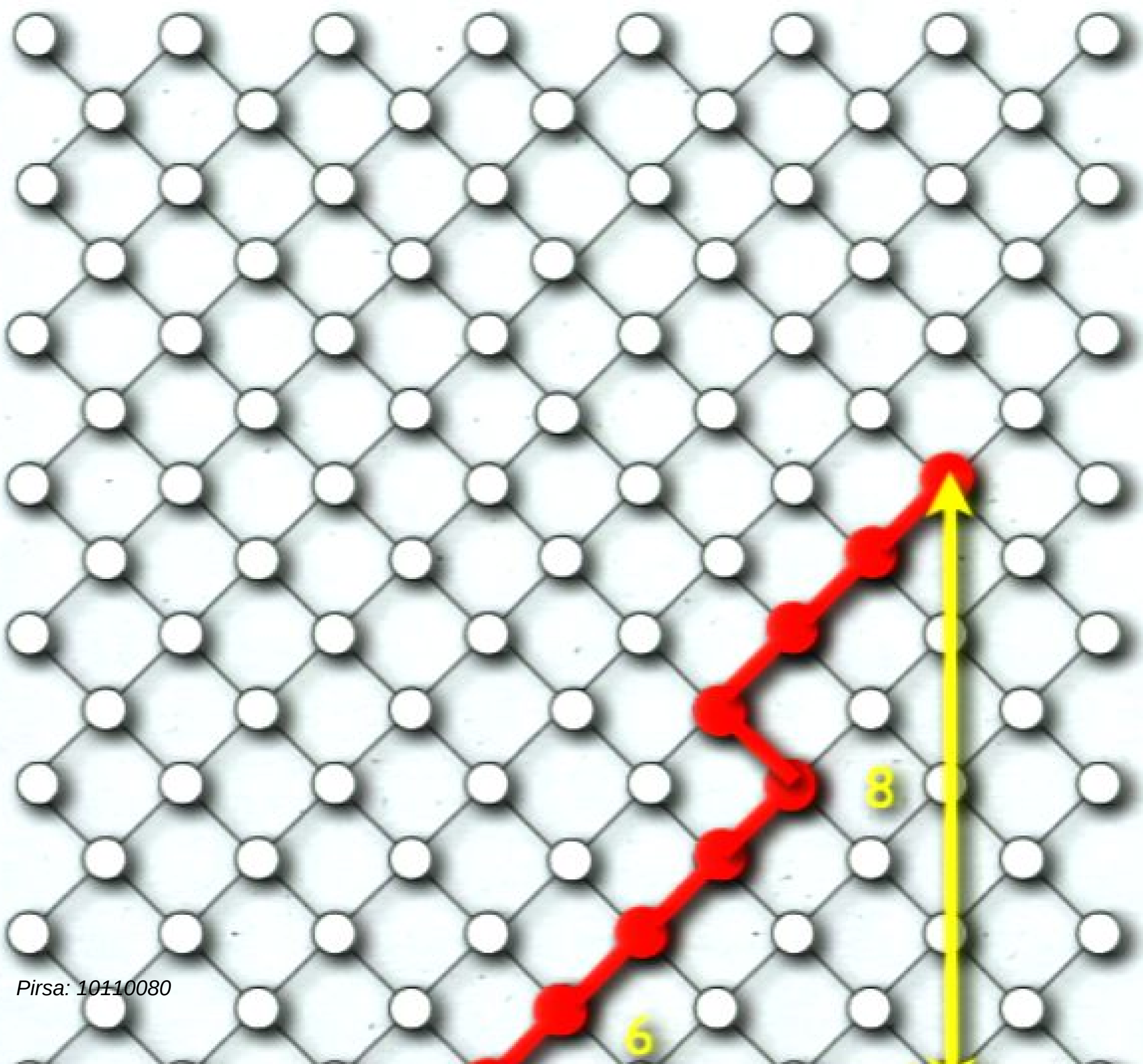


+ + + + - + + +

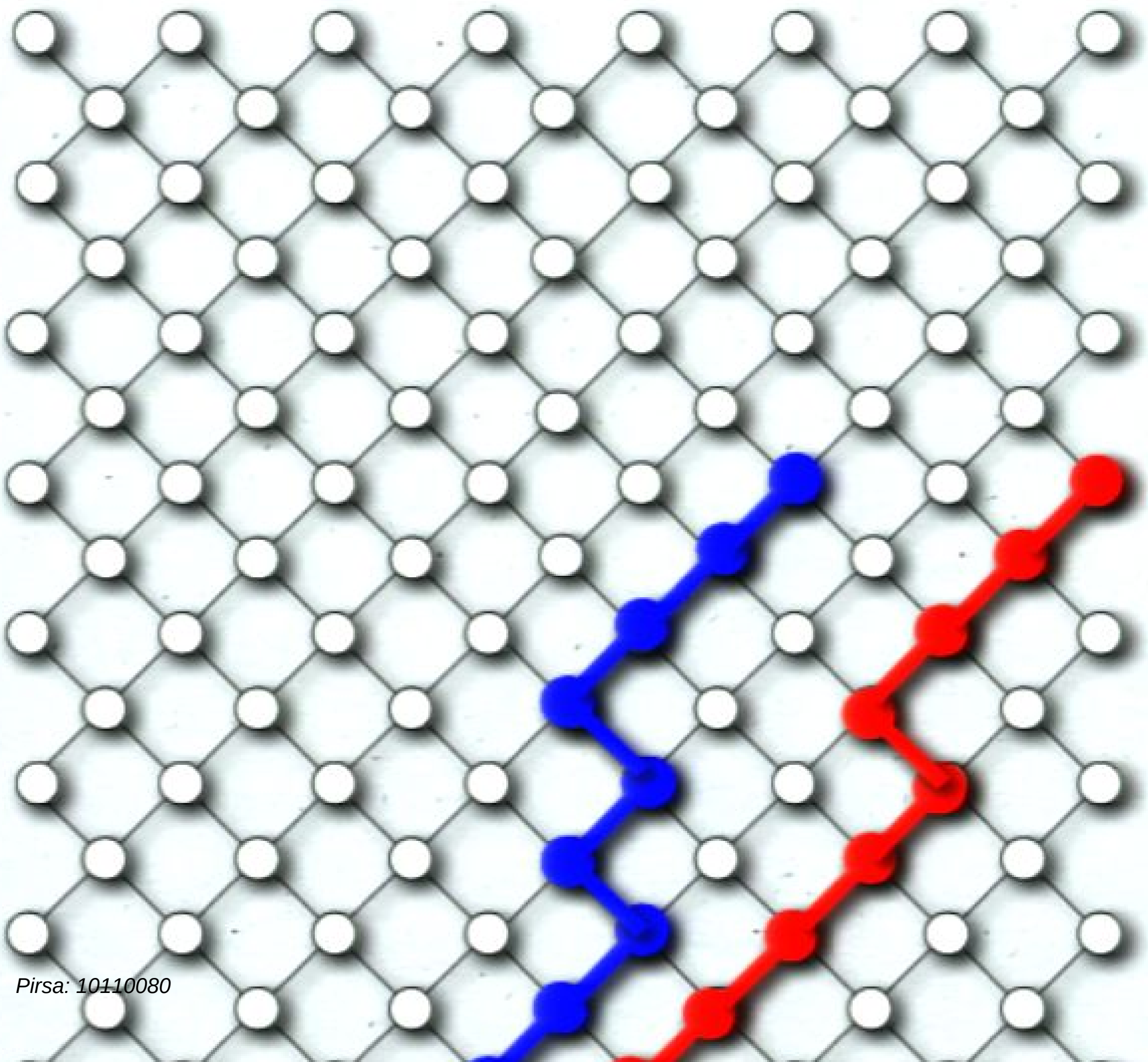
$$p = \frac{7}{8} \quad q = \frac{1}{8}$$

Average velocity:

$$v = p - q = \frac{3}{4}$$

SPECIAL RELATIVITY FROM RANDOMNESS

(from Irving Stein)



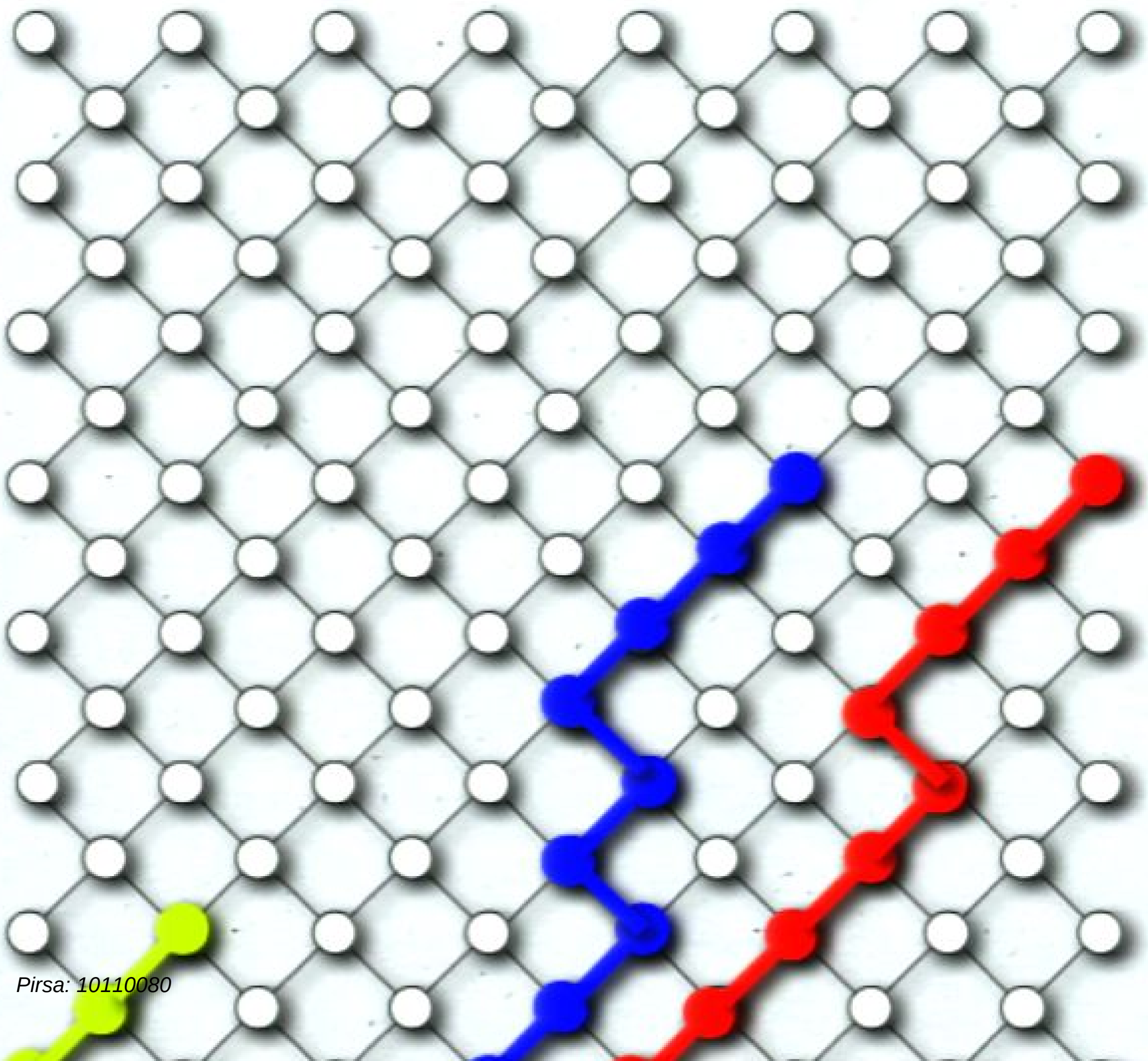
+ + - + - + + +

+ + + + - + + +

$$v_{12} = v_1 + v_2 = \frac{5}{4}$$

SPECIAL RELATIVITY FROM RANDOMNESS

(from Irving Stein)



+ + - + - + + +

+ + + + - + + +

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SPECIAL RELATIVITY FROM RANDOMNESS

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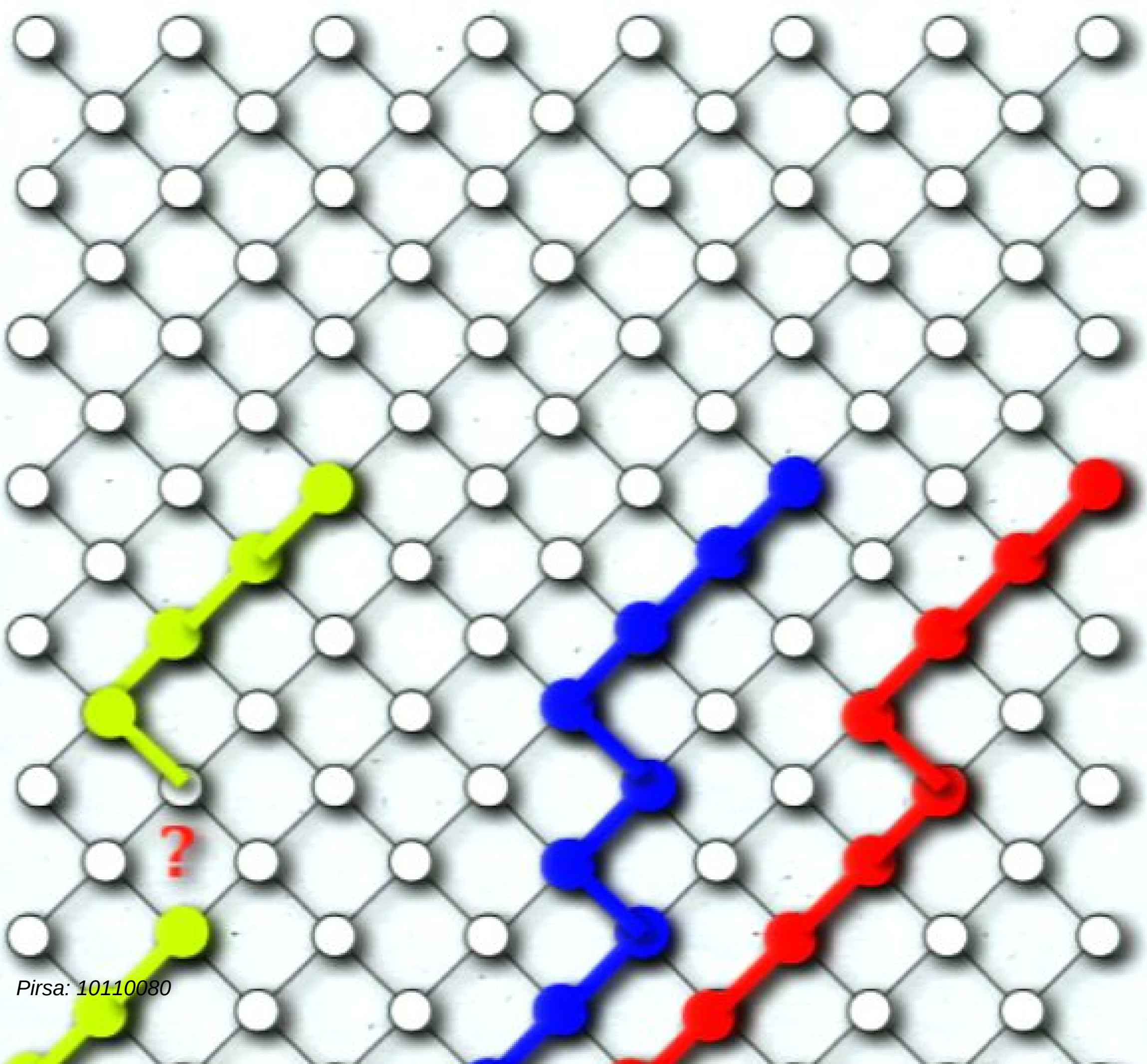

+ + - + - + + +

+ + + + - + + +

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SPECIAL RELATIVITY FROM RANDOMNESS

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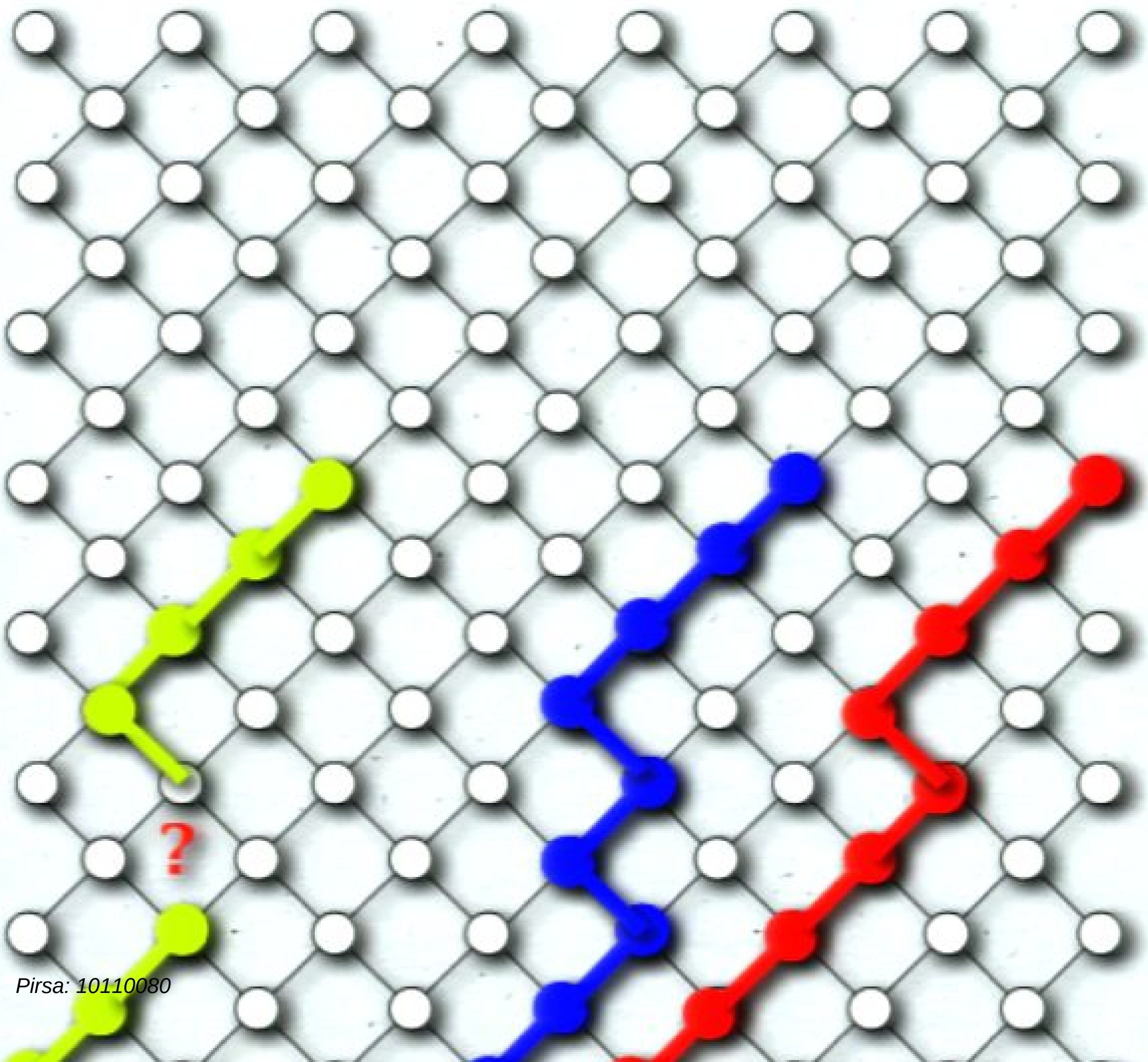

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+ + + + - + + +

+ +   + - + + +

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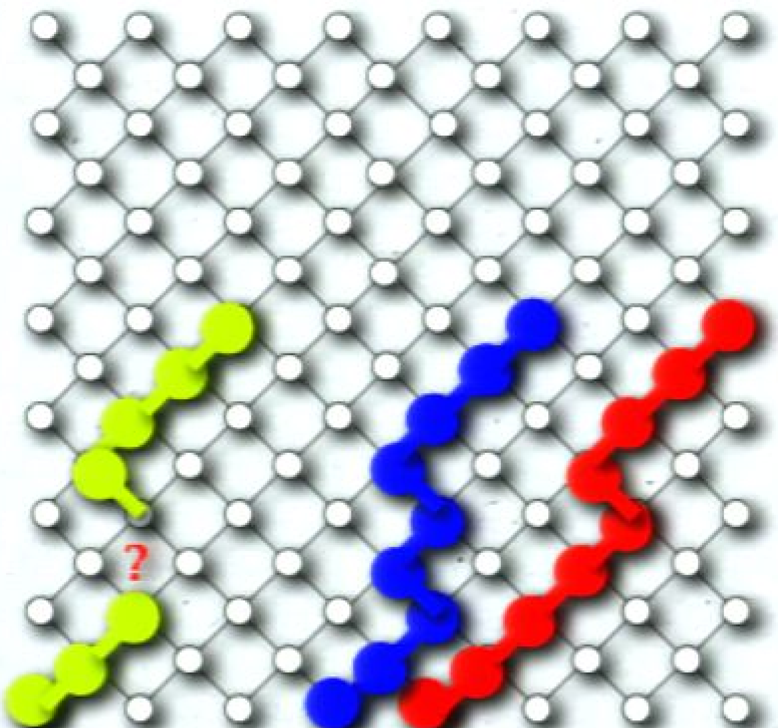

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+ +   + - + + +

SPECIAL RELATIVITY FROM RANDOMNESS

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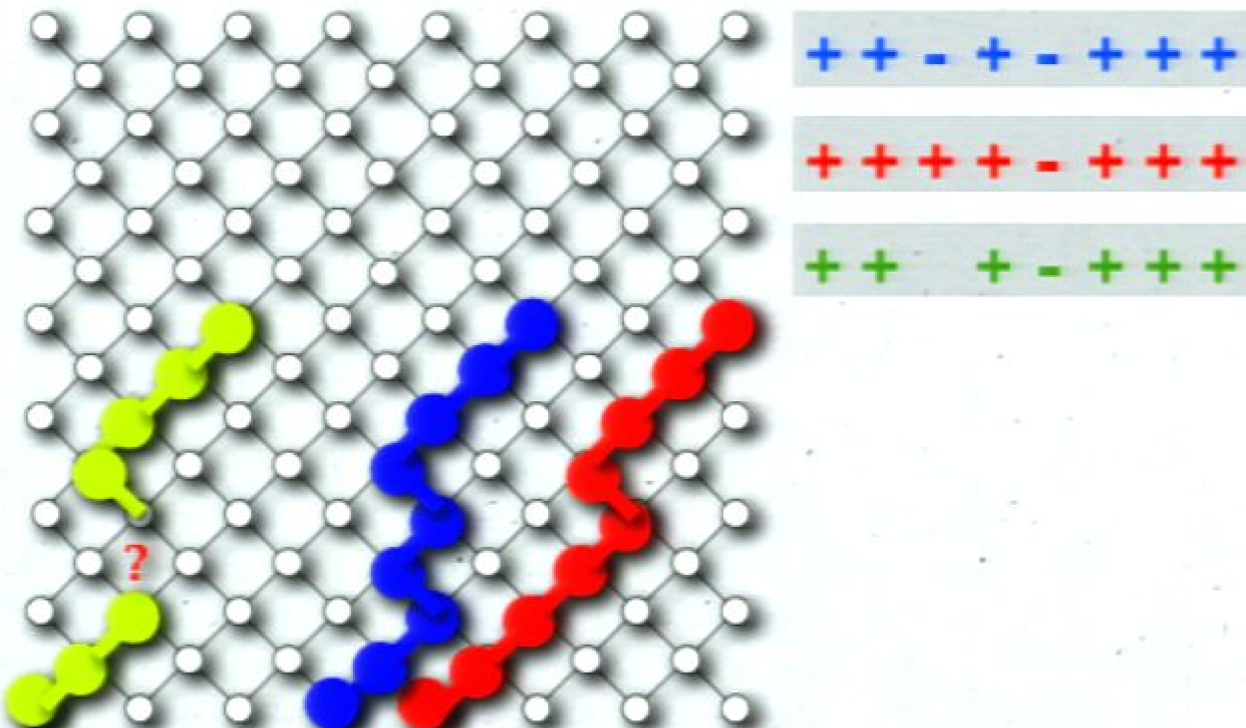

$$p_{12} = \frac{p_1 p_2}{p_1 p_2 + q_1 q_2}$$

$$q_{12} = \frac{q_1 q_2}{p_1 p_2 + q_1 q_2}$$

SPECIAL RELATIVITY FROM RANDOMNESS

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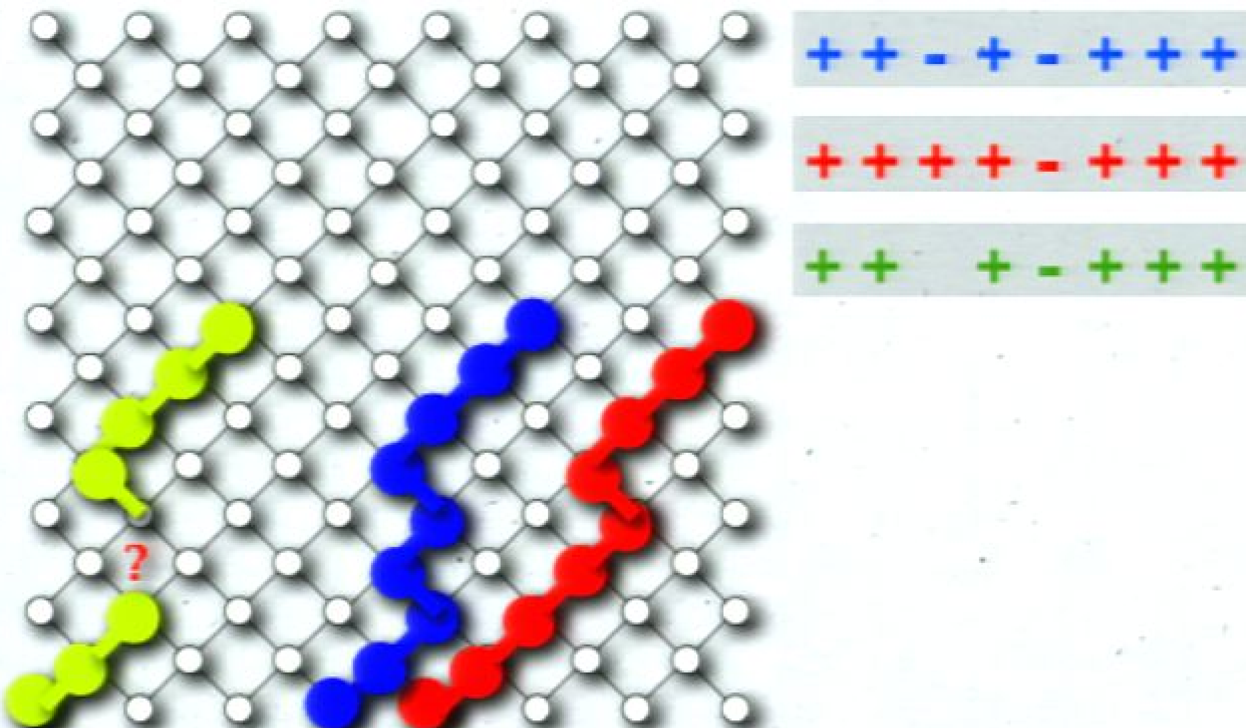

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SPECIAL RELATIVITY FROM RANDOMNESS

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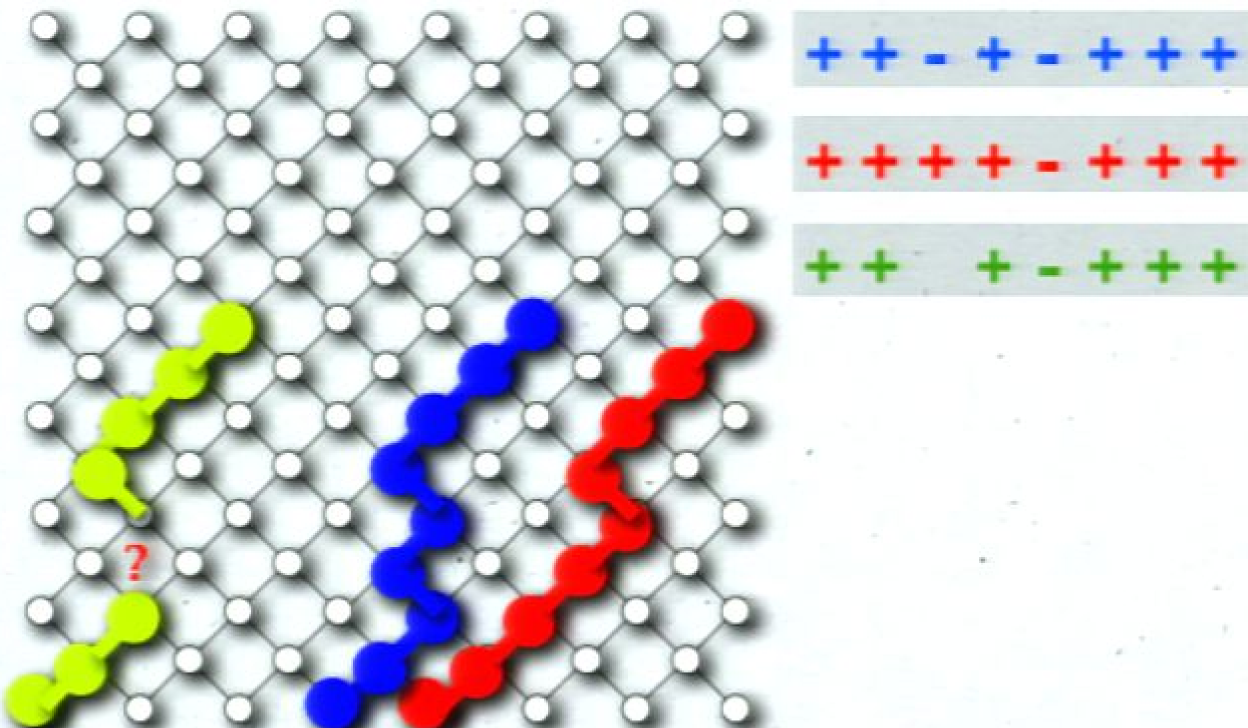

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$$v_{12} = \frac{v_1 + v_2}{1 + v_1 v_2}$$

SPECIAL RELATIVITY FROM RANDOMNESS

Kevin S. Brown (Kent, WA)

SPECIAL RELATIVITY FROM RANDOMNESS

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$p(v) = v^2$ a probability!

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v_x v_y (orthogonal = independent)

SPECIAL RELATIVITY FROM RANDOMNESS

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$$p(a \cup b) = p(a) + p(b) - p(a \cap b) = p(a) + p(b) - p(a)p(b)$$

SPECIAL RELATIVITY FROM RANDOMNESS

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composition of orthogonal speeds in SR!

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$$p(v_x \cup v_y) = v_x^2 + v_y^2$$ (Galileo, disjoint events)

SPECIAL RELATIVITY FROM RANDOMNESS

Kevin S. Brown (Kent, WA)

★ ★ ★ ★ ★ ★ ★ ★

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composition of orthogonal speeds in SR!

$$1 - p(v_x \cup v_y) = [1 - p(v_x)][1 - p(v_y)]$$

$$\overline{v_x \cup v_y} = \overline{v_x} \cap \overline{v_y}$$

de Morgan!

