SPECIAL RELATIVITY FROM QUANTUM THEORY SIMULATION OF QUANTUM FIELDS BY A QUANTUM COMPUTER AS A NEW TYPE OF QFT

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The principle of the *Quantumness*

Paolo Perinotti

Giulio Chiribella
(currently at PI)

The principle of the *Quantumness*

INFORMATIONAL

- Causality
- Local discriminability
- Conservation of information
- Atomicity of the Evolution
- Discriminability of Non-Internal States
- Efficient Lossless Information Encoding

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The principle of the *Quantumness*

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- Causality — Phys. Rev. A **81** 062348 (2010)
- Local discriminability
- Conservation of information

- Atomicity of the Evolution — In preparation
- Discriminability of Non-Internal States
- Efficient Lossless Information Encoding

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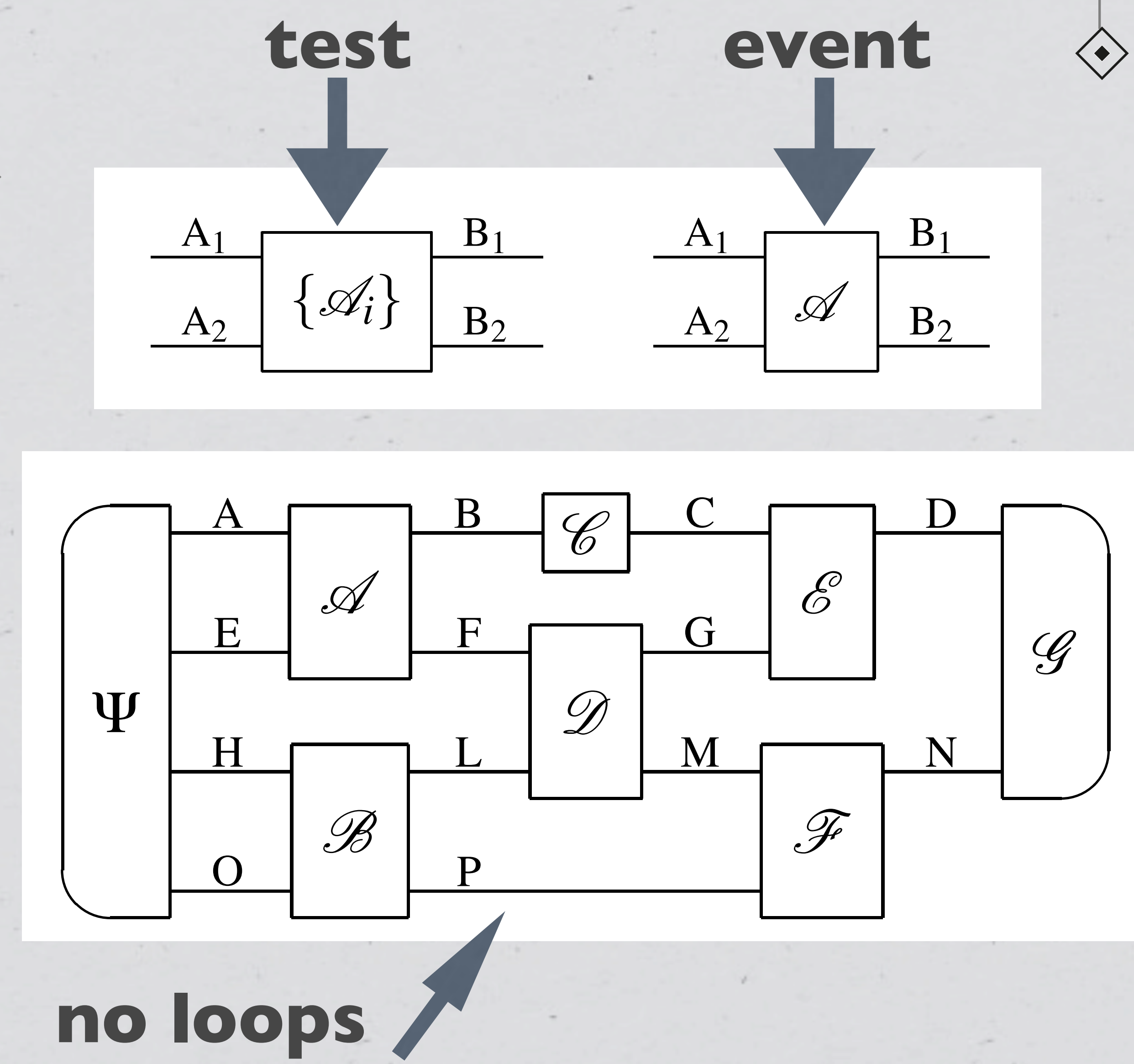
Operational framework



DAG (directed acyclic graph)

- **Probabilistic operational theory:** every test from the trivial system to the trivial system is associated to a probability distribution of outcomes.

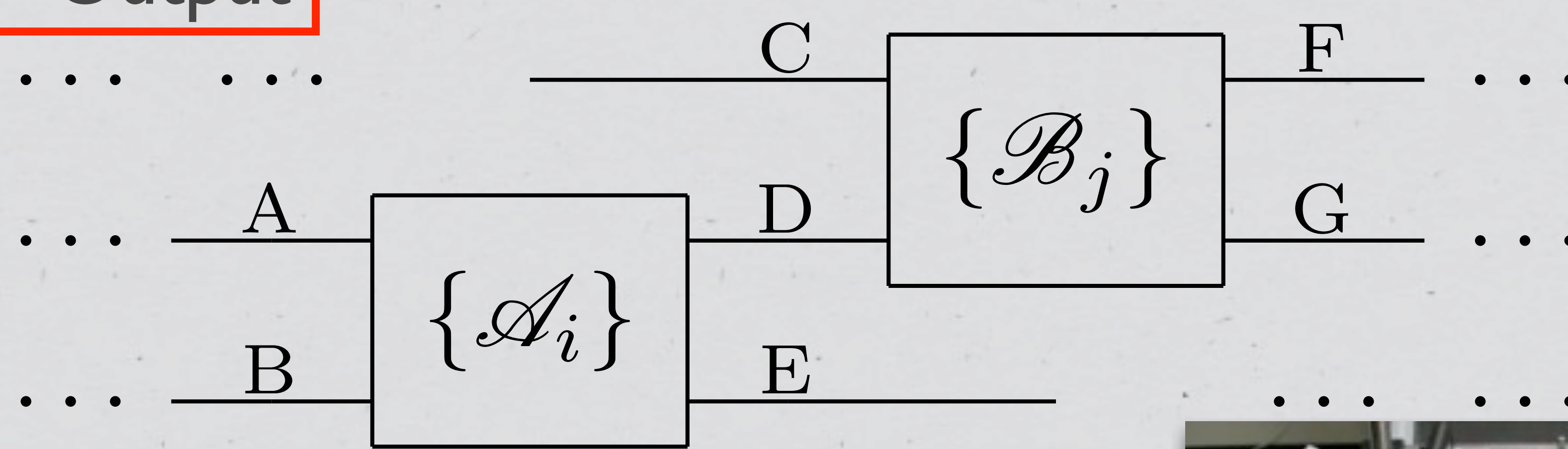
D'Ariano in *Philosophy of Quantum Information and Entanglement*, A. Bokulich and G. Jaeger (CUP, Cambridge UK, 2010)

Chiribella, D'Ariano, and Perinotti, Phys. Rev. A **81** 062348 (2010)

Causal probabilistic theories

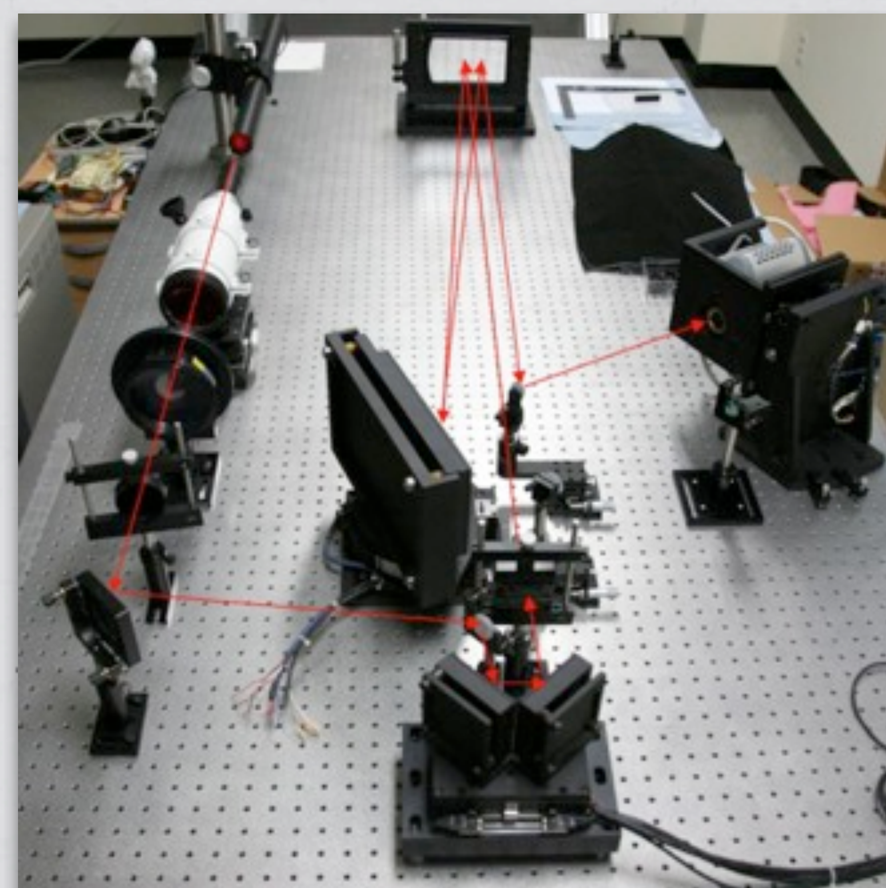
Input → Output

DAG



A theory is *causal* if for any two tests that are input-output connected the marginal probability of the input event is independent on the choice of the output test.

G. M. D'Ariano in *Philosophy of Quantum Information and Entanglement*, A. Bokulich and G. Jaeger (CUP, Cambridge UK, 2010).



SKIP

THE PRINCIPLE OF THE QUANTUMNESS

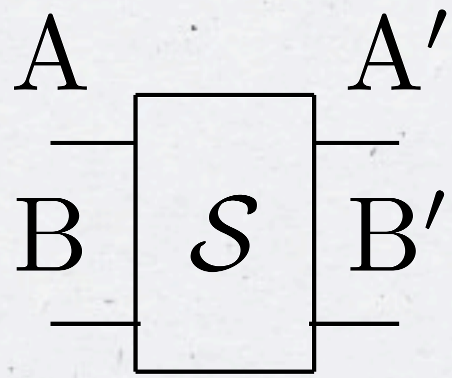
WHAT IS INFORMATION PROCESSING?

- A **computer** processes the **input** information to produce the **output** one.

- Software provides the rules for processing information written in **subroutines**, each one with its own input and output.

- The same **information processing** can be achieved by different subroutines, in the sense that the same input-output relation is achieved by different codes.

We will represent a processing in form of a box with wires as follows:

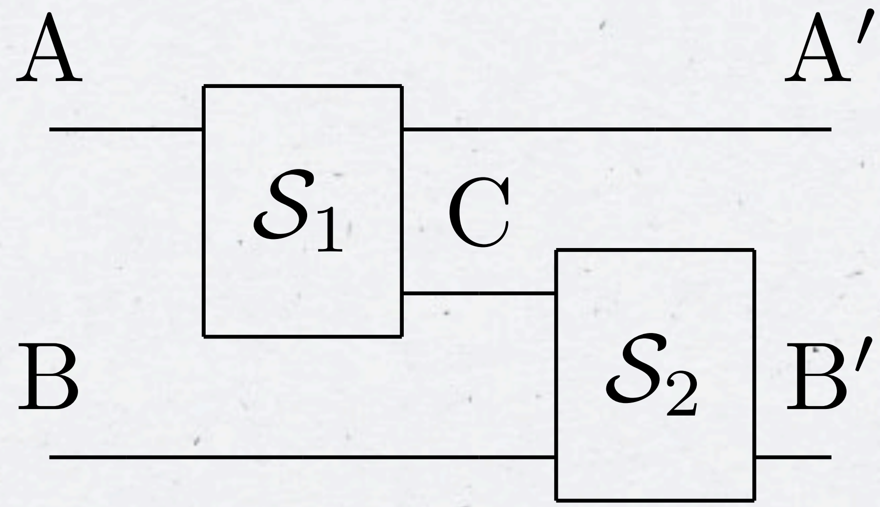


the left/right wires represent the kind of registers on which the input/output of the processing are read/written, respectively (different letters denote generally different types of register).

THE PRINCIPLE OF THE QUANTUMNESS

★ ★ ★ ★ WHAT IS INFORMATION PROCESSING? ★ ★ ★ ★

We can **compose processings** connecting input with outputs of the same type as follows:



If we send the output to the input of a previously called processing **we will not draw a loop**, but instead we will redraw the same box twice, whence **a box precisely represents a single call of the processing**, and **the whole circuit will represent the entire run**, not a flow diagram.

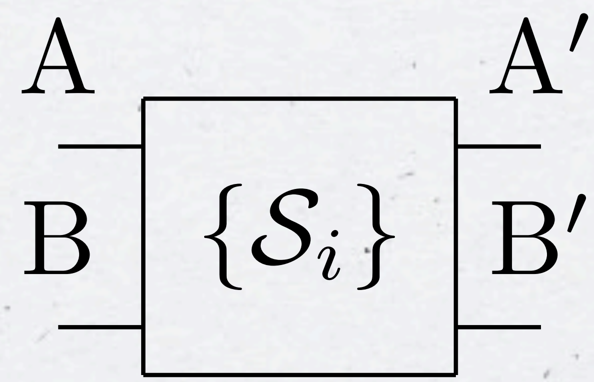
THE PRINCIPLE OF THE QUANTUMNESS

WHAT IS INFORMATION PROCESSING?

★ ★ ★ ★ ★ ★ ★ ★

A **subroutine can generally be divided into alternative subroutines**

For example, in evaluating the factorial we can consider the two alternatives---`n=0` and `n>0`---and use the subroutine "`return 1`" for `n=0` or the subroutine "`return n*f(n-1)`" for `n>0`. The subroutine for evaluating `f(n)` is then the collection of the two alternative subroutines---and the same can be said for their respective processings `f(0)` and `f(n>0)`. We will represent the set of alternative processings as a single box as follows



where $\mathcal{S}_i$ for different *i* represent alternative processings. We will call the processing `f(n)` the **coarse graining** of the two processings `f(0)` and `f(n>0)`. We will name the set of all possible constituents of a processing its **refinement set**, and call a processing with trivial refinement set **indivisible**.

THE PRINCIPLE OF THE QUANTUMNESS

WHAT IS INFORMATION PROCESSING?

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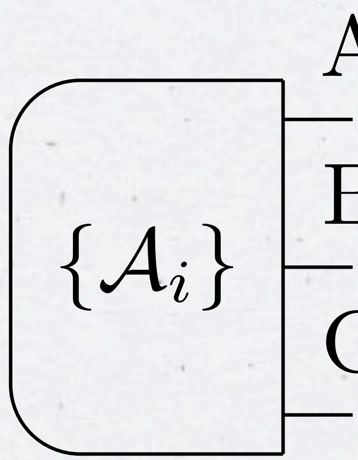
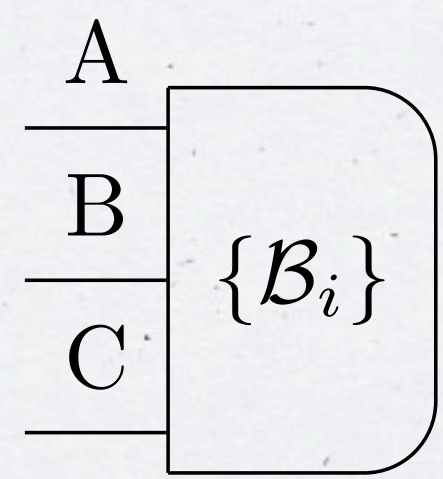
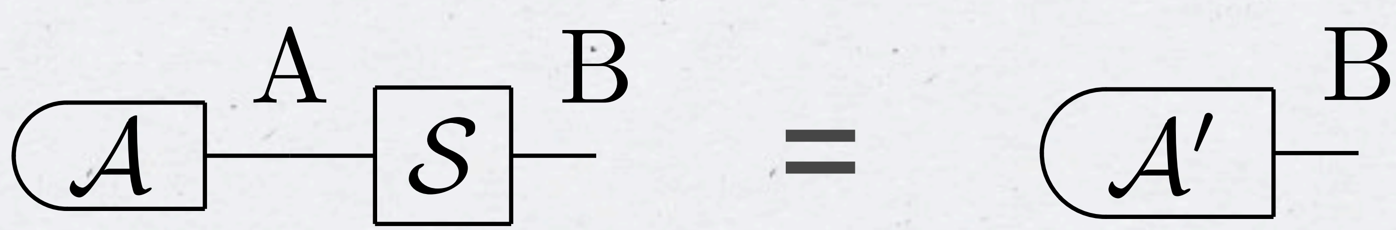
The data-input and data-output are themselves information processings---the **initialization** and **readout**, respectively. They will be represented as follows





Notice that **also an initialization can be divisible**, and this will correspond to a random choice of different initializations.

An initialization followed by a processing can be itself regarded as a new initialization



THE PRINCIPLE OF THE QUANTUMNESS

WHAT IS INFORMATION PROCESSING?

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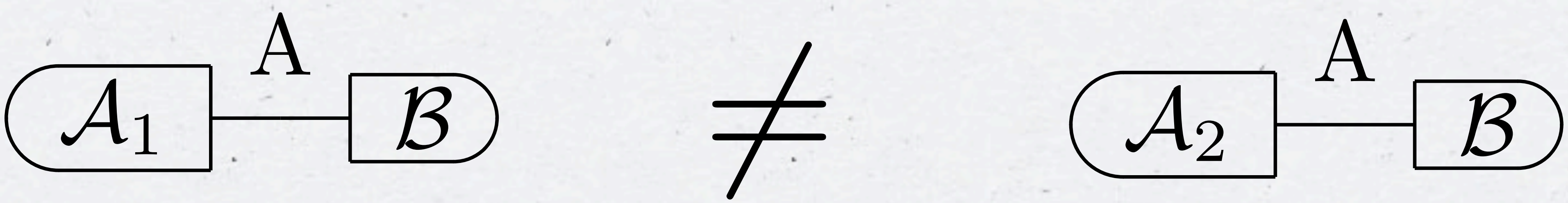
The **domain** of a processing is the set of its possible initializations, its **range** the set of its possible readouts.

An initialization is **specific** when its refinement set is not the whole set of initializations.

Two initializations $\mathcal{A}_1$ and $\mathcal{A}_2$ are **discriminable** when:



and the discrimination is **perfect** when $\mathcal{B}$ always occurs for $\mathcal{A}_1$ and never occurs for $\mathcal{A}_2$

THE PRINCIPLE OF THE QUANTUMNESS

POSTULATES

★ ★ ★ ★ ★ ★ ★ ★

P1. ***Causality:*** The occurrence of a component processing cannot depend on the choice of the processing of its output (i. e. information flows only from input to output).

P2. ***Local Readability:*** We can discriminate two initializations of multiple registers by readouts on single registers.

P3. ***Reversibility and Indivisibility of Computation:*** Every information processing can be achieved with a reversible one by adding a register in an indivisible initialization.

P4. ***Indivisibility of Processing Composition:*** The processing corresponding to the input-output sequence of two indivisible processings is itself indivisible.

P5. ***Discriminability of Specific Initializations:*** For any specific initialization there exists another initialization that can be perfectly discriminated from it.

P6. ***Lossless Compressibility:*** For any initialization there exists an encoding which is perfectly decodeable on its refinement set, and the encoded initialization is not specific.

SKIP

THE PRINCIPLE OF THE QUANTUMNESS

POSTULATES

P1. ***Causality:*** The occurrence of a component processing cannot depend on the choice of the processing of its output (information flows only from input to output).

P1 seems so obvious that has been systematically overlooked in the literature (e.g. Hardy), whereas in fact one can construct explicitly an information-processing theory which violates P1. It allows to "normalize" quantum states by multiplication by a constant. Relaxing postulate P1 may provide a natural framework for a theory of quantum gravity.

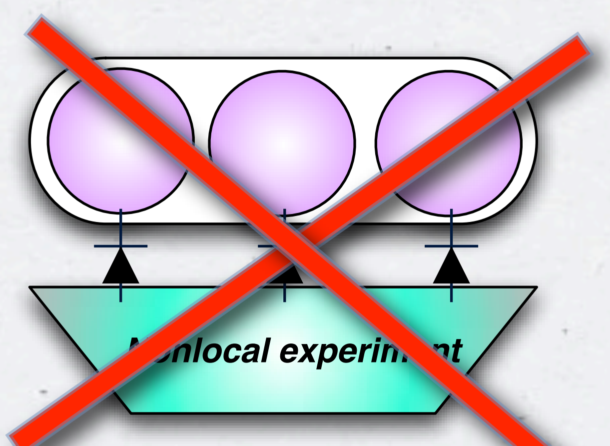
THE PRINCIPLE OF THE QUANTUMNESS

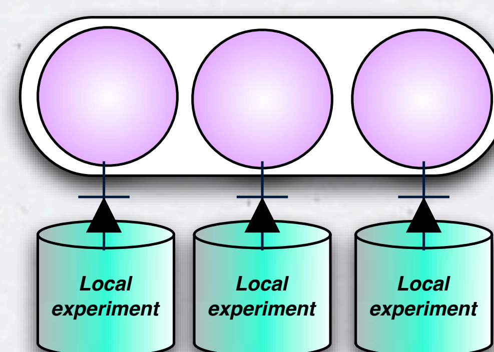
POSTULATES

P2. ***Local Readability:*** We can discriminate two initializations of multiple registers by readouts on single registers.

P2 (Local Discriminability) is the origin of the complex tensor product in QT, (e.g. a QT over real Hilbert spaces would not satisfy it.)