SPECIAL RELATIVITY FROM RANDOMNESS

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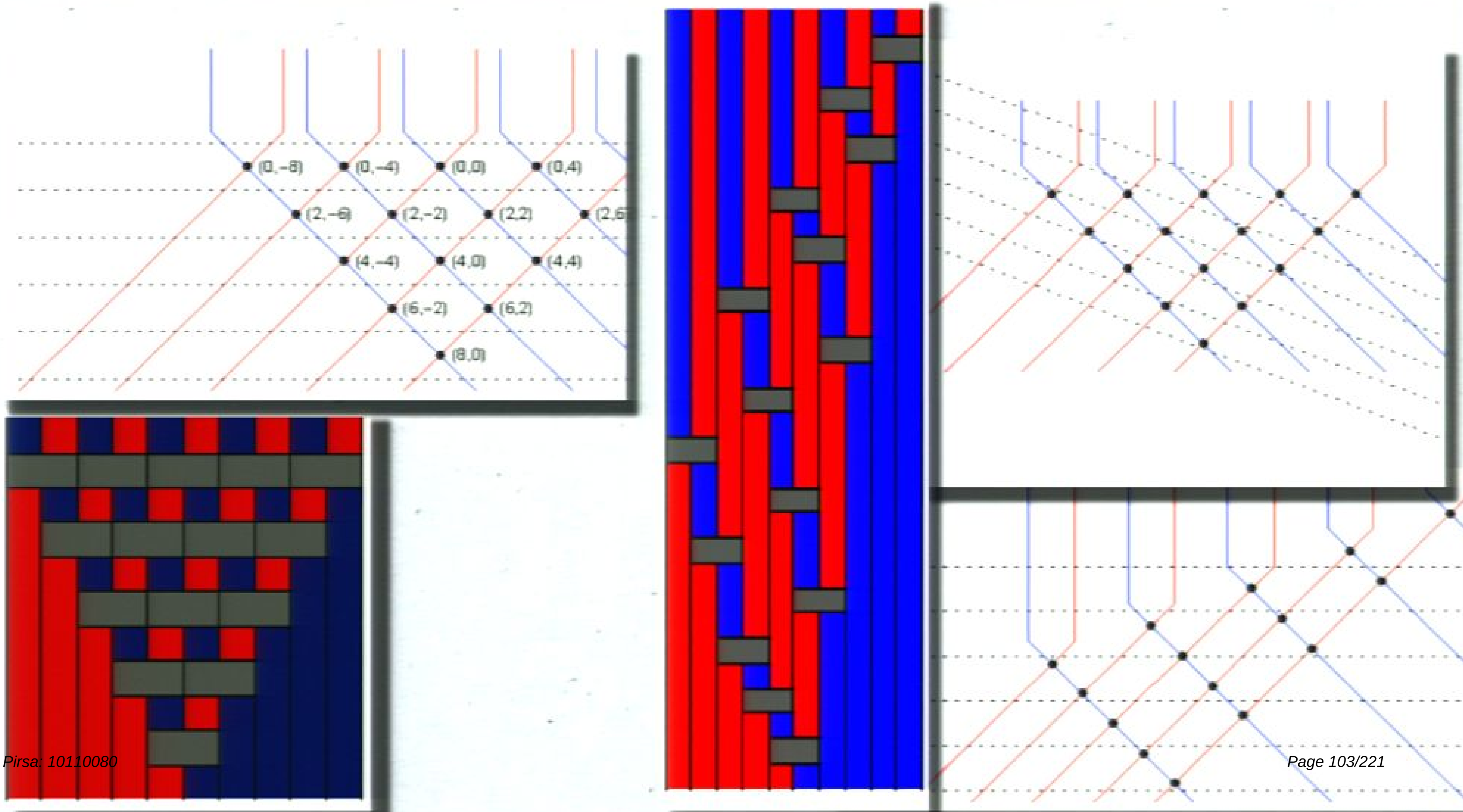
de Morgan!

SPECIAL RELATIVITY WITHOUT SPACE

Stephen Wolfram, *A New Kind of Science*



WHAT IS THE INFORMATIONAL MEANING OF INERTIAL MASS AND $\hbar$

AND HOW THE QUANTUM FIELD EMERGES

THE INFORMATION FLOW

ONE-DIMENSIONAL FLOW

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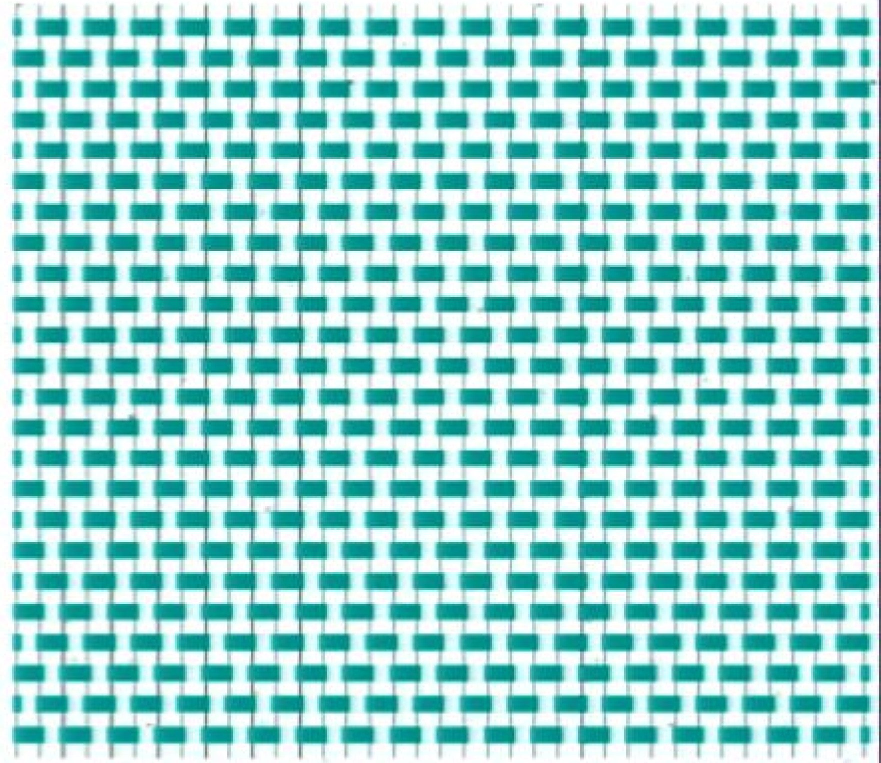
Information can flow only in two directions



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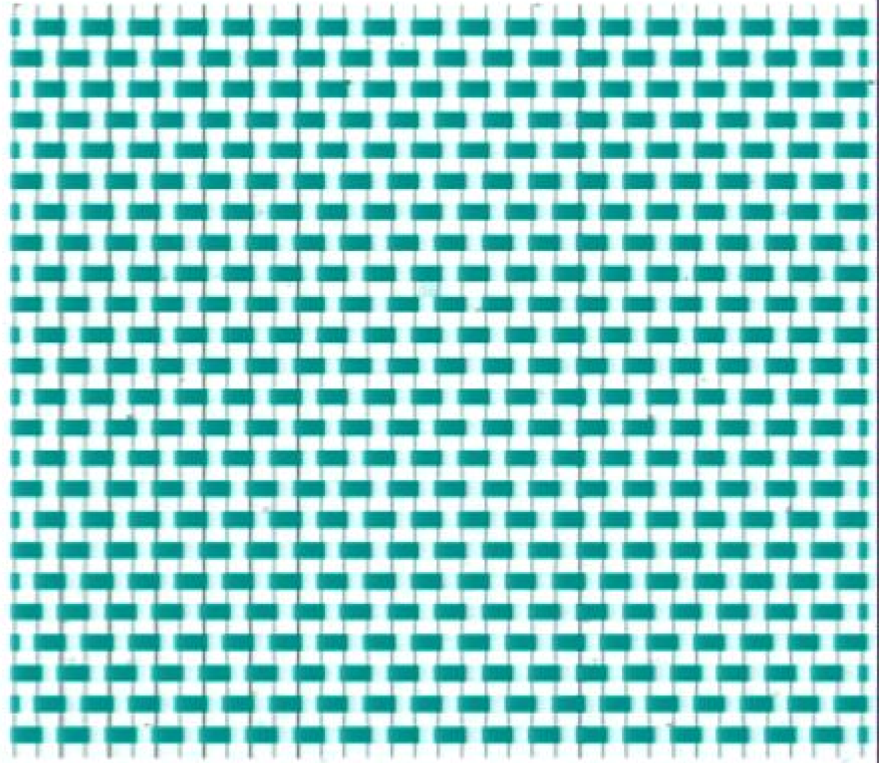

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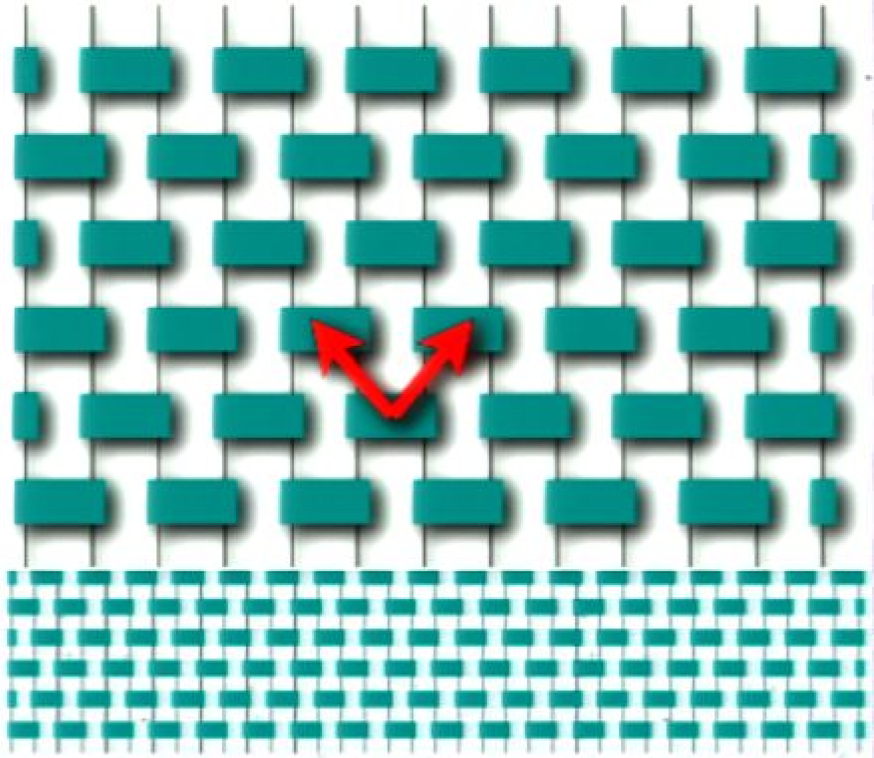

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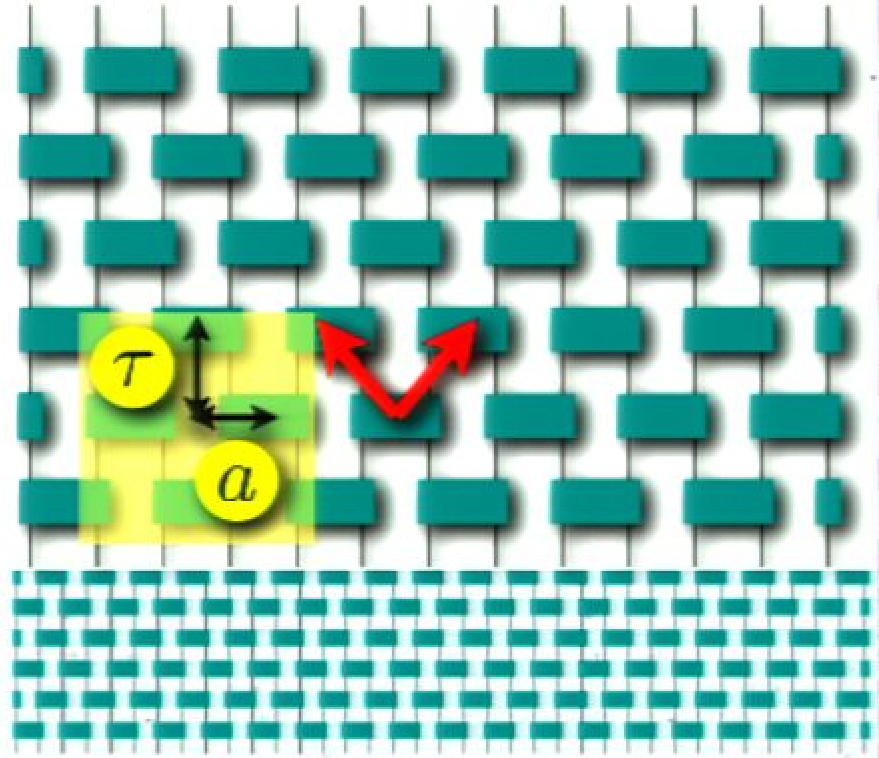
$$v = a/\tau$$



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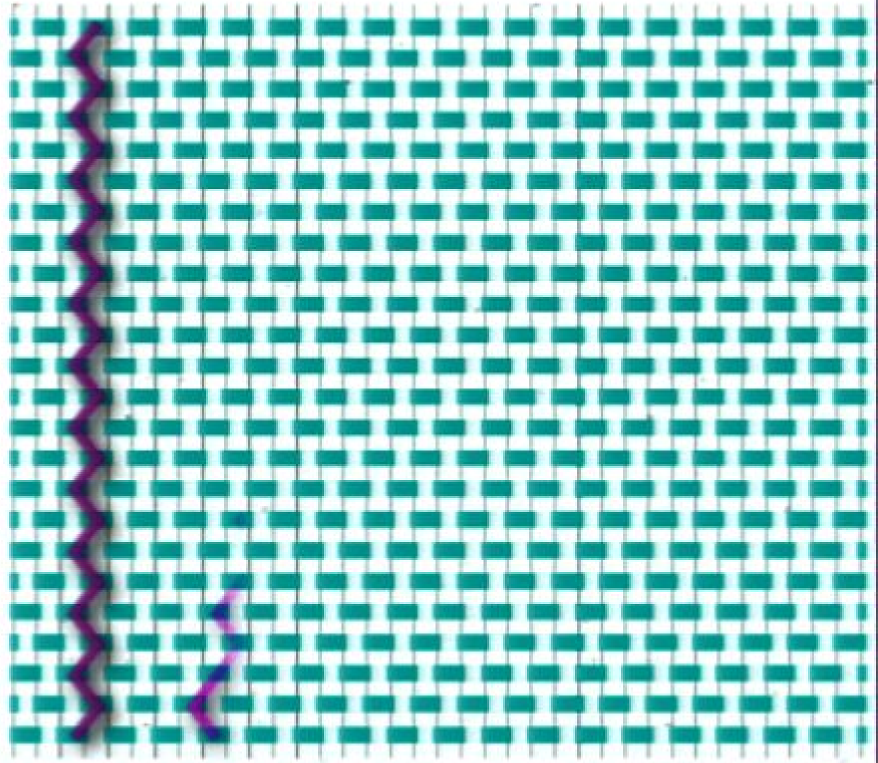
Constant average speed: periodic change of direction $v = a/\tau$



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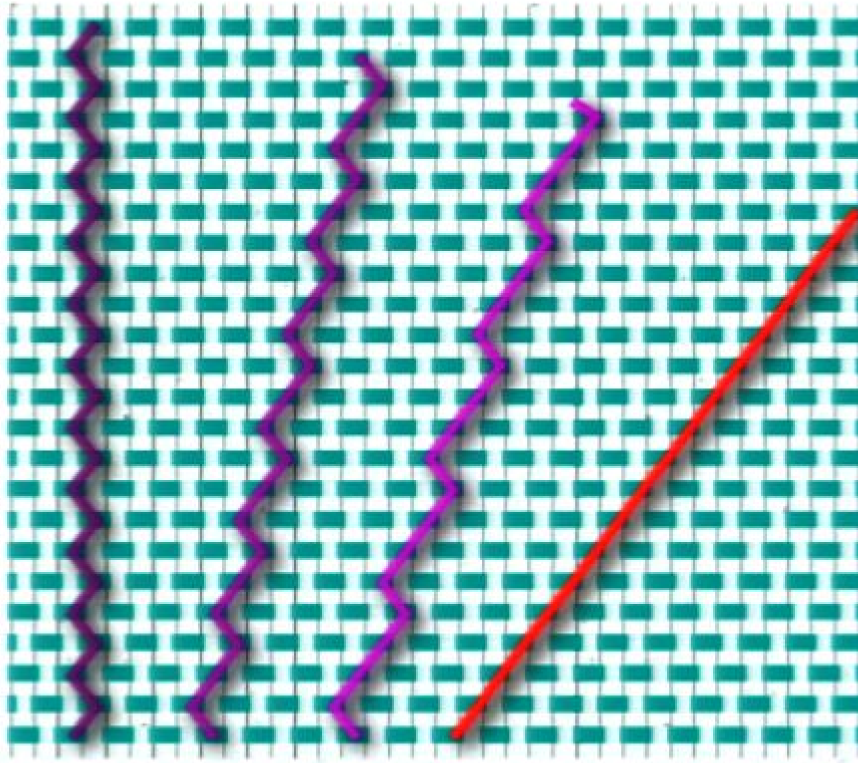

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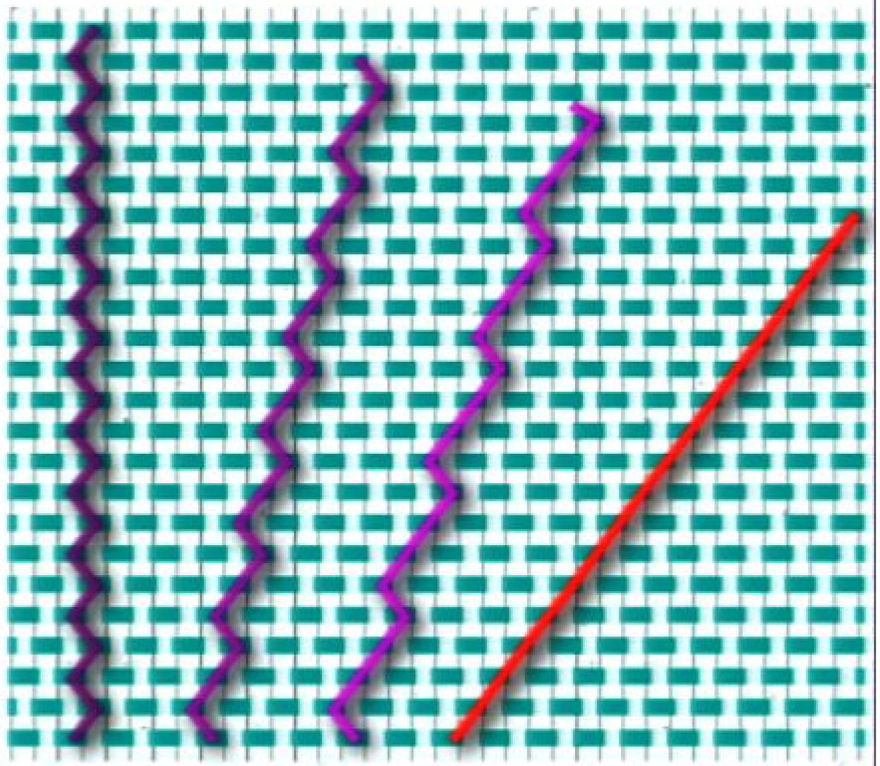

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coupling between ϕ^+ and ϕ^- with
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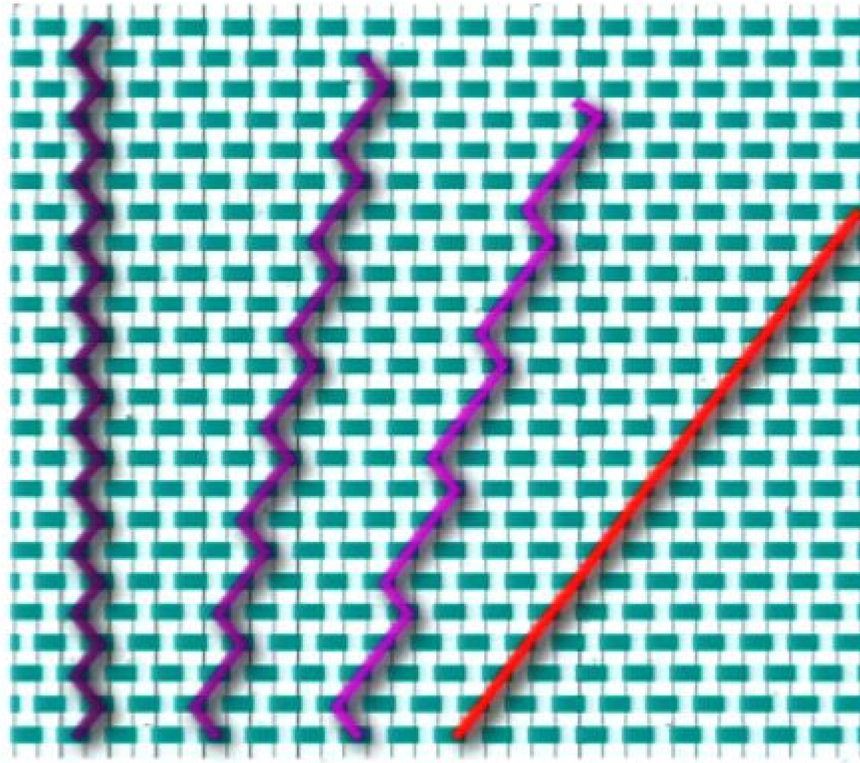

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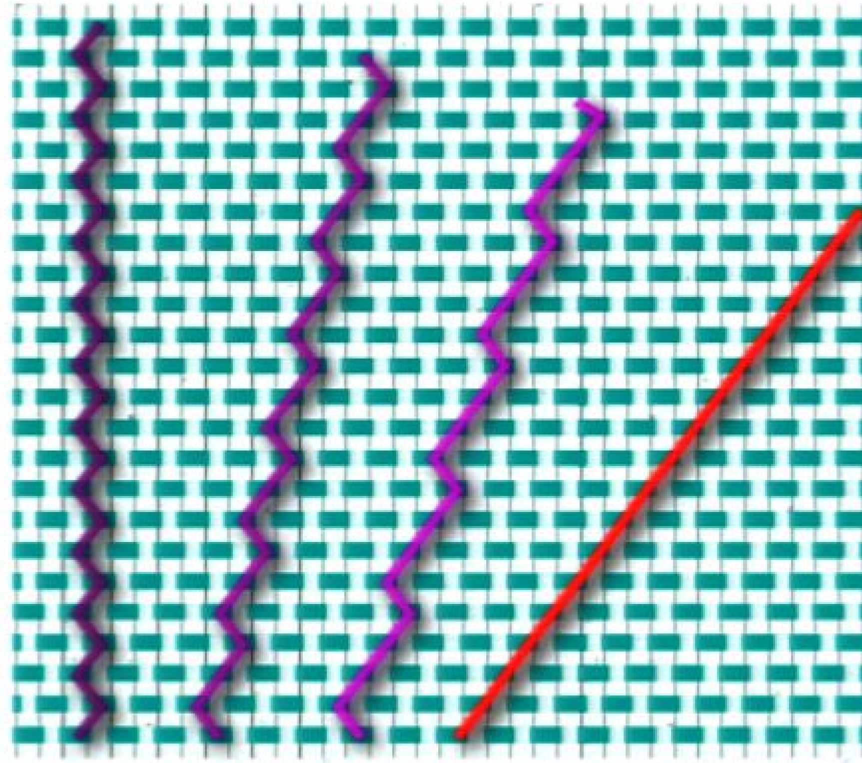

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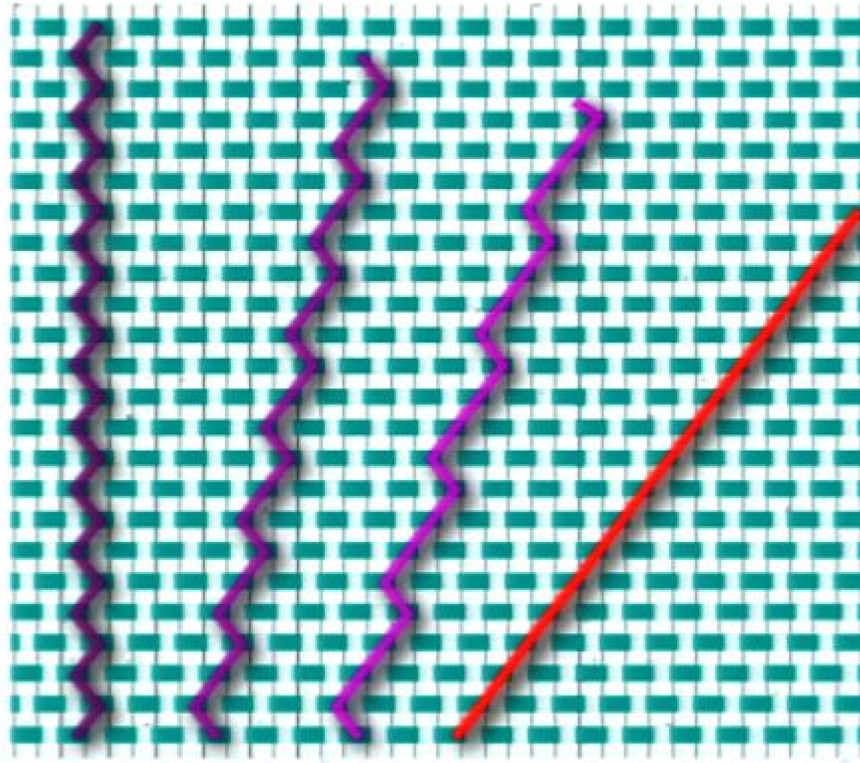

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(spinless) ***Dirac equation!***

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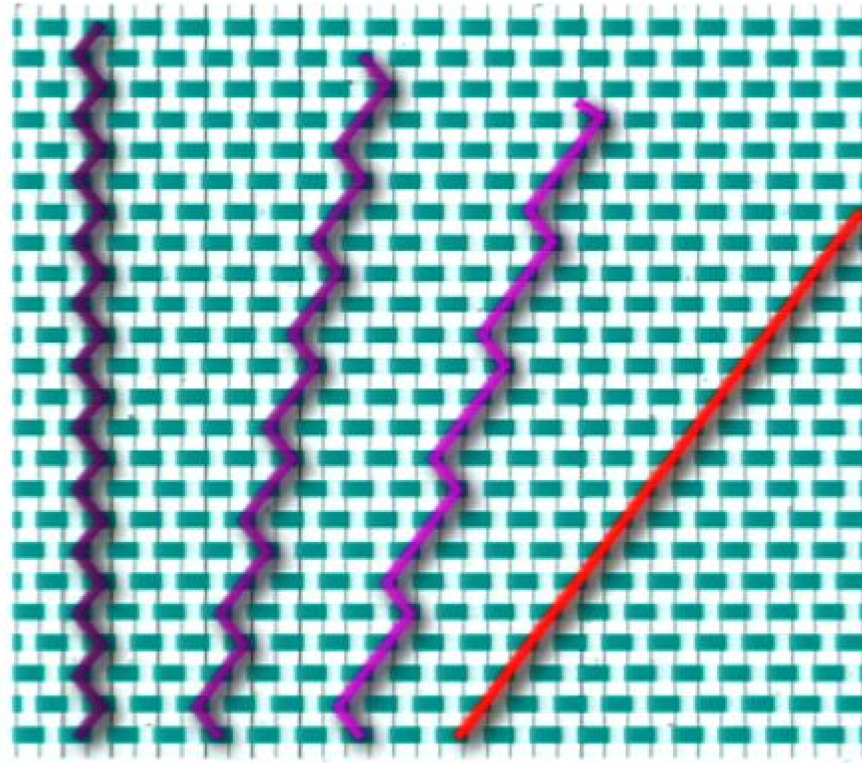

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No need of imposing

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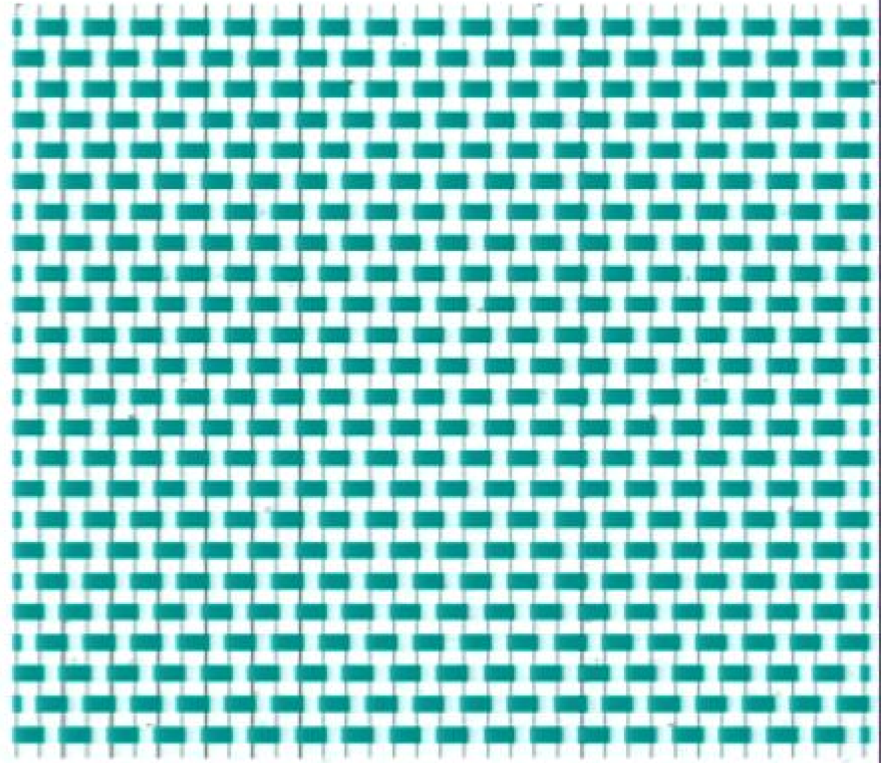

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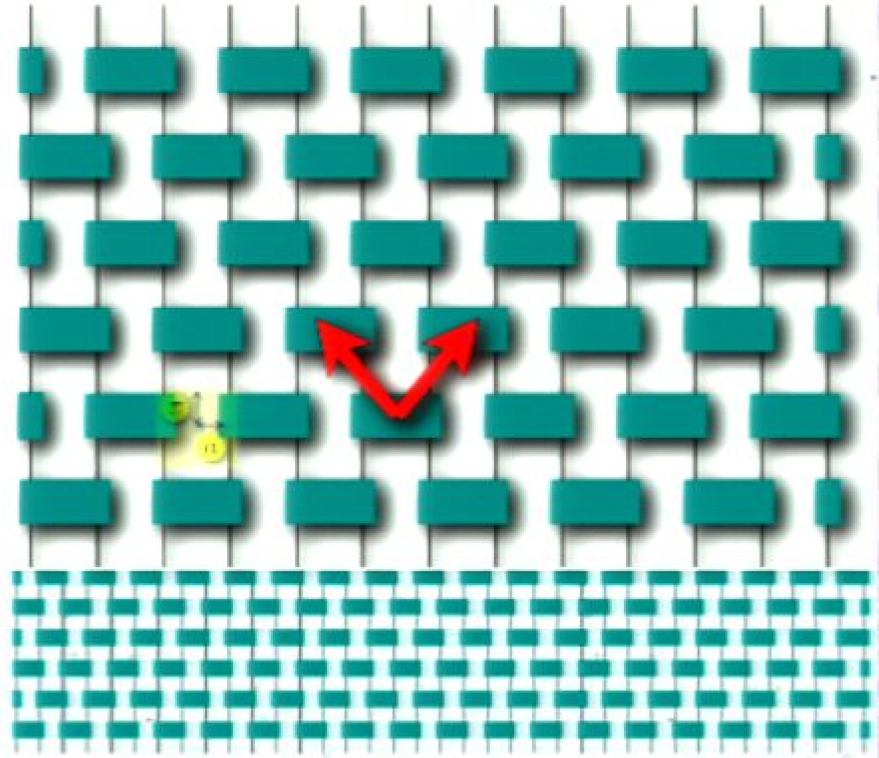

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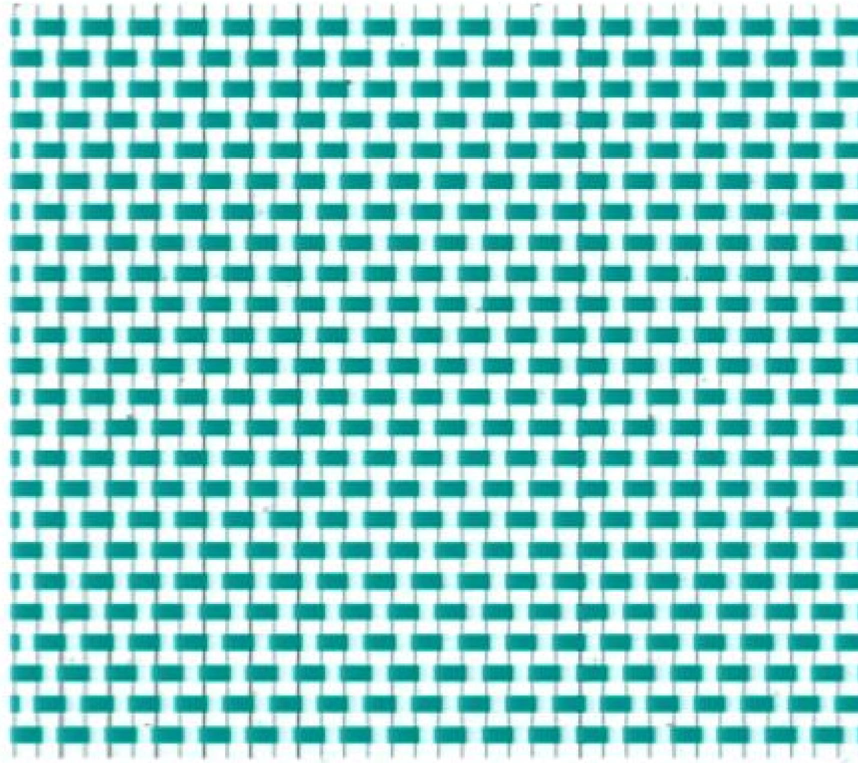

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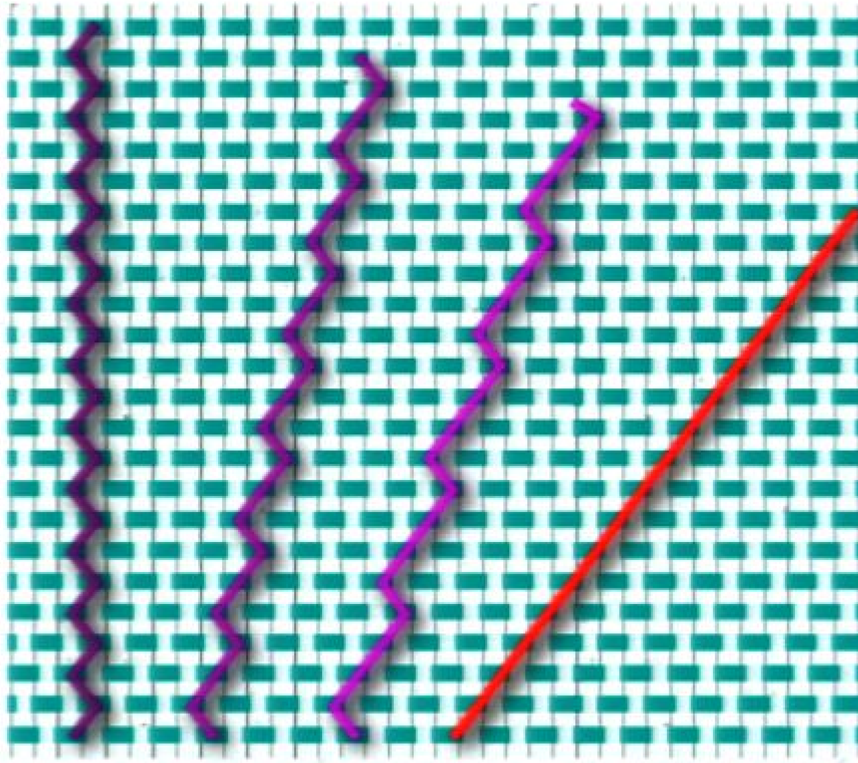

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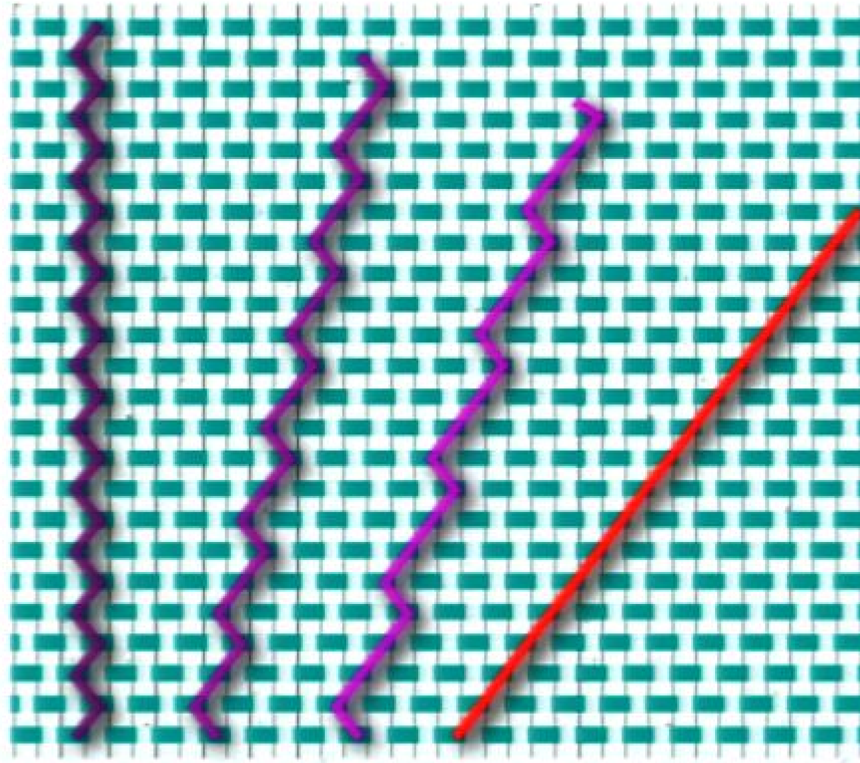

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$\hbar$: conversion factor between the informational notion (in s^{-1}) and the customary notion (in Kg) of the inertial mass

THE INFORMATION FLOW

SIMULATING A QUANTUM FIELD

Simulation of QFT with a quantum computer, with gates performing infinitesimal transformations:

THE INFORMATION FLOW

SIMULATING A QUANTUM FIELD

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Simulation of QFT with a quantum computer, with gates performing infinitesimal transformations:

⬇

In order to have average speed equal to *c* you need infinite maximal speed.

THE INFORMATION FLOW

SIMULATING A QUANTUM FIELD

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Simulation of QFT with a quantum computer, with gates performing infinitesimal transformations:

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THE INFORMATION FLOW

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Relativity is derived from the computational

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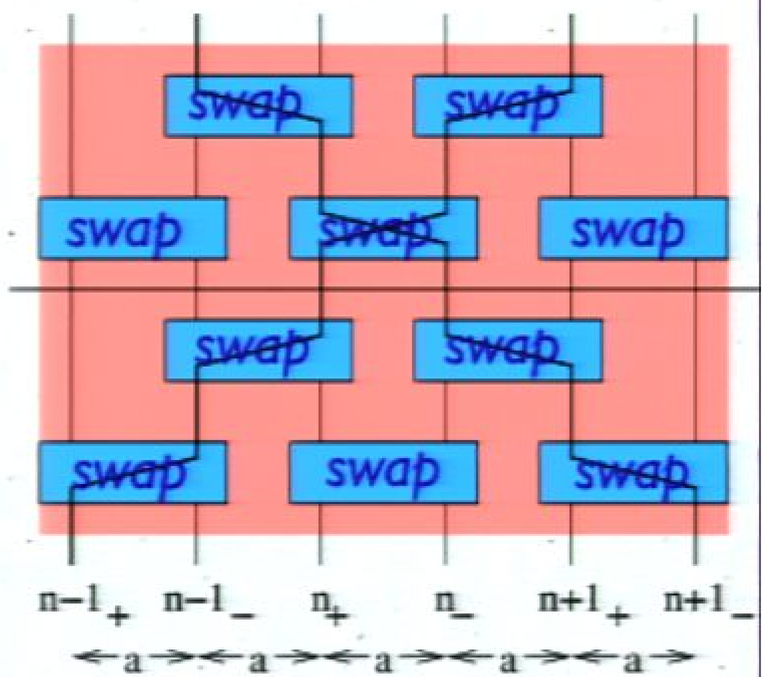

Relativity is derived from the computational → We must have finite

THE INFORMATION FLOW

LINEAR FLOW

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Each gate evolves the field linearly:

$$z_n(t=1) = U z_n U^\dagger = \sum_k U_{nk} z_k$$

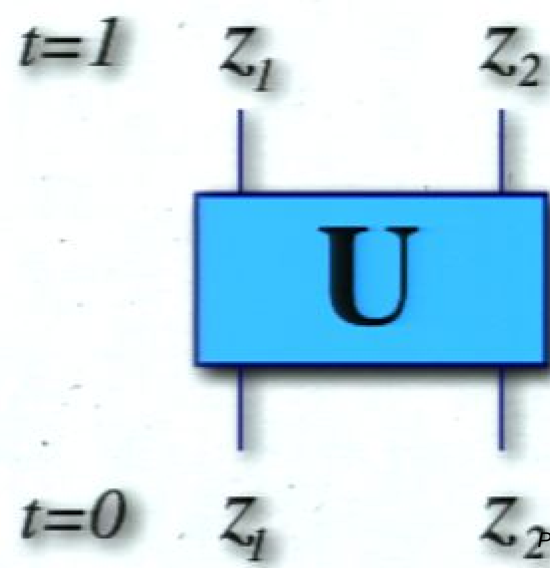
$$\mathbf{U} := \|U_{ij}\|$$ unitary matrix

(anti)commutation relations are preserved

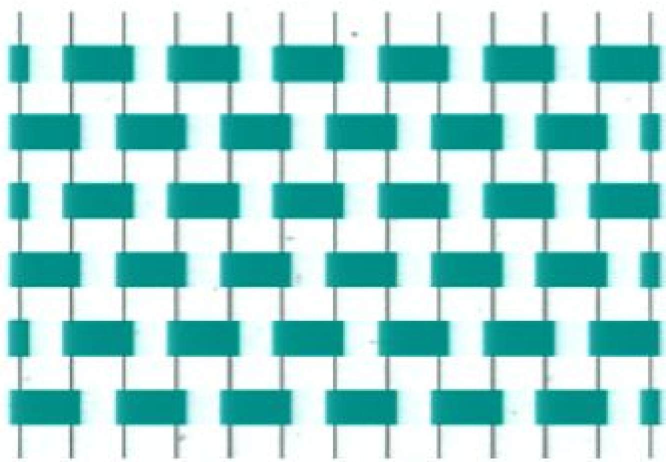
$$[z_i, z_j^\dagger]_\pm = \delta_{ij}$$

Evolution from bipartite gates:

$$\begin{bmatrix} z_1 \\ z_2 \end{bmatrix}_{t=1} = U \begin{bmatrix} z_1 \\ z_2 \end{bmatrix} U^\dagger = \mathbf{U} \begin{bmatrix} z_1 \\ z_2 \end{bmatrix}$$



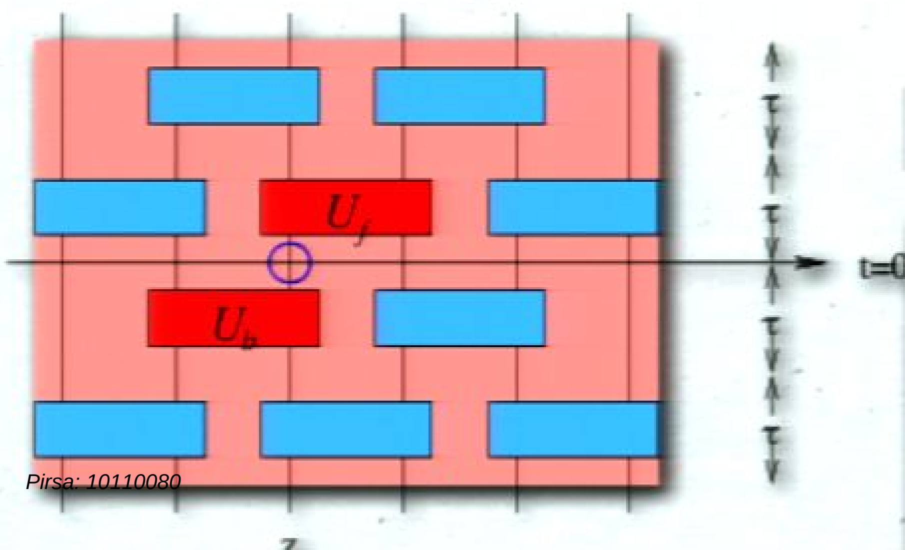
QC SIMULATION OF QFT



Coarse-grained discrete derivatives:

$$\widehat{\partial}_t z = \frac{1}{2k\tau}[z(k\tau) - z(-k\tau)]$$

$$\widehat{\partial}_x = \frac{1}{4ka}(\delta_+^k - \delta_-^k)$$



"HAMILTONIAN"

$$\mathrm{H}_{\mathrm{gate}}^{(2\mathrm{n})} z = \frac{i}{2n\tau}[z(n\tau) - z(-n\tau)] = i\widehat{\partial}_t z$$

$$\mathrm{H}_{\mathrm{gate}}^{(2)} z = \frac{i}{2\tau}(U_f z U_f^\dagger - U_b^\dagger z U_b)$$

QC SIMULATION OF QFT

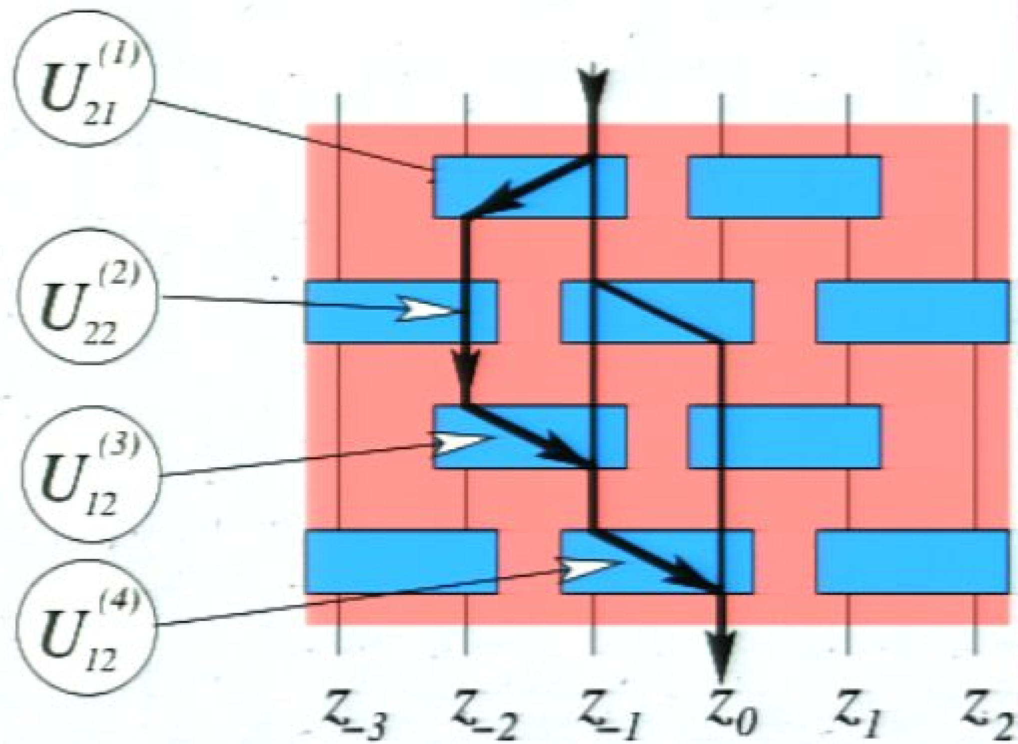
We need to develop a *path-sum calculus* over the circuit:

1. Number all the input wires at each gate, from the leftmost to the rightmost one, and do the same for the output wires

2. We say that a wire l is in the past-cone of the wire k if there is a path from *l* to k passing through gates.

3. For any output wire k and any input wire l in its causal past cone, consider all paths connecting k with l

4. The following linear expansion holds

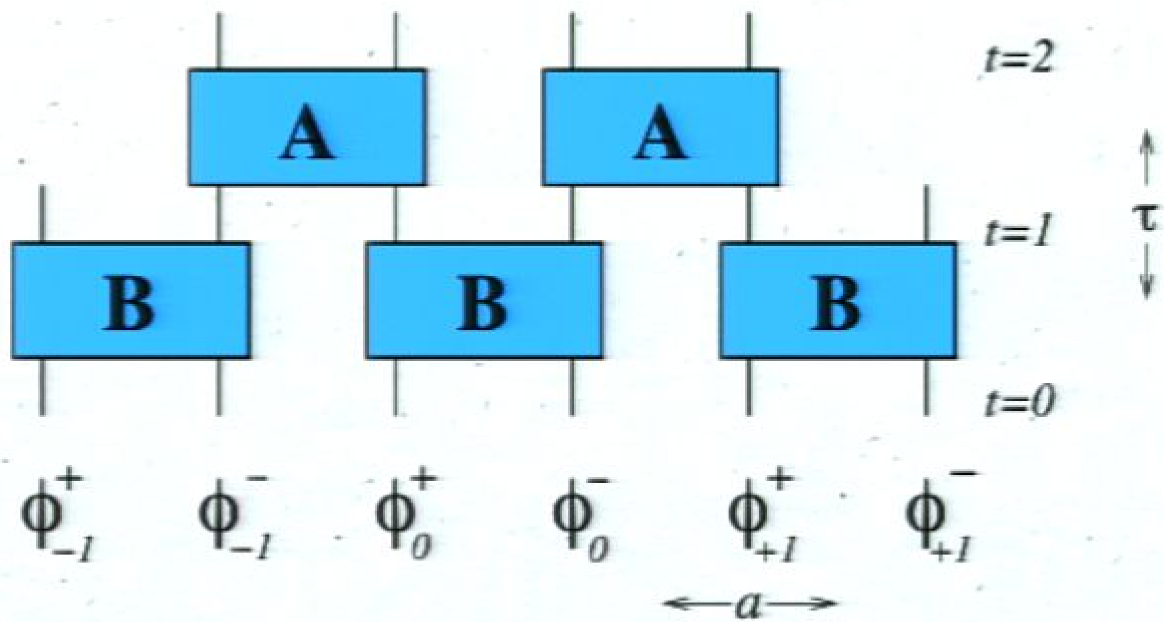


$$z_l(t) = \sum U^{(1)}_{i_1 i_2} U^{(2)}_{i_2 i_3} \ldots U^{(n)}_{i_n i_{n+1}} z_k(0)$$

QC SIMULATION OF QFT

"Hamiltonian"

$$\mathrm{H}^{(4)}_{\mathrm{gate}} = \frac{i}{4\tau}\begin{bmatrix} A_{21}B_{21}\delta_- - B^\dagger_{12}A^\dagger_{12}\delta_+ + A_{22}B_{11} - B^\dagger_{11}A^\dagger_{22} & (A_{21}B_{22} - B^\dagger_{11}A^\dagger_{21})\delta_- + A_{22}B_{12} - B^\dagger_{12}A^\dagger_{11} \\ (A_{12}B_{11} - B^\dagger_{22}A^\dagger_{12})\delta_+ + A_{11}B_{21} - B^\dagger_{21}A^\dagger_{22} & A_{12}B_{12}\delta_+ - B^\dagger_{21}A^\dagger_{21}\delta_- + A_{11}B_{22} - B^\dagger_{22}A^\dagger_{11} \end{bmatrix}$$



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Hermiticity is satisfied:

$$\langle\phi_n^\pm|\mathrm{H}^{(4)}_{\mathrm{gate}}|\phi_n^\pm\rangle = \langle\phi_n^\pm|\mathrm{H}^{(4)}_{\mathrm{gate}}|\phi_n^\pm\rangle^* \Longrightarrow i(A_{aa}B_{bb} - A^\dagger_{aa}B^\dagger_{bb}) \in \mathbb{R},$$

$$\langle\phi_n^\pm|\mathrm{H}^{(4)}_{\mathrm{gate}}|\phi_n^\mp\rangle = \langle\phi_n^\mp|\mathrm{H}^{(4)}_{\mathrm{gate}}|\phi_n^\pm\rangle^* \Longrightarrow (A_{22}B_{12} - A^\dagger_{11}B^\dagger_{12}) = -(A_{11}B_{21} - A^\dagger_{22}B^\dagger_{21})^*,$$

$$\langle\phi_{n+1}^\pm|\mathrm{H}^{(4)}_{\mathrm{gate}}|\phi_n^\pm\rangle = \langle\phi_n^\pm|\mathrm{H}^{(4)}_{\mathrm{gate}}|\phi_{n+1}^\pm\rangle^* \Longrightarrow A^\dagger_{ab}B^\dagger_{ab} = A^*_{ba}B^*_{ba},$$

$$\langle\phi_n^+|\mathrm{H}^{(4)}_{\mathrm{gate}}|\phi_{n-1}^-\rangle = \langle\phi_n^-|\mathrm{H}^{(4)}_{\mathrm{gate}}|\phi_{n+1}^+\rangle^* \Longrightarrow A_{21}B_{22} - A^\dagger_{21}B^\dagger_{11} = -(A_{12}B_{11} - A^\dagger_{12}B^\dagger_{22})^*.$$

OBSERVATIONAL CONSEQUENCES: MASS-DEPENDENT REFRACTION INDEX OF VACUUM

QC SIMULATION OF QFT

THE SPINLESS DIRAC EQUATION

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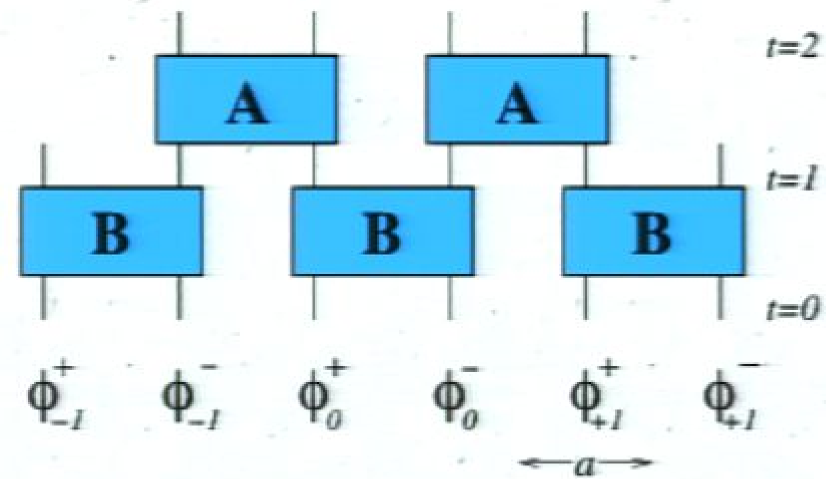
Write the "Hamiltonian" as follows:

(inverse) refraction index

$$\mathrm{H}^{(4)}_{\mathrm{gate}} = c(\mathbf{H} + i\mathbf{K}\widehat{\partial}_x) = ic\zeta\widehat{\partial}_x + \omega\sigma_x, \quad \omega = c\lambda^{-1}$$

$$\begin{aligned}
H_{11} &= -\tfrac{1}{2a}\Im(A_{21}B_{21} + A_{22}B_{11}) = 0,\\
H_{12} &= \tfrac{i}{4a}(A_{21}B_{22} - A^*_{12}B^*_{11} + A_{22}B_{12} - A^*_{11}B^*_{21}) = \lambda^{-1}\\
H_{22} &= -\tfrac{1}{2a}\Im(A_{12}B_{12} + A_{11}B_{22}) = 0,\\
K_{11} &= -\Re(A_{21}B_{21}) = \zeta,\\
K_{22} &= \Re(A_{12}B_{12}) = -\zeta,\\
K_{12} &= -\tfrac{1}{2}(A_{21}B_{22} - A^*_{12}B^*_{11}) = 0.
\end{aligned}$$



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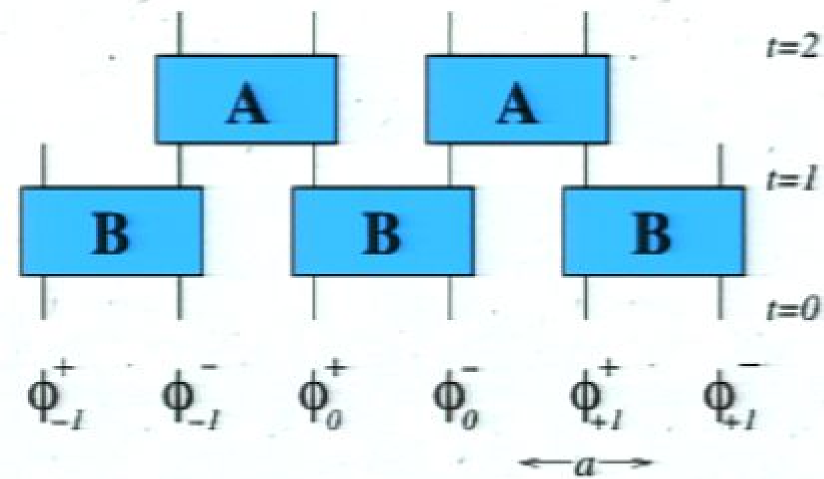

$$\mathbf{A} = \begin{bmatrix} e^{i\phi}\cos\theta & e^{i\psi}\sin\theta \\ -e^{-i\psi}\sin\theta & e^{-i\phi}\cos\theta \end{bmatrix}$$

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QC SIMULATION OF QFT

THE SPINLESS DIRAC EQUATION

Write the "Hamiltonian" as follows: (inverse) refraction index

$$\mathrm{H}^{(4)}_{\mathrm{gate}} = c(\mathbf{H} + i\mathbf{K}\widehat{\partial}_x) = ic\zeta\widehat{\partial}_x + \omega\sigma_x, \quad \omega = c\lambda^{-1}$$

$$H_{11} = -\tfrac{1}{2a}\Im(A_{21}B_{21} + A_{22}B_{11}) = 0,$$
$$H_{12} = \tfrac{i}{4a}(A_{21}B_{22} - A^*_{12}B^*_{11} + A_{22}B_{12} - A^*_{11}B^*_{21}) = \lambda^{-1}$$
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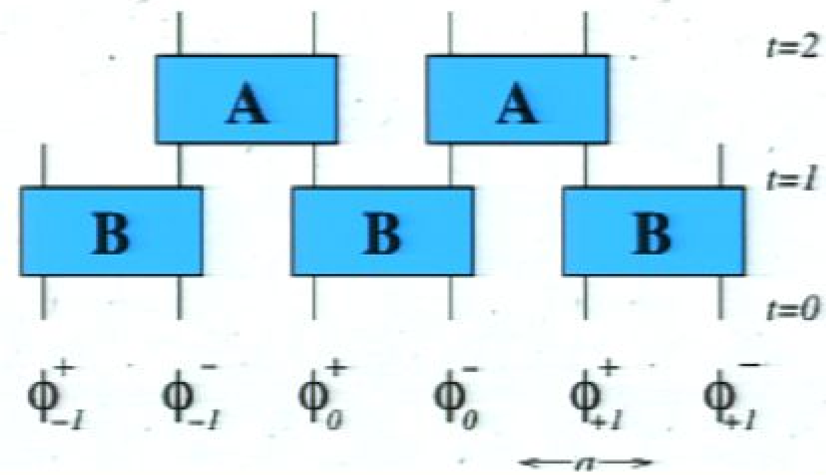

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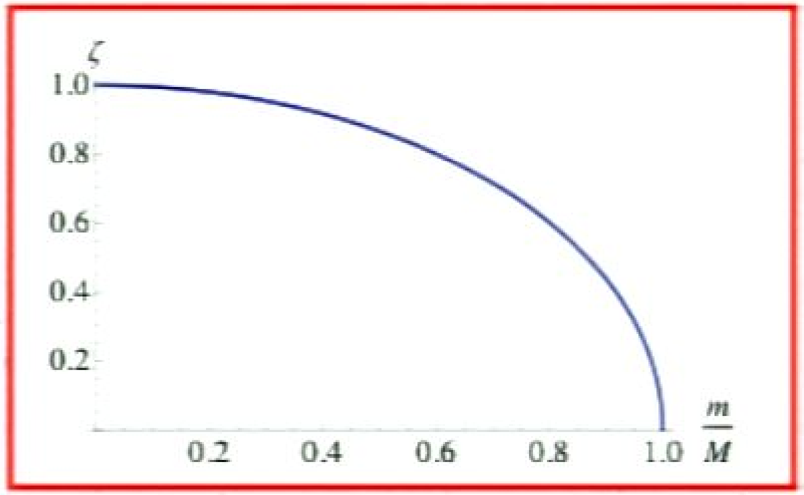
$$\sin\theta = \zeta = \sqrt{1 - \left(\frac{2a}{\lambda}\right)^2}$$

MASS-DEPENDENT REFRACTION INDEX OF VACUUM

General phenomenon due to unitariety

$$\sin\theta = \zeta = \sqrt{1 - \left(\frac{2a}{\lambda}\right)^2}$$



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Proof. We need the gate-Hamiltonian:

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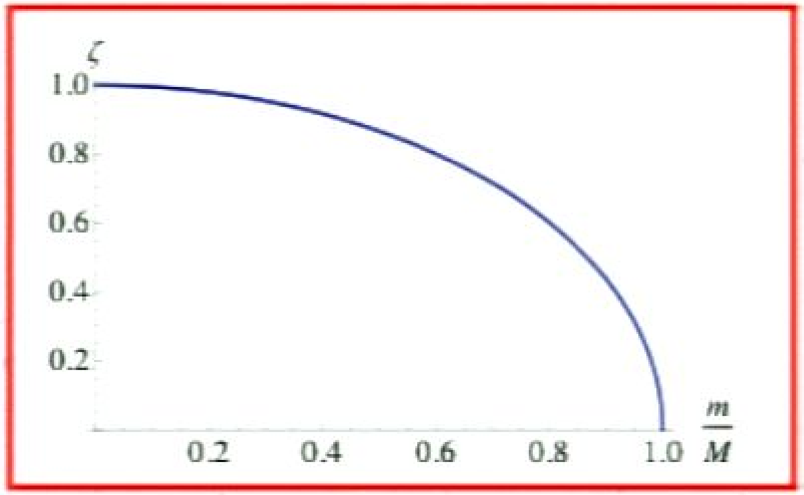

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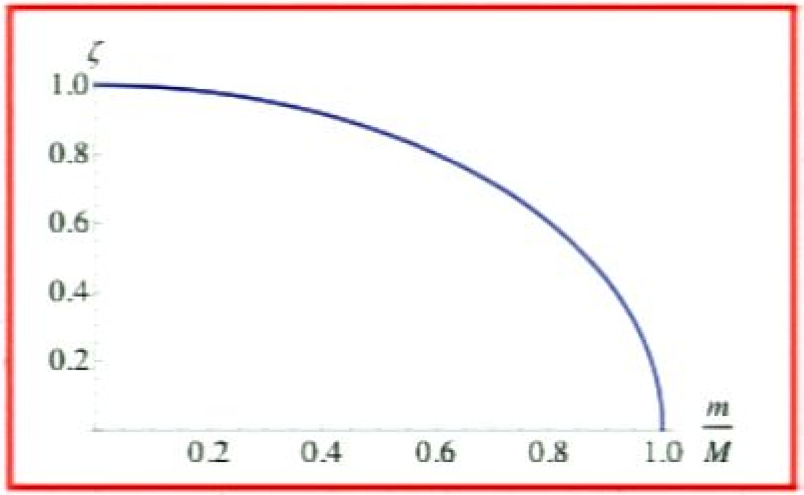

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The Hamiltonian is Hermitian, whence:

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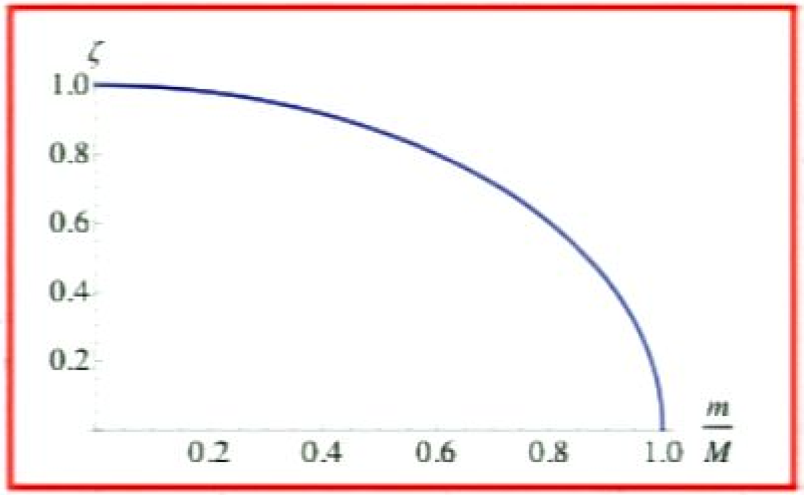

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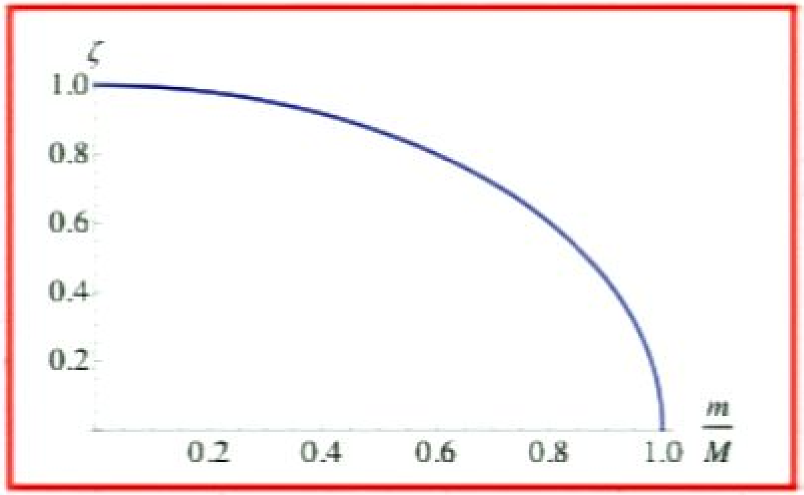