It plays a crucial role in reducing experimental complexity in physics, by guaranteeing that only local (although jointly executed) measurements are sufficient to retrieve a complete information of a composite system, including all correlations between the components.





Holism  **Reductionism**

THE PRINCIPLE OF THE QUANTUMNESS

POSTULATES

P3. ***Reversibility and Indivisibility of Computation:*** Every information processing can be achieved with a reversible one by adding a register in an indivisible initialization.

- P3 is the synthesis of both **parallelism** (the indivisibility of initialization) and **reversibility of quantum computation**, the former being recognized as the main power of QT since D. Deutsch, the latter being one of the pillars of modern computer science since C. Bennett's.
- It is the most "quantum" postulate
- All postulates apart from P3 are satisfied by classical theory, P3 is not satisfied by PR boxes
- There is currently no known theory satisfying P1, P2, and P3 apart from QT.
- It is the basis of most quantum information protocols:
  - teleportation,
  - conditions for error correction,
  - no-cloning theorem,
  - ancilla-assisted tomography, ...
  - One can interpret the postulate as a statement of conservation of information, *a la* Everett.

THE PRINCIPLE OF THE QUANTUMNESS

POSTULATES

★ ★ ★ ★ ★ ★ ★ ★

P4. ***Indivisibility of Processing Composition:*** The processing corresponding to the input-output sequence of two indivisible processings is itself indivisible.

It looks obviously true. However, there is no reason why the same processing obtained by composing two ones could not be itself achieved in principle by a subroutine which is divisible.

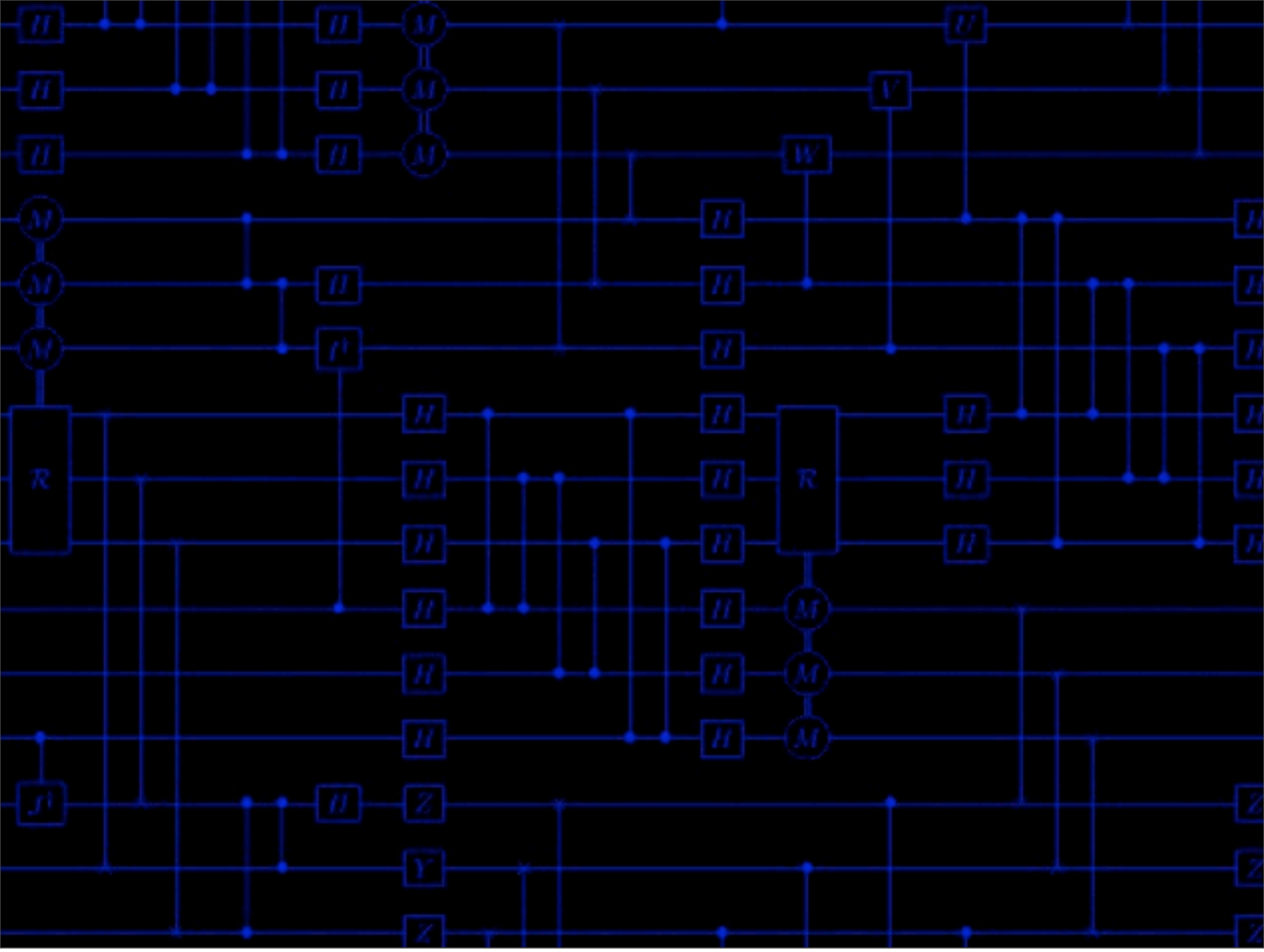
P5. ***Discriminability of Specific Initializations:*** For any specific initialization there exists another initialization that can be perfectly discriminated from it.

This also looks obvious, however, it is easy to construct a theory that violates it.

P6. ***Lossless Compressibility:*** For any initialization there exists an encoding which is perfectly decodeable on its refinement set, and the encoded initialization is not specific.

This also looks obvious for a conventional information theory (it would mean that e.g. one can always encode the initializations corresponding to integers 0-7 on a register of only 3 bits without loss!) This principle is the starting point of Shannon's and Schumacher's compression. P6 becomes non trivial in a more general information-processing framework, e.g. if one has different types of registers with the same number of perfectly discriminable initializations. In our derivation of QT P5 and P6 are essential for quantum-logical structure of QT.

What is out of there?

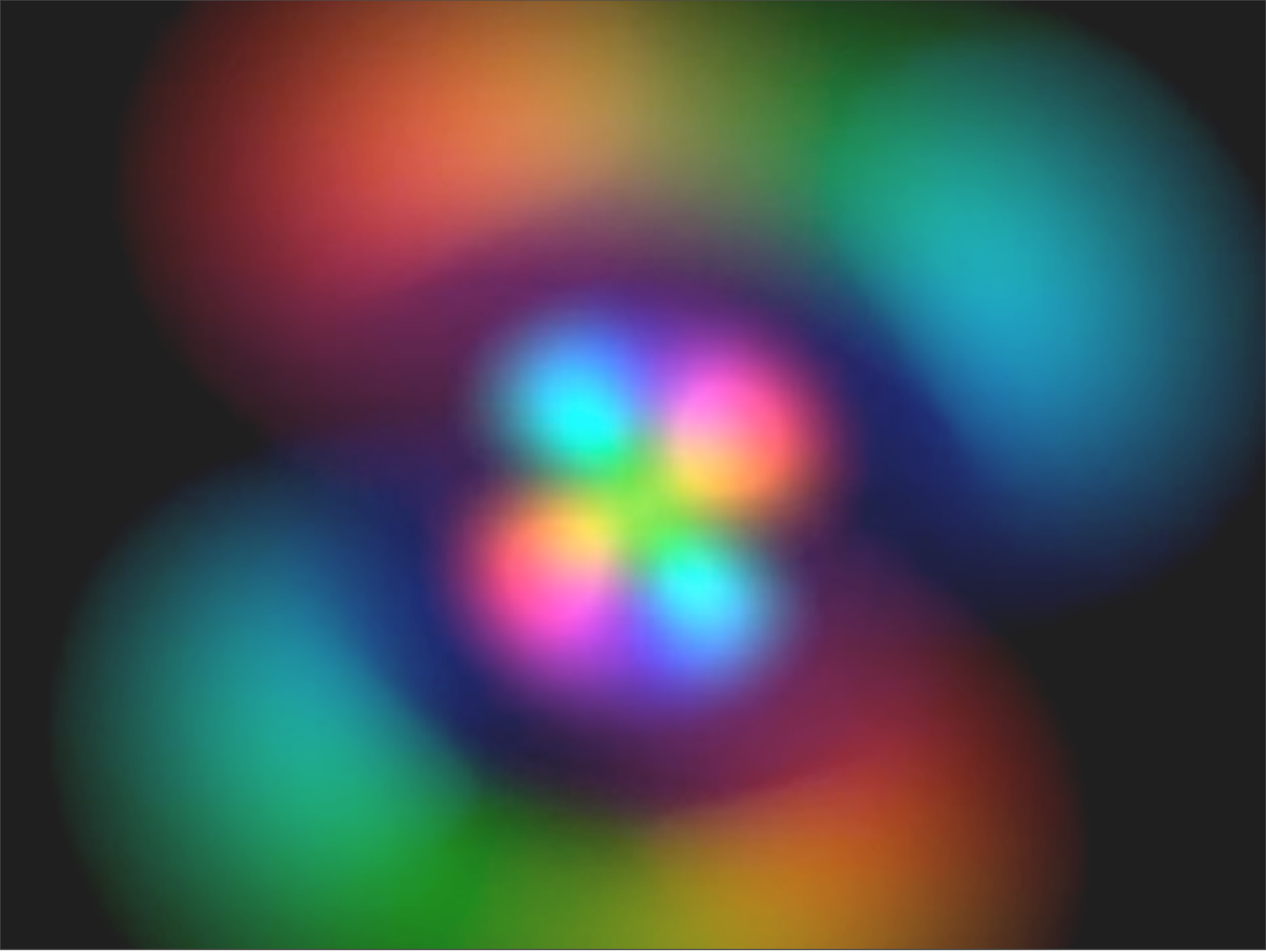


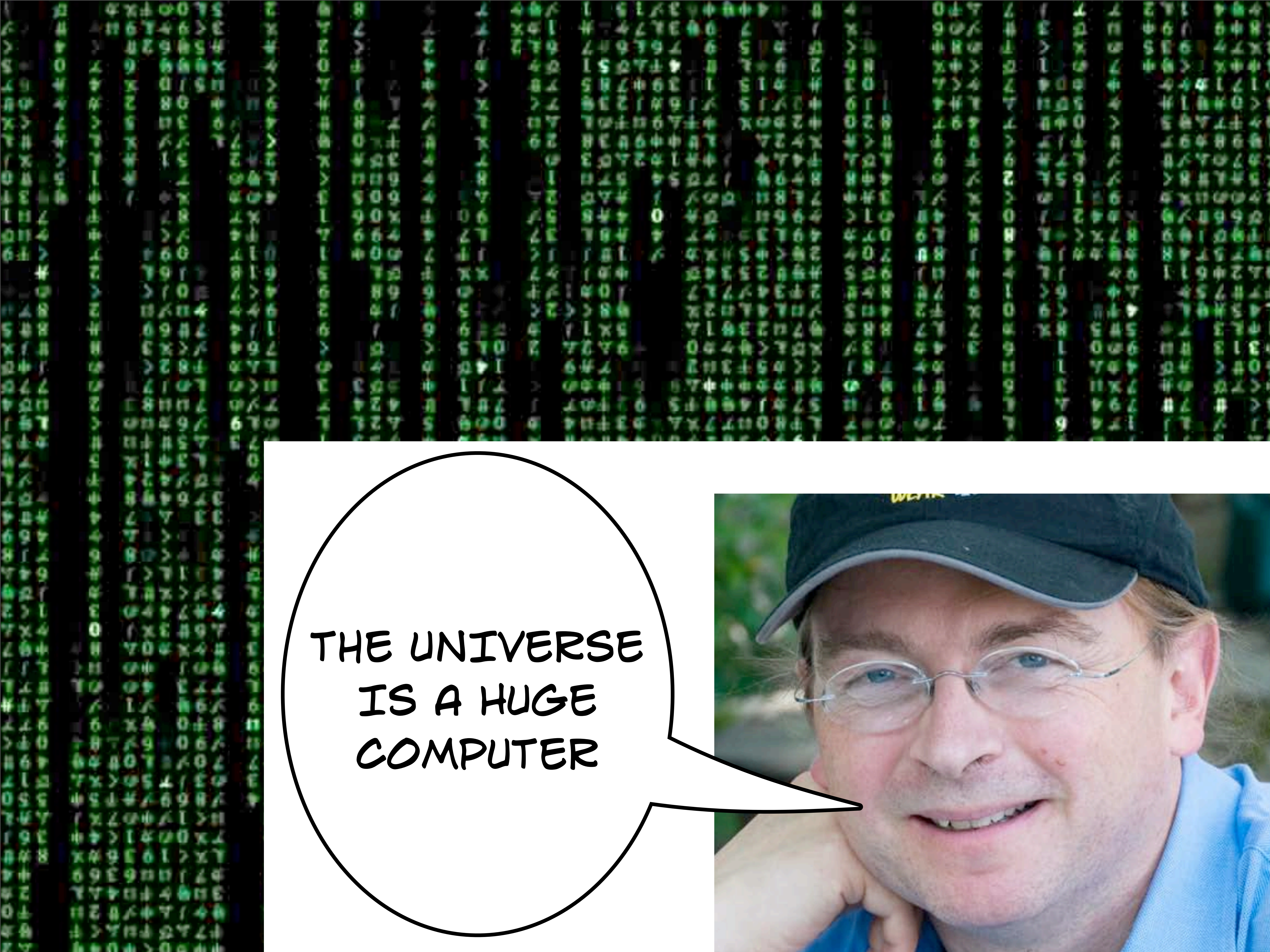
Physics is Information

"It from Bit"

"Information is physical"

(Bit from It)




THE UNIVERSE
IS A HUGE
COMPUTER

The *Quantumness* of Relativity

A QUANTUM-COMPUTER SIMULATION OF QUANTUM FIELD THEORY

BECOMES A NEW FIELD THEORY

arXiv: 1001.1088 [v1] 7 Jan [v6] 9 Feb 2010, PIRSA:10020037

AIP CP **1232,** *QUANTUM THEORY: Reconsideration of Foundations-5,* A.Y. Khrennikov ed., ISBN: 978-0-7354-0777-0

The *Quantumness* of Relativity

...

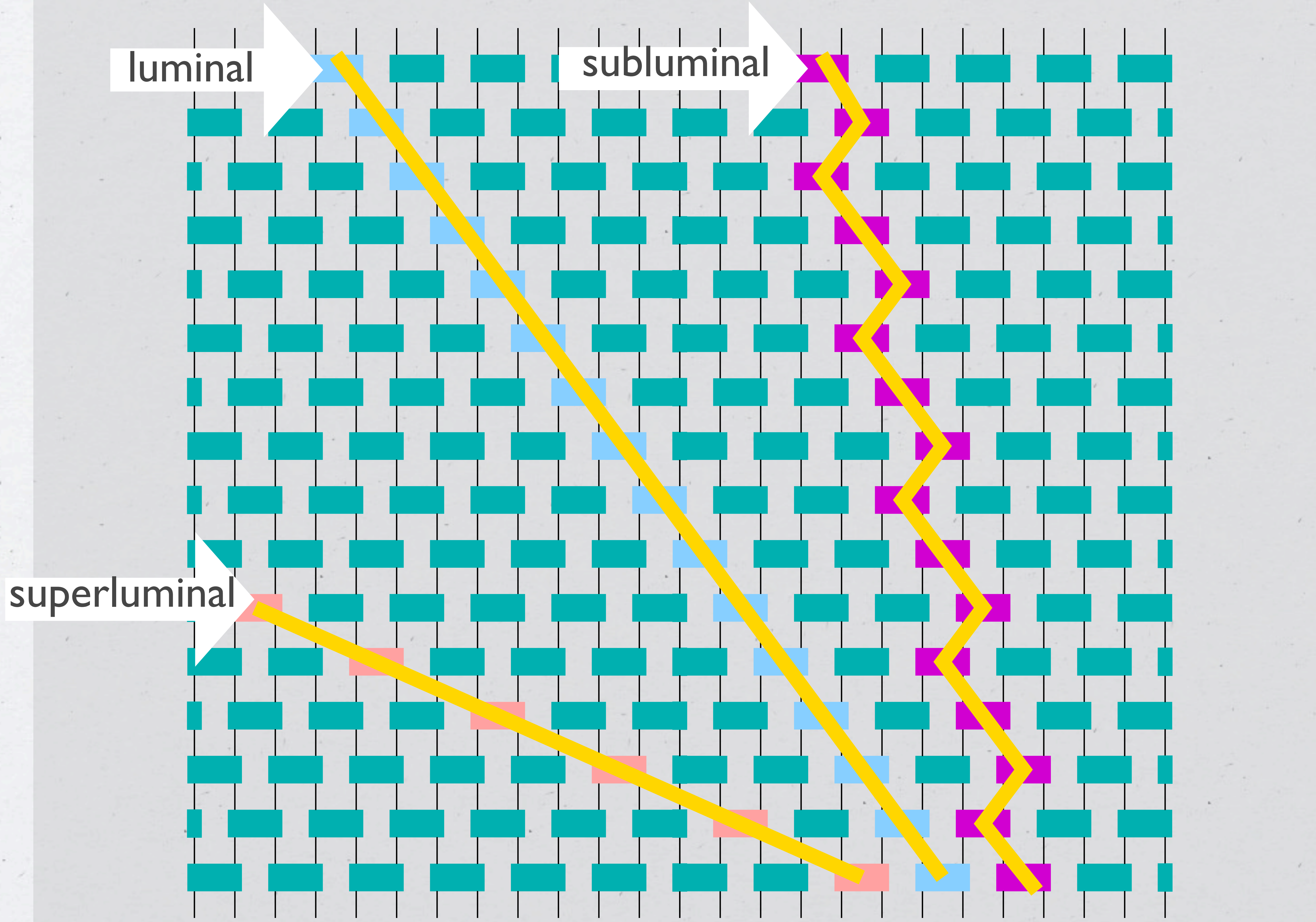
AND WITH OBSERVATIONAL CONSEQUENCES

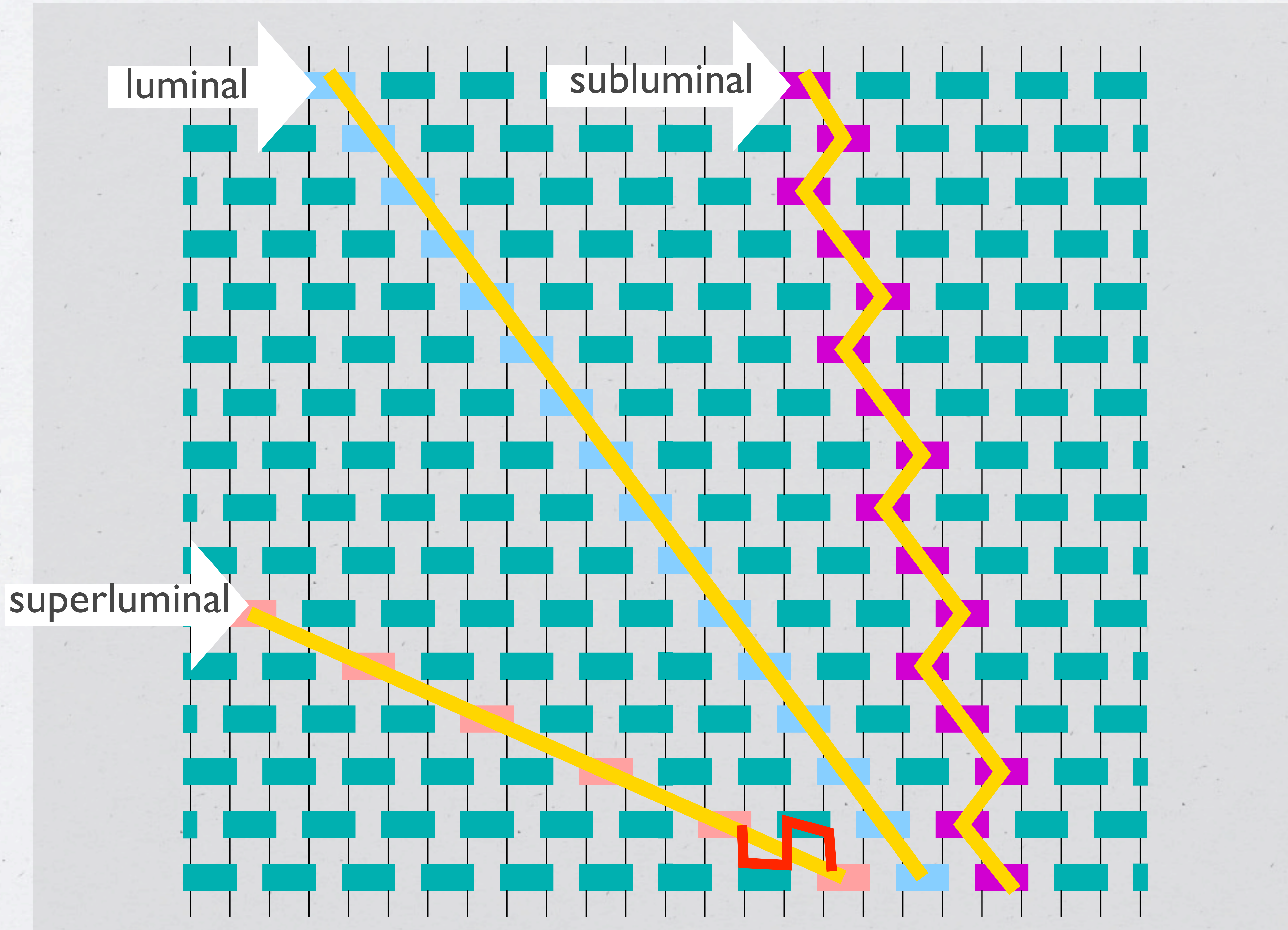
(upcoming quant-ph)

arXiv: 1001.1088 [v1] 7 Jan [v6] 9 Feb 2010, PIRSA:10020037

AIP CP **1232,** *QUANTUM THEORY: Reconsideration of Foundations-5,* A.Y. Khrennikov ed., ISBN: 978-0-7354-0777-0

HOW RELATIVITY EMERGES FROM THE COMPUTATION?


luminal
subluminal
superluminal


luminal
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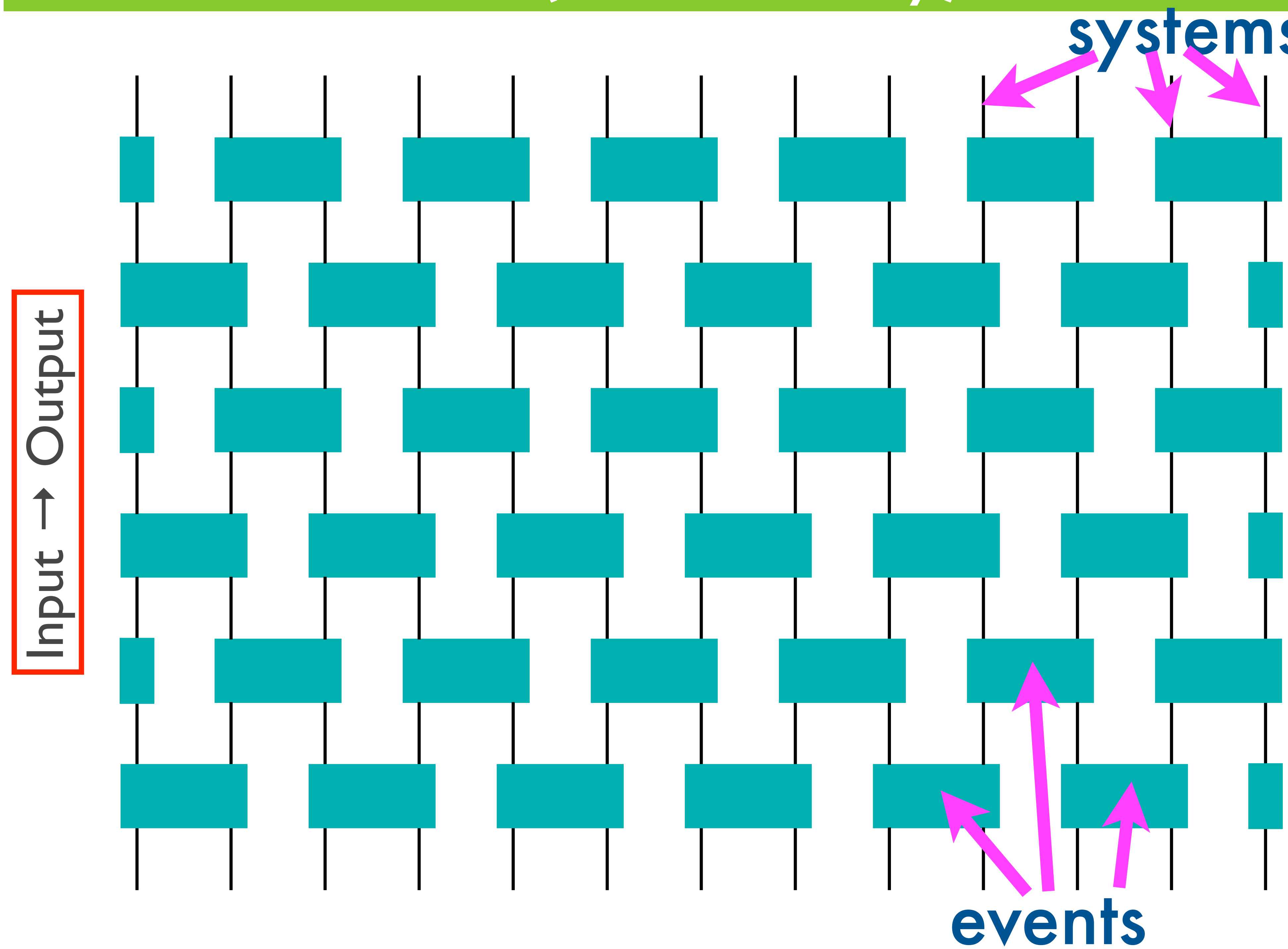
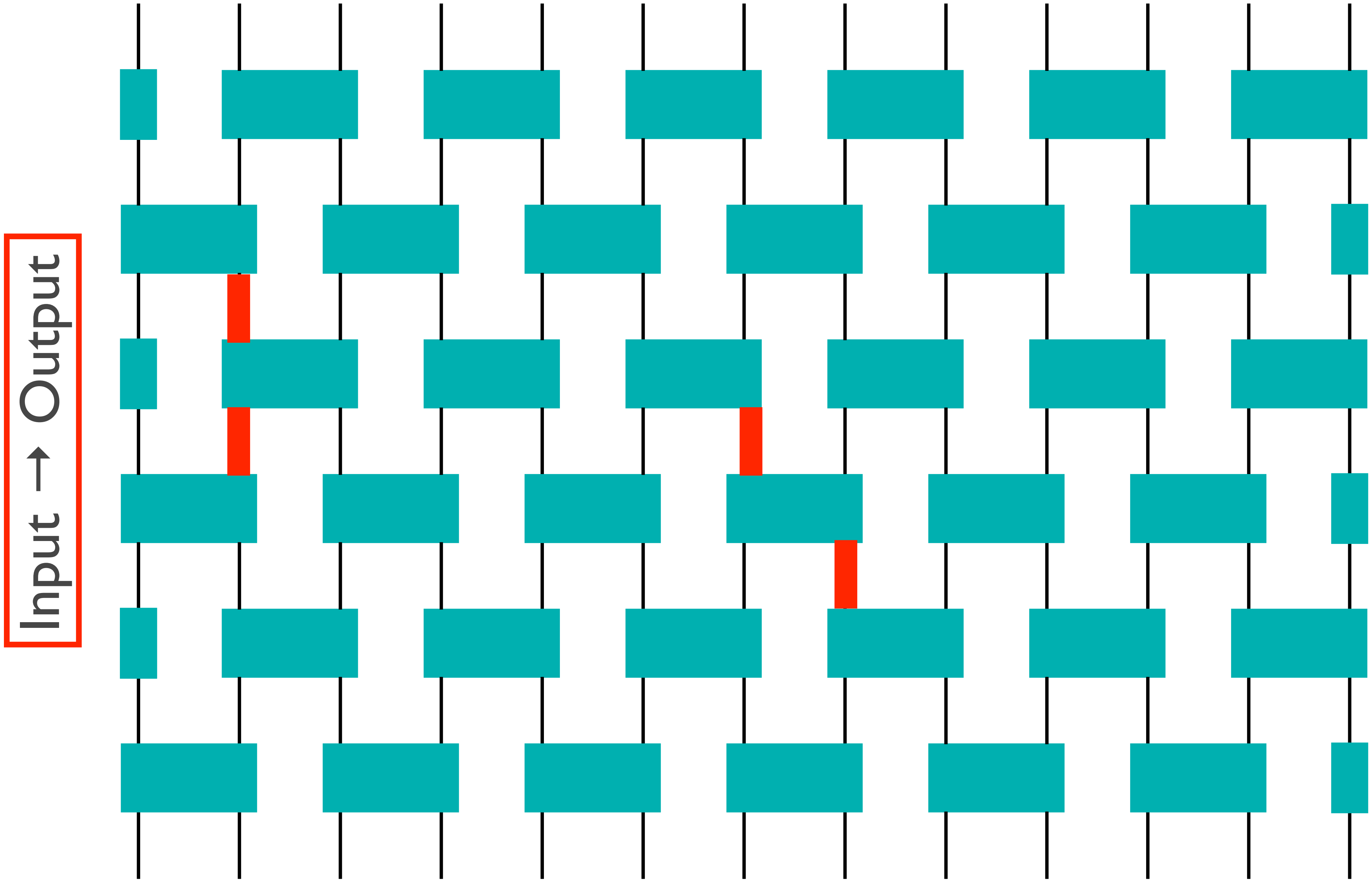
Relativity from QT

(from causality)



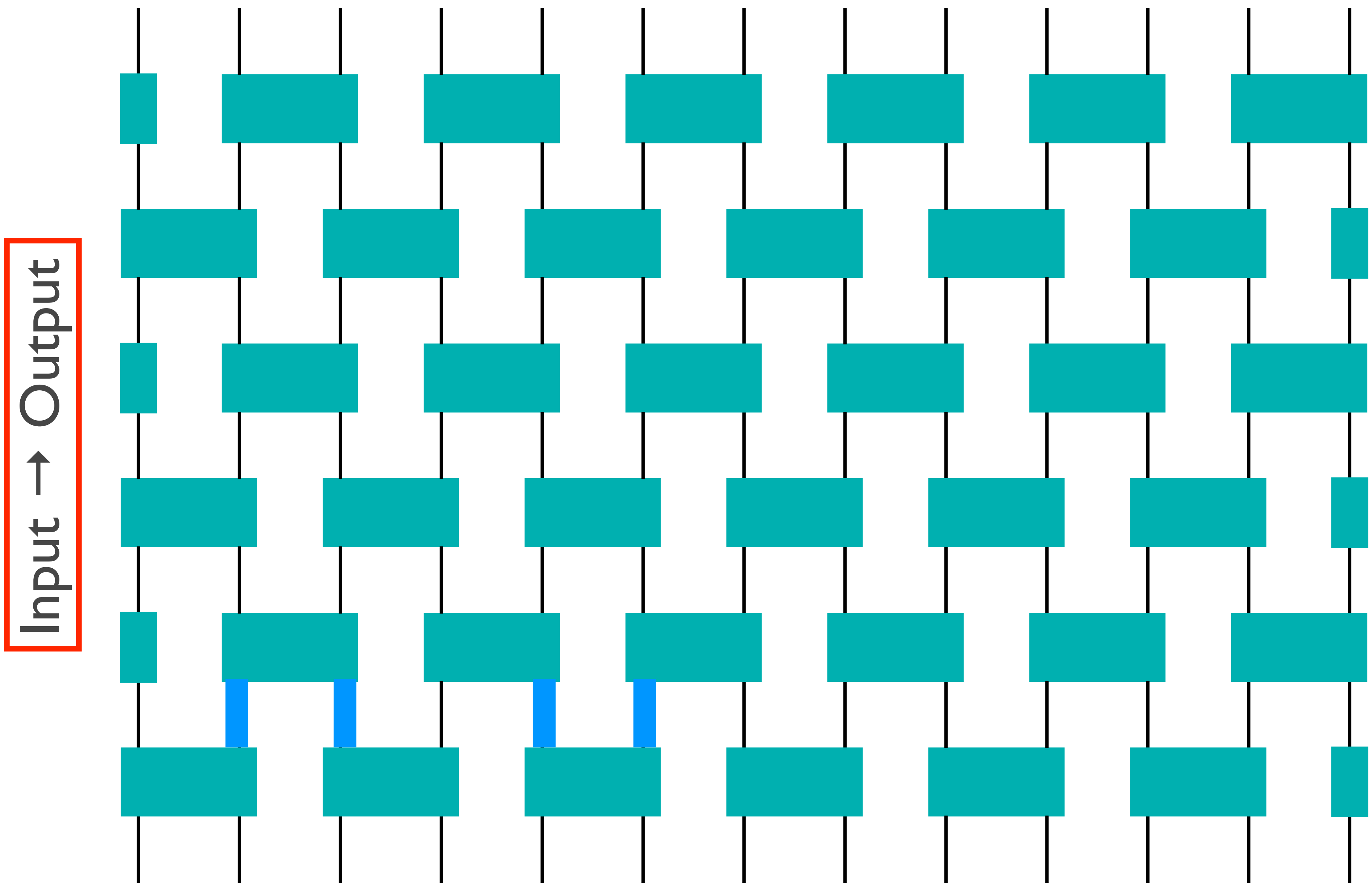
Relativity from QT
(from causality)

causal contiguity



Relativity from QT

(from causality)



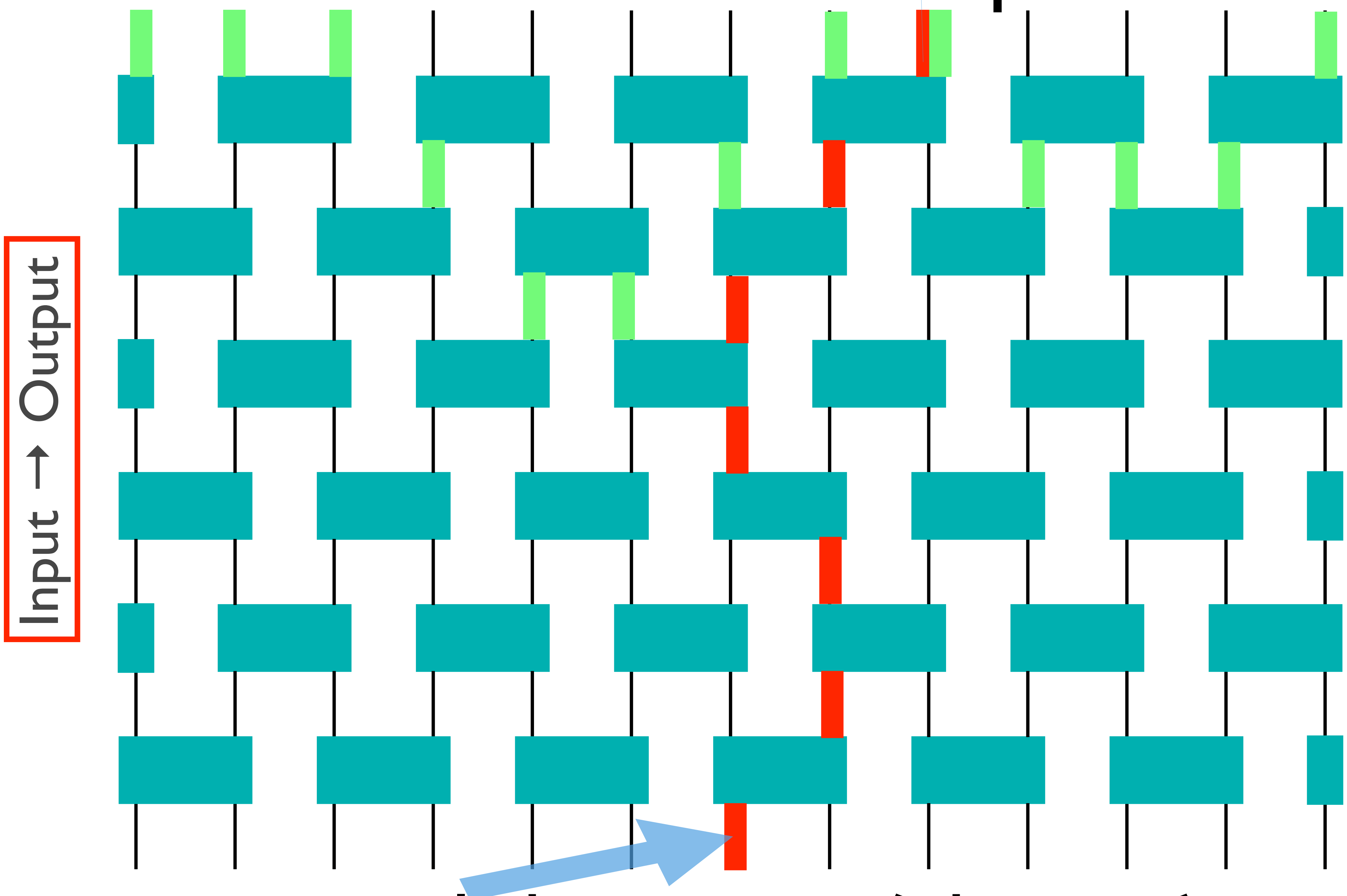
a-causal contiguity

slice

Relativity from QT

(from causality)

causal antichain = space



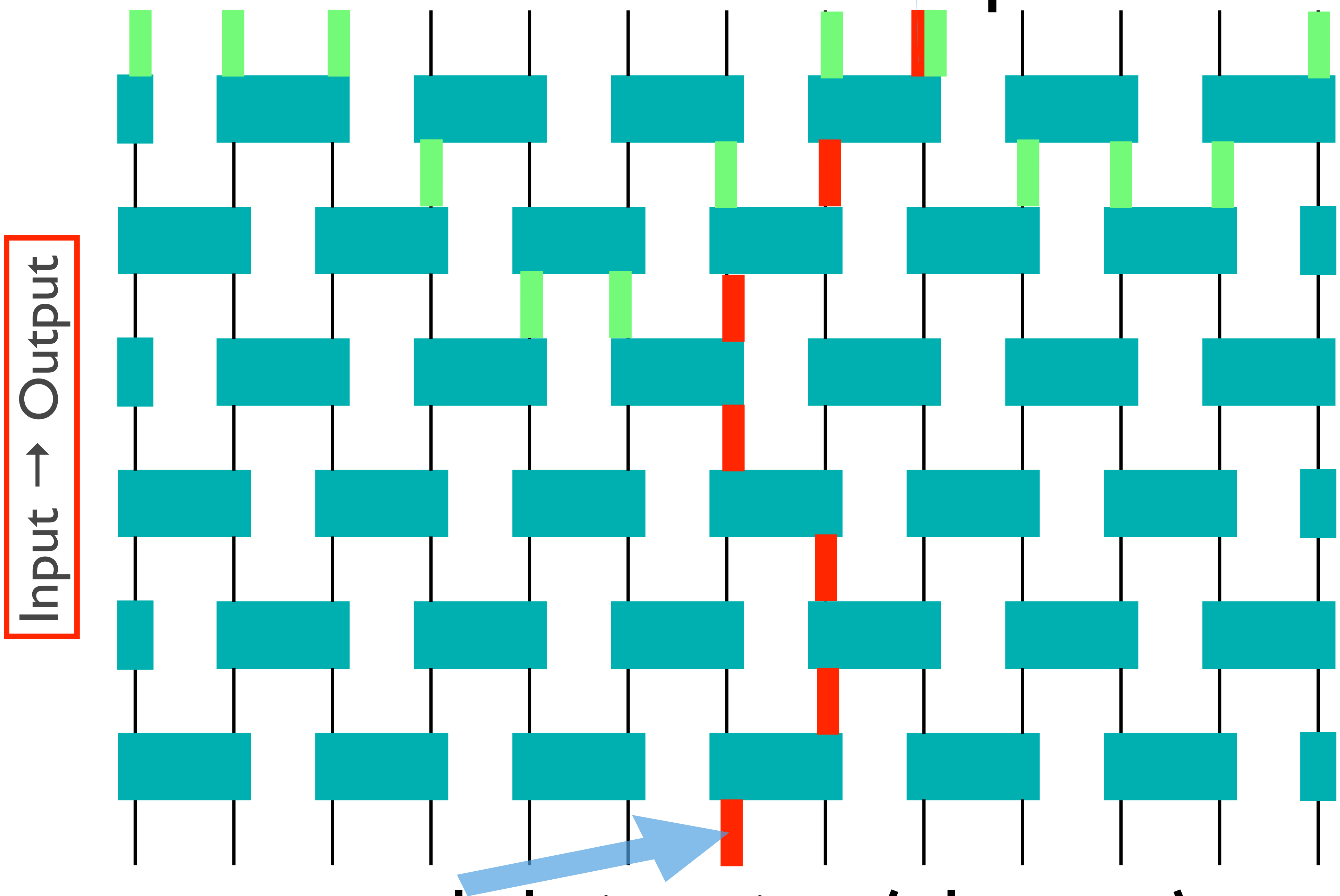
causal chain = time (observer)

Relativity from QT

(from causality)

topology (Alexandrov)

causal antichain = space



causal chain = time (observer)

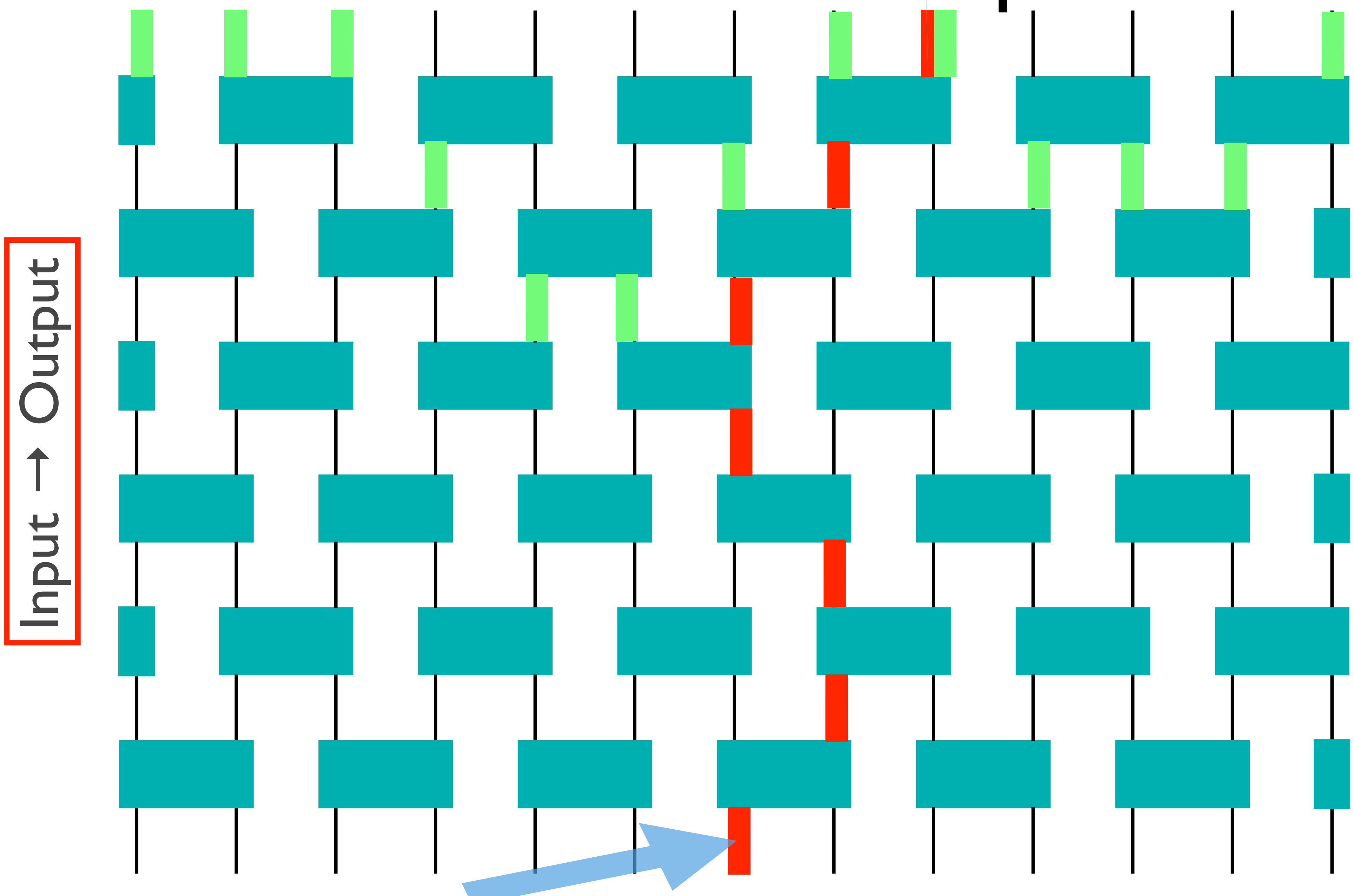
Relativity from QT

(from causality)

topology (Alexandrov)

metric = event-counting

causal antichain = space



causal chain = time (observer)