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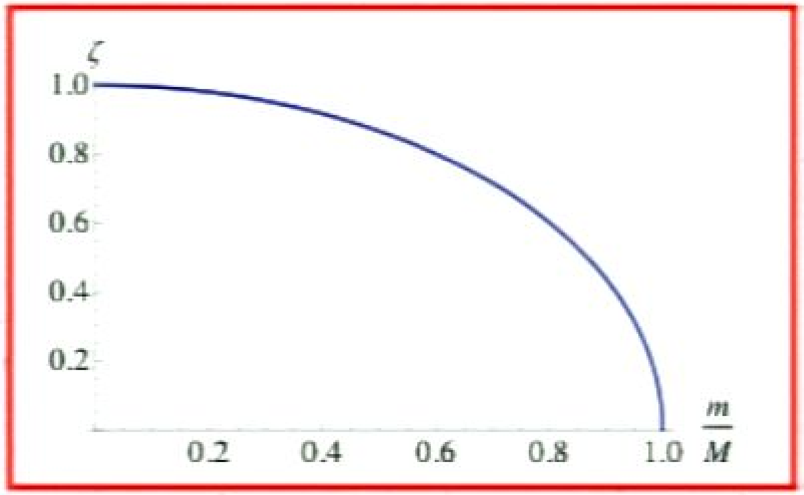

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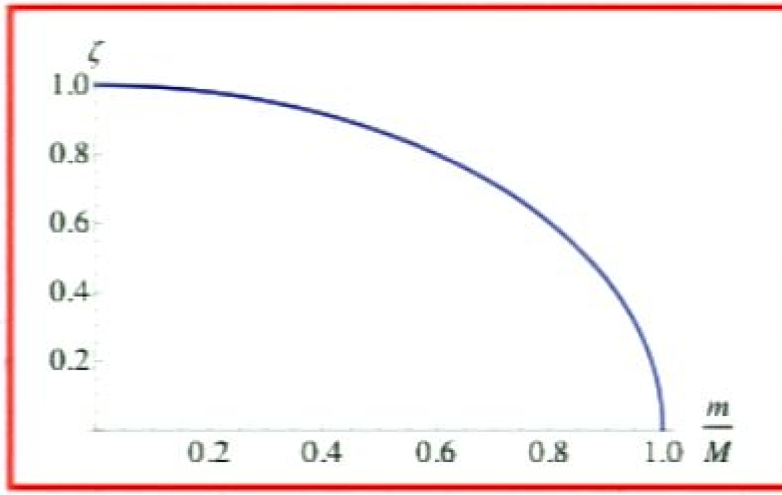

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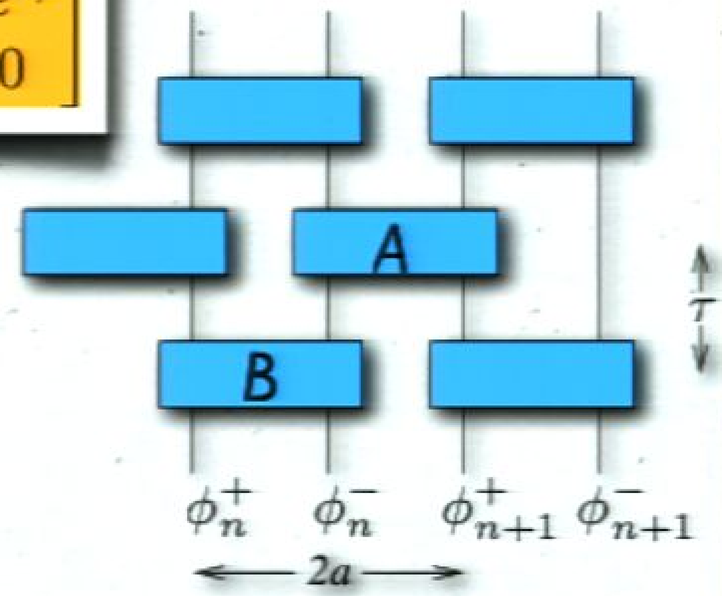
QC SIMULATION OF QFT

SIMPLE SCALAR FIELD IN 1 SPACE DIM.

$$\mathbf{A} = \begin{bmatrix} e^{i\phi}\cos\theta & e^{i\psi}\sin\theta \\ -e^{-i\psi}\sin\theta & e^{-i\phi}\cos\theta \end{bmatrix} \qquad \mathbf{B} = \begin{bmatrix} 0 & ie^{i\phi} \\ -ie^{-i\phi} & 0 \end{bmatrix}$$



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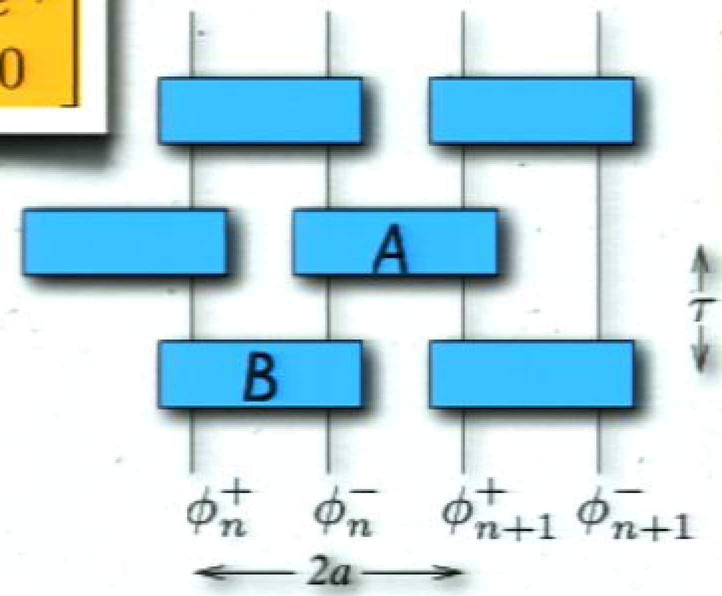

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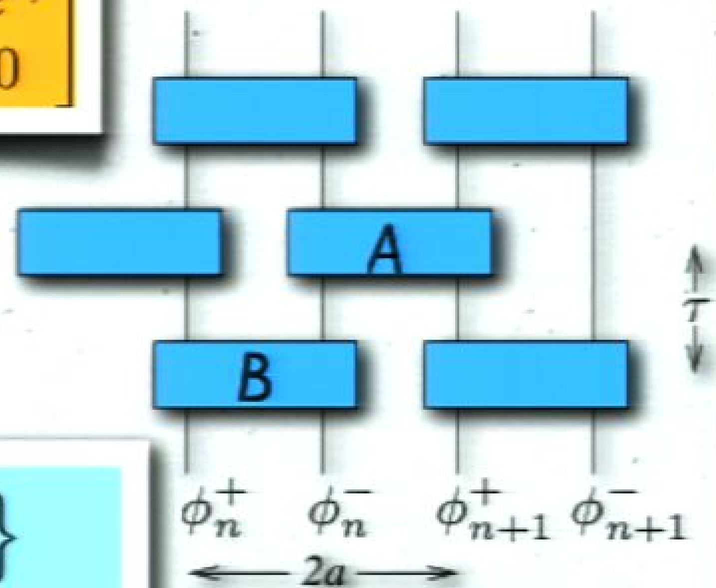

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For both Bose and Fermi fields one has:

$$A = \exp\left\{i\theta\left[\phi_n^{+\dagger}\phi_{n-1}^- + \phi_{n-1}^{-\dagger}\phi_n^+\right]\right\}$$

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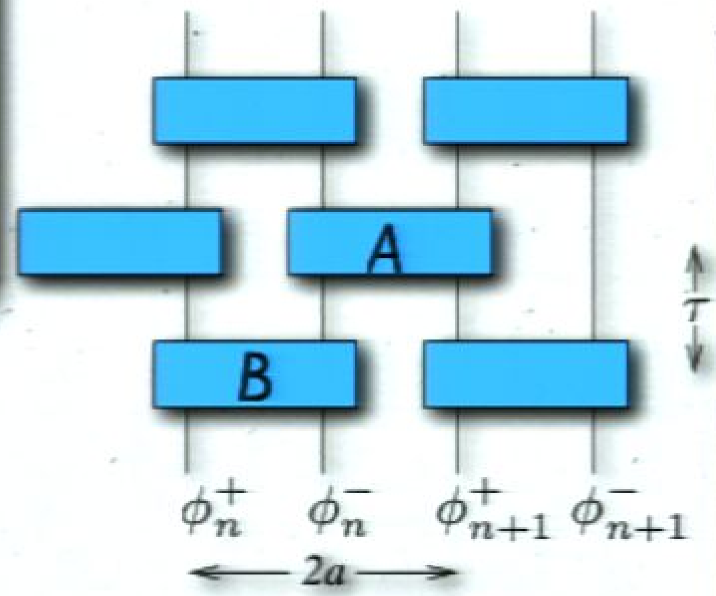
Commuting	Anticommuting
Harmonic oscillator	*Clifford algebra*
$[a_l, a_k^\dagger] = \delta_{lk}$	$\phi_n^+ = \sigma_{2n}^- \prod_{k=-\infty}^{n-1} \sigma_{2k+1}^z \sigma_{2k}^z$
$\phi_n^+ = a_{2n} \quad \phi_n^- = a_{2n+1}$	$\phi_n^- = \sigma_{2n+1}^- \sigma_{2n}^z \prod_{k=-\infty}^{n-1} \sigma_k^z$



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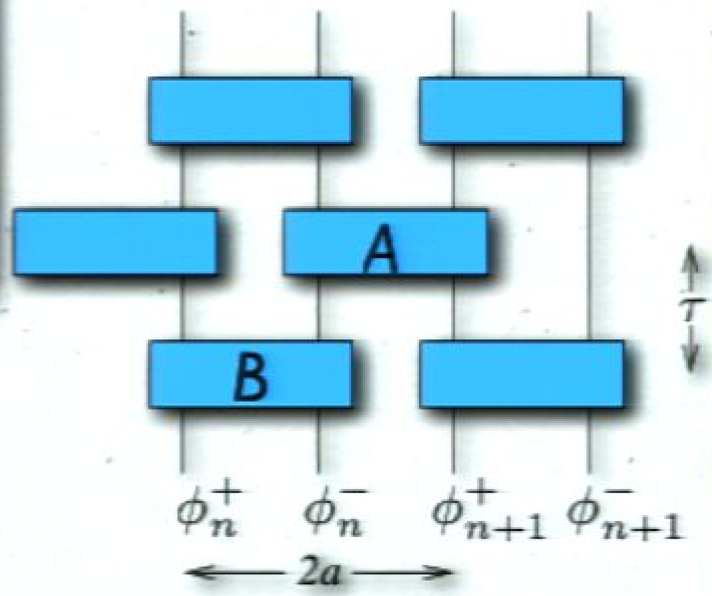

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Gates act on local algebras only!

QC SIMULATION OF QFT

CONNECTION WITH THE USUAL QFT

Global field Hamiltonian, i. e. such that: $[H, \phi_l] = \mathrm{H}_{\mathrm{gate}}^{(2n)} \phi_l$

$$H = -\sum_l \phi_l^\dagger \mathrm{H}_{\mathrm{gate}}^{(2n)} \phi_l \qquad (*)$$

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For a given field theory to be simulable by a homogeneous quantum computer in the discrete approximation $\phi(la) = a^{-\frac{1}{2}} \phi_l$ one needs the field Hamiltonian that can be written in the form (*) with the $n \geqslant 1$ satisfying the bound

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All known QFT are QC-simulable!

FIRST QUANTIZATION

EMERGENCE OF CCR

Constant of motion (number of "particles")

$$N = \sum_n \phi_n^\dagger \phi_n = \sum_n \sigma_n^3$$

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$$[X^\alpha, P^\beta] = i\hbar \delta_{\alpha\beta} I_\alpha$$

FIRST QUANTIZATION

Single-"particle" Schrödinger equation in ppm representation:

$$\Psi = \begin{bmatrix} \cdots \\ \langle \phi_n^+ | \Psi \rangle \\ \langle \phi_n^- | \Psi \rangle \\ \langle \phi_{n+1}^+ | \Psi \rangle \\ \langle \phi_{n+1}^- | \Psi \rangle \\ \cdots \end{bmatrix} \qquad i\widehat{\partial}_t \langle \phi_n^\alpha | \Psi \rangle = \langle \mathbf{0} | [\mathrm{H}_{\mathrm{gate}}^{(4)} \phi_n]^\alpha | \Psi \rangle = \sum_{m\beta} H_{n\alpha, m\beta} \langle \phi_m^\beta | \Psi \rangle$$

$$H = c \begin{bmatrix} \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ \cdots & \cdots & 0 & \lambda & \frac{i\zeta}{4a} & 0 & 0 & 0 & \cdots & \cdots \\ \cdots & \cdots & \lambda & 0 & 0 & -\frac{i\zeta}{4a} & 0 & 0 & \cdots & \cdots \\ \cdots & \cdots & -\frac{i\zeta}{4a} & 0 & 0 & \lambda & \frac{i\zeta}{4a} & 0 & \cdots & \cdots \\ \cdots & \cdots & 0 & \frac{i\zeta}{4a} & \lambda & 0 & 0 & -\frac{i\zeta}{4a} & \cdots & \cdots \\ \cdots & \cdots & 0 & 0 & -\frac{i\zeta}{4a} & 0 & 0 & \lambda & \cdots & \cdots \\ \cdots & \cdots & 0 & 0 & 0 & \frac{i\zeta}{4a} & \lambda & 0 & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \end{bmatrix}$$

$$i\widehat{\partial}_t \Psi = H \Psi$$

QC SIMULATION OF QFT

QCFT FOR MORE THAN 1 SPACE DIM?

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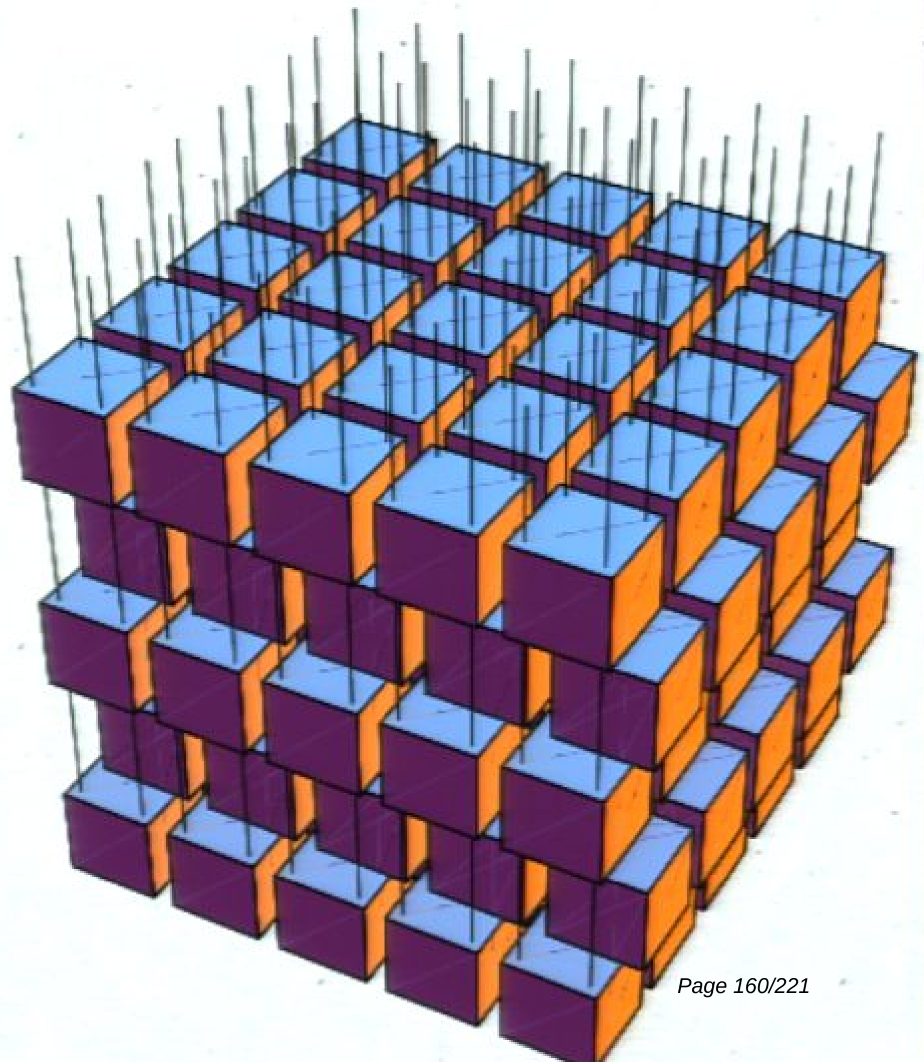
Need six space field operators...



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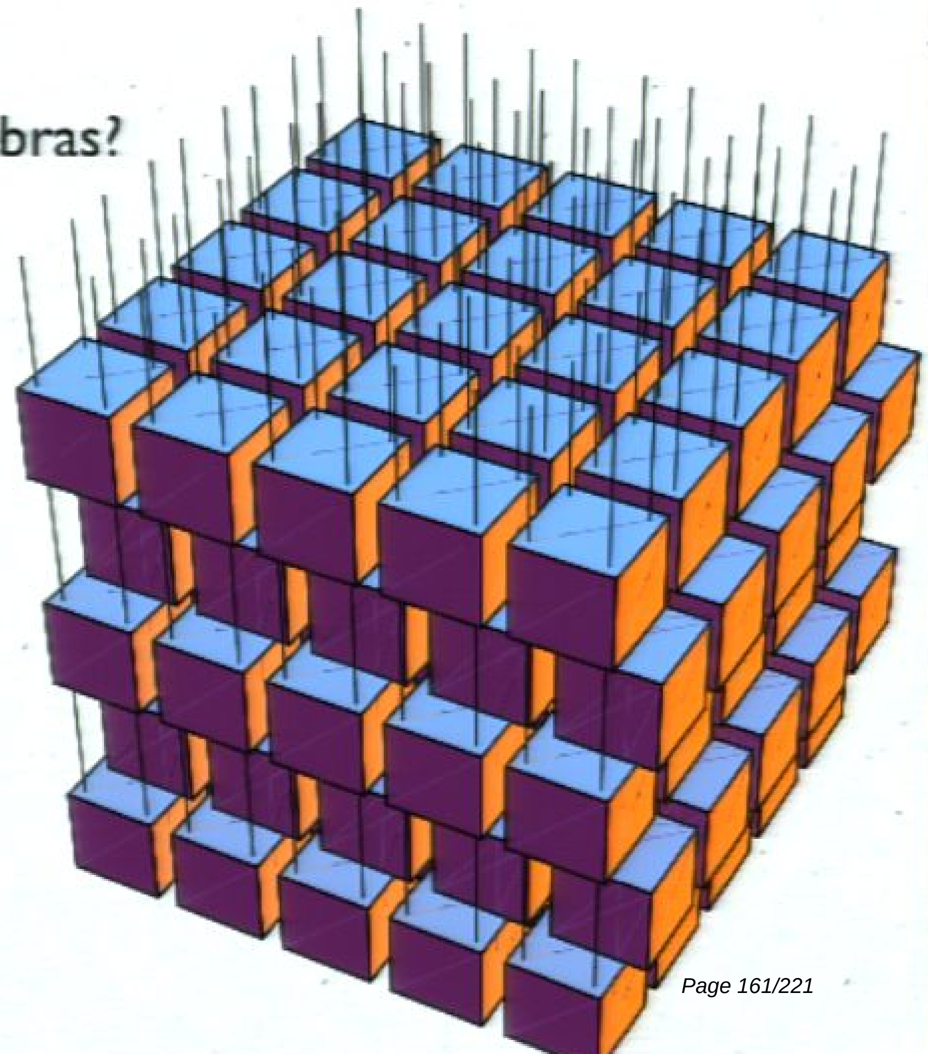
Do we need fields?



QC SIMUL... CFT?

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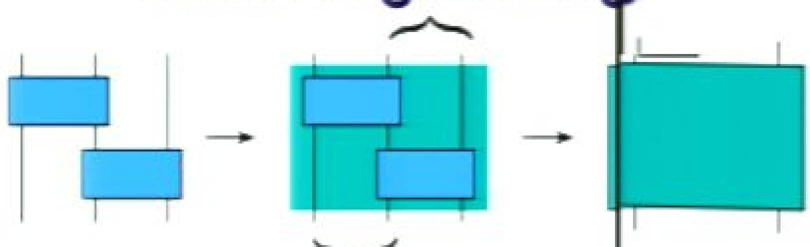
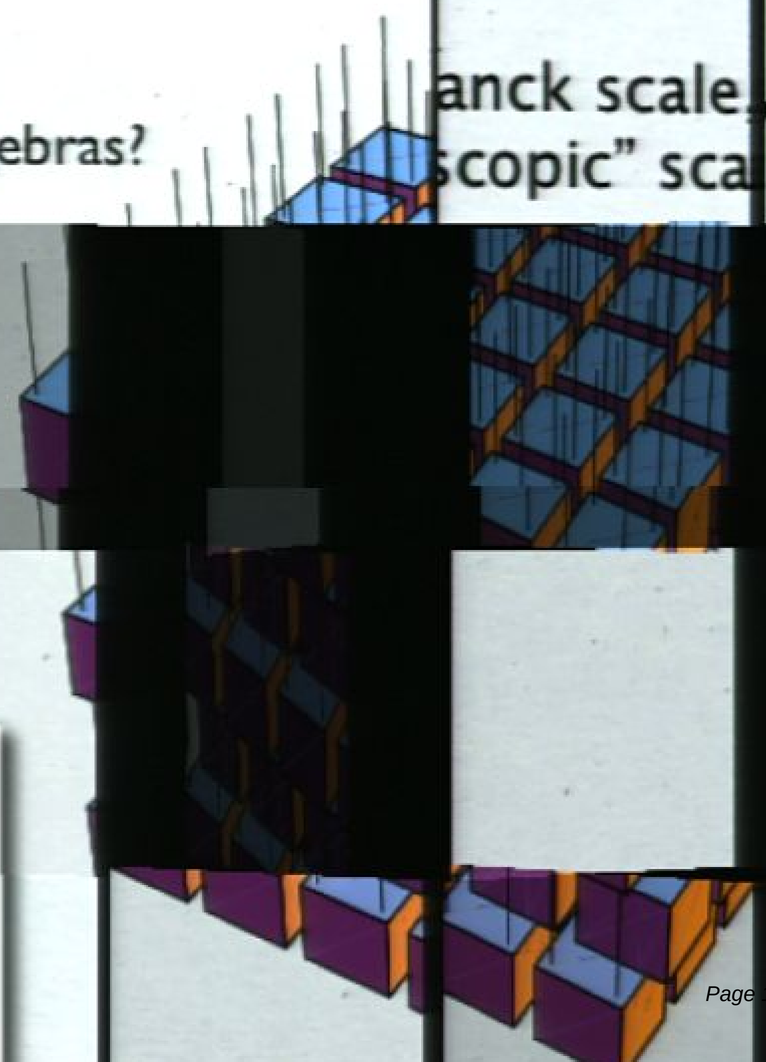
Coarse-graining





A NEW QCFT?

COMPARE WITH THE USUAL QFT

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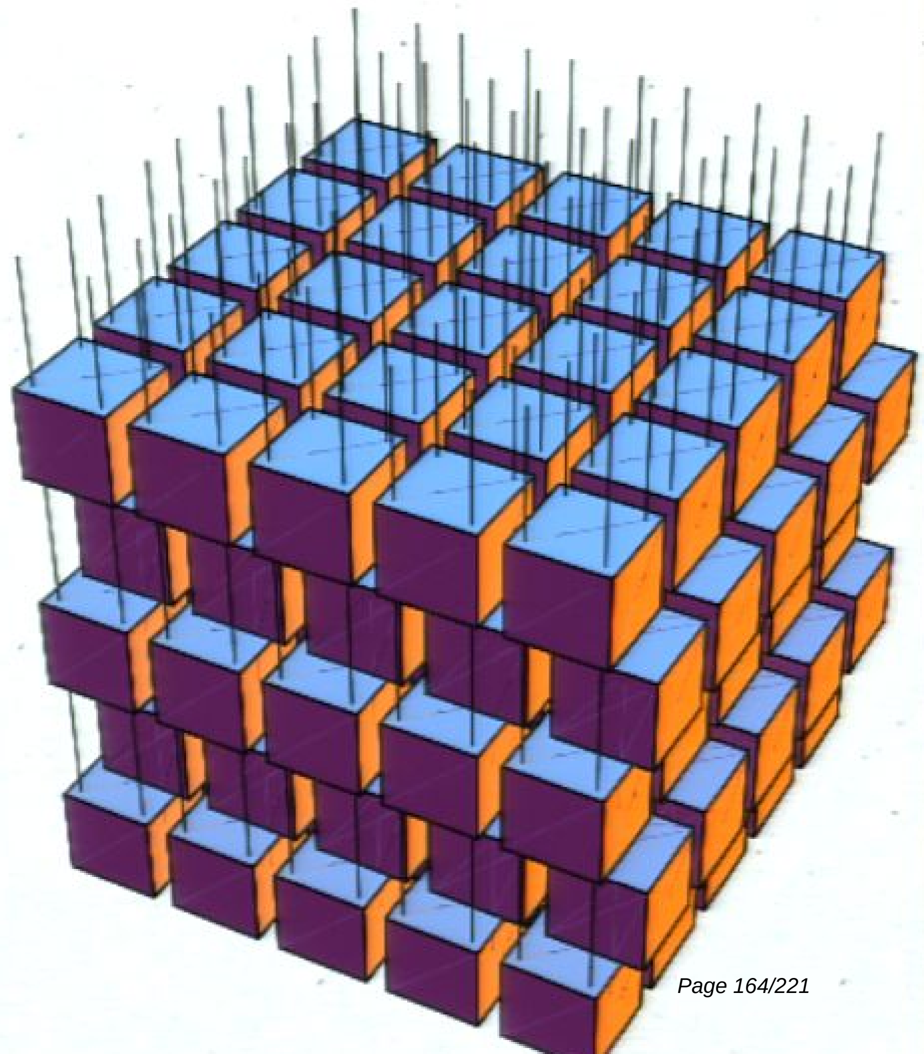

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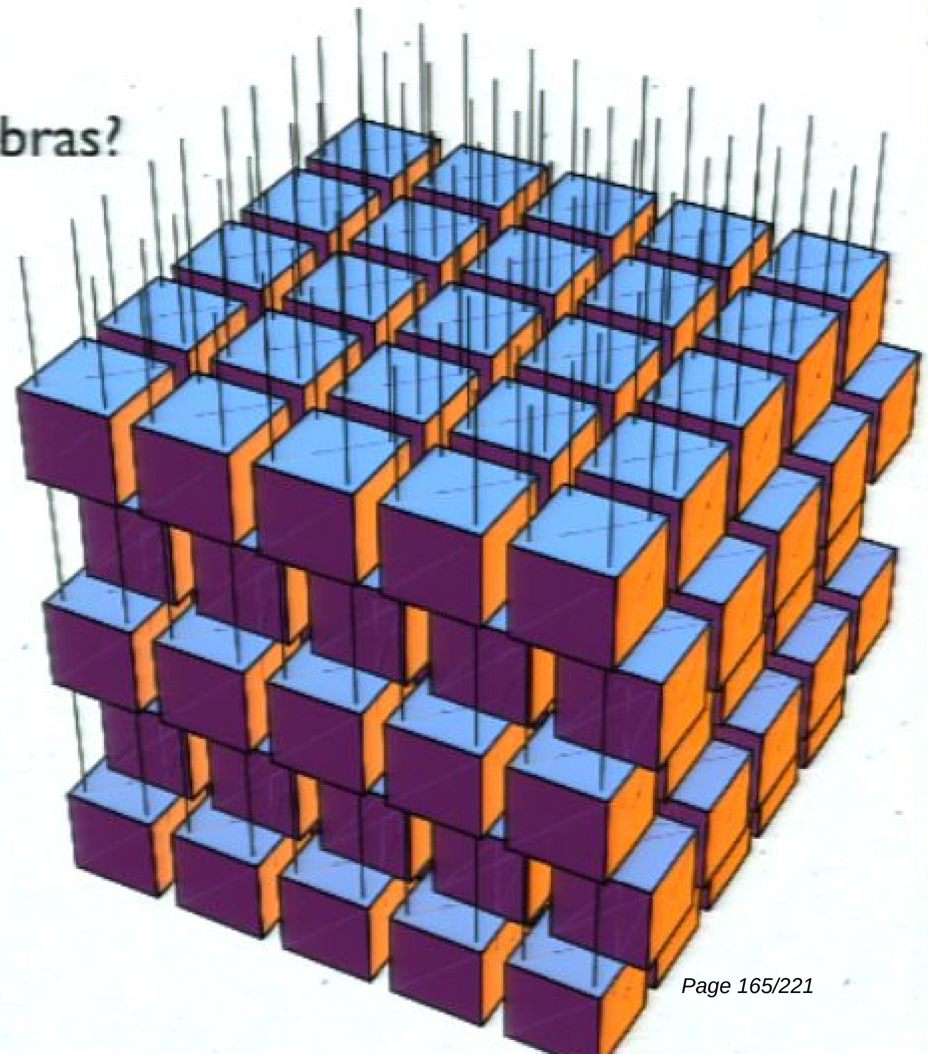

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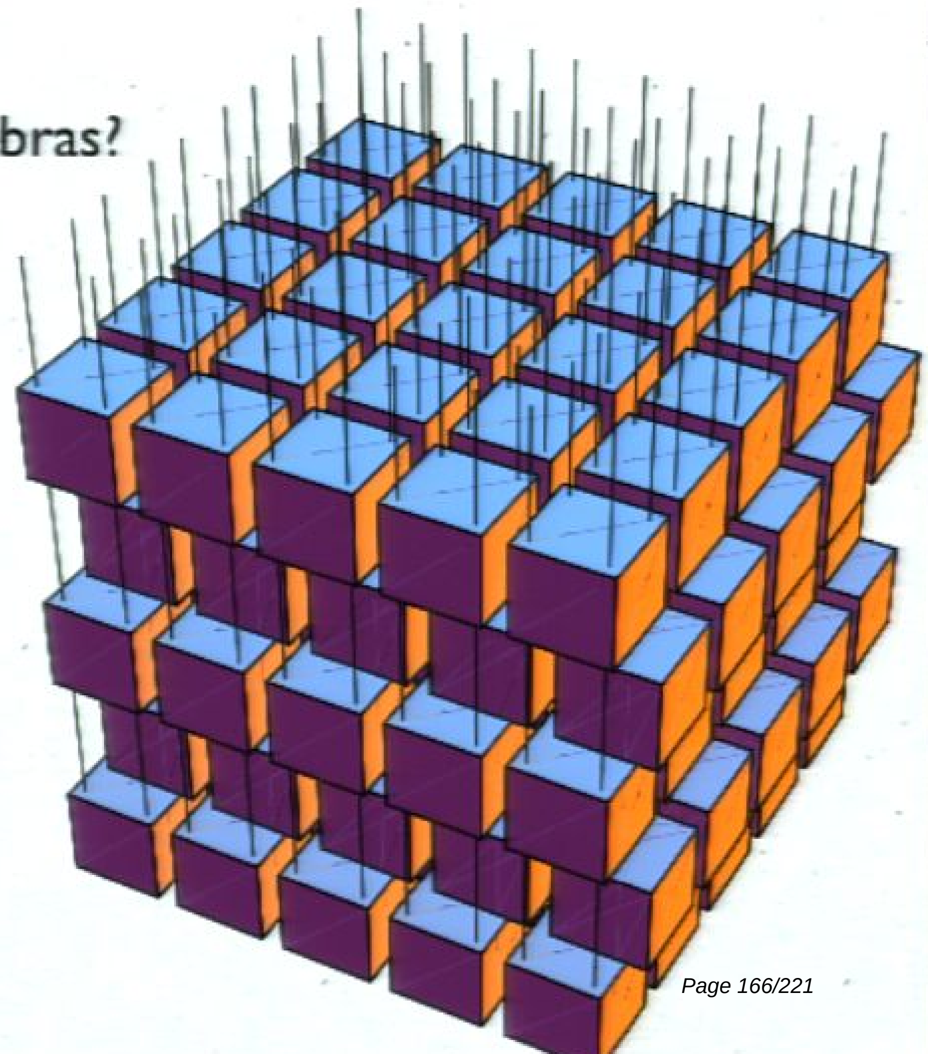

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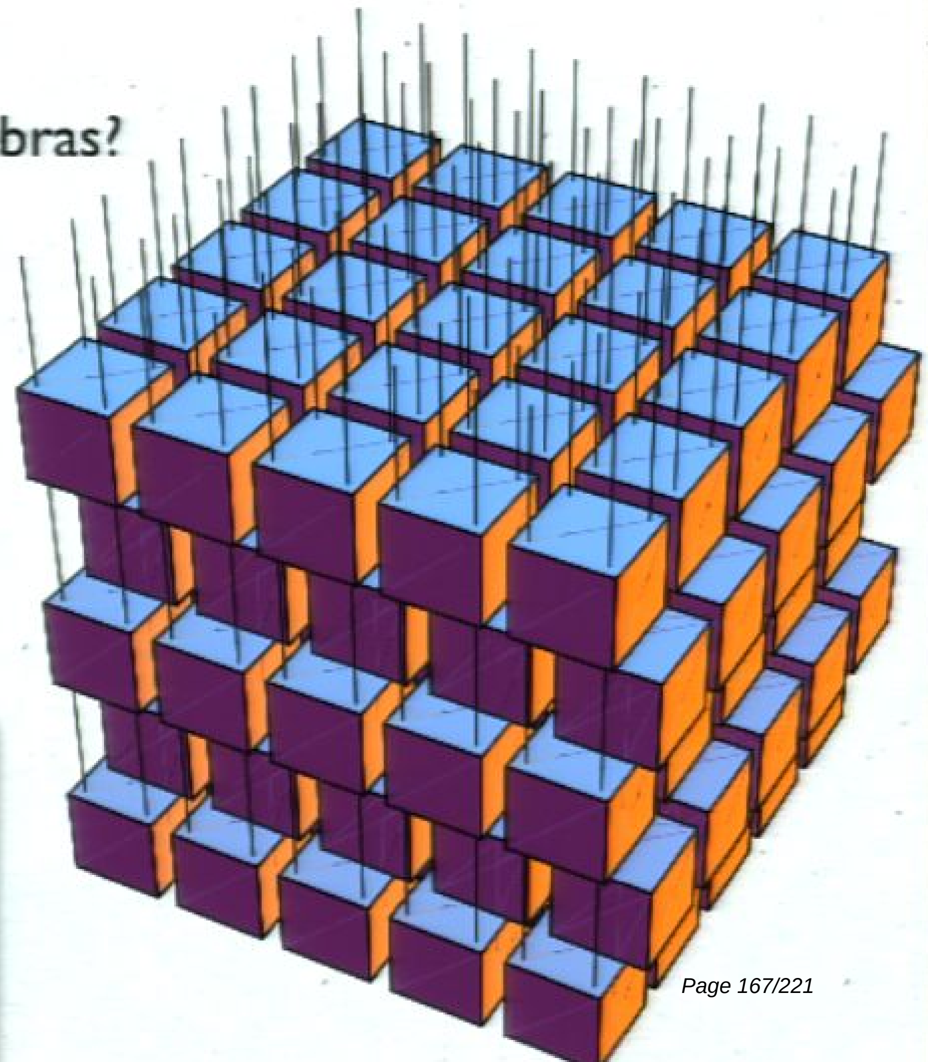

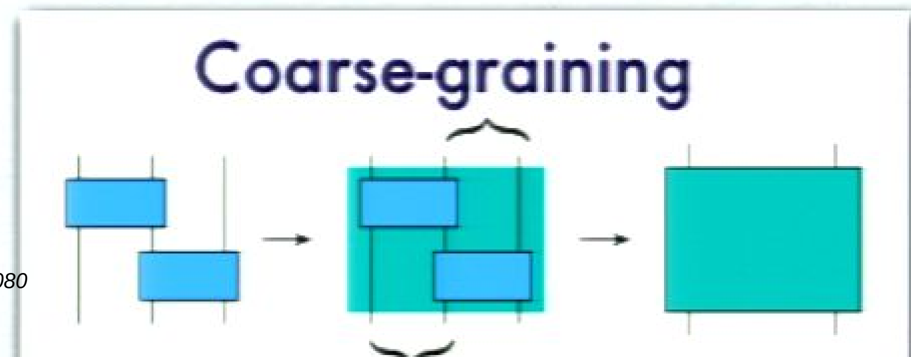

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QCFT solve many problems t hat plague QFT:

* Feynman's path integral
* u.v. renormalization
* no need of quantization rul es (emergent)
* problems related to the con tinuous
* ...

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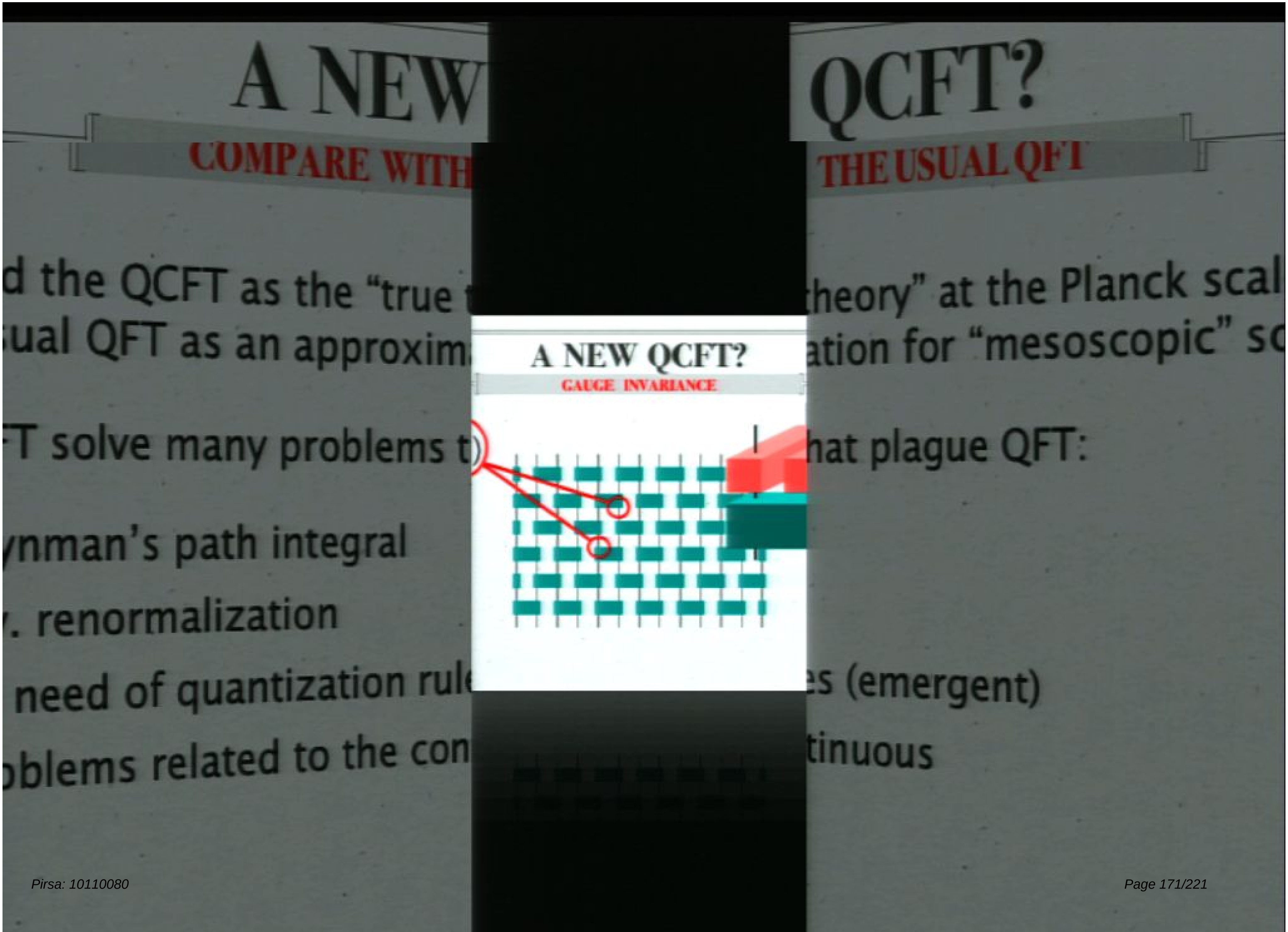
A NEW
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COMPARE WITH
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GAUGE INVARIANCE

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COMPARE WITH THE USUAL QFT

Regard the QCFT as the "true theory" at the Planck scale, and the usual QFT as an approximation for "mesoscopic" scale

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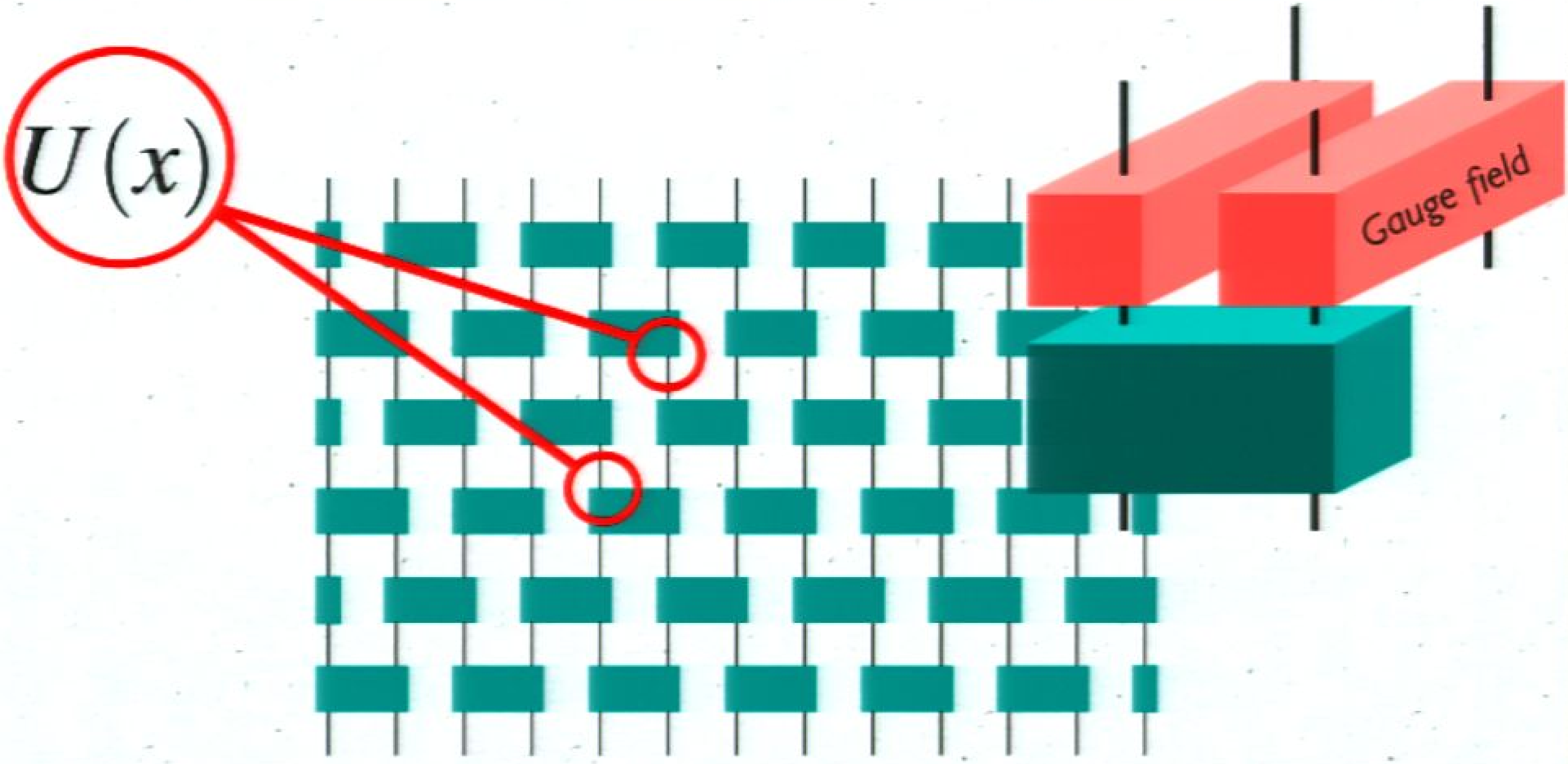
Regard the QCFT as the “true theory” at the Planck scale, and the usual QFT as an approximation for “mesoscopic” scale

QCFT solve many problems that plague QFT:

* Feynman’s path integral
* u.v. renormalization
* no need of quantization rules (emergent)
* problems related to the continuous
* ...

A NEW QCFT?

GAUGE INVARIANCE



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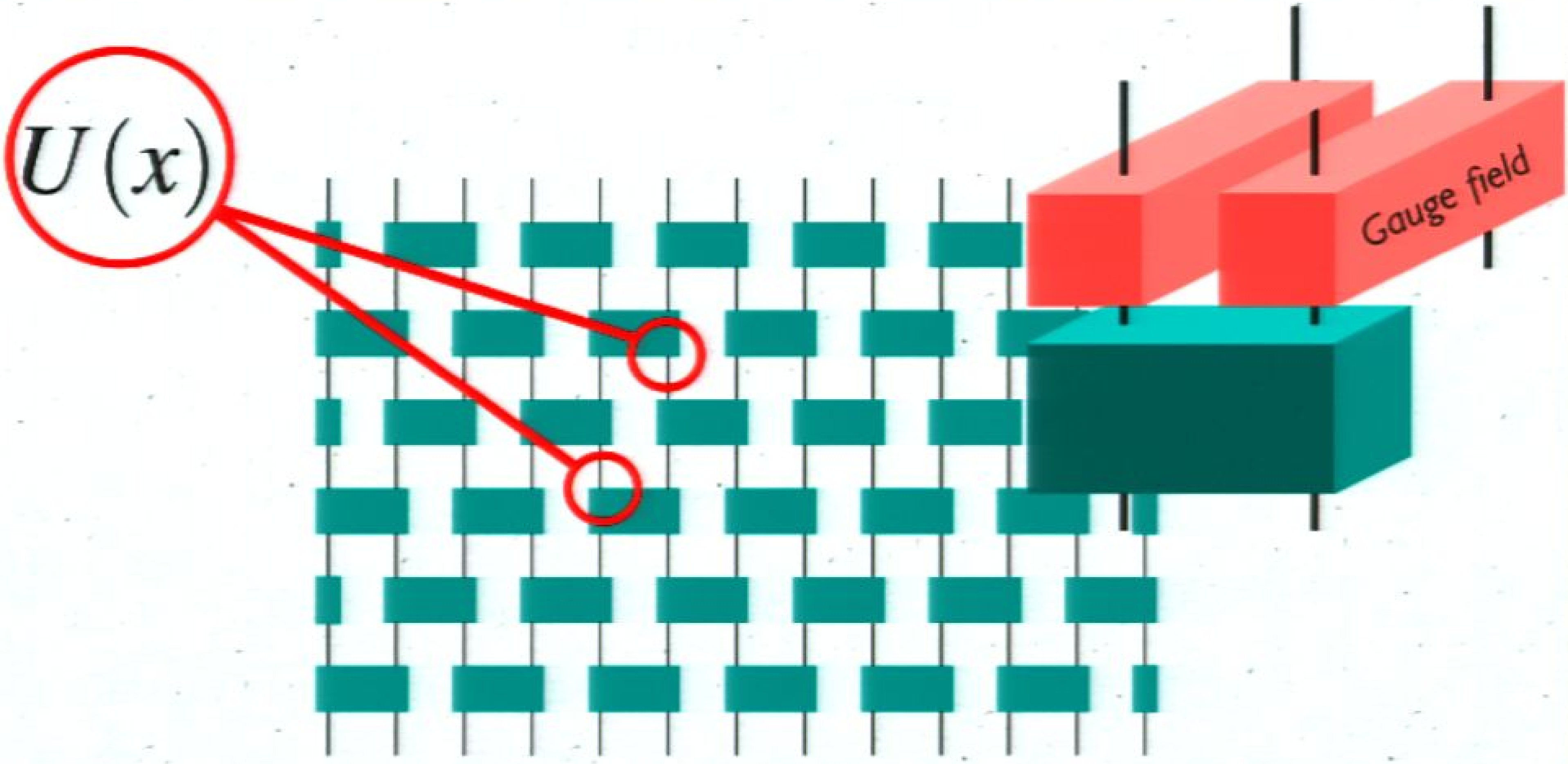


Natively nonabelian Gauge theory!
and on ... foliation !!!

Good for
QGravity?

CONCLUSIONS

PHYSICS IS INFORMATION

★ ★ ★ ★ ★ ★ ★ ★

- Quantum Theory is an information theory
- Space-time and relativistic covariance emerge from the information processing
- Information flow is the free QFT
- Physics is emergent (inertial mass, Planck constant, quantization rules, ...)
- A new QCFT:
  - has no space-background (QG-ready)
  - doesn't need quantization
  - cures many problems that plague QFT
  - opens a route to foundations of QFT

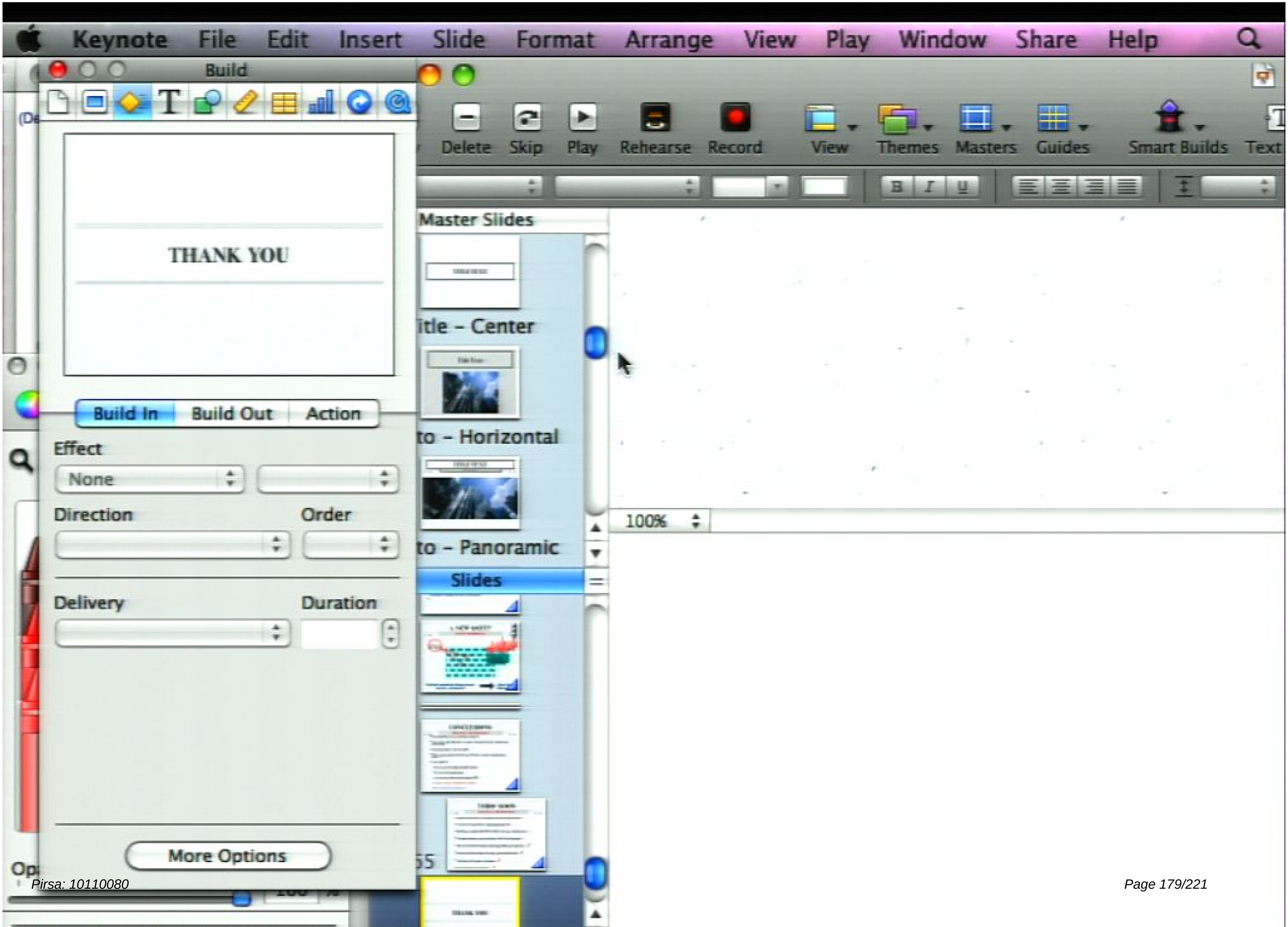
TODO SOON

PHYSICS IS INFORMATION

★ ★ ★ ★ ★ ★ ★ ★

* Quantization rules as emergent (needs interpretation) ✔
* General correspondence Lagrangian-gates ✔
* Build up a complete QCFT for Dirac in 3 space dimensions ✔
* Emergent unitary representation of the Lorentz group ✔
* The need of the field (anticommuting fields, parastatistics,...)?
* Informational meaning of energy, gravitational mass,...?
* Violations of Lorentz-covariance...?

THANK YOU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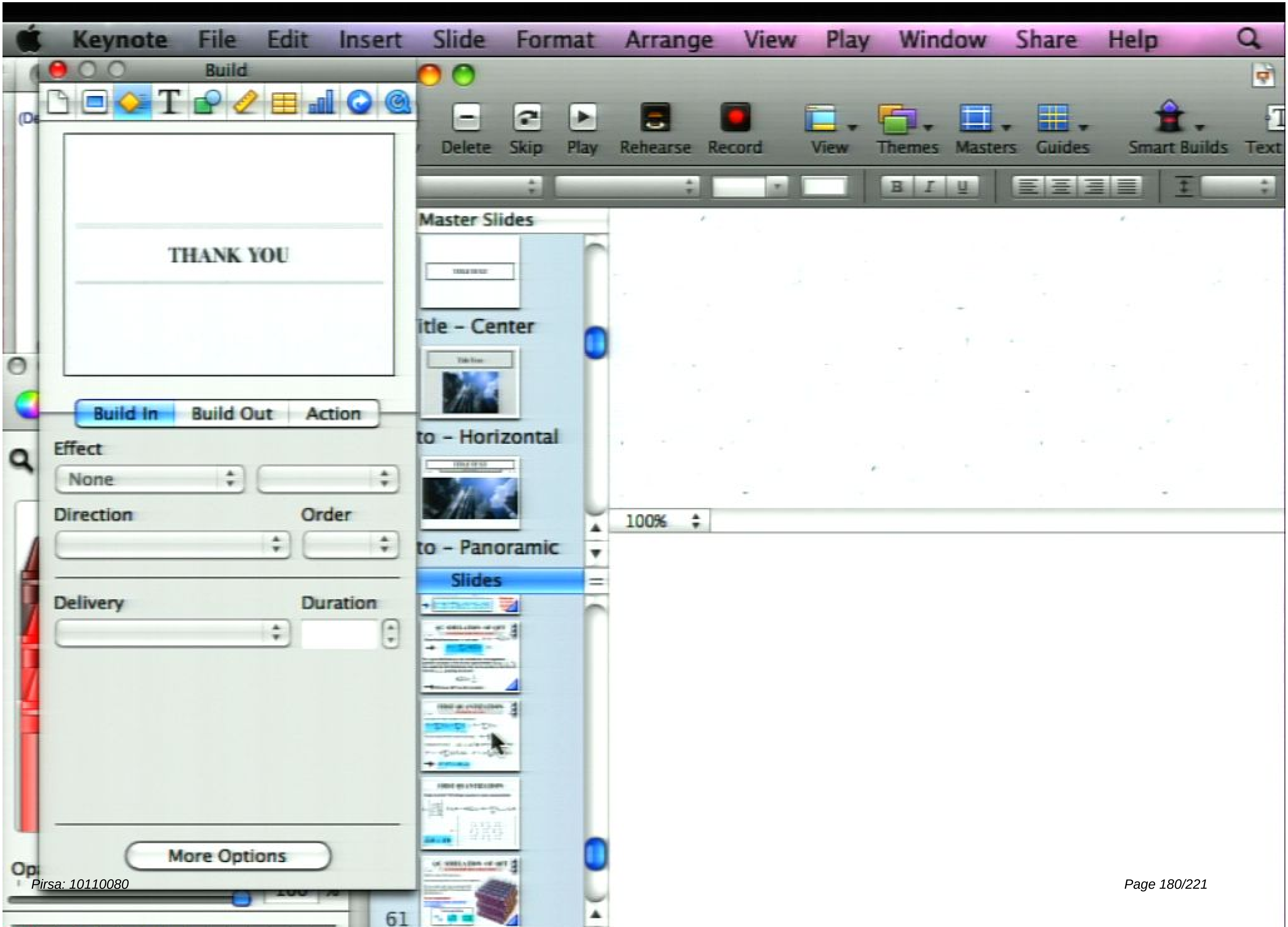
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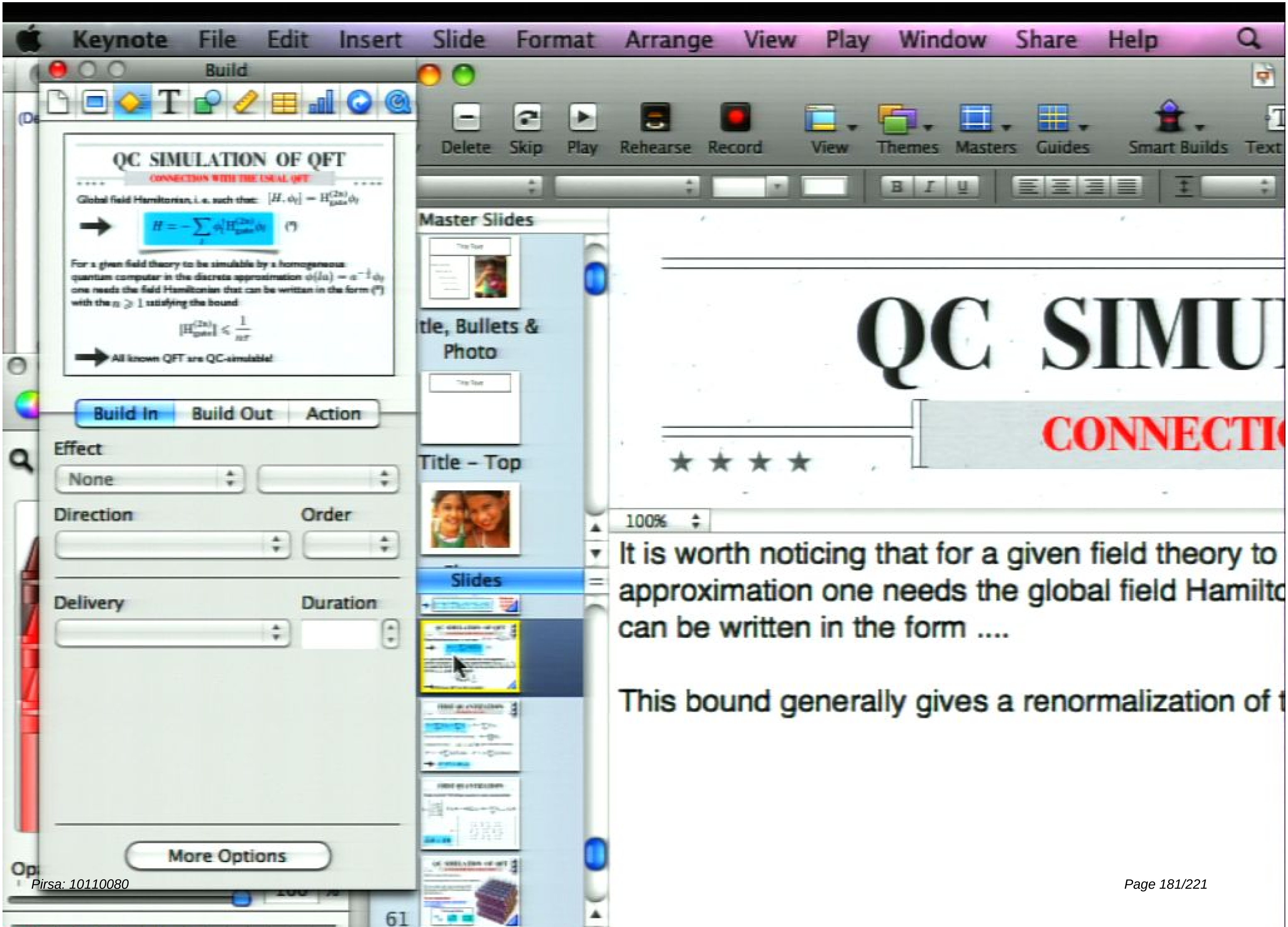
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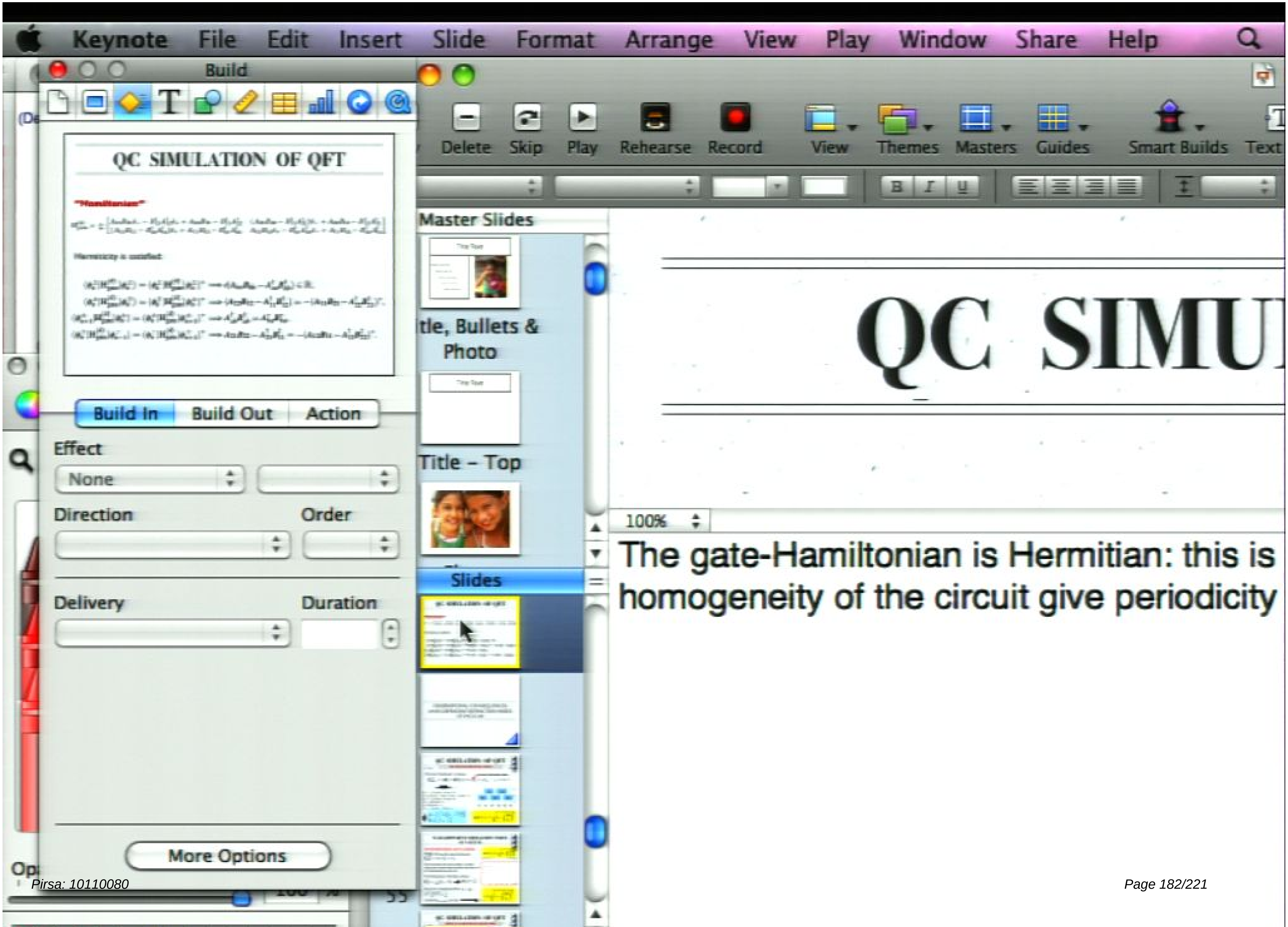
It is worth noticing that for a given field theory to
approximation one needs the global field Hamilto
can be written in the form ....
This bound generally gives a renormalization of t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QC SIMU
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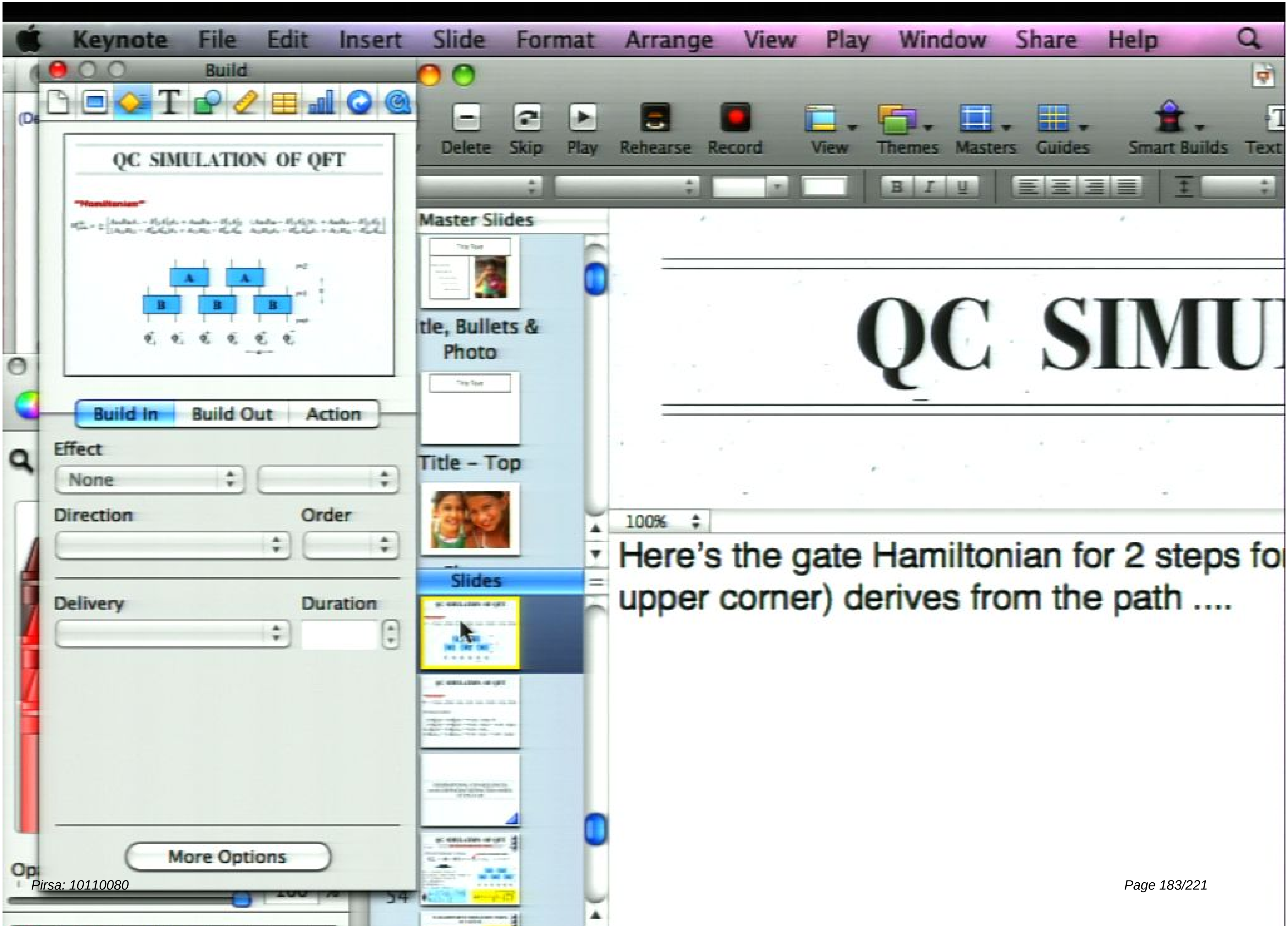
The gate-Hamiltonian is Hermitian: this is
homogeneity of the circuit give periodicity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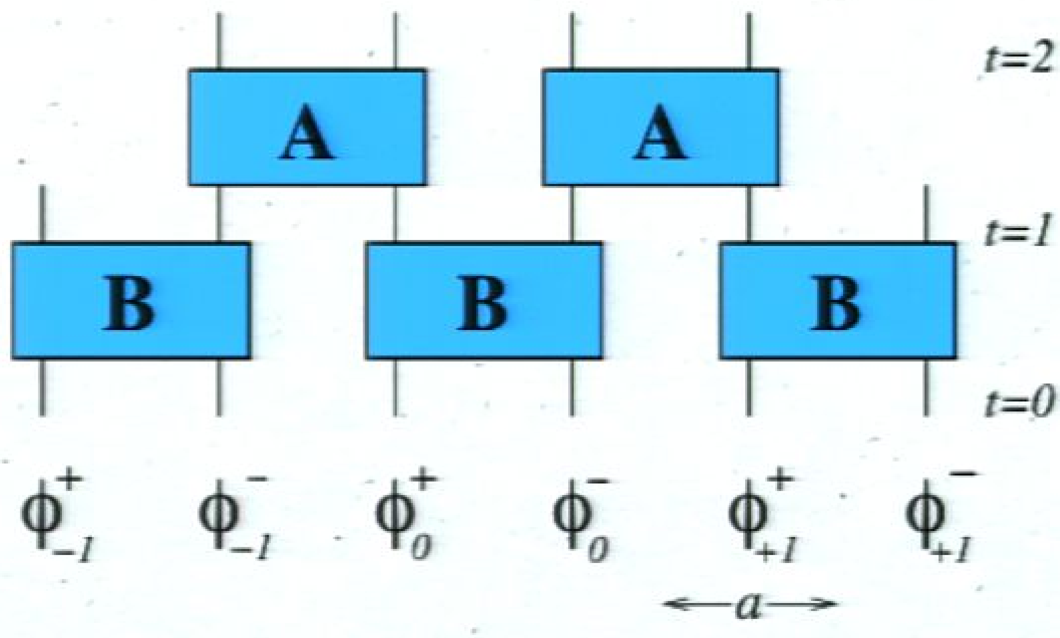
QC SIMU
100%
Here's the gate Hamiltonian for 2 steps fo
upper corner) derives from the path ....