Relativity from QT

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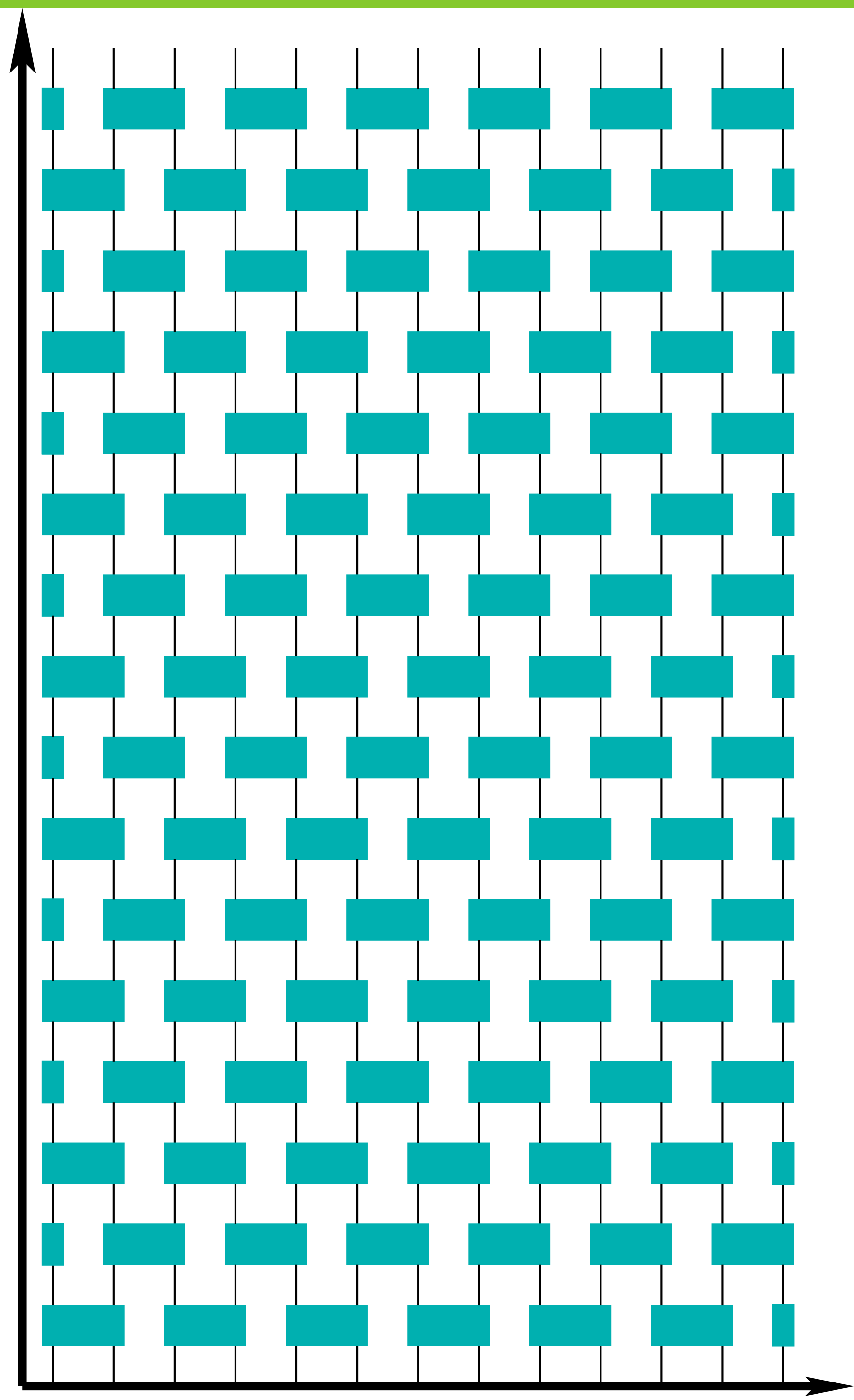
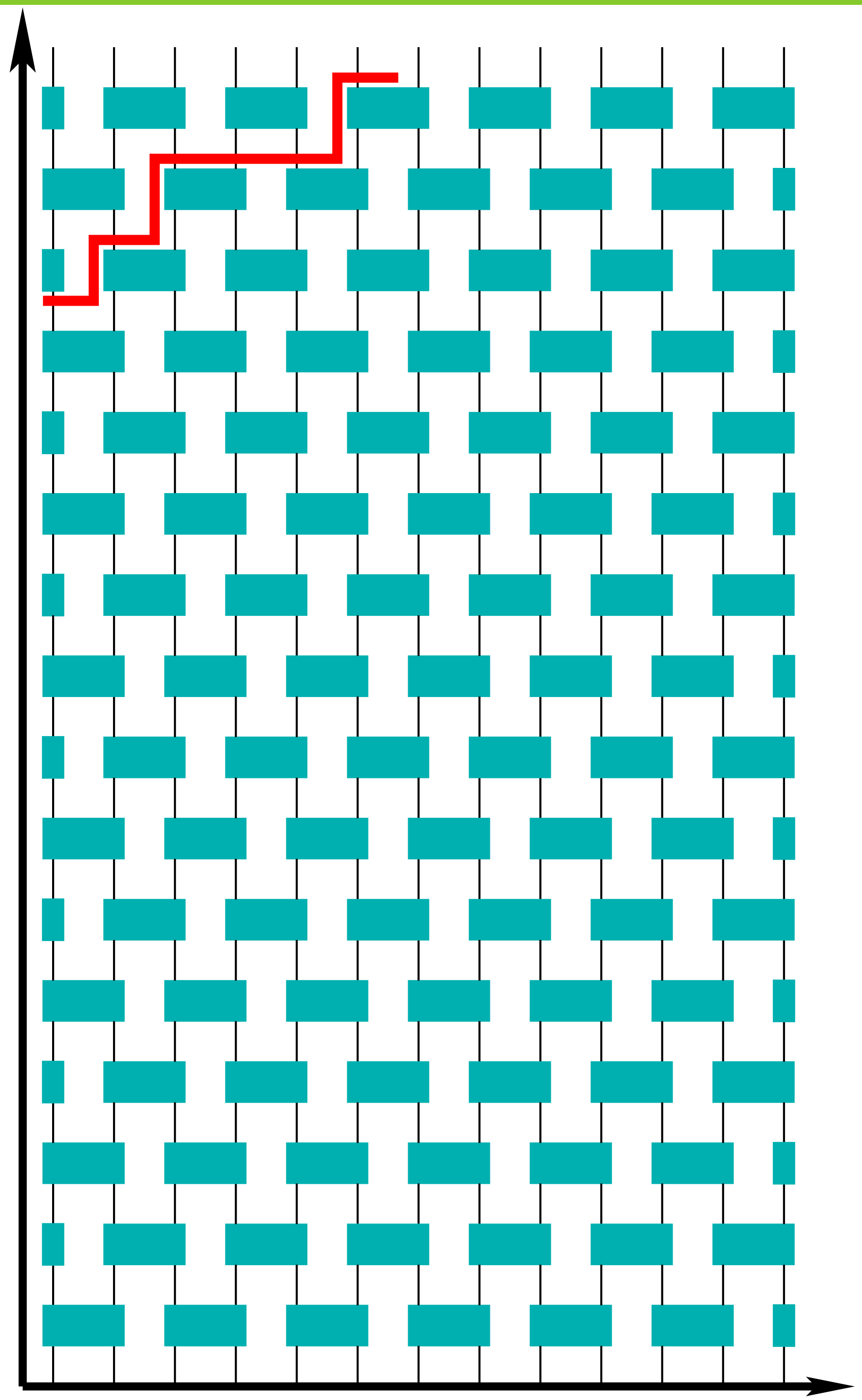


Relativity from QT

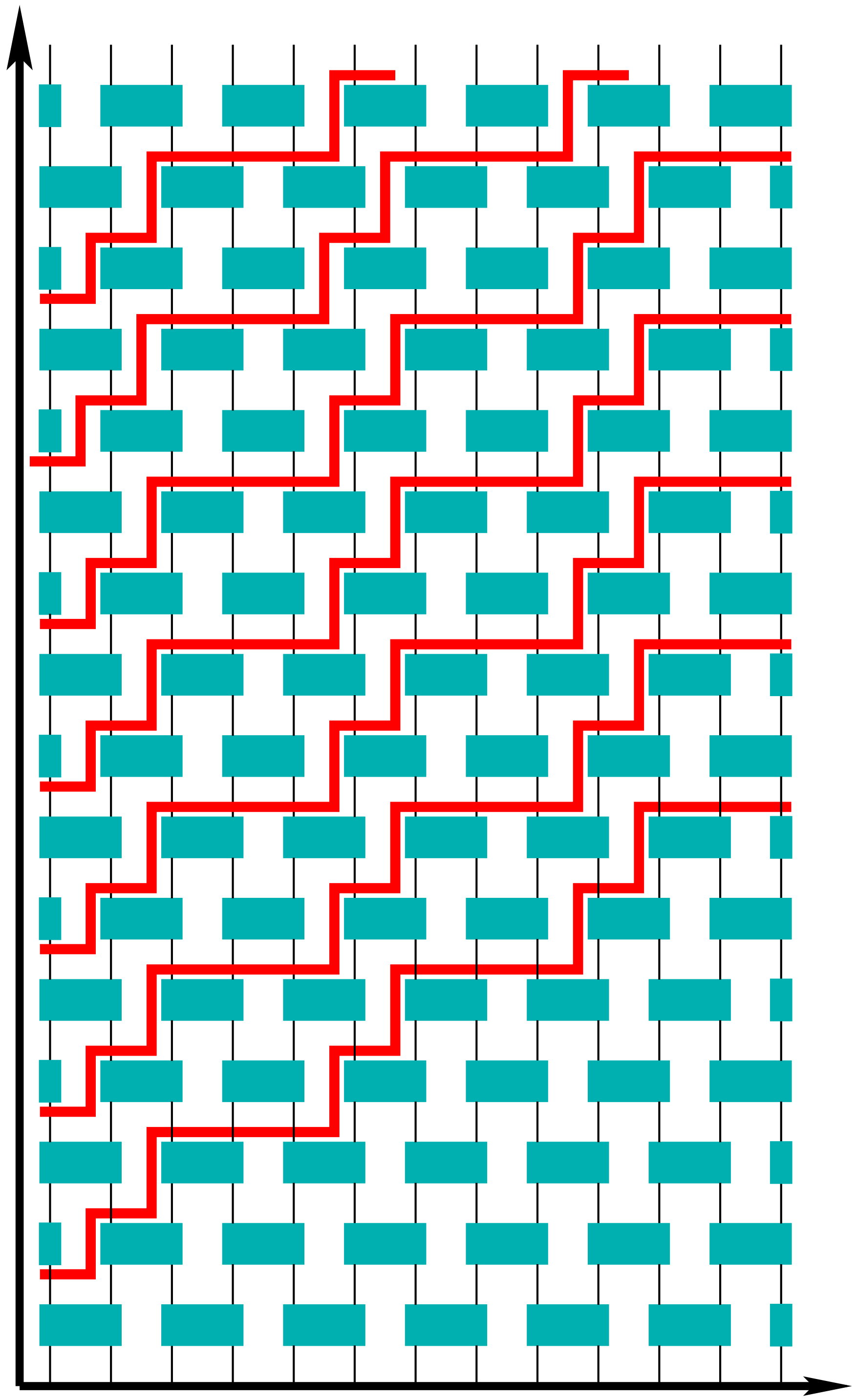
(from causality)



build a uniform foliation

Relativity from QT

(from causality)



build a
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Relativity from QT

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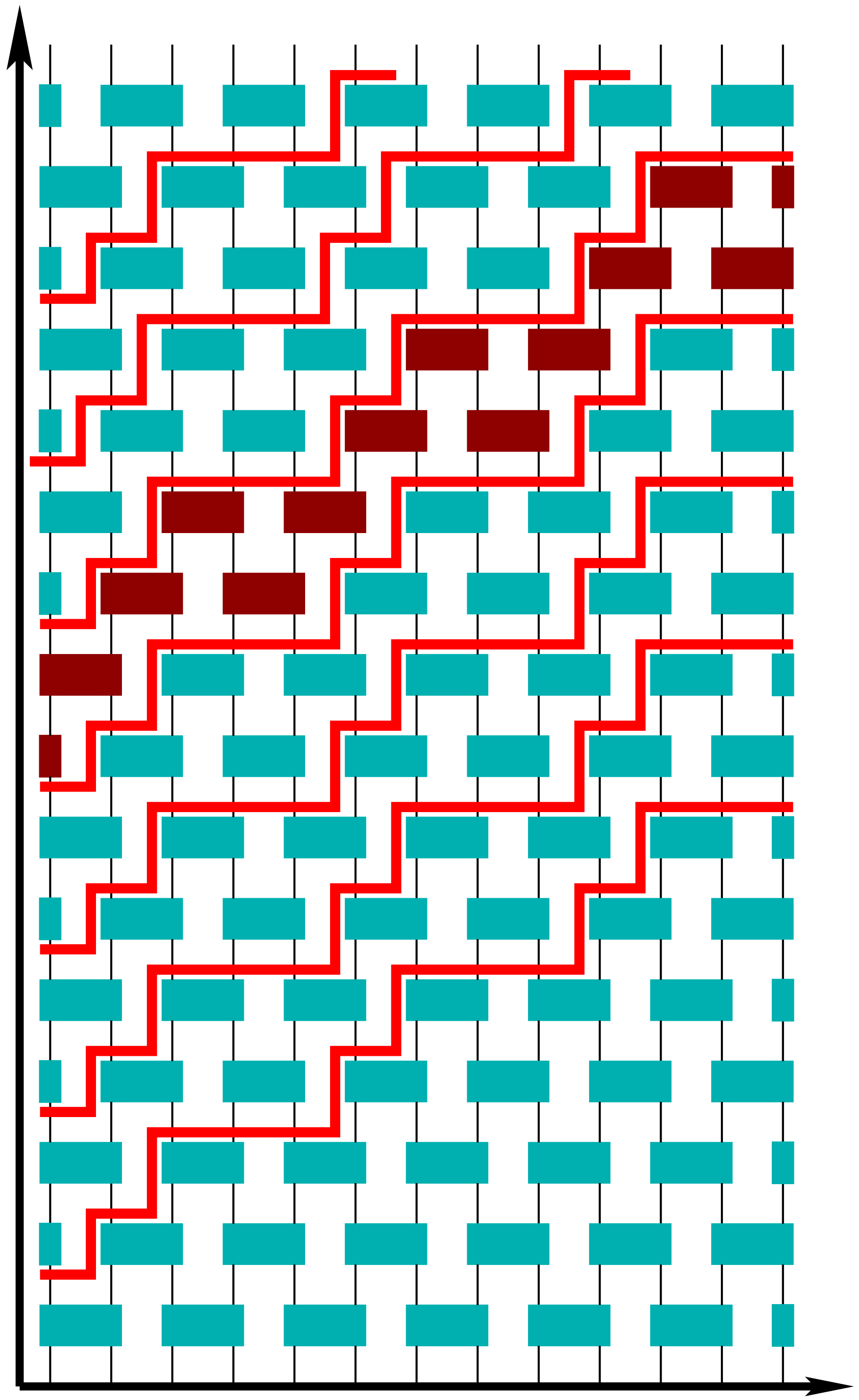
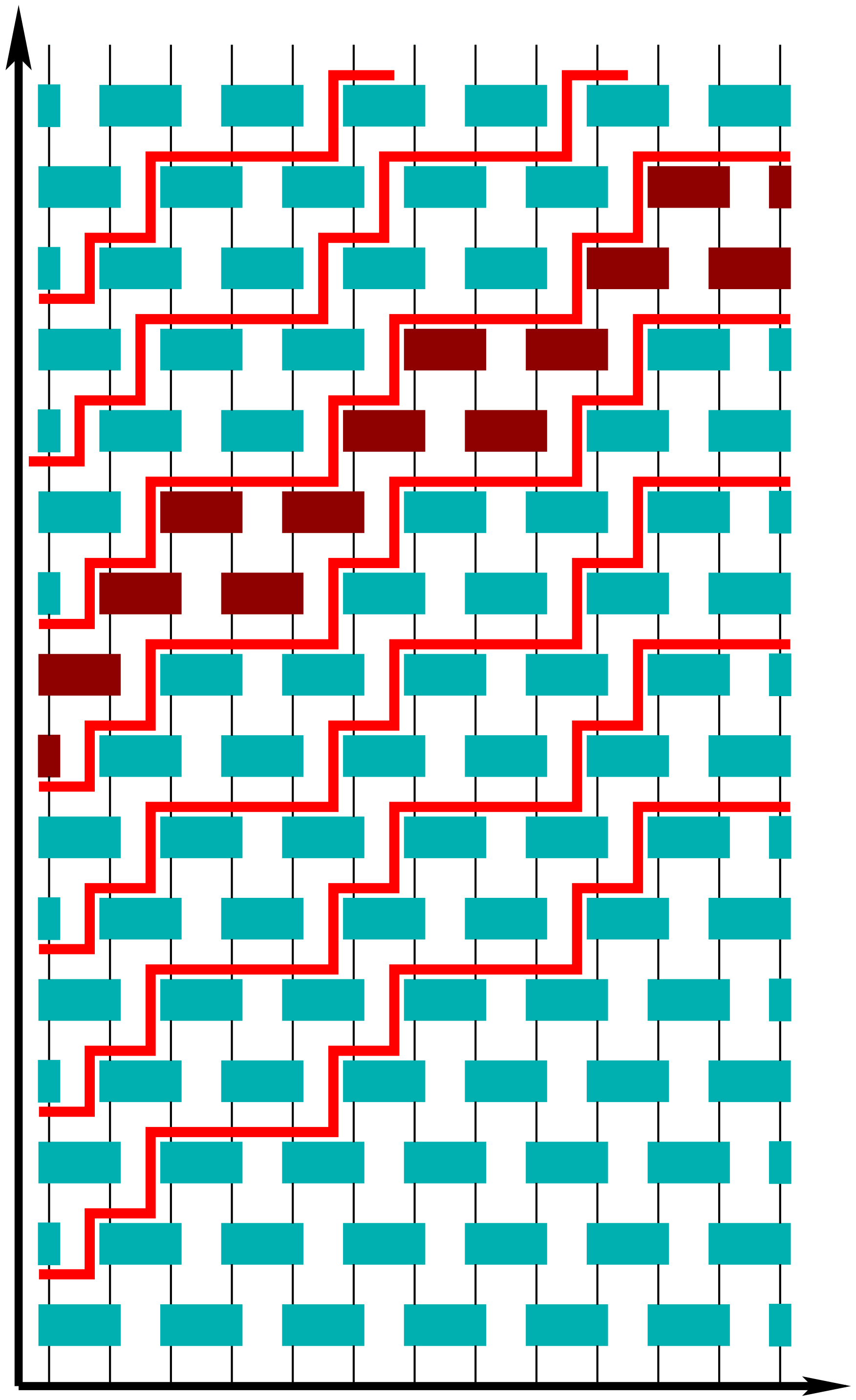


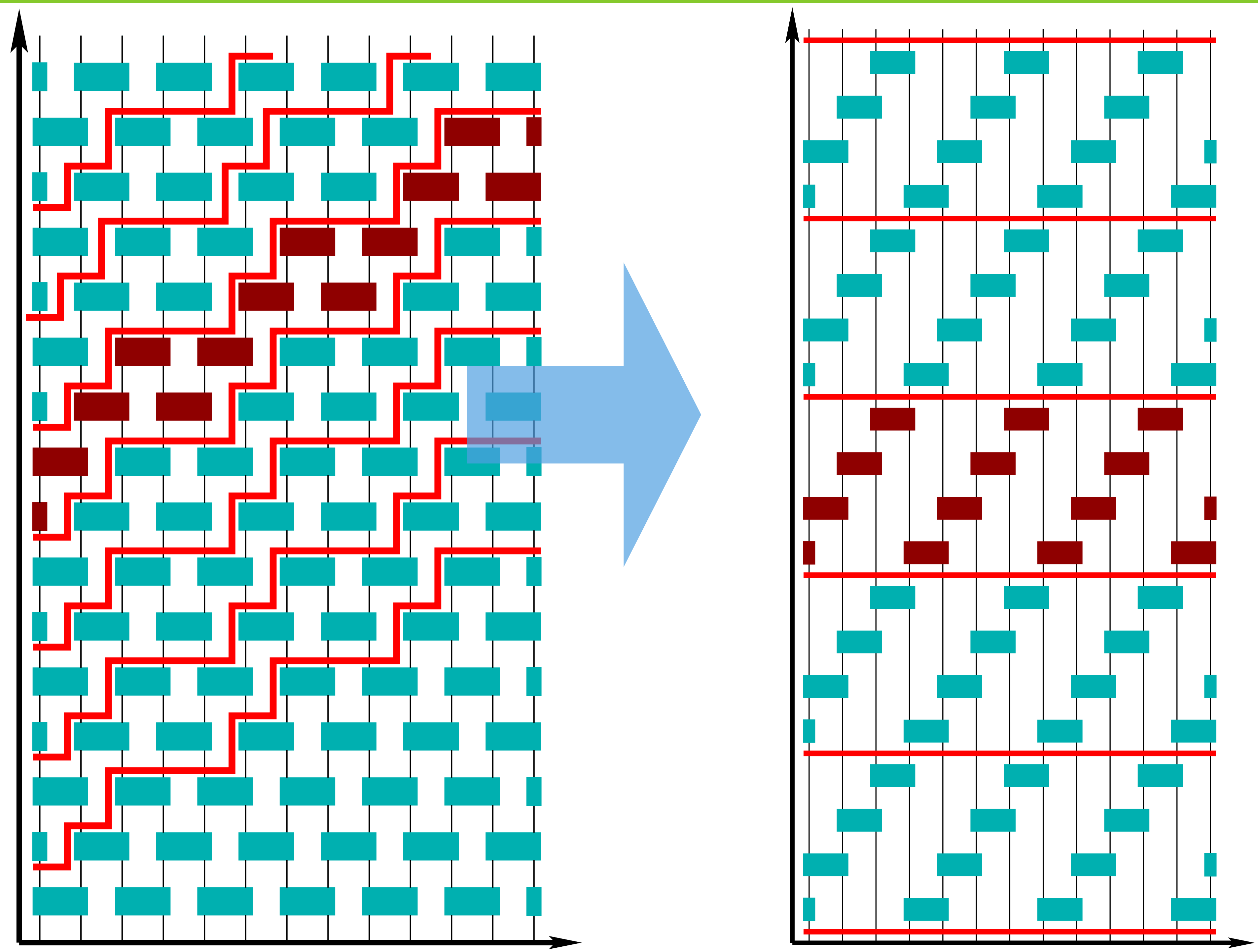
build a uniform foliation

Relativity from QT

(from causality)