QC SIMULATION OF QFT

"Hamiltonian"

$$\mathrm{H}^{(4)}_{\mathrm{gate}} = \frac{i}{4\tau}\begin{bmatrix} A_{21}B_{21}\delta_- - B^\dagger_{12}A^\dagger_{12}\delta_+ + A_{22}B_{11} - B^\dagger_{11}A^\dagger_{22} & (A_{21}B_{22} - B^\dagger_{11}A^\dagger_{21})\delta_- + A_{22}B_{12} - B^\dagger_{12}A^\dagger_{11} \\ (A_{12}B_{11} - B^\dagger_{22}A^\dagger_{12})\delta_+ + A_{11}B_{21} - B^\dagger_{21}A^\dagger_{22} & A_{12}B_{12}\delta_+ - B^\dagger_{21}A^\dagger_{21}\delta_- + A_{11}B_{22} - B^\dagger_{22}A^\dagger_{11} \end{bmatrix}$$



QC SIMULATION OF QFT

THE SPINLESS DIRAC EQUATION

Write the "Hamiltonian" as follows:

(inverse) refraction index

$$\mathrm{H}^{(4)}_{\mathrm{gate}} = c(\mathbf{H} + i\mathbf{K}\widehat{\partial}_x) = ic\zeta\widehat{\partial}_x + \omega\sigma_x, \quad \omega = c\lambda^{-1}$$

$$
\begin{aligned}
H_{11} &= -\tfrac{1}{2a}\Im(A_{21}B_{21} + A_{22}B_{11}) = 0,\\
H_{12} &= \tfrac{i}{4a}(A_{21}B_{22} - A^*_{12}B^*_{11} + A_{22}B_{12} - A^*_{11}B^*_{21}) = \lambda^{-1}\\
H_{22} &= -\tfrac{1}{2a}\Im(A_{12}B_{12} + A_{11}B_{22}) = 0,\\
K_{11} &= -\Re(A_{21}B_{21}) = \zeta,\\
K_{22} &= \Re(A_{12}B_{12}) = -\zeta,\\
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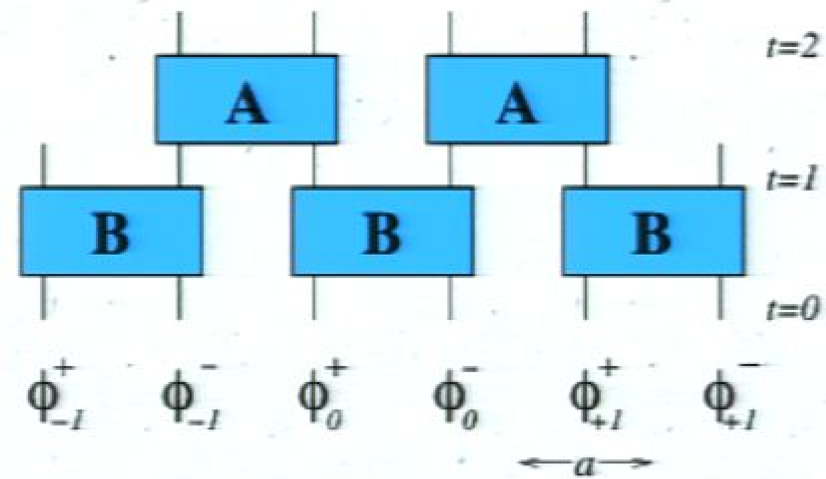

$$\mathbf{A} = \begin{bmatrix} e^{i\phi}\cos\theta & e^{i\psi}\sin\theta \\ -e^{-i\psi}\sin\theta & e^{-i\phi}\cos \end{bmatrix}$$

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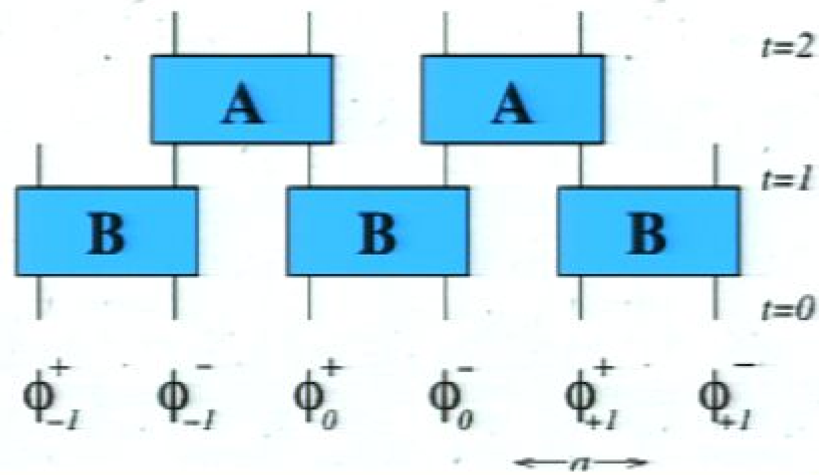

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$$\sin\theta = \zeta = \sqrt{1 - \left(\frac{2a}{\lambda}\right)^2}$$

MASS-DEPENDENT REFRACTION INDEX OF VACUUM

General phenomenon due to unitariety

Proof. We need the gate-Hamiltonian:

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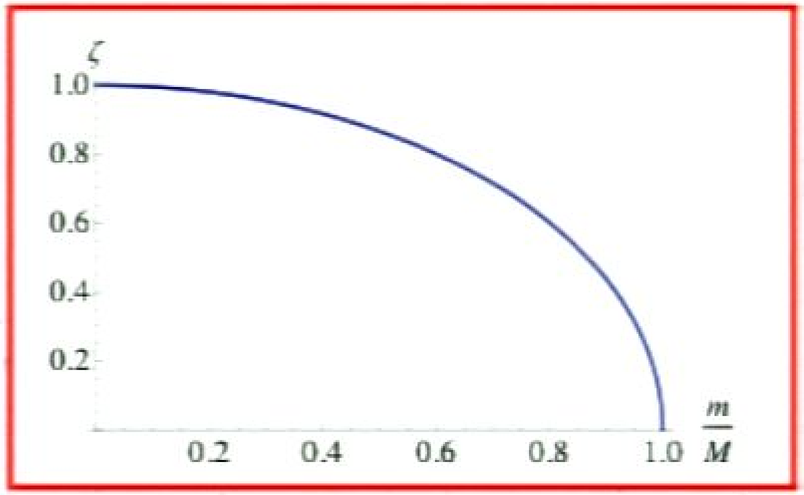

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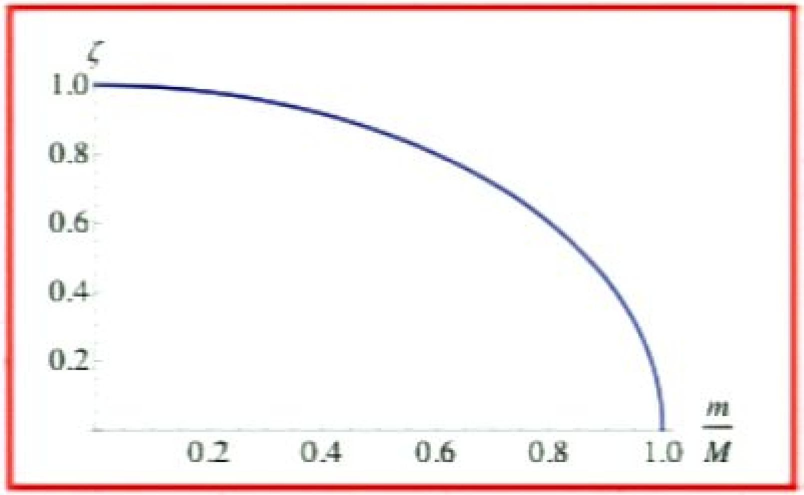

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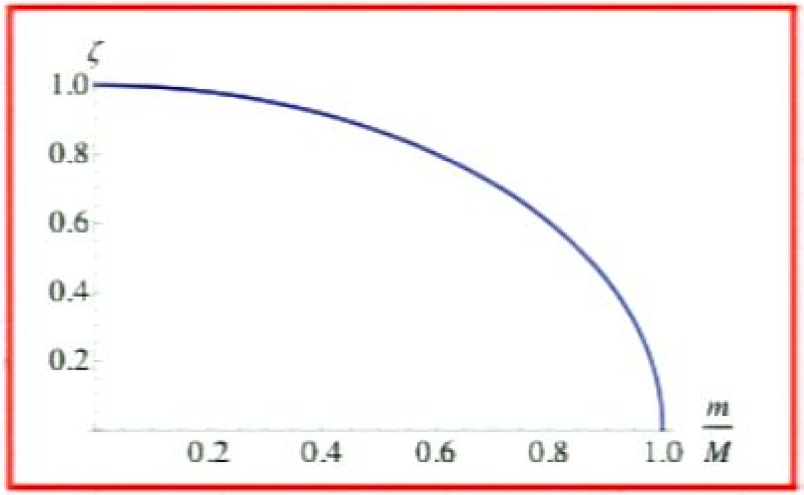

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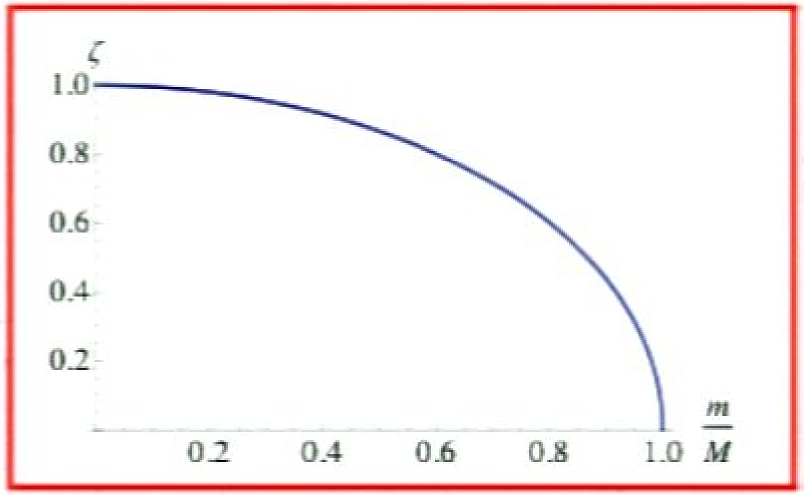

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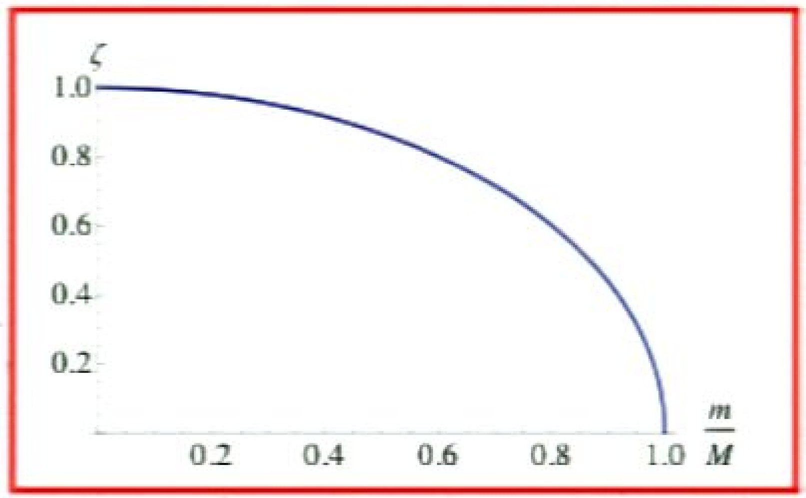

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The norm is obtained by FT at $k = \frac{\pi}{2a}$

$$\frac{\sqrt{\zeta^2 + 4\tau^2\omega^2}}{2\tau} \leqslant \frac{1}{2\tau}$$

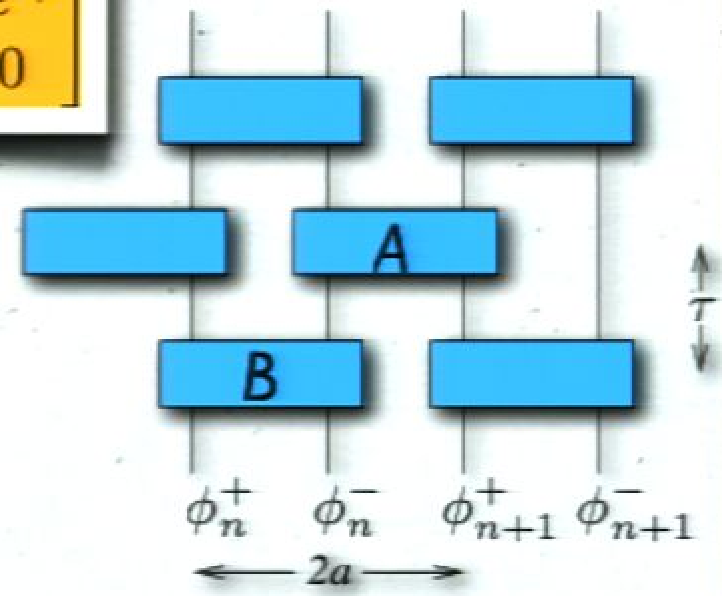
namely for ... one has:

$$\zeta \leqslant \sqrt{1 - \left(\frac{2a}{\lambda}\right)^2}$$

QC SIMULATION OF QFT

SIMPLE SCALAR FIELD IN 1 SPACE DIM.

$$\mathbf{A} = \begin{bmatrix} e^{i\phi}\cos\theta & e^{i\psi}\sin\theta \\ -e^{-i\psi}\sin\theta & e^{-i\phi}\cos\theta \end{bmatrix} \quad \mathbf{B} = \begin{bmatrix} 0 & ie^{i\phi} \\ -ie^{-i\phi} & 0 \end{bmatrix}$$



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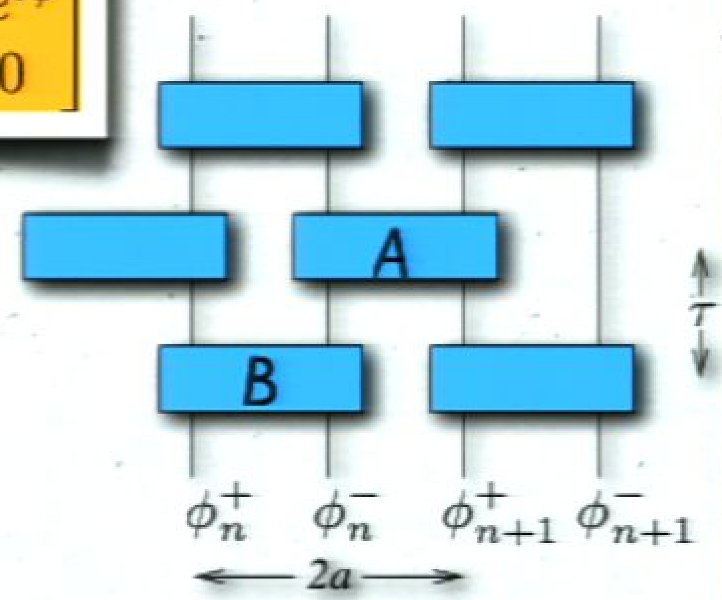

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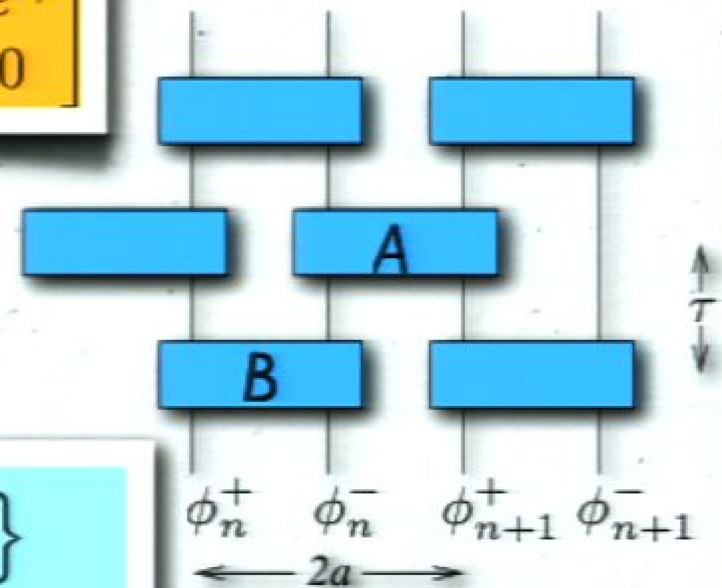

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For both Bose and Fermi fields one has:

$$A = \exp\left\{i\theta\left[\phi_n^{+\dagger}\phi_{n-1}^{-} + \phi_{n-1}^{-}{}^{\dagger}\phi_n^{+}\right]\right\}$$

$$B = \exp\left\{i\tfrac{\pi}{2}\left[\phi_n^{+\dagger}\phi_n^{-} + \phi_n^{-\dagger}\phi_n^{+}\right]\right\}$$

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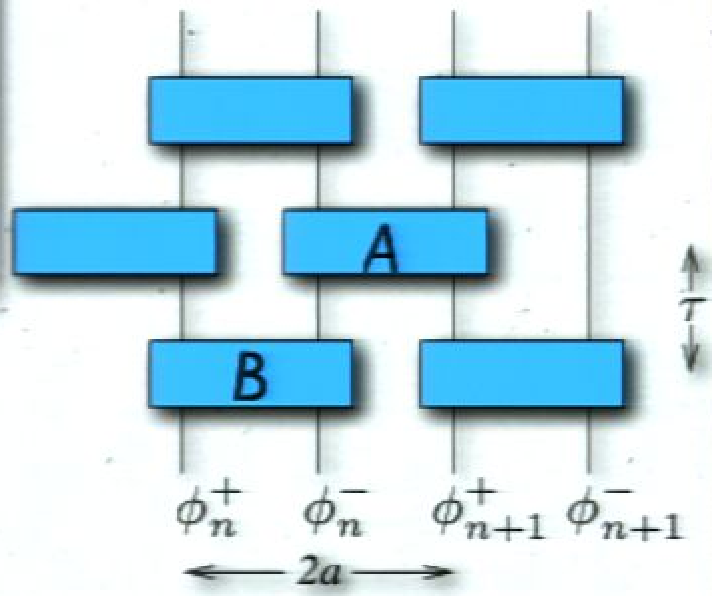

Commuting	Anticommuting
Harmonic oscillator	*Clifford algebra*
$[a_l, a_k^\dagger] = \delta_{lk}$	$\phi_n^+ = \sigma_{2n}^- \prod_{k=-\infty}^{n-1} \sigma_{2k+1}^z \sigma_{2k}^z$
$\phi_n^+ = a_{2n} \quad \phi_n^- = a_{2n+1}$	$\phi_n^- = \sigma_{2n+1}^- \sigma_{2n}^z \prod_{k=-\infty}^{n-1} \sigma_k^z$

A

B

QC SIMULATION OF QFT

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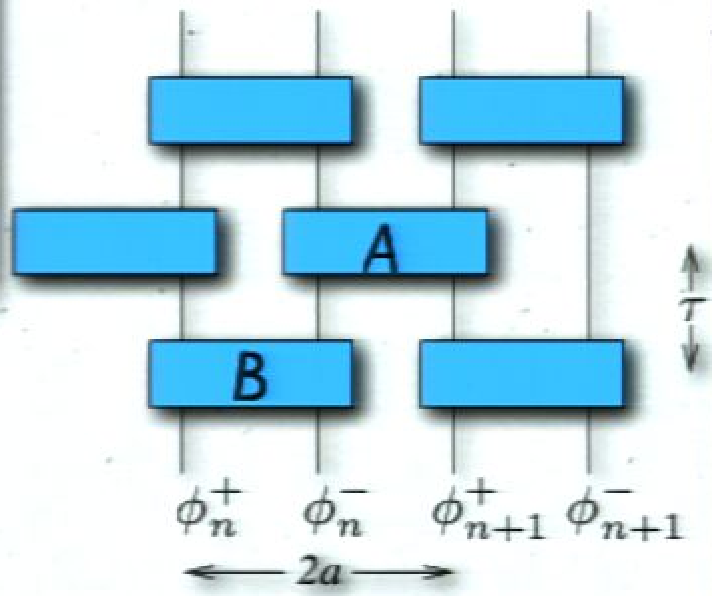

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$$A = \exp\left[-i\theta\left(\sigma_{2n-1}^{-}\sigma_{2n}^{+} + \sigma_{2n-1}^{+}\sigma_{2n}^{-}\right)\right]$$

$$B = \exp\left[-i\tfrac{\pi}{2}\left(\sigma_{2n}^{+}\sigma_{2n+1}^{-} + \sigma_{2n}^{-}\sigma_{2n+1}^{+}\right)\right]$$

Gates act on local algebras only!

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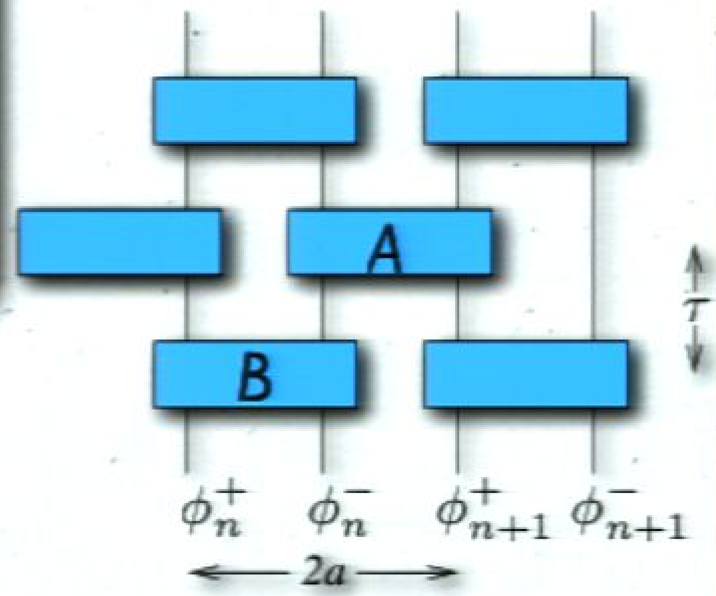

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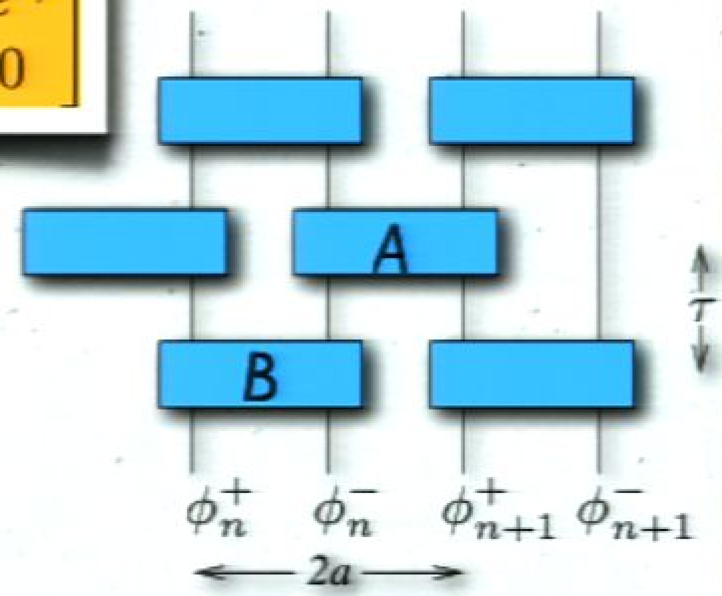
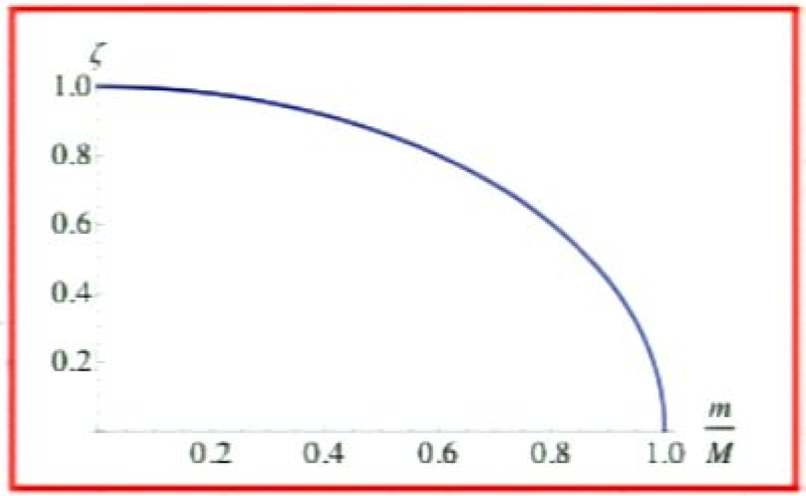


MASS-DEPENDENT REFRACTION INDEX OF VACUUM

General phenomenon due to unitariety

$$\sin\theta = \zeta = \sqrt{1 - \left(\frac{2a}{\lambda}\right)^2}$$



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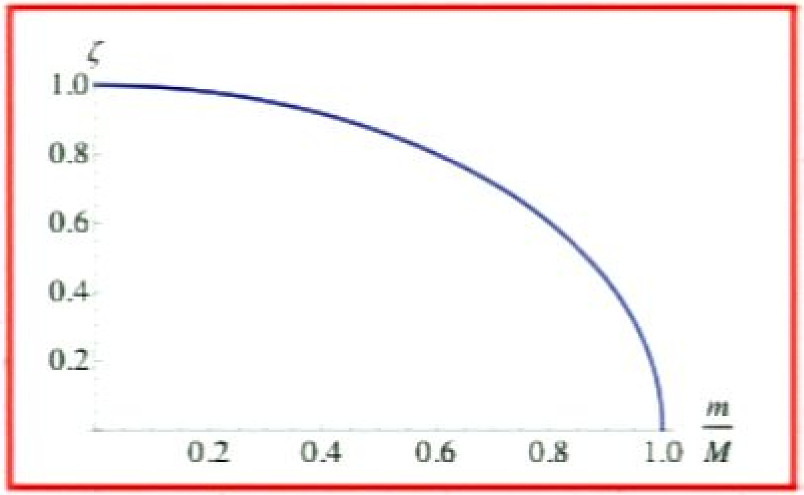