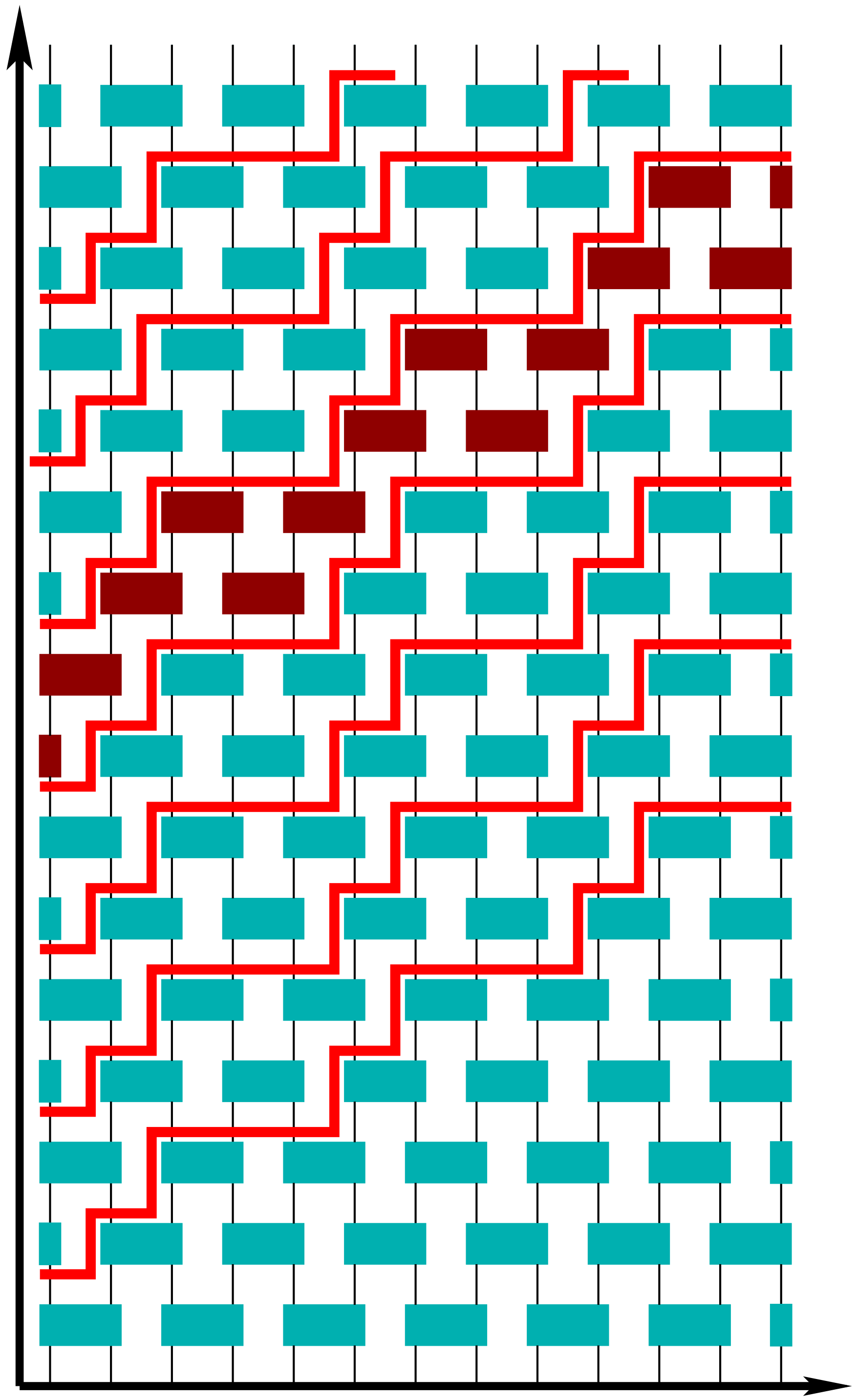
Relativity from QT
(from causality)



change reference

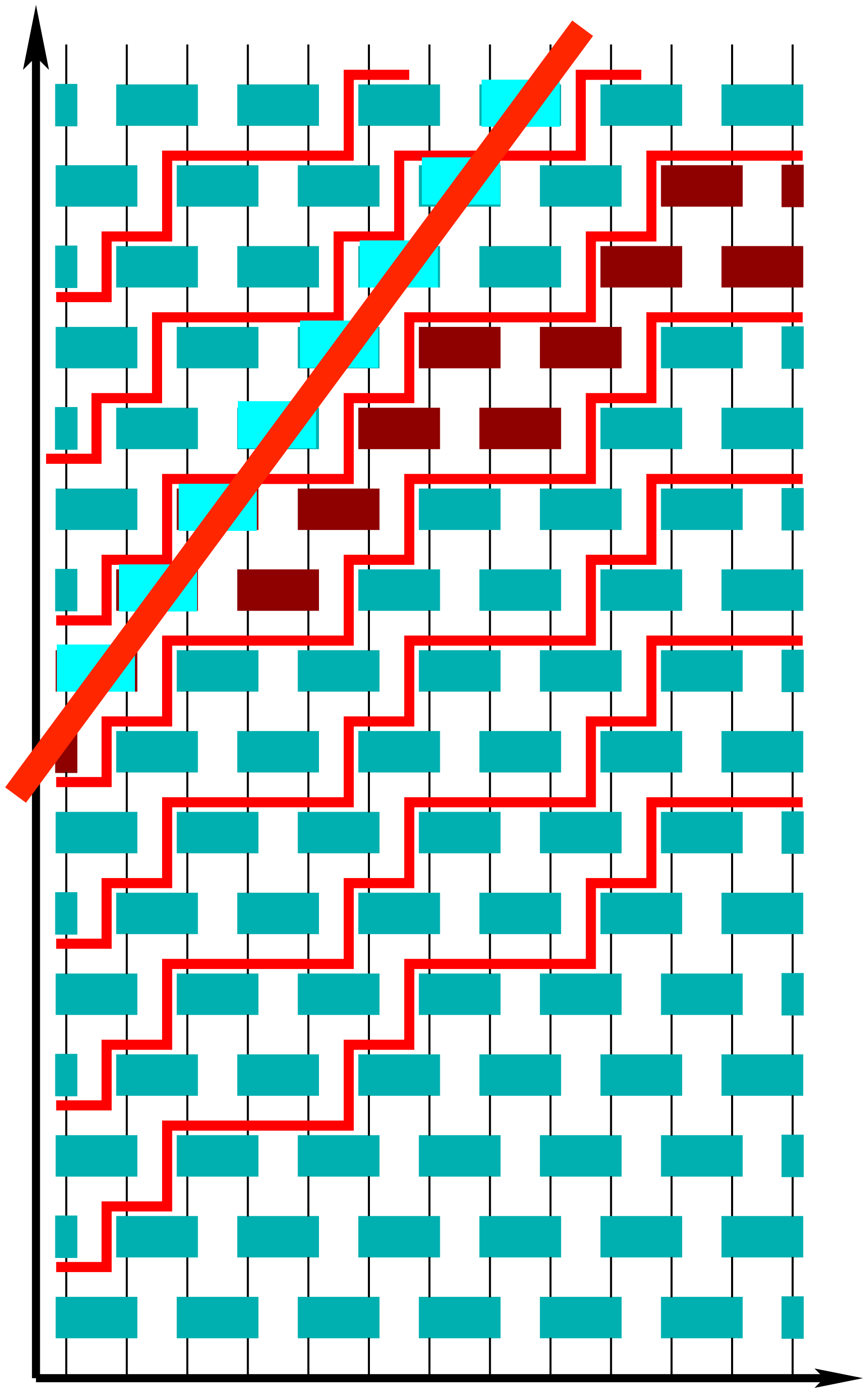
Relativity from QT

(from causality)



Relativity from QT

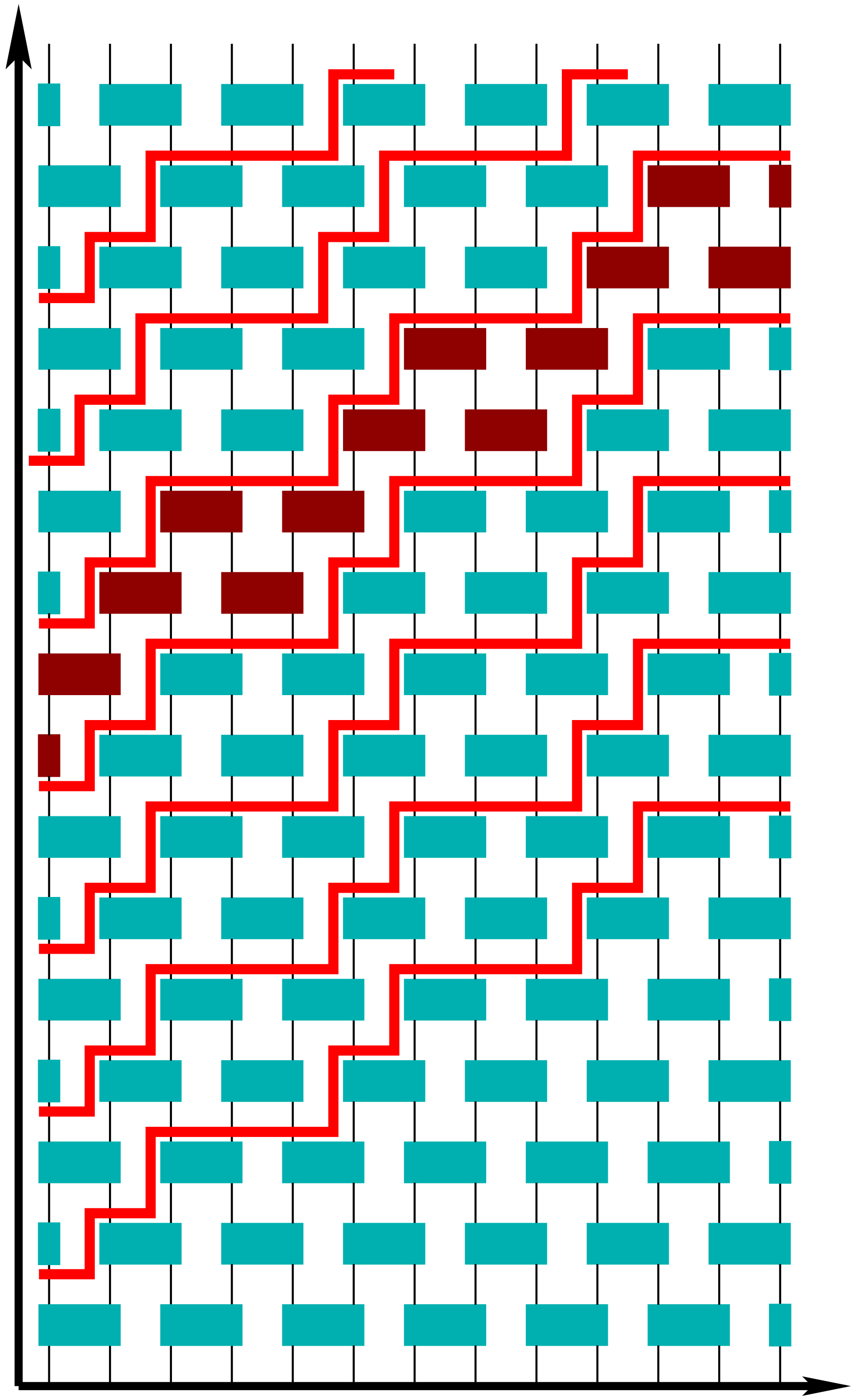
(from causality)



speed of light

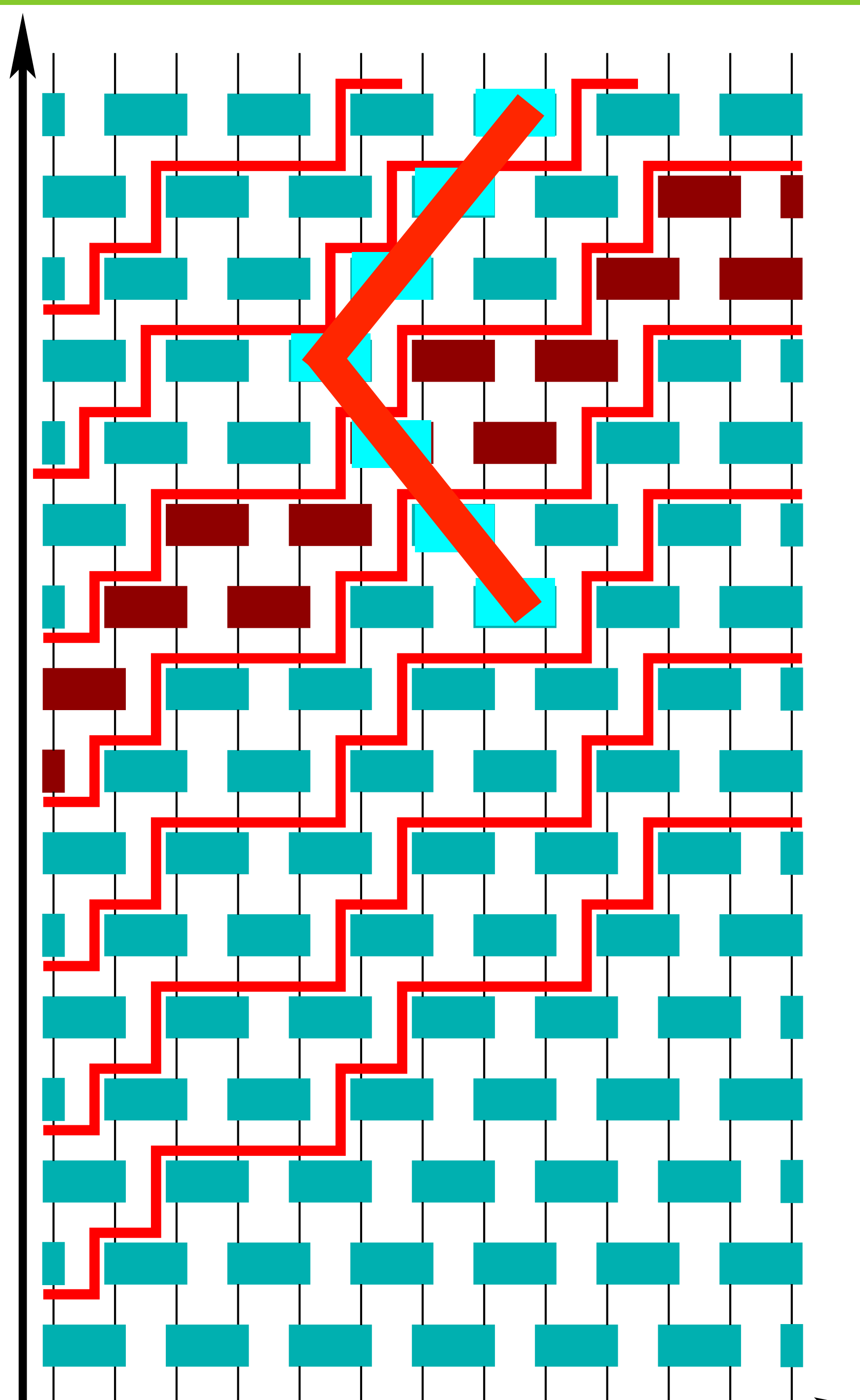
Relativity from QT

(from causality)



Relativity from QT

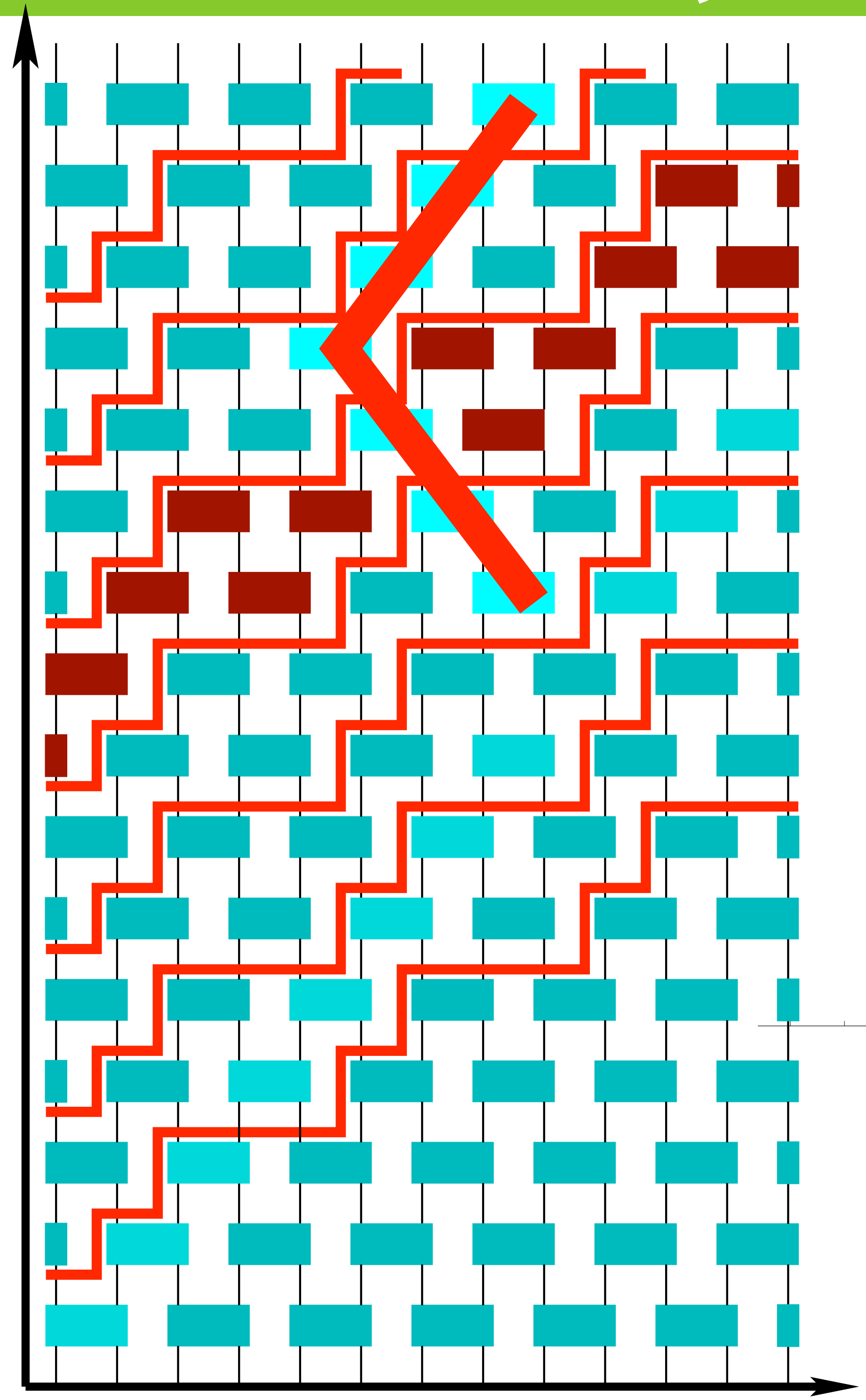
(from causality)

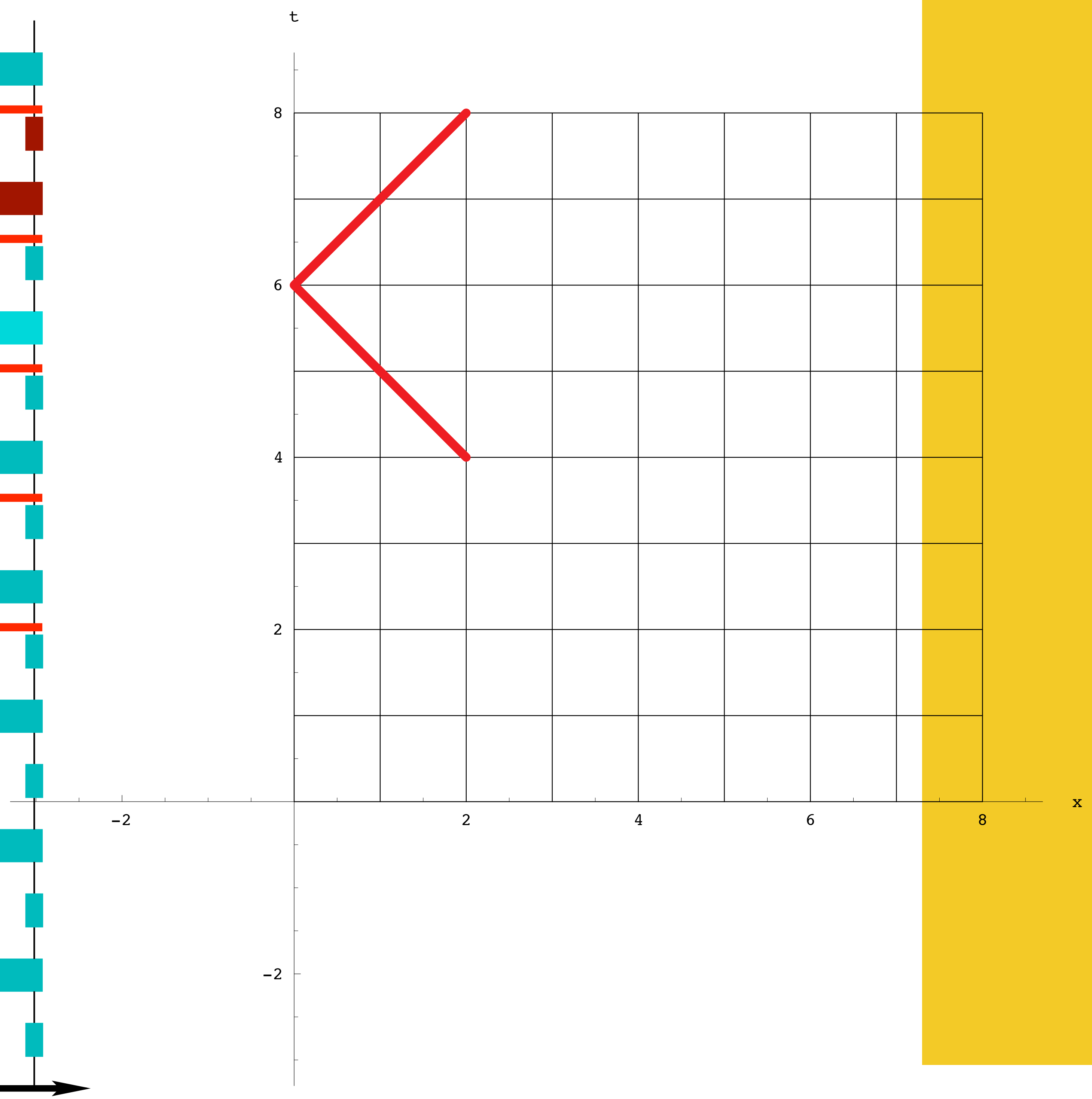


clock tic-tac

Relativity from QT

(from causality)





Relativity from QT

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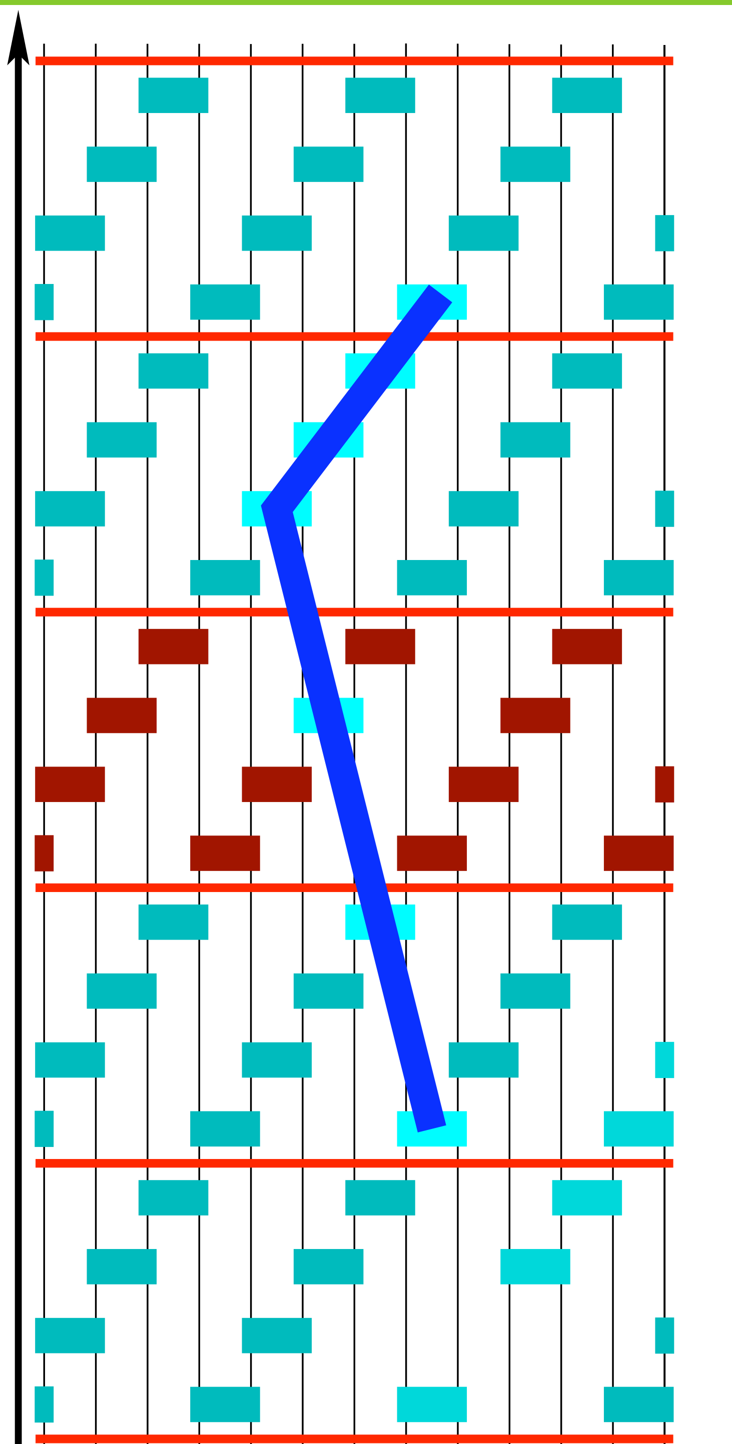
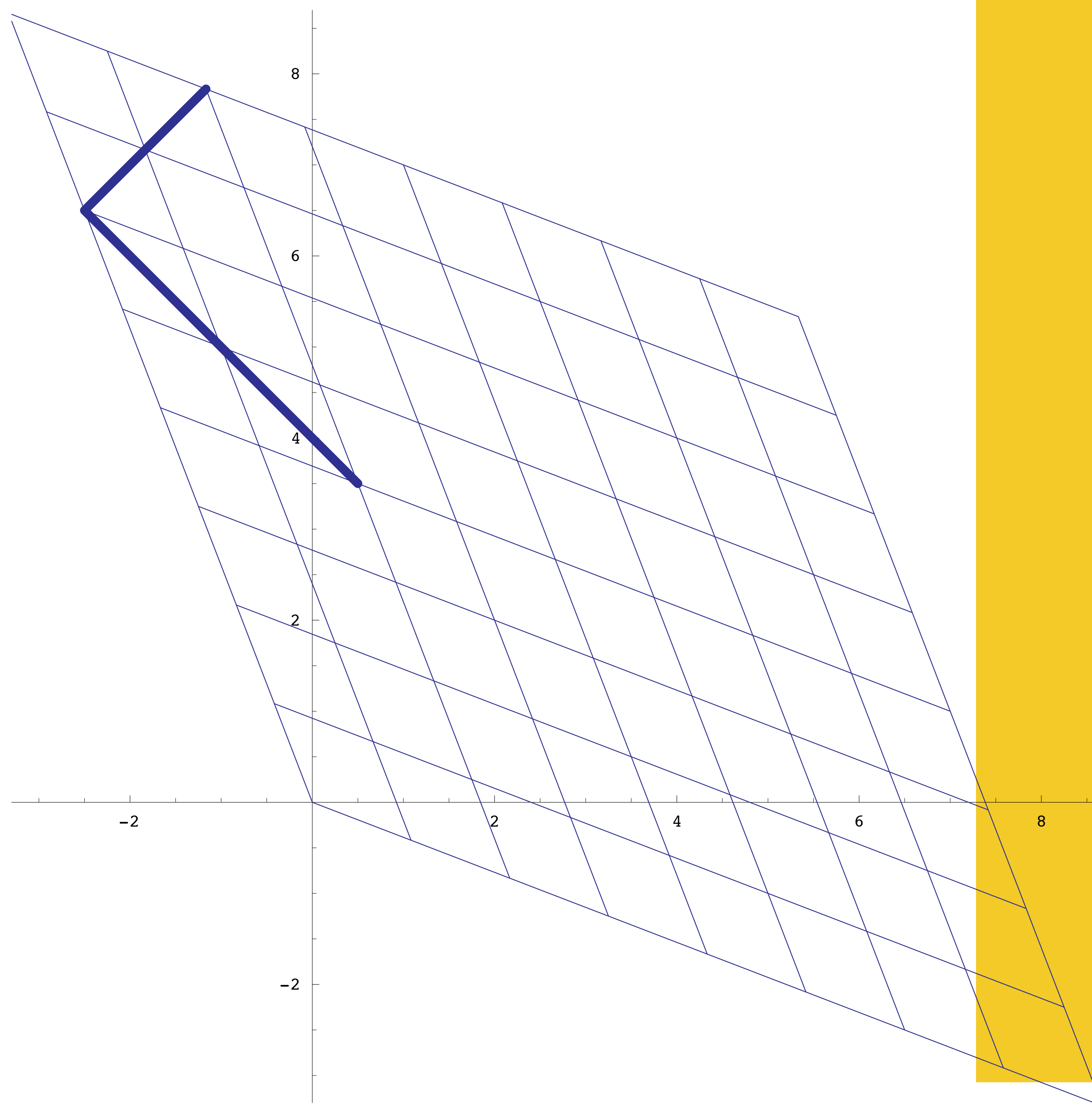
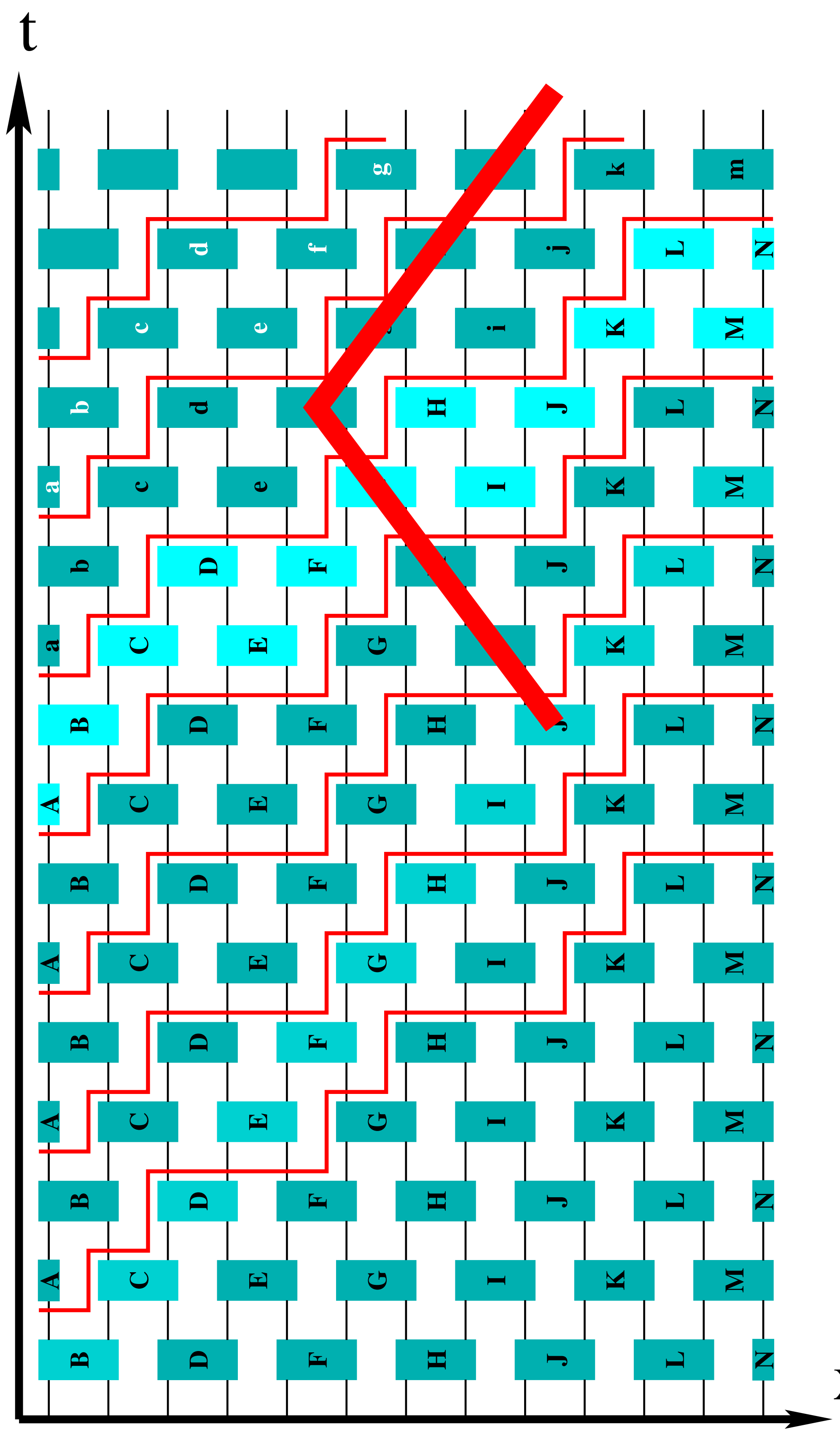
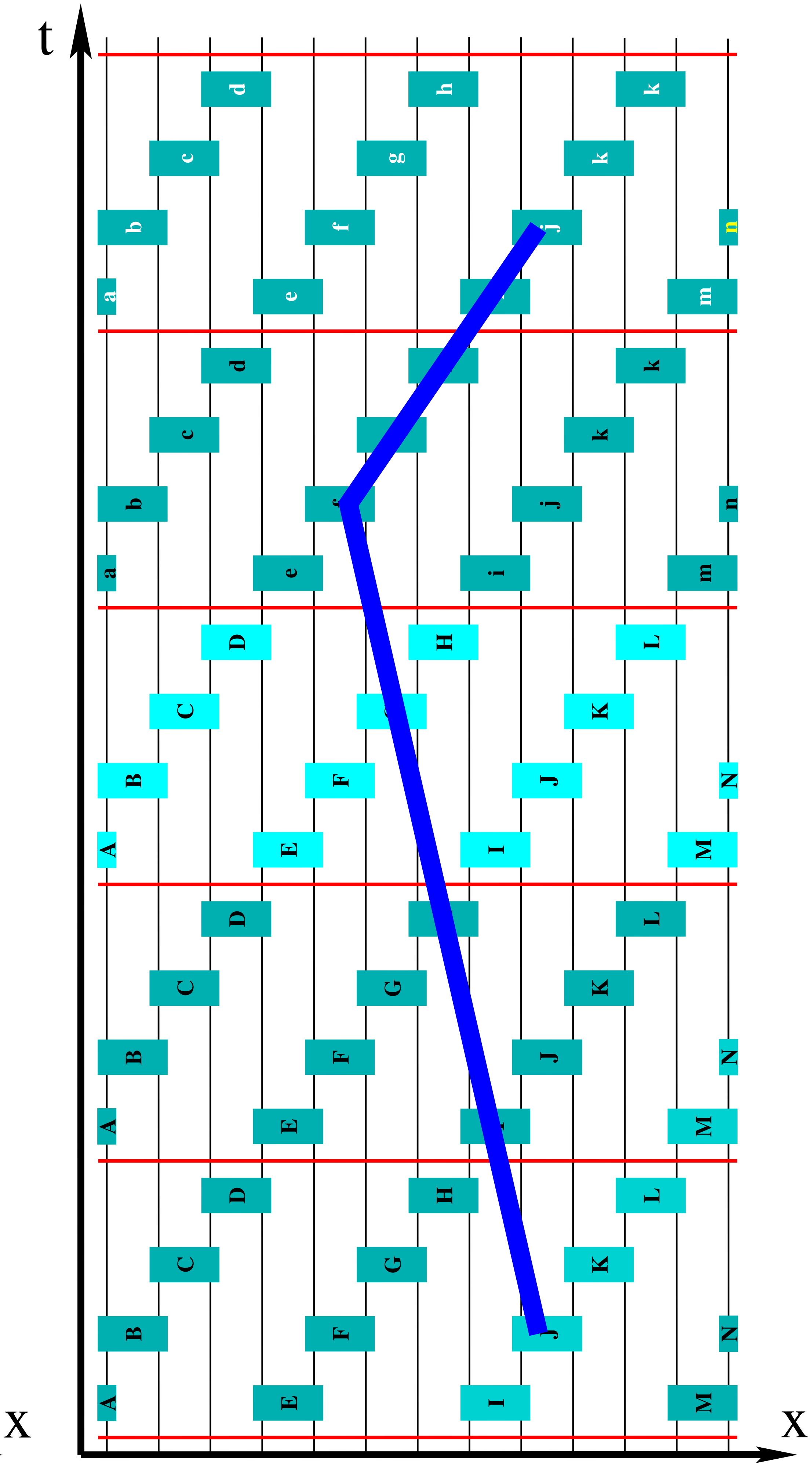