The Hamiltoni

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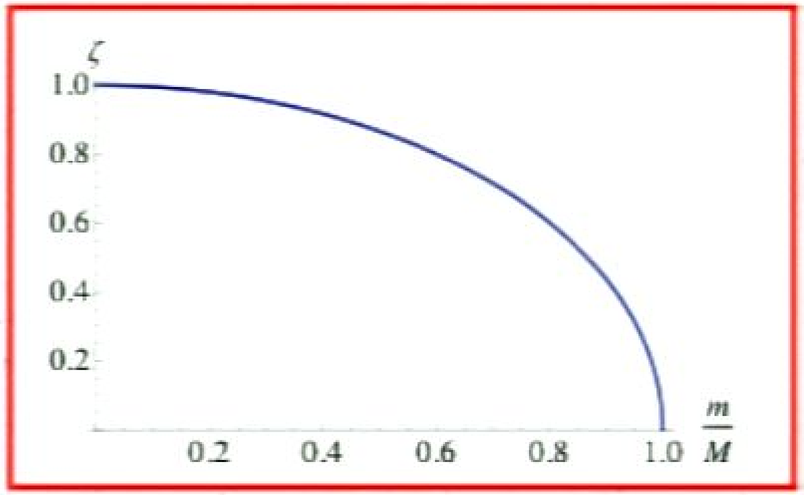

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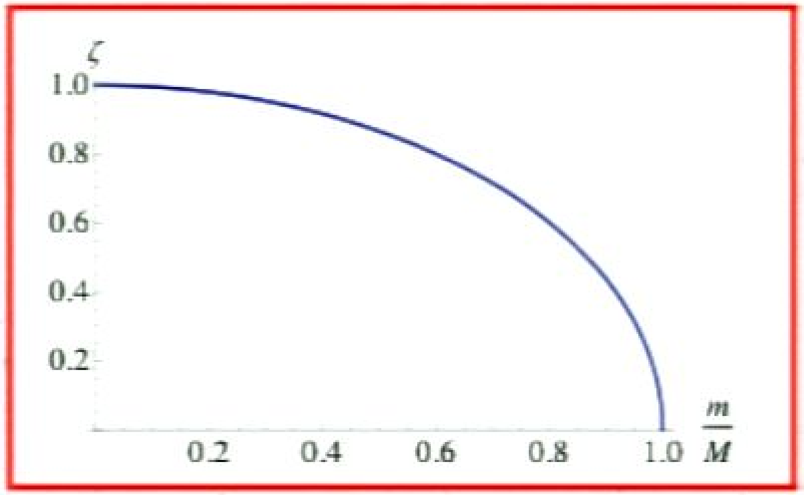
$$\frac{\sqrt{\zeta^2 + 4\tau^2\omega^2}}{2\tau} \leqslant \frac{1}{2\tau}$$

namely for $\omega = c\lambda^{-1}$ one has:

$$\sin\theta = \zeta = \sqrt{1 - \left(\frac{2a}{\lambda}\right)^2}$$

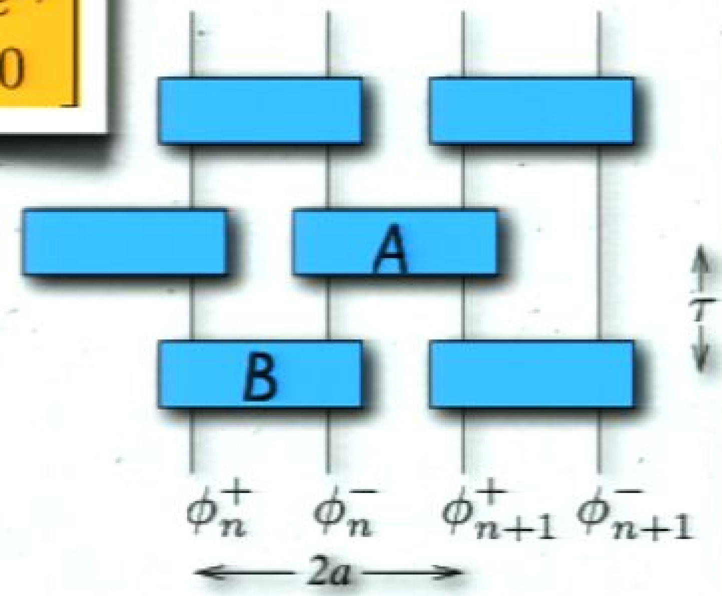


$$\zeta \leqslant \sqrt{1 - \left(\frac{2a}{\lambda}\right)^2}$$

QC SIMULATION OF QFT

SIMPLE SCALAR FIELD IN 1 SPACE DIM.

$$\mathbf{A} = \begin{bmatrix} e^{i\phi}\cos\theta & e^{i\psi}\sin\theta \\ -e^{-i\psi}\sin\theta & e^{-i\phi}\cos\theta \end{bmatrix} \quad \mathbf{B} = \begin{bmatrix} 0 & ie^{i\phi} \\ -ie^{-i\phi} & 0 \end{bmatrix}$$



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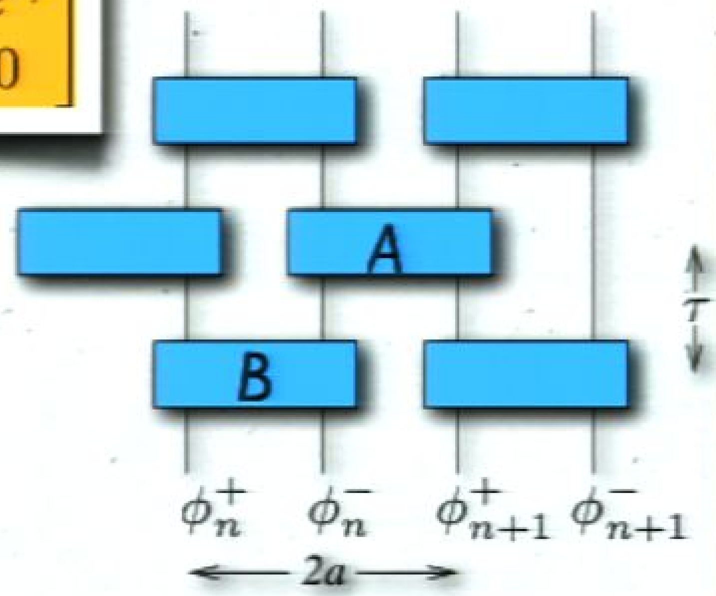

W. l. g. fix $\phi = 0,\ \psi = -\pi/2$

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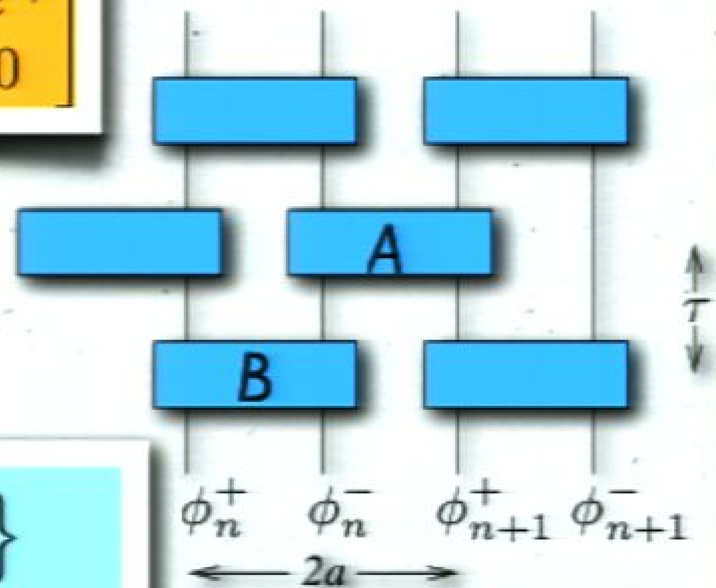

W. l. g. fix $\phi = 0,\ \psi = -\pi/2$

For both Bose and Fermi fields one has:

$$A = \exp\left\{i\theta\left[\phi_n^{+\dagger}\phi_{n-1}^- + \phi_{n-1}^{-\ \dagger}\phi_n^+\right]\right\}$$

$$B = \exp\left\{i\tfrac{\pi}{2}\left[\phi_n^{+\dagger}\phi_n^- + \phi_n^{-\dagger}\phi_n^+\right]\right\}$$

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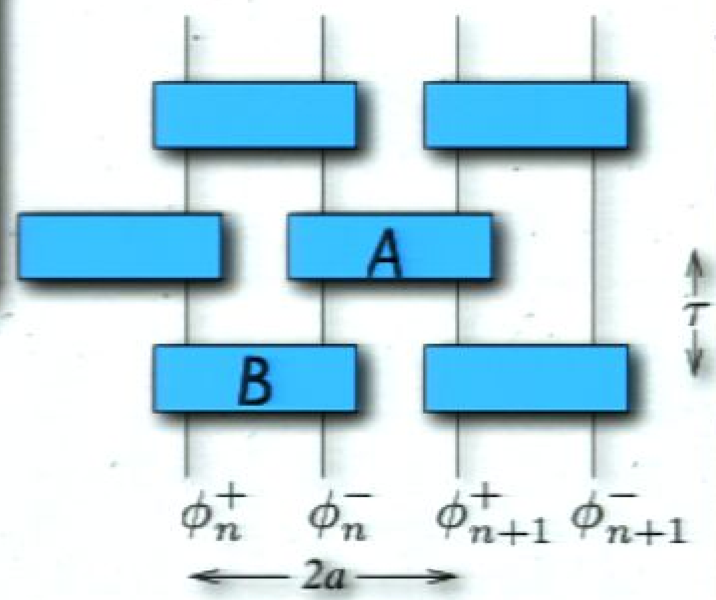

Commuting	Anticommuting
Harmonic oscillator	*Clifford algebra*
$[a_l, a_k^\dagger] = \delta_{lk}$	$\phi_n^+ = \sigma_{2n}^- \prod_{k=-\infty}^{n-1} \sigma_{2k+1}^z \sigma_{2k}^z$
$\phi_n^+ = a_{2n} \quad \phi_n^- = a_{2n+1}$	$\phi_n^- = \sigma_{2n+1}^- \sigma_{2n}^z \prod_{k=-\infty}^{n-1} \sigma_k^z$

QC SIMULATION OF QFT

SIMPLE SCALAR FIELD IN 1 SPACE DIM.

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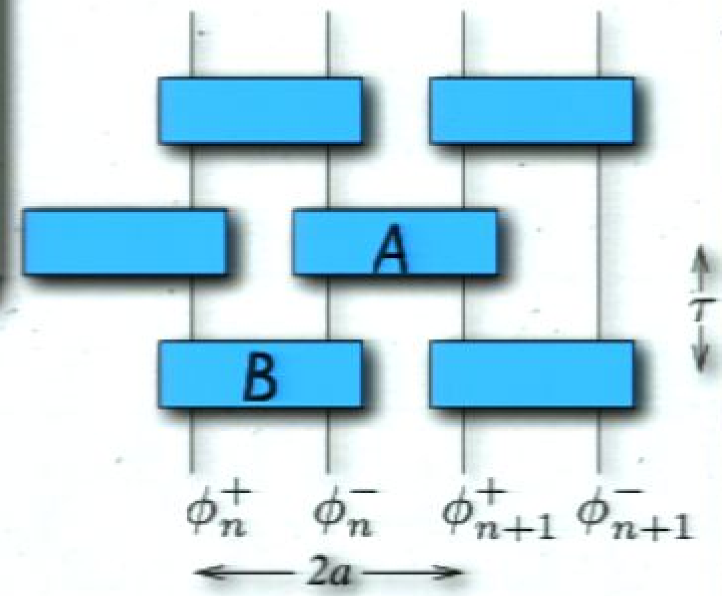

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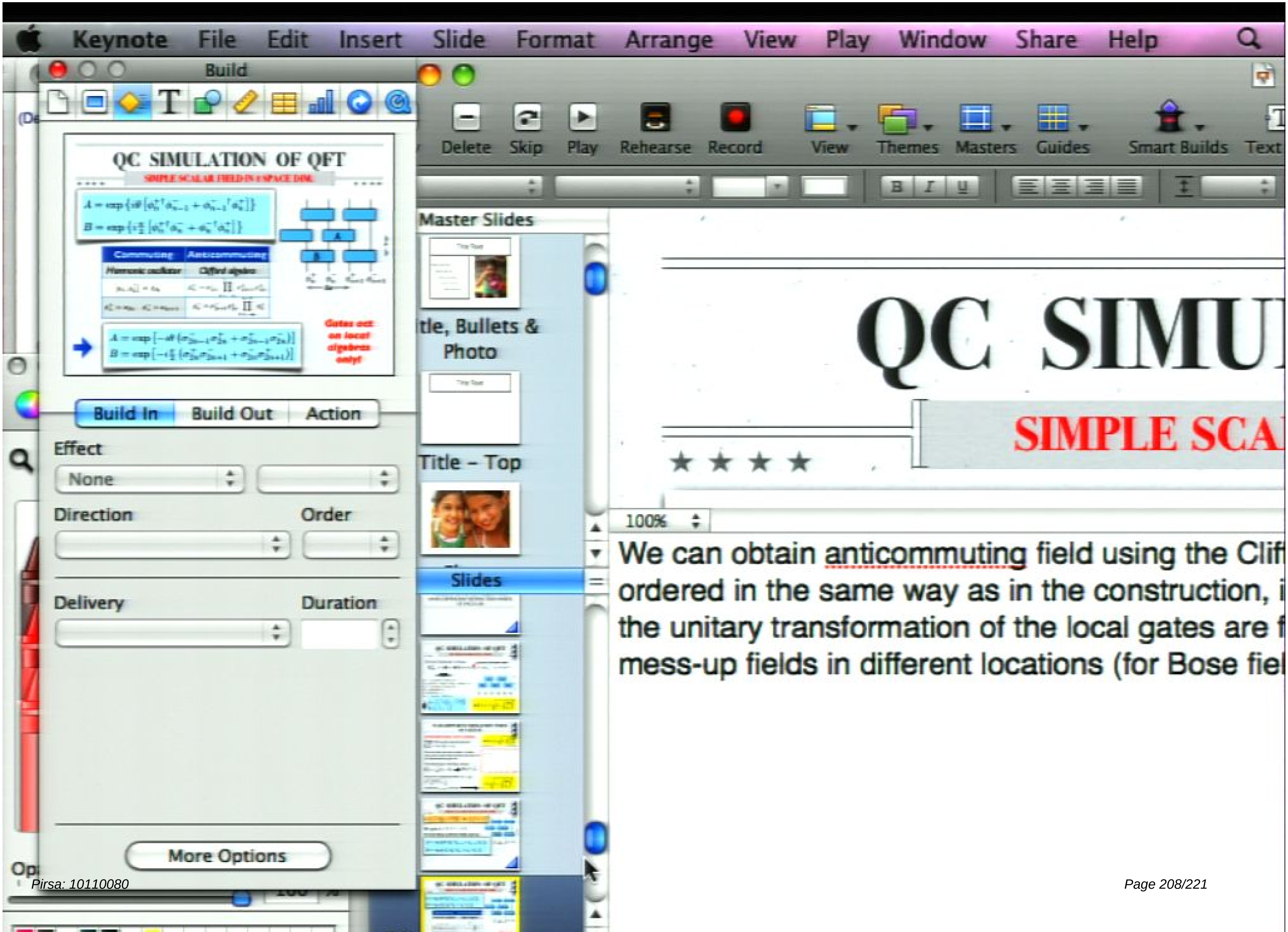
$\phi_n^+ = a_{2n} \quad \phi_n^- = a_{2n+1}$	$\phi_n^- = \sigma_{2n+1}^- \sigma_{2n}^z \prod_{k=-\infty}^{n-1} \sigma_k^z$

$$A = \exp\left[-i\theta\left(\sigma_{2n-1}^-\sigma_{2n}^+ + \sigma_{2n-1}^+\sigma_{2n}^-\right)\right]$$

$$B = \exp\left[-i\tfrac{\pi}{2}\left(\sigma_{2n}^+\sigma_{2n+1}^- + \sigma_{2n}^-\sigma_{2n+1}^+\right)\right]$$

Gates act on local algebras only!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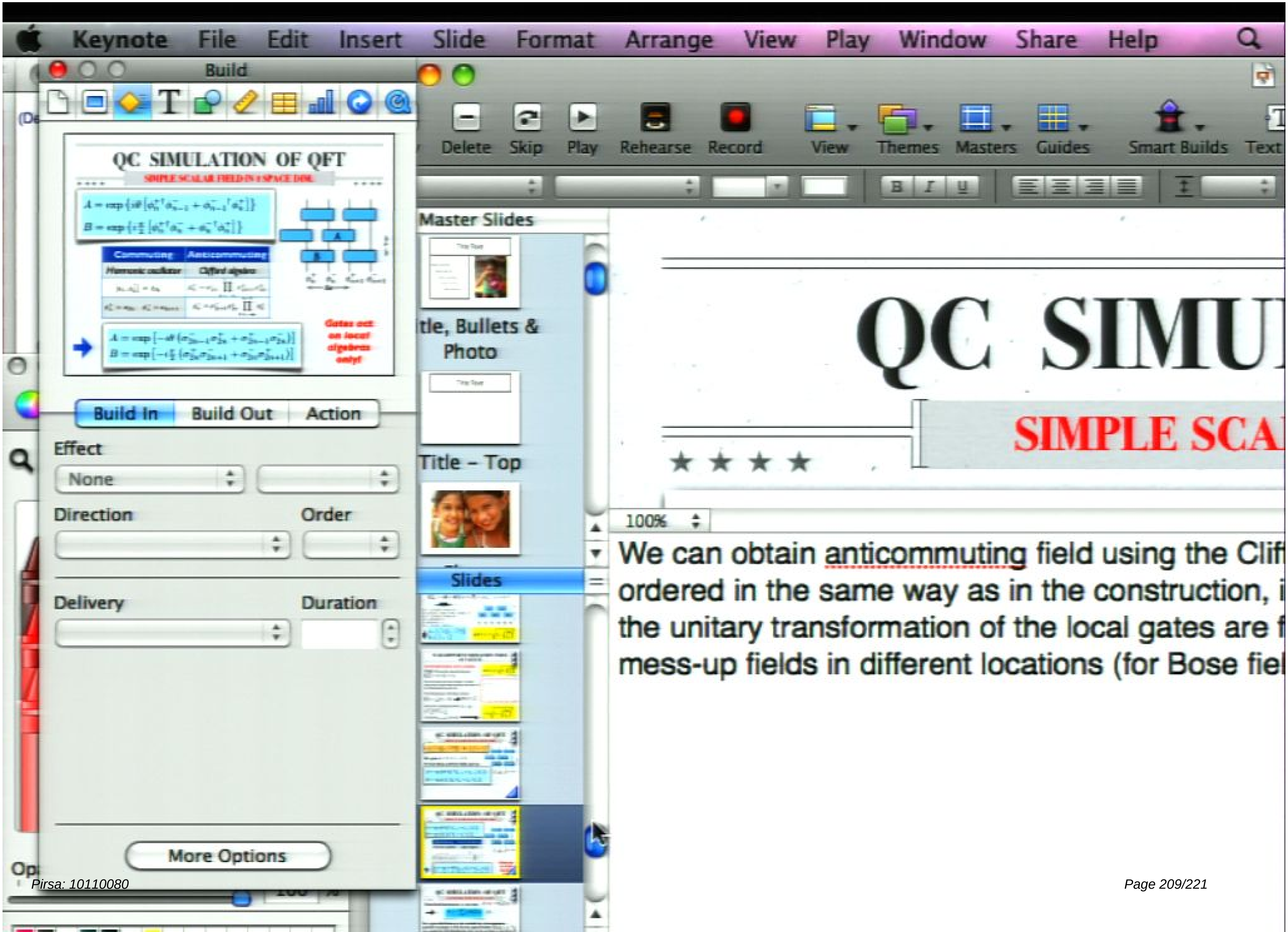
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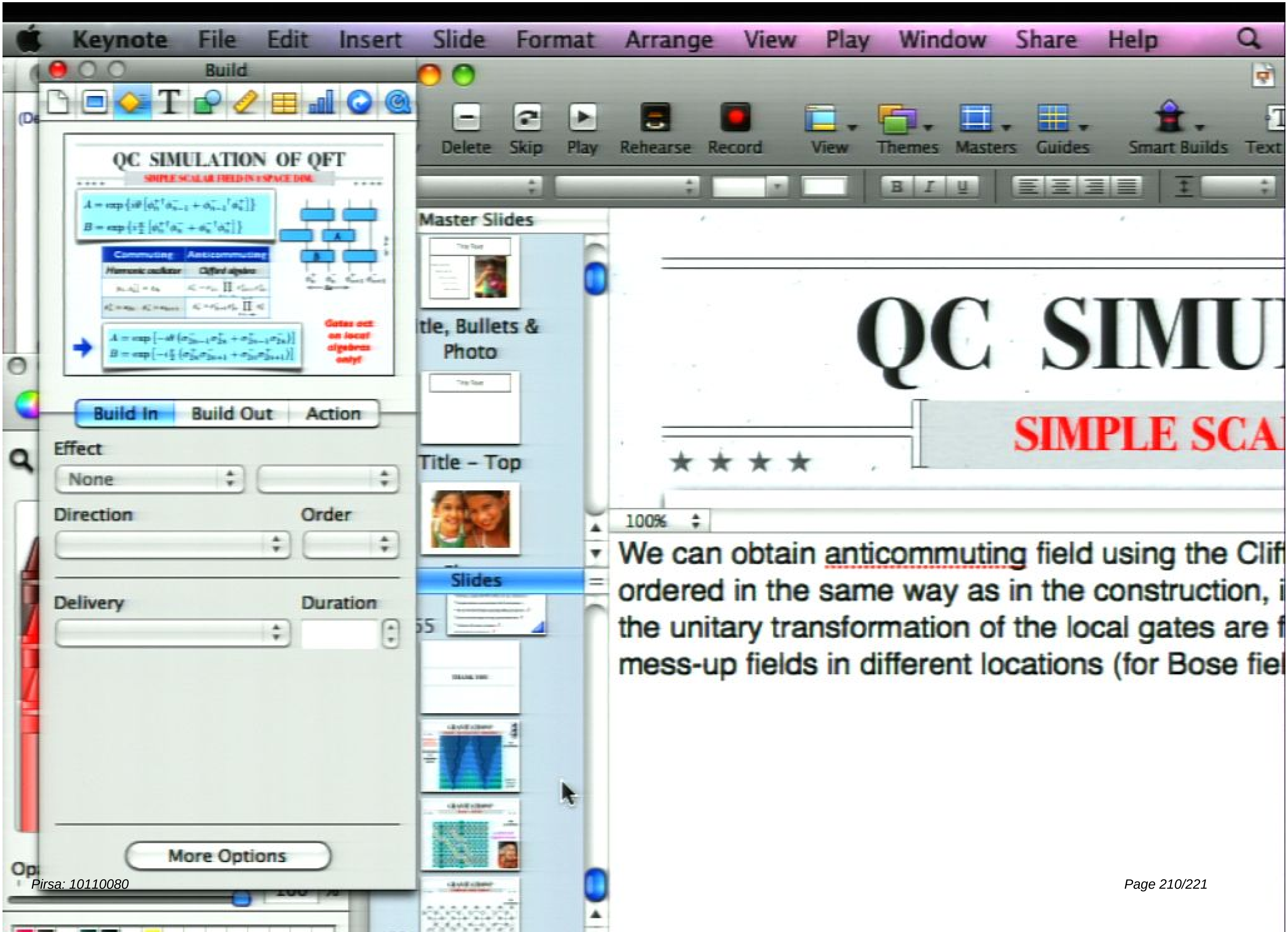
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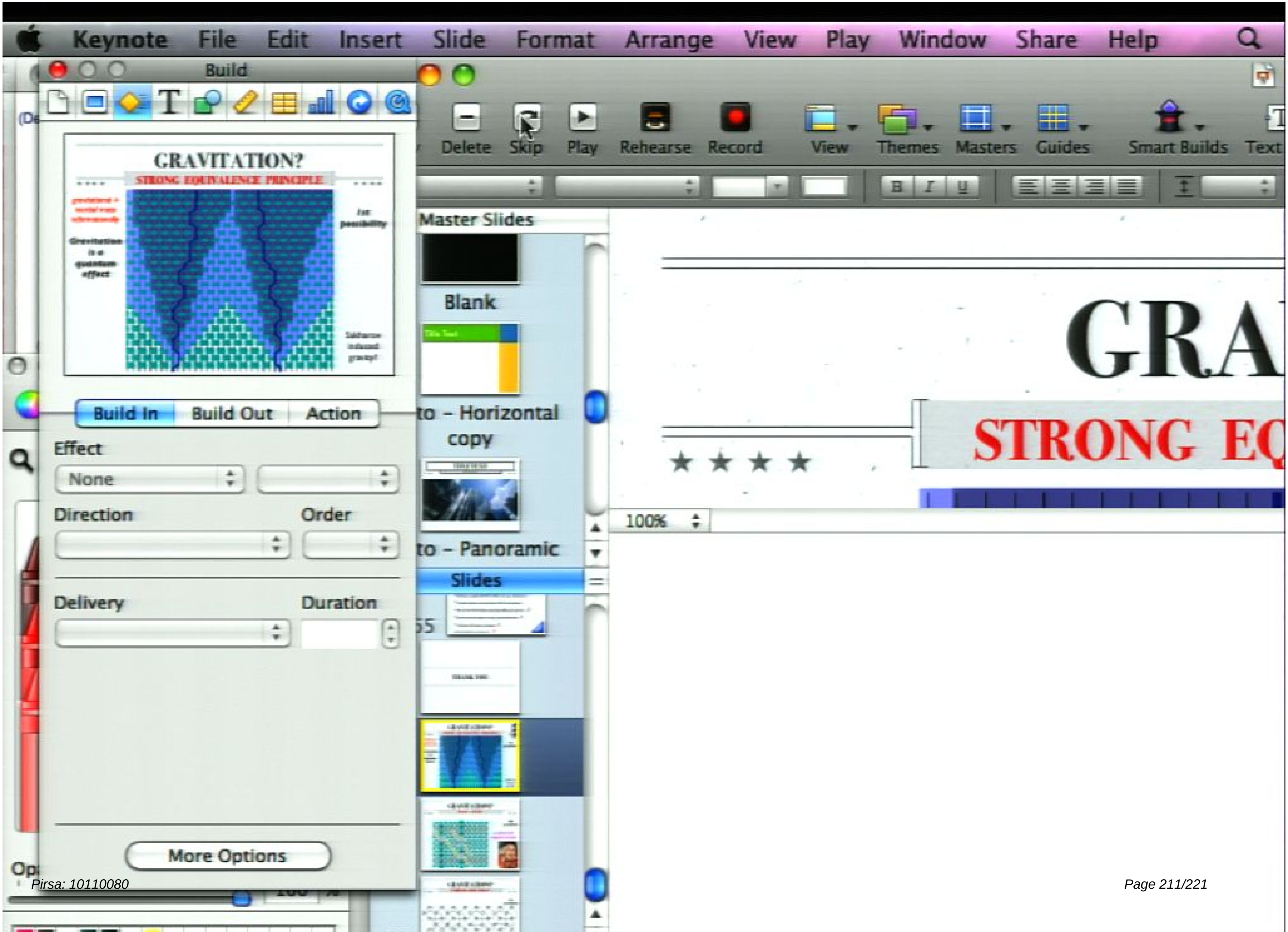
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GRAVITATION?

STRONG EQUIVALENCE PRINCIPLE

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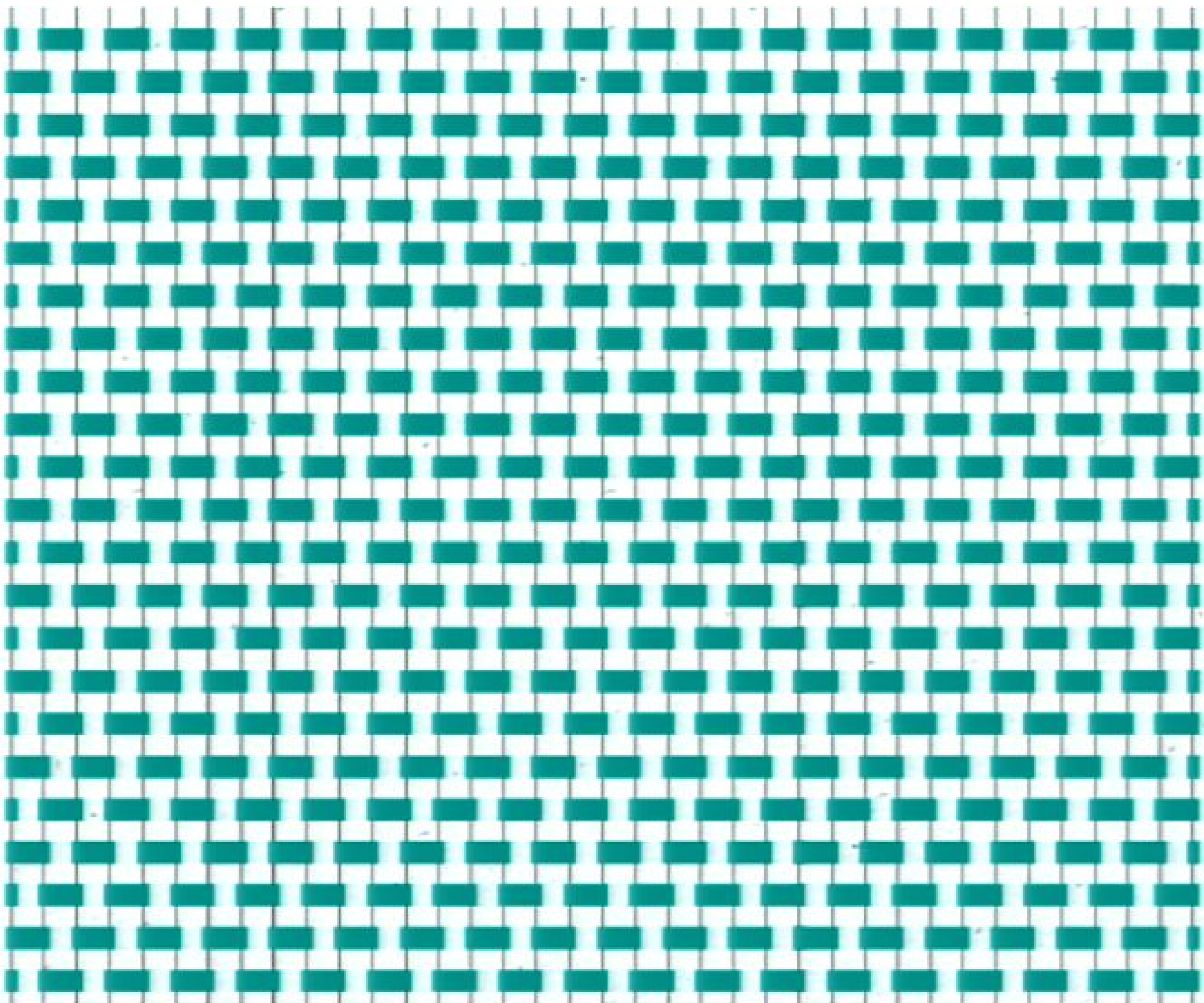
gravitational = inertial mass informationally

Gravitation is a quantum effect



1st possibility

Sakharov induced gravity?

GRAVITATION?