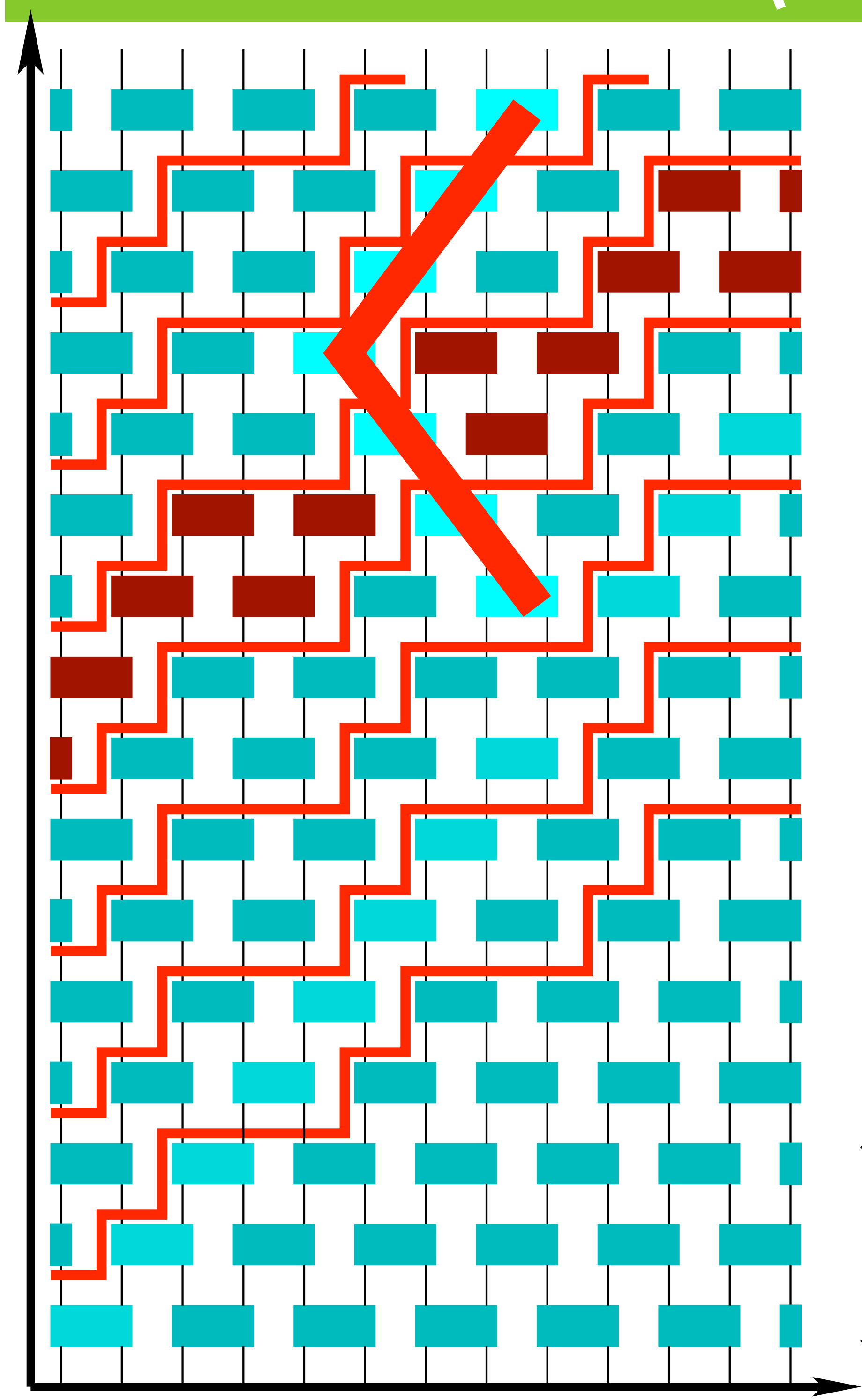


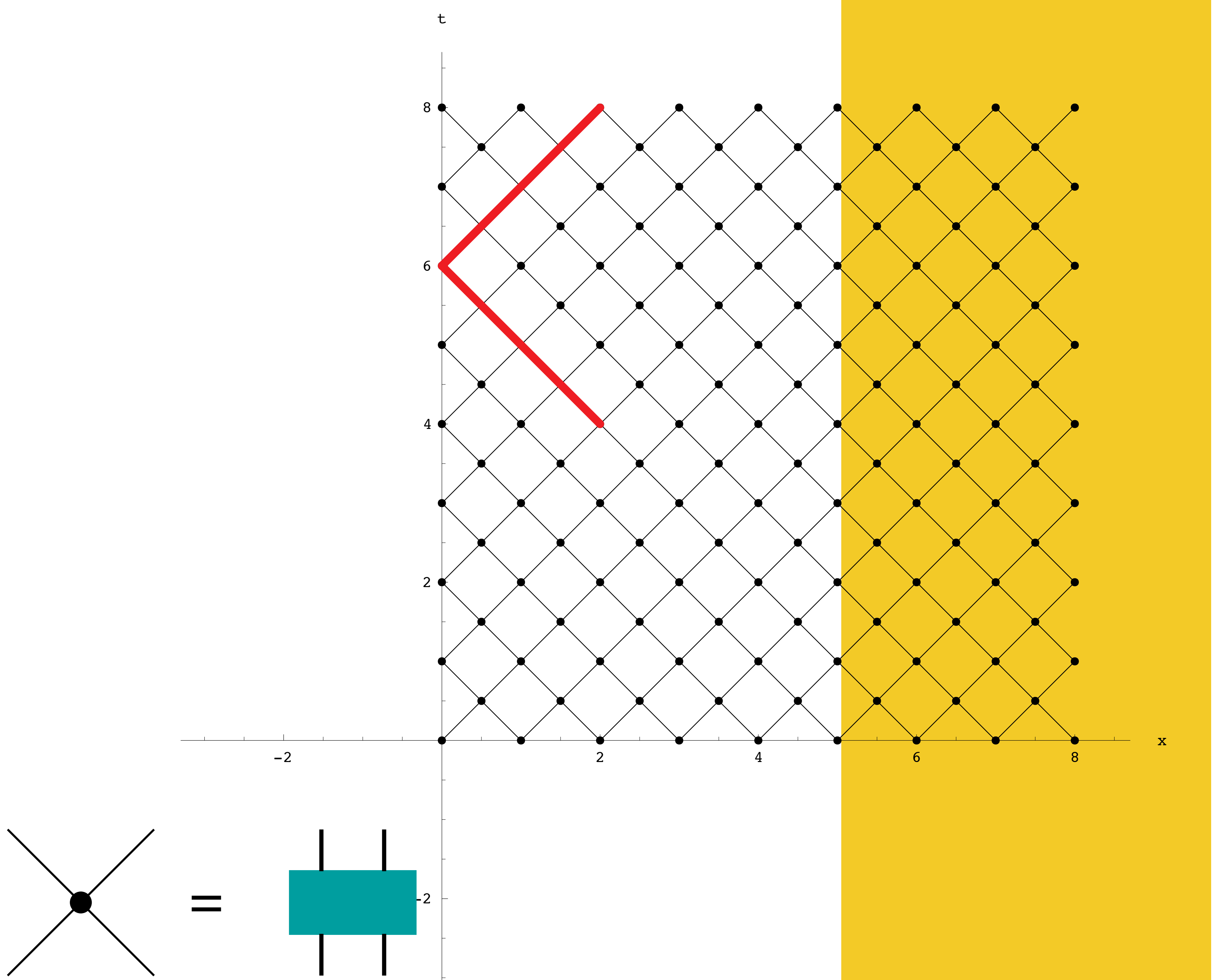


Time dilation and space contraction

Relativity from QT

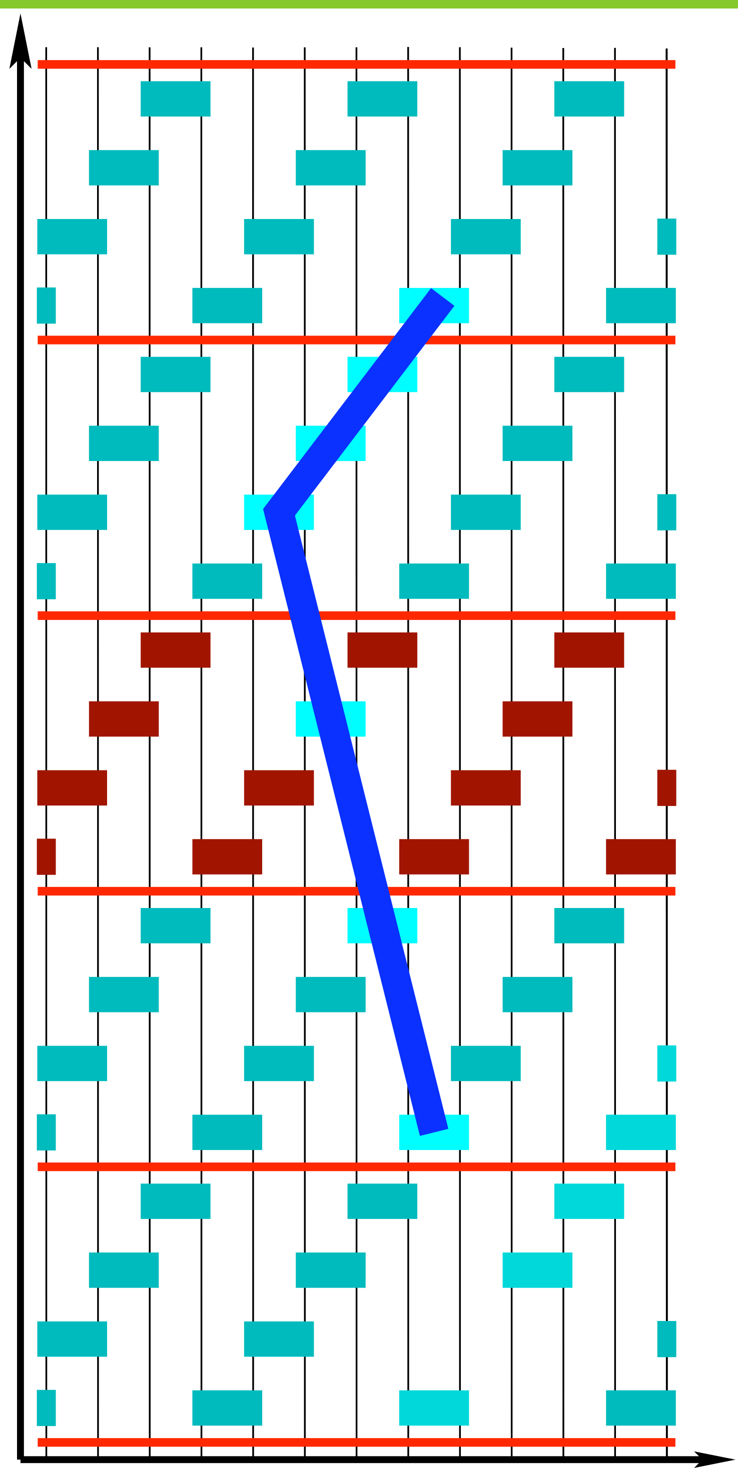
(from causality)

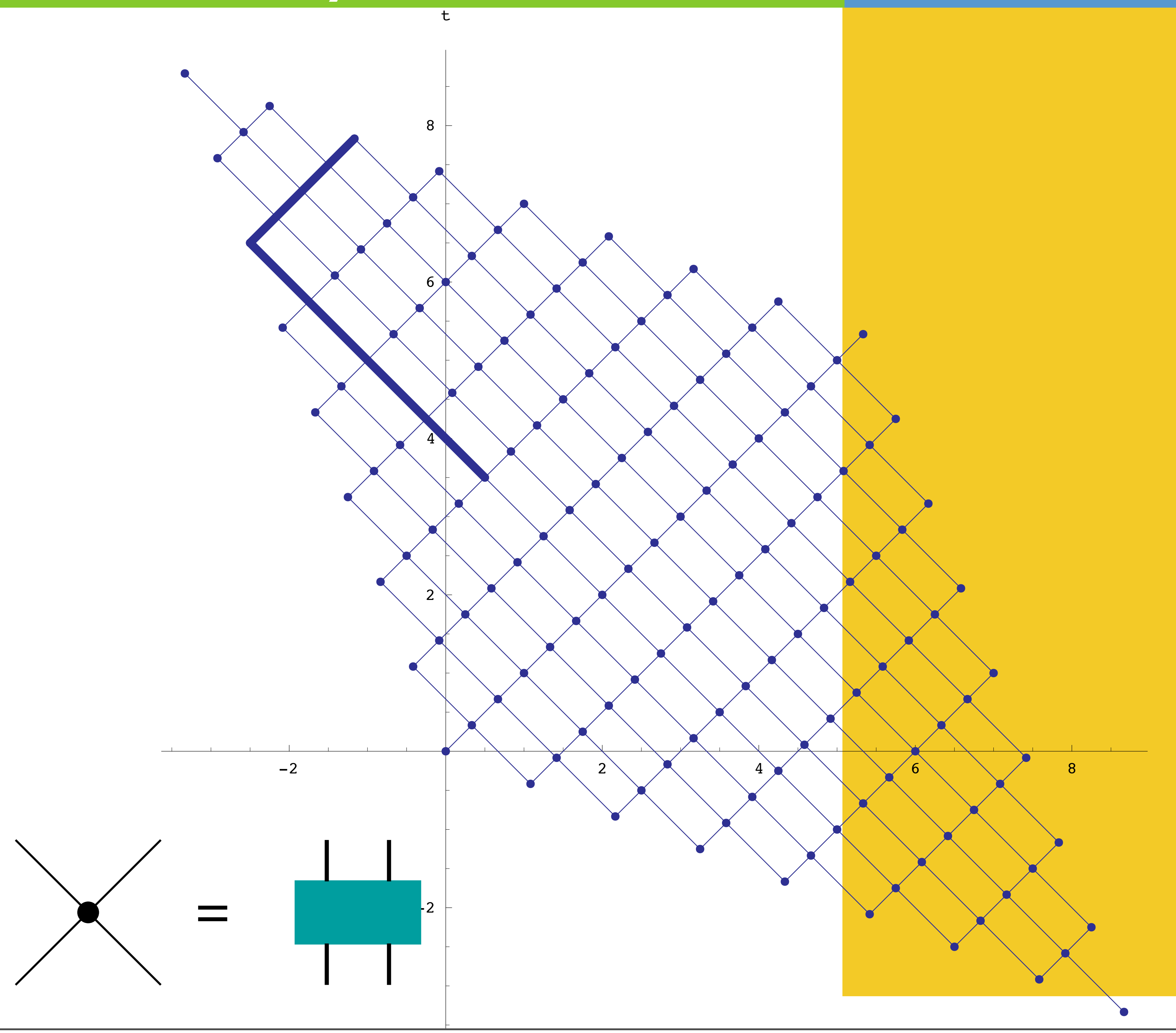




Relativity from QT

(from causality)





Relativity from QT

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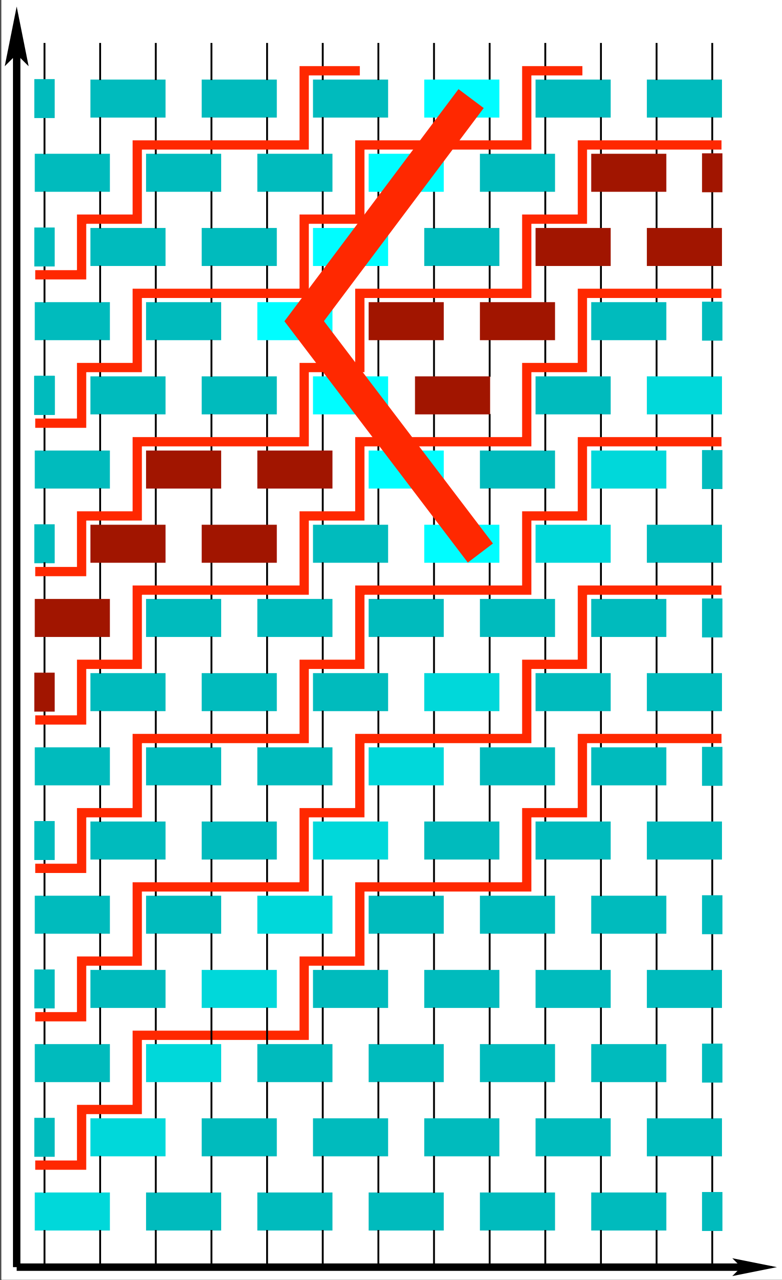
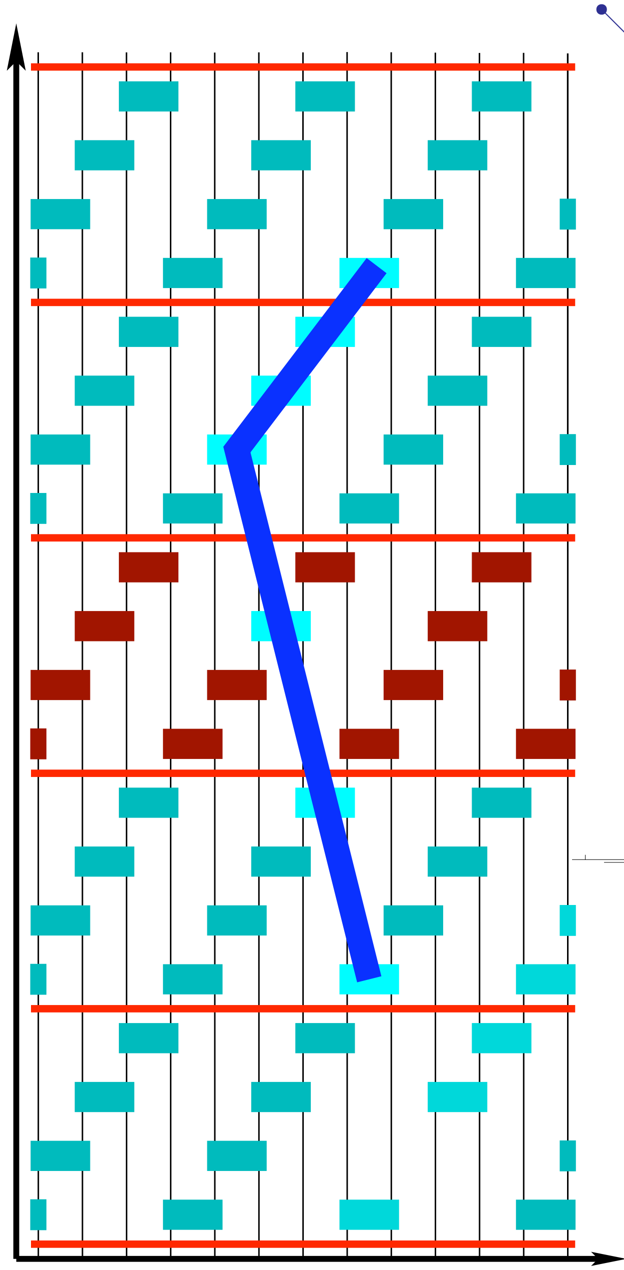
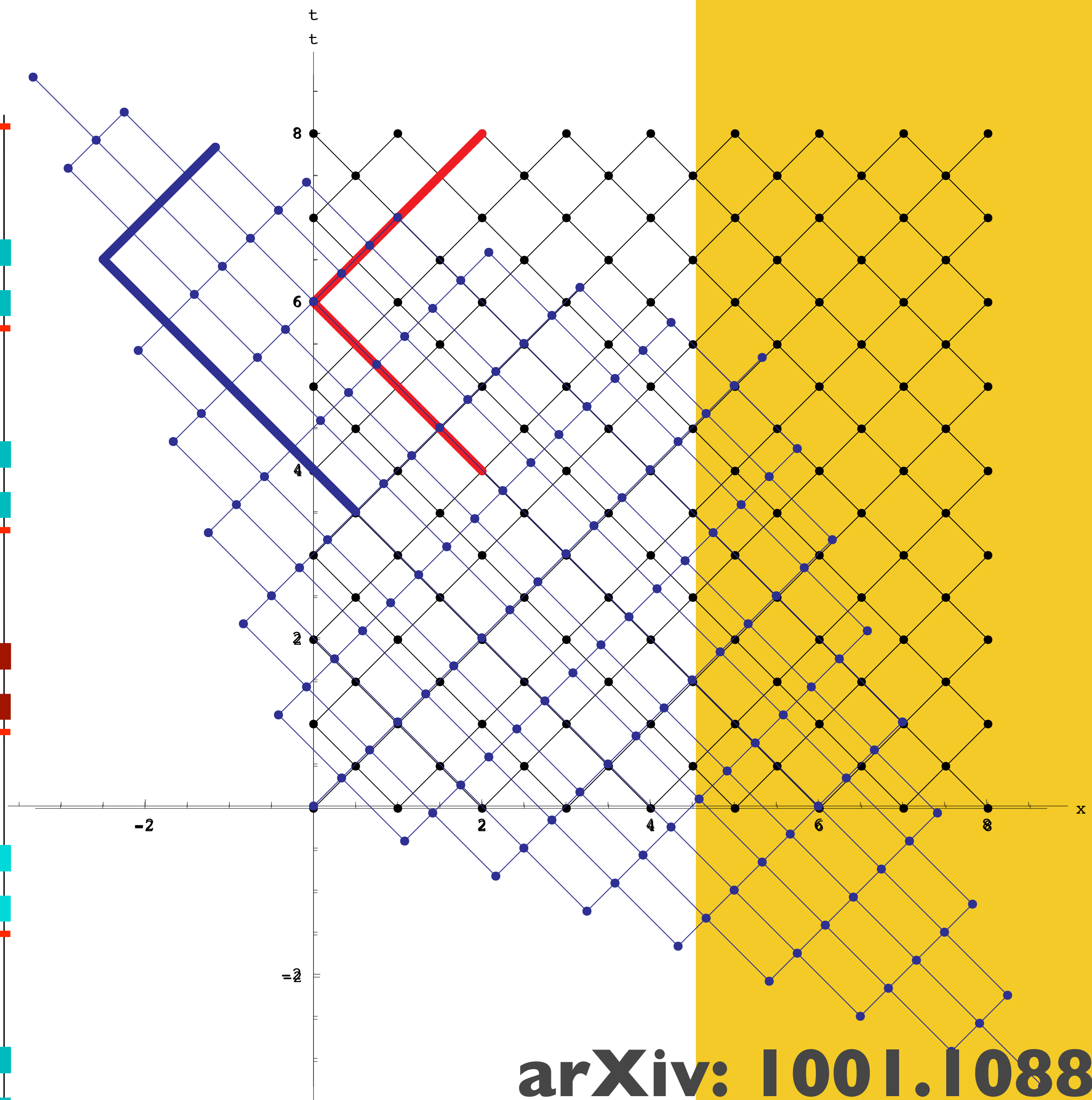






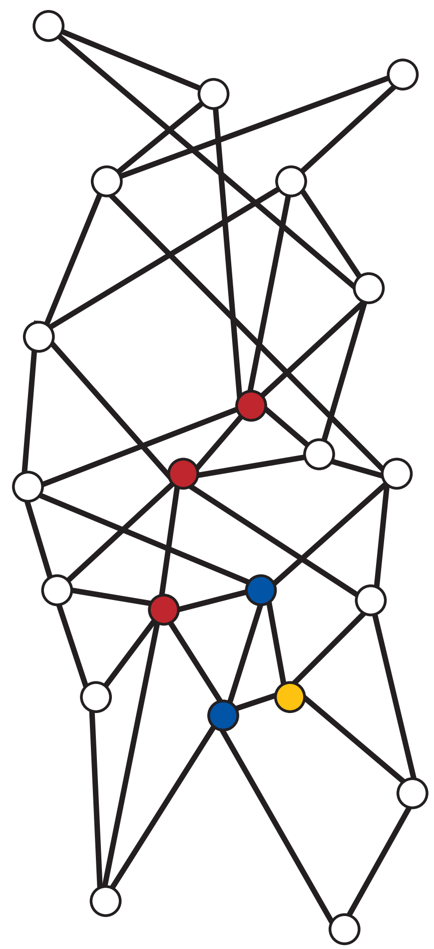
arXiv: 1001.1088

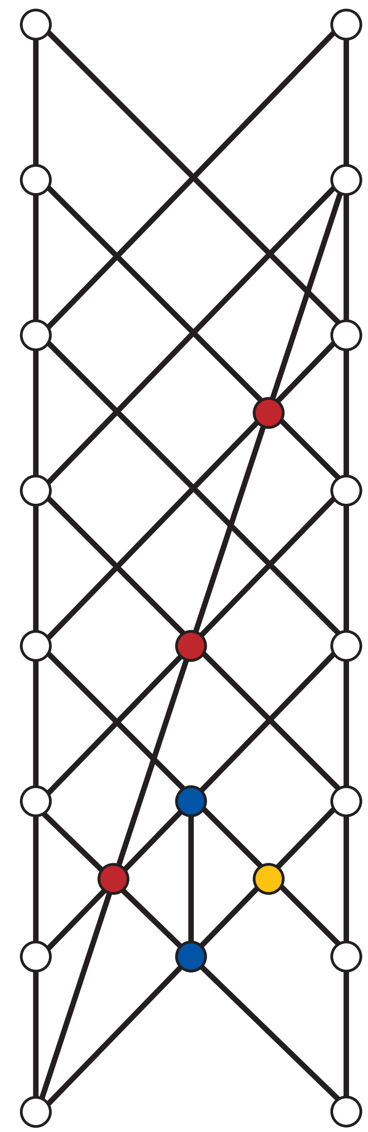
WE GOT RELATIVITY FROM PURE CAUSALITY!