STRONG EQUIVALENCE PRINCIPLE

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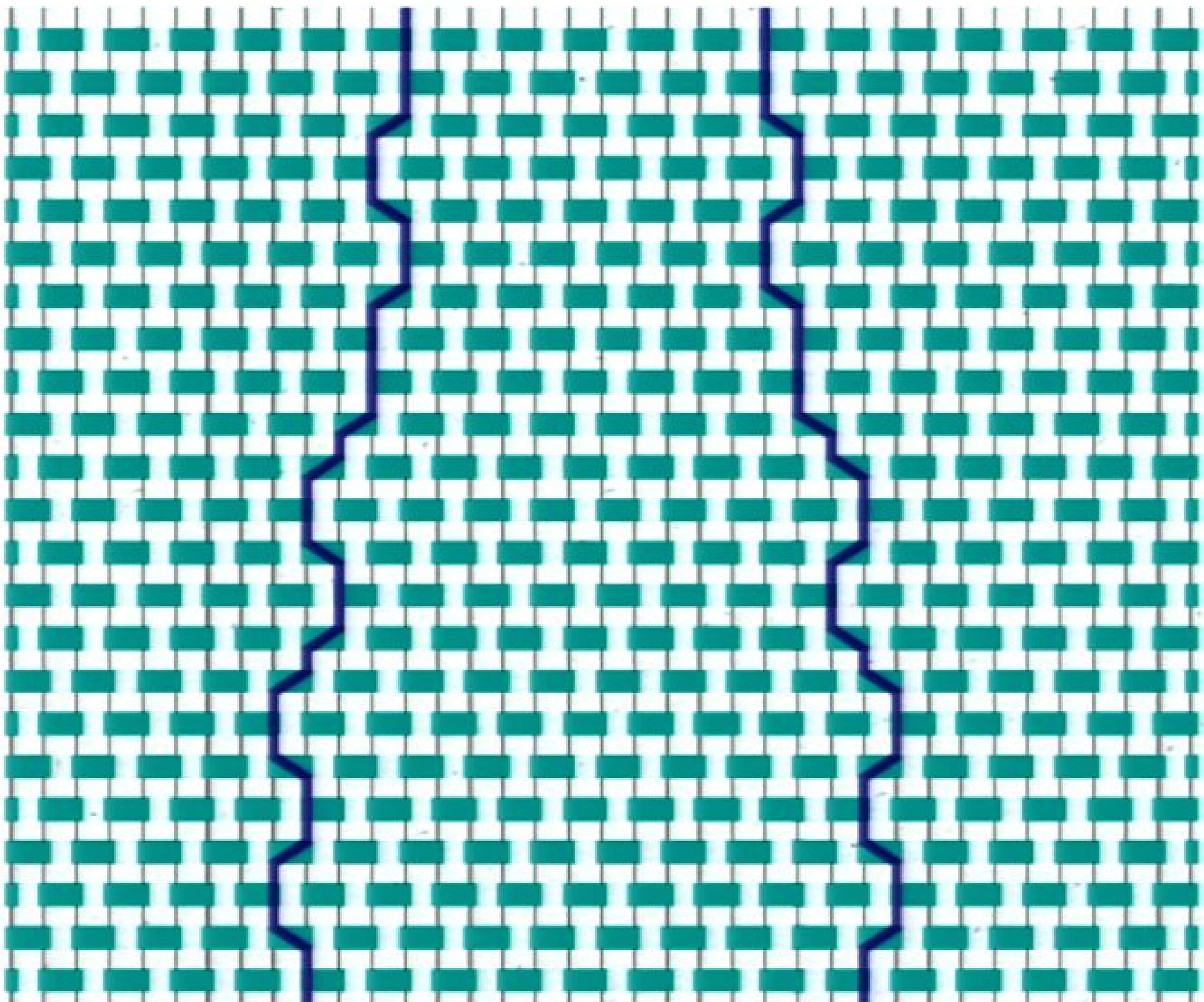

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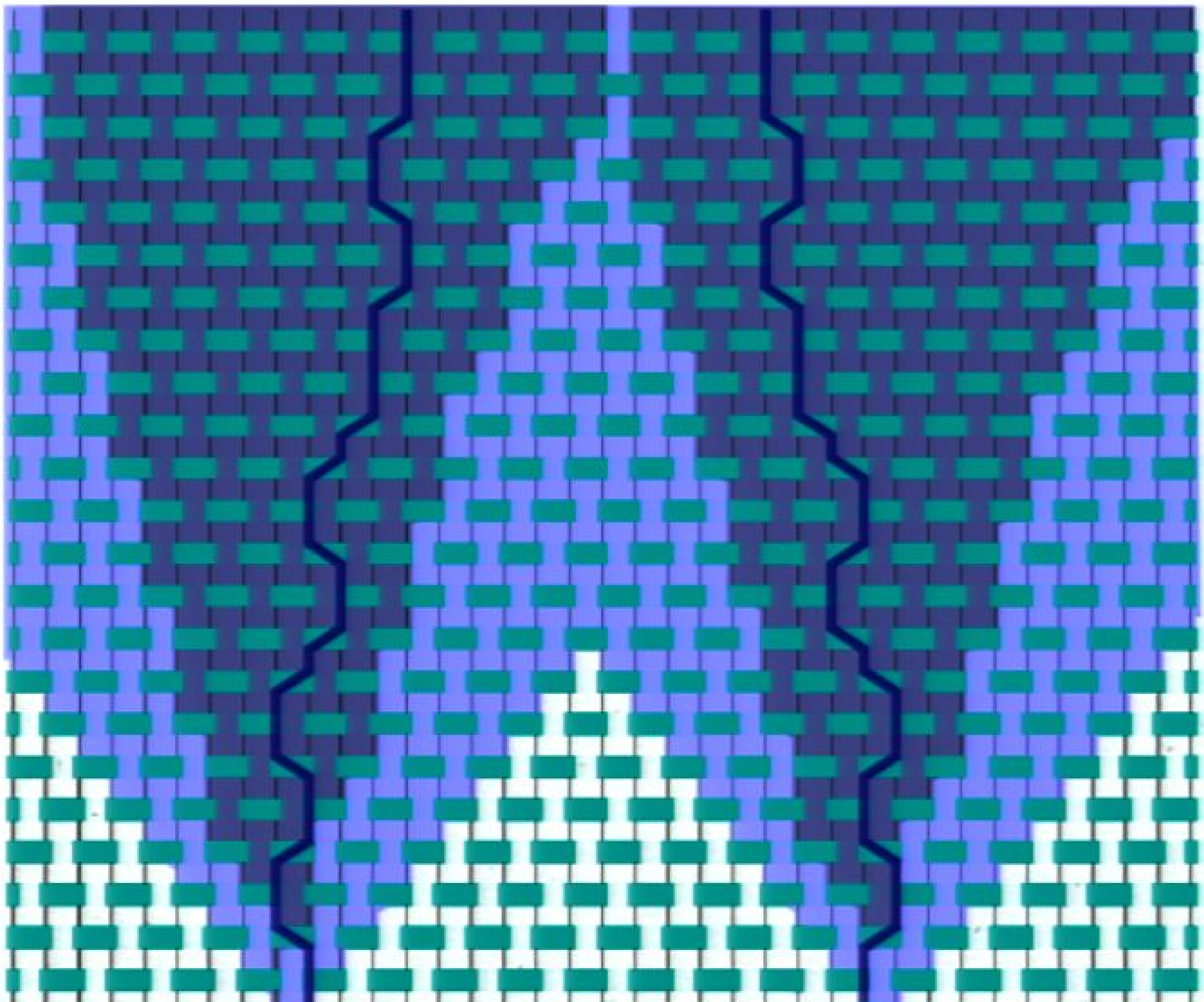
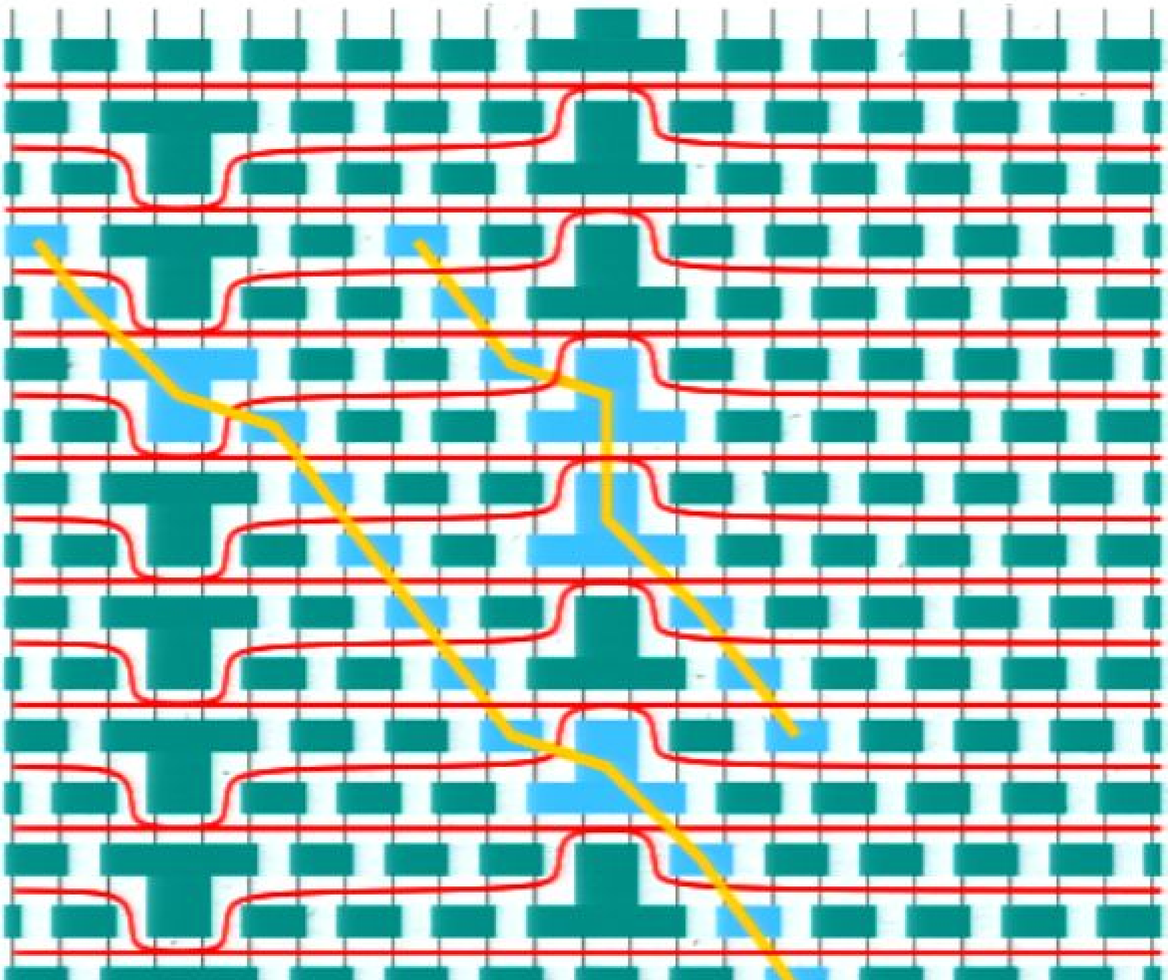


Ist possibility

Sakharov induced gravity?

GRAVITATION?

MASS = EVENT



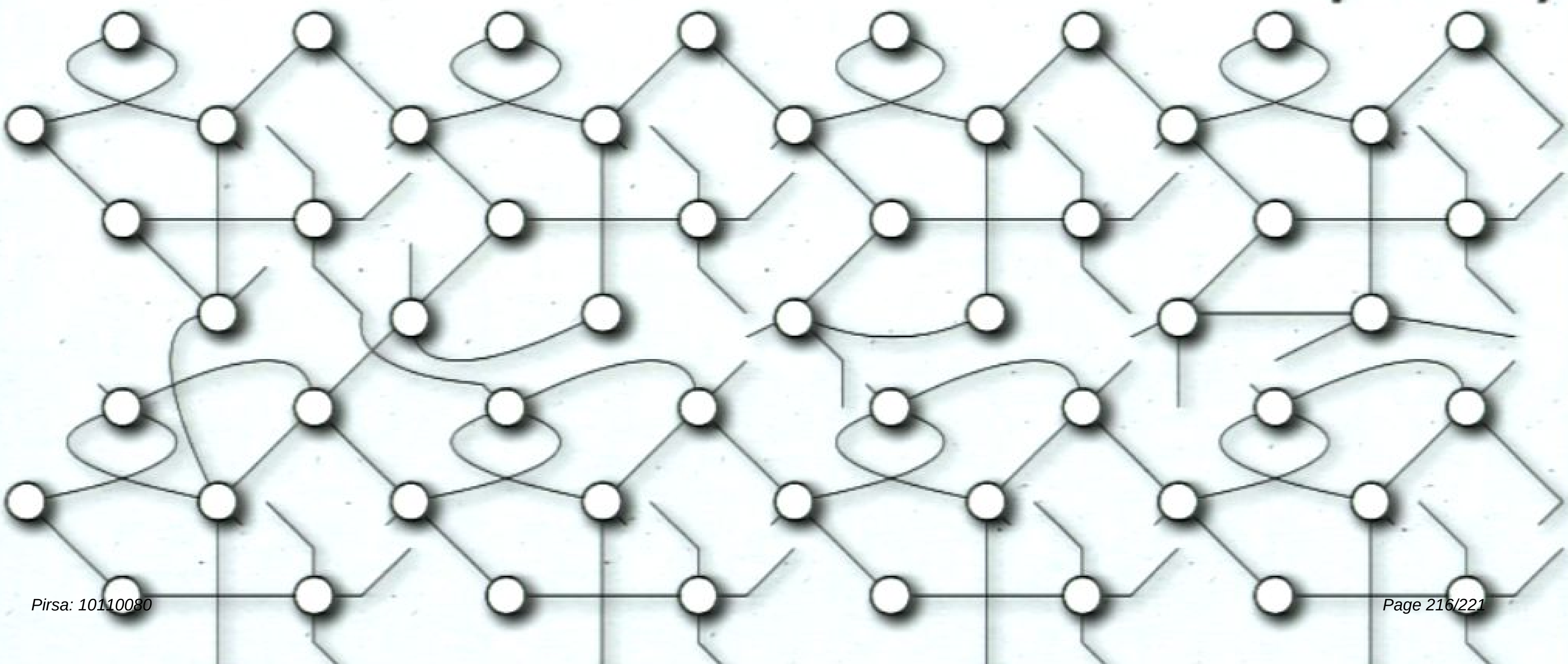
2nd possibility

positive and negative masses

GRAVITATION?

THIRD QUANTIZATION?

3rd possibility



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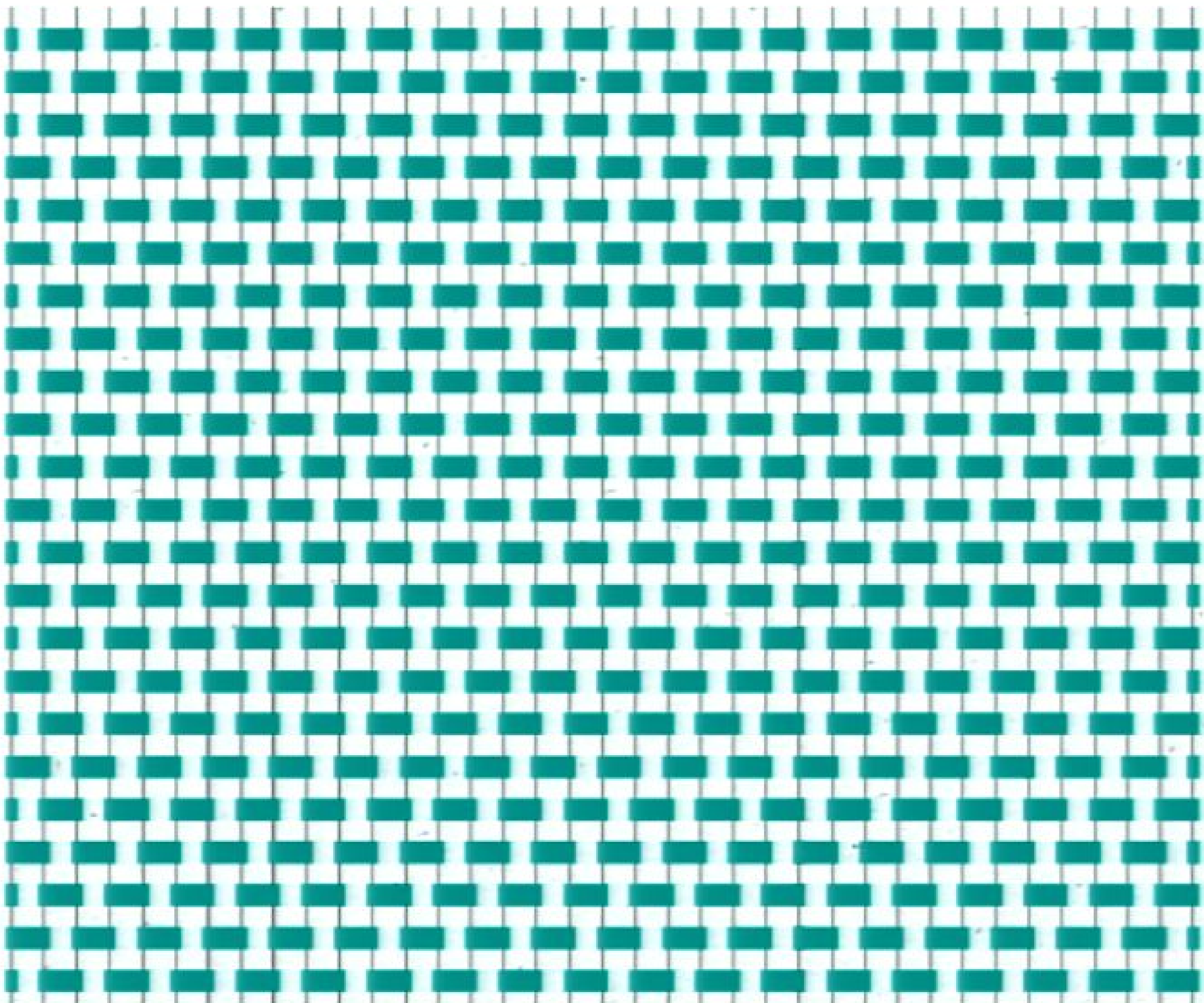

1st possibility

Sakharov induced gravity?

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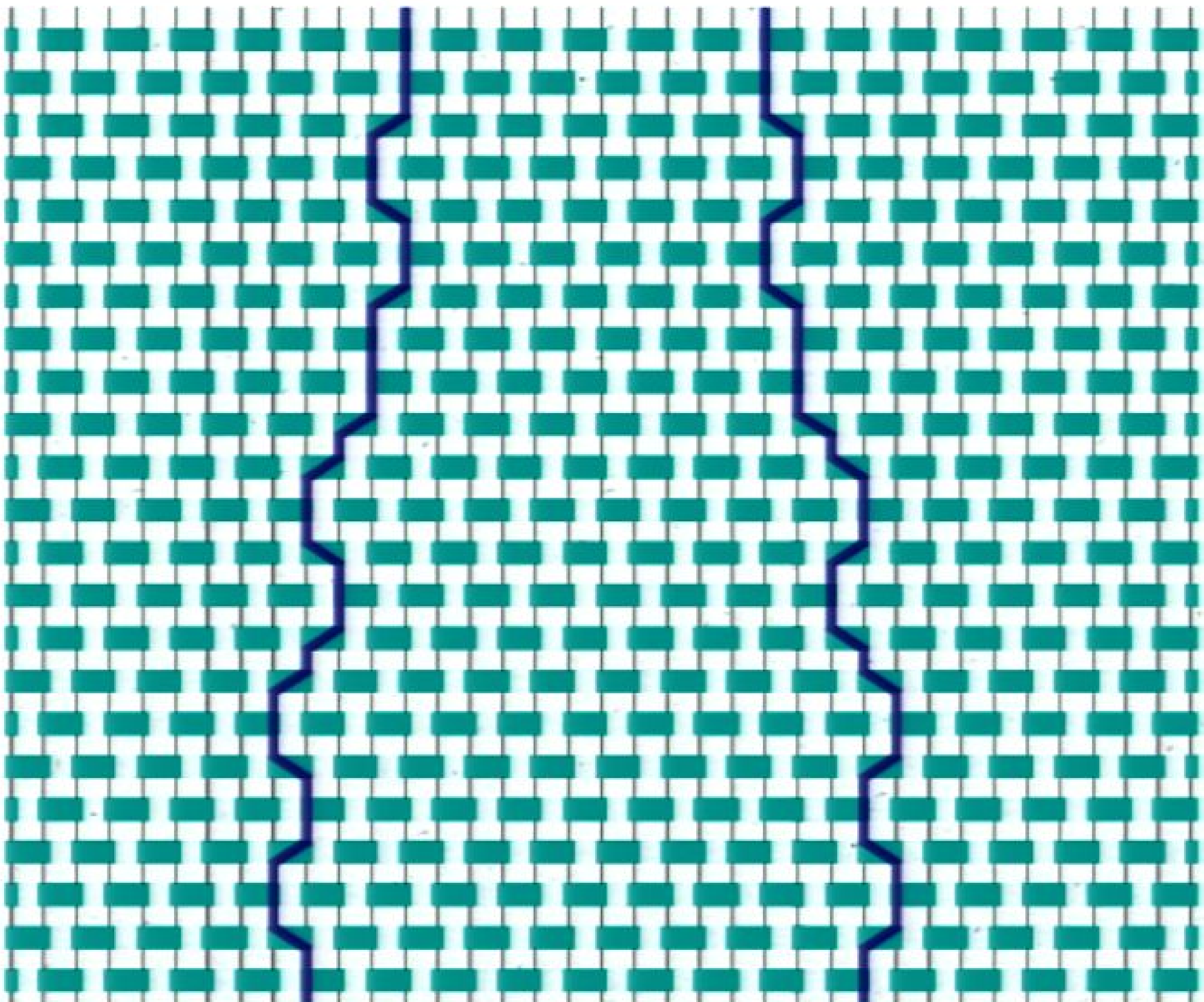

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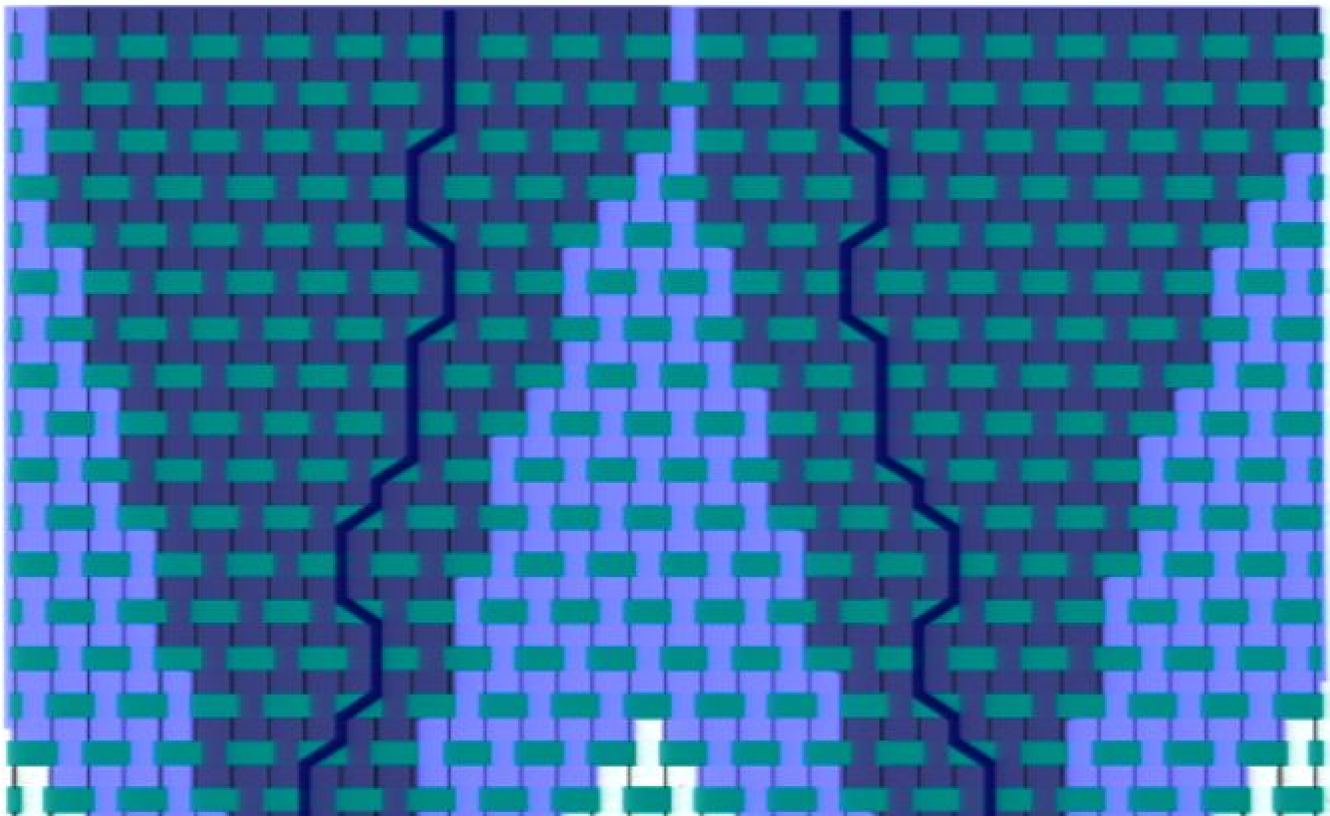

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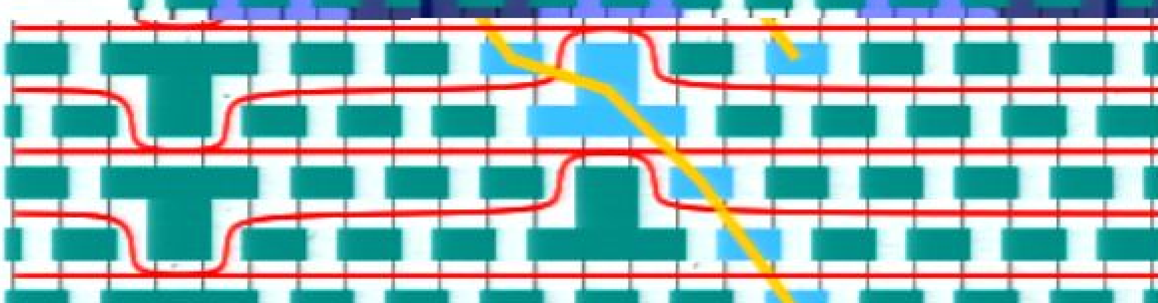

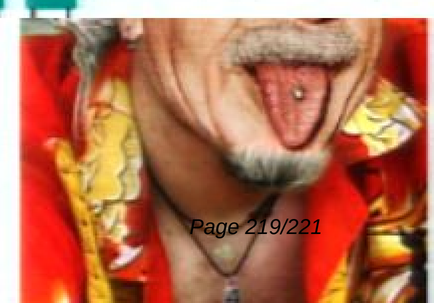

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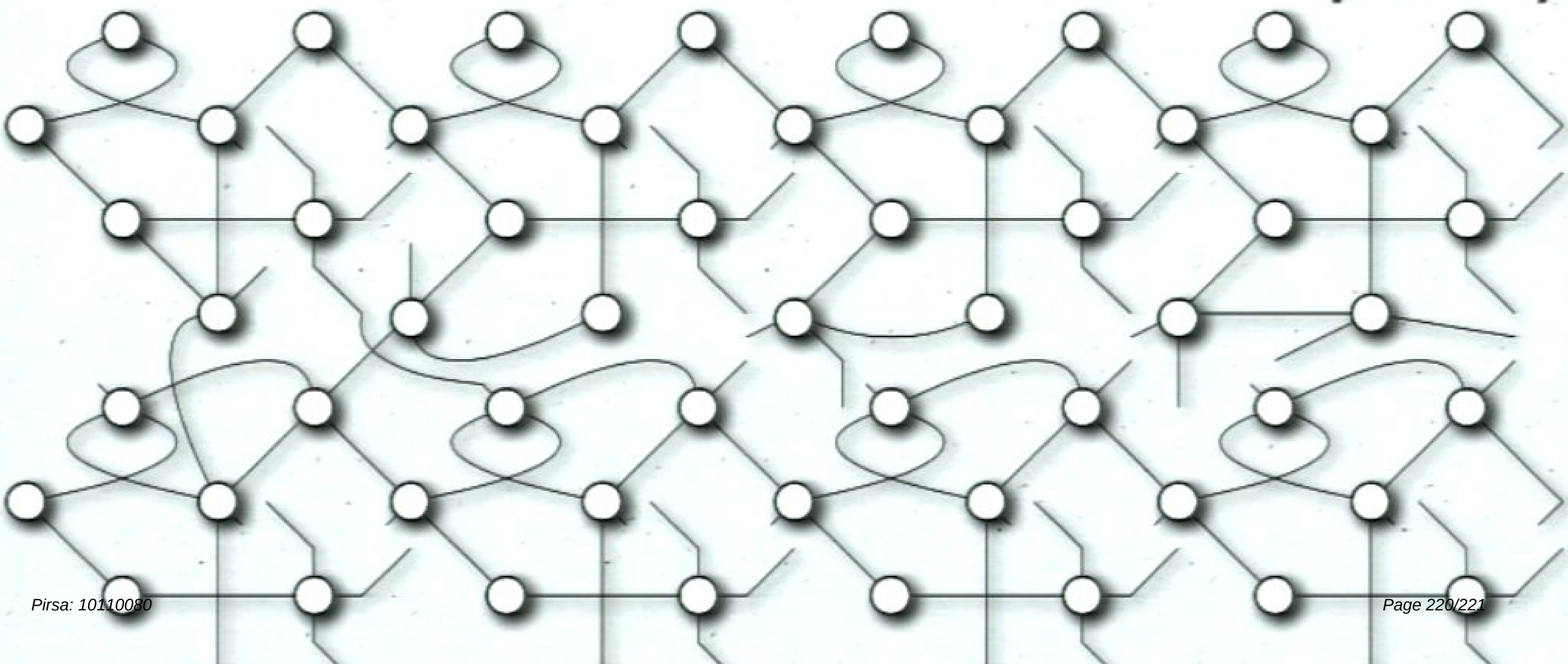

GRAVITATION?

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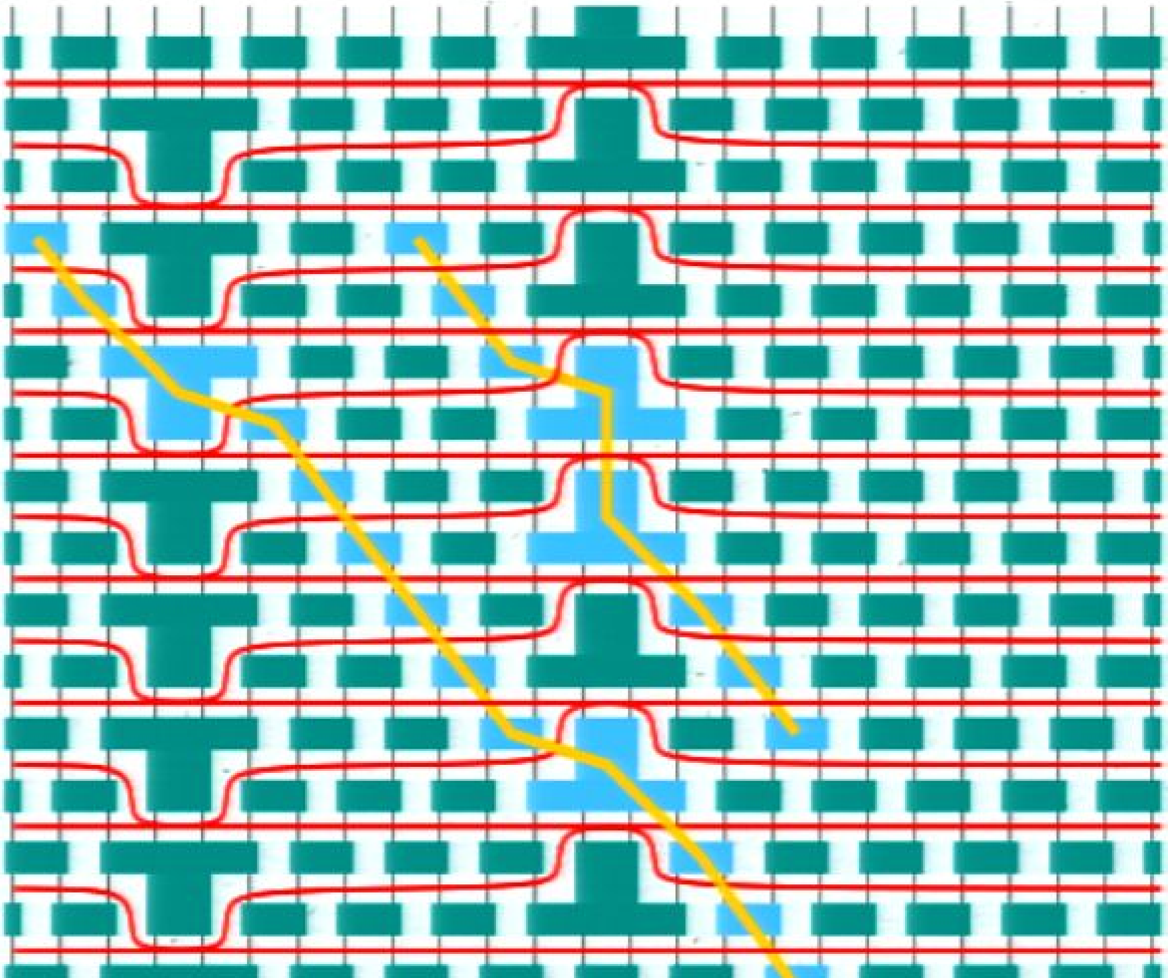

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