WE GOT MUCH MORE:

FROM PURE CAUSALITY WE GOT SPACE AND TIME ENDOWED WITH RELATIVITY!

Relativity from causality

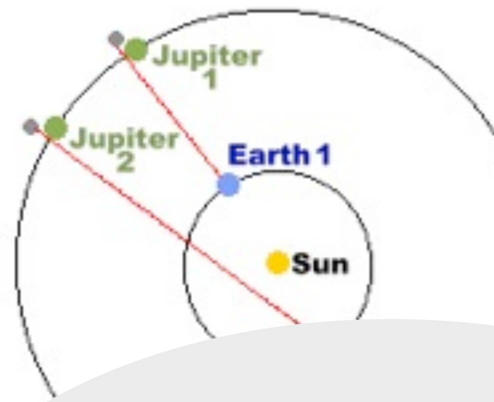


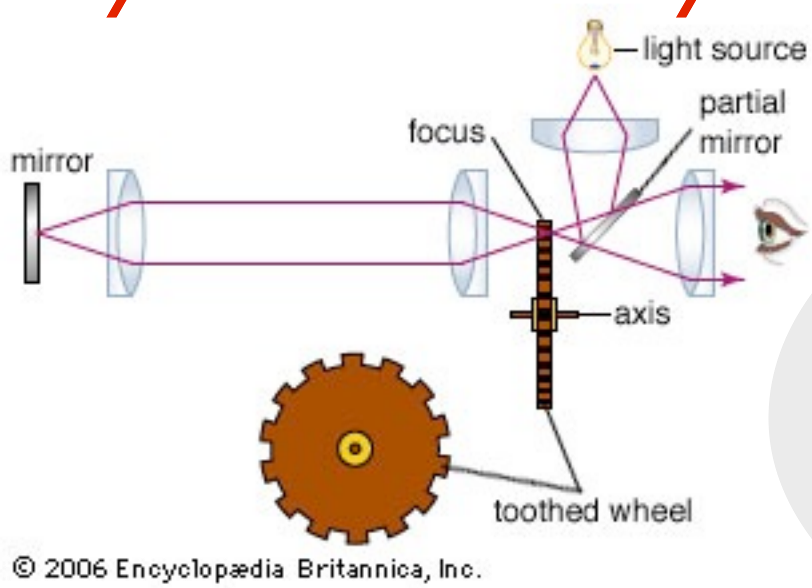


K. H. Knuth, N. Bahreyni, *A Derivation of Special Relativity from Causal Sets*, arXiv: 1005.4172<http://lanl.arxiv.org/abs/1005.4172v1> [math-ph] [v1] 23 May 2010

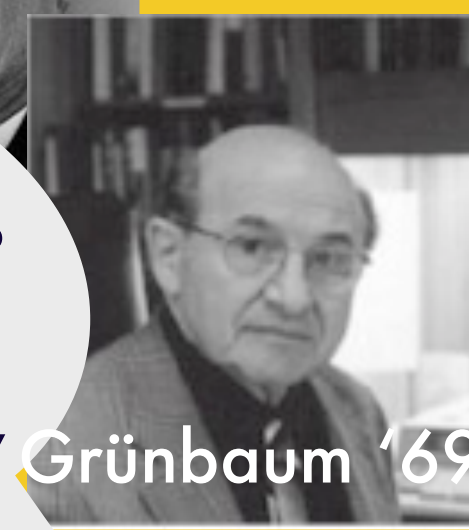
Conventionality of simultaneity, homogeneity, ...

The causal network manifests the *conventionality of simultaneity*.

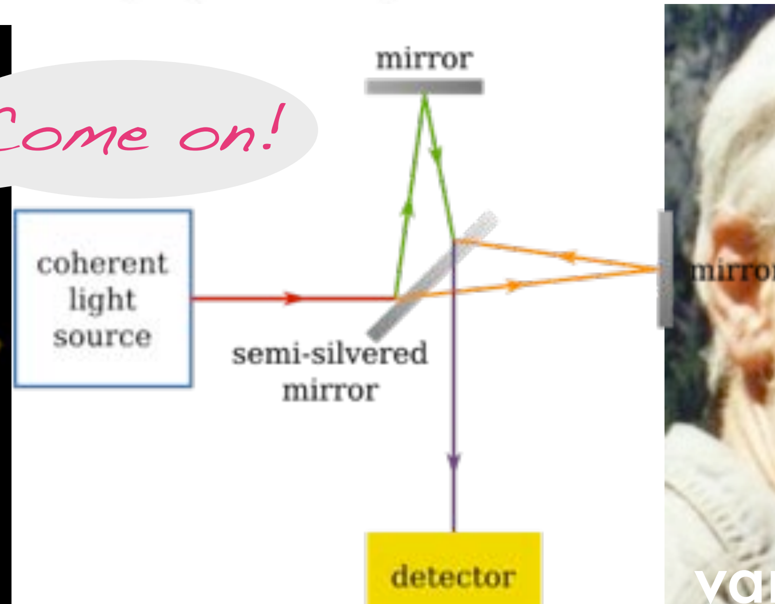




To determine simultaneity of distant events we need to know a speed, to measure a speed we need to know simultaneity of different events ... We can only determine the two-way average speed of light ...



Come on!



Relativity from QT

A theory of quantum gravity based on quantum computation

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Keywords: quantum computation, quantum gravity

Abstract: This paper proposes a method of unifying quantum mechanics and gravity based on quantum computation. In this theory, fundamental processes are described in terms of pairwise interactions between quantum degrees of freedom. The geometry of spacetime is a construct, derived from the underlying quantum information processing. The computation gives rise to a superposition of four-dimensional spacetimes, each of which obeys the Einstein-Regge equations. The theory makes explicit predictions for the back-reaction of the metric to computational 'matter,' black-hole evaporation, holography, and quantum cosmology.

Lorentz transformations from causality and topological homogeneity

GMD and
A. Tosini
1008.4805

Causal Network

SKIP

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Causal Network

A *causal set* is a set N of elements called events $a,b,c...,\in N$ equipped with a partial order relation $\preccurlyeq$ which is:

1. Reflexive: $\forall a \in N$ we have $a \preccurlyeq a$
2. Antisymmetric: $\forall a,b \in N$, we have $a \preccurlyeq b \preccurlyeq a \Rightarrow a = b$
3. Transitive: $\forall a,b,c \in N, a \preccurlyeq b \preccurlyeq c \Rightarrow a \preccurlyeq c$
4. Locally finite: $\forall a,c \in C$, $|\{b \in N : a \preccurlyeq b \preccurlyeq c\}| < \infty$

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causal network (CN): causal set unbounded in all directions

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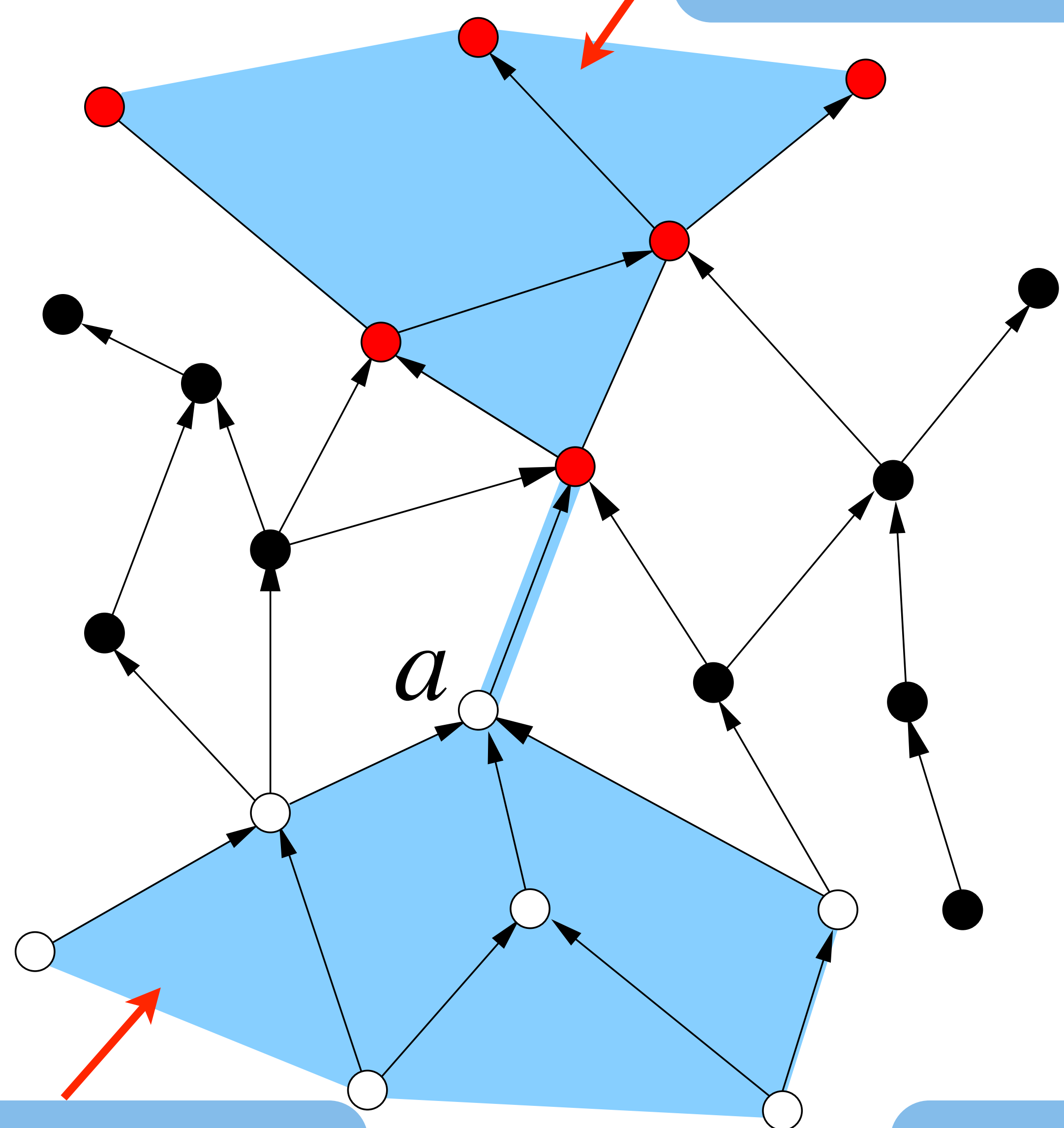
$$\mathsf{J}_a^+ := \{b \in : a \prec b\}$$



$$\mathsf{J}_a^- := \{b \in : b \prec a\}$$

$$\mathsf{J}_a := \mathsf{J}_a^- \cup \mathsf{J}_a^+$$

"Light" cones

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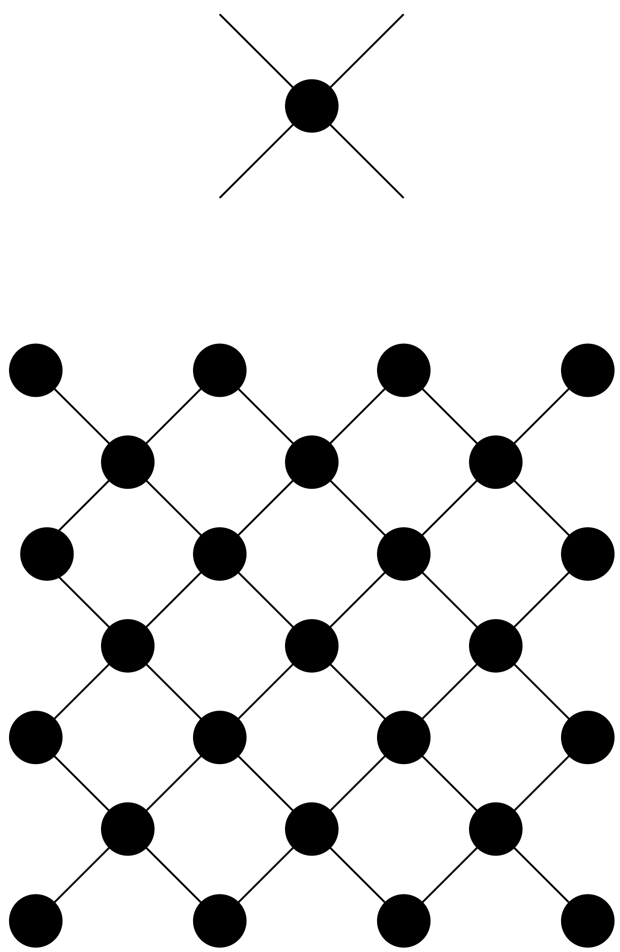
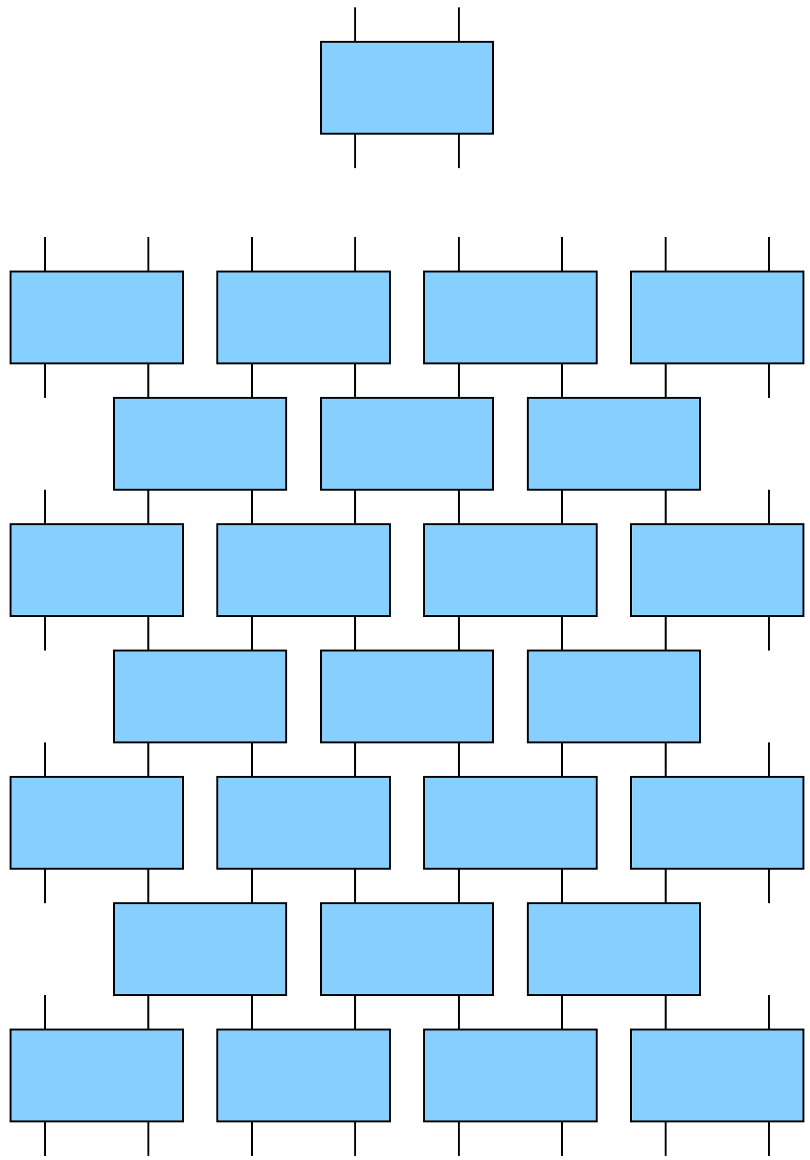


(Galileo principle)



topological homogeneity

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causal chain: $\mathsf{C}(a,b) := \{c_i\}_{i=1}^N$

with $a \equiv c_1 \prec c_2 \prec \ldots c_N \equiv b$

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

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

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

observer: $\mathsf{O}_a = \{o_i\}_{i\in\mathbb{Z}}$

with $o_i \preceq o_{i+1} \; \forall i \in \mathbb{Z}$ and $a = o_0$

Causal chain
= observer

We now define simultaneity of events a and b—denoted as $a \sim_{\mathsf{O}} b$—as follows

$$a \sim_{\mathsf{O}} b \Leftarrow \inf_{b^* \in \mathsf{J}_b^+} |\mathsf{O}_a(a, b^*)|_\pm = \inf_{a^* \in \mathsf{J}_a^+} |\mathsf{O}_b(b, a^*)|_\pm. \quad (2)$$

Depending on the shape of the observer chain, one may have situations in which there are no synchronous events. However, it is easy to see that for an observer that is topologically homogeneous (i. e. periodic) there always exist infinitely many simultaneous events. Moreover, modulo event coarse-graining, without loss of generality we can restrict only to observers with a zig-zag with a single period, with $\alpha \geq 1$ steps to the right and $\beta \geq 1$ steps to the left (we will call them *simply periodic*). Each ziz-zag

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Simultaneity

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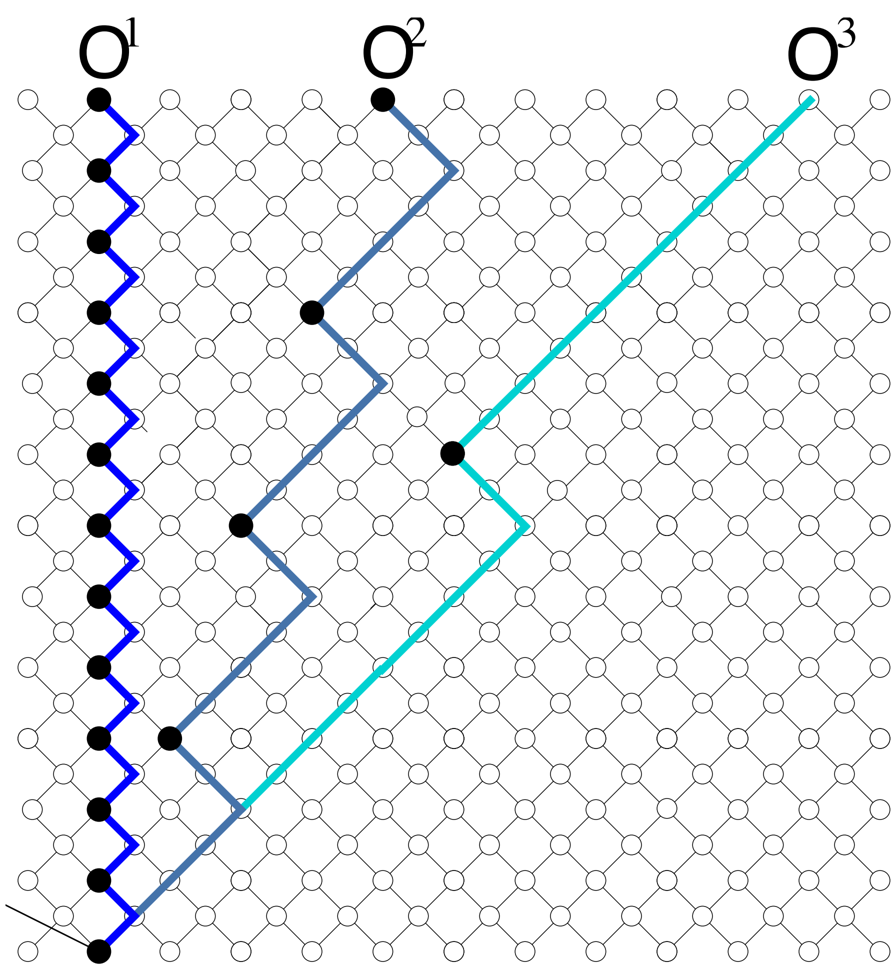

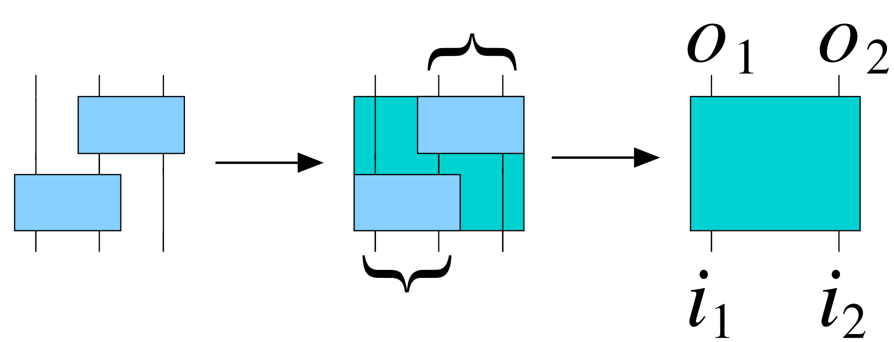

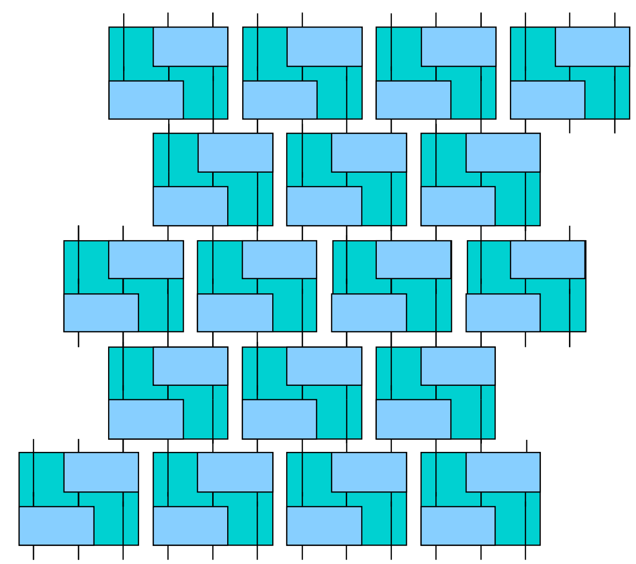

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Foliation

The given notion of simultaneity allows us to associate each observer with a *foliation* of the CN. For each event $o_i \in \mathsf{O}_a$ there is a *leaf* $\mathsf{L}_i(\mathsf{O}_a)$, which is the set of events simultaneous to o_i with respect to the observer O_a, namely

$$\mathsf{L}_i(\mathsf{O}_a) := \{b \in \mathsf{N} : a \sim_{\mathsf{O}} o_i\}. \tag{3}$$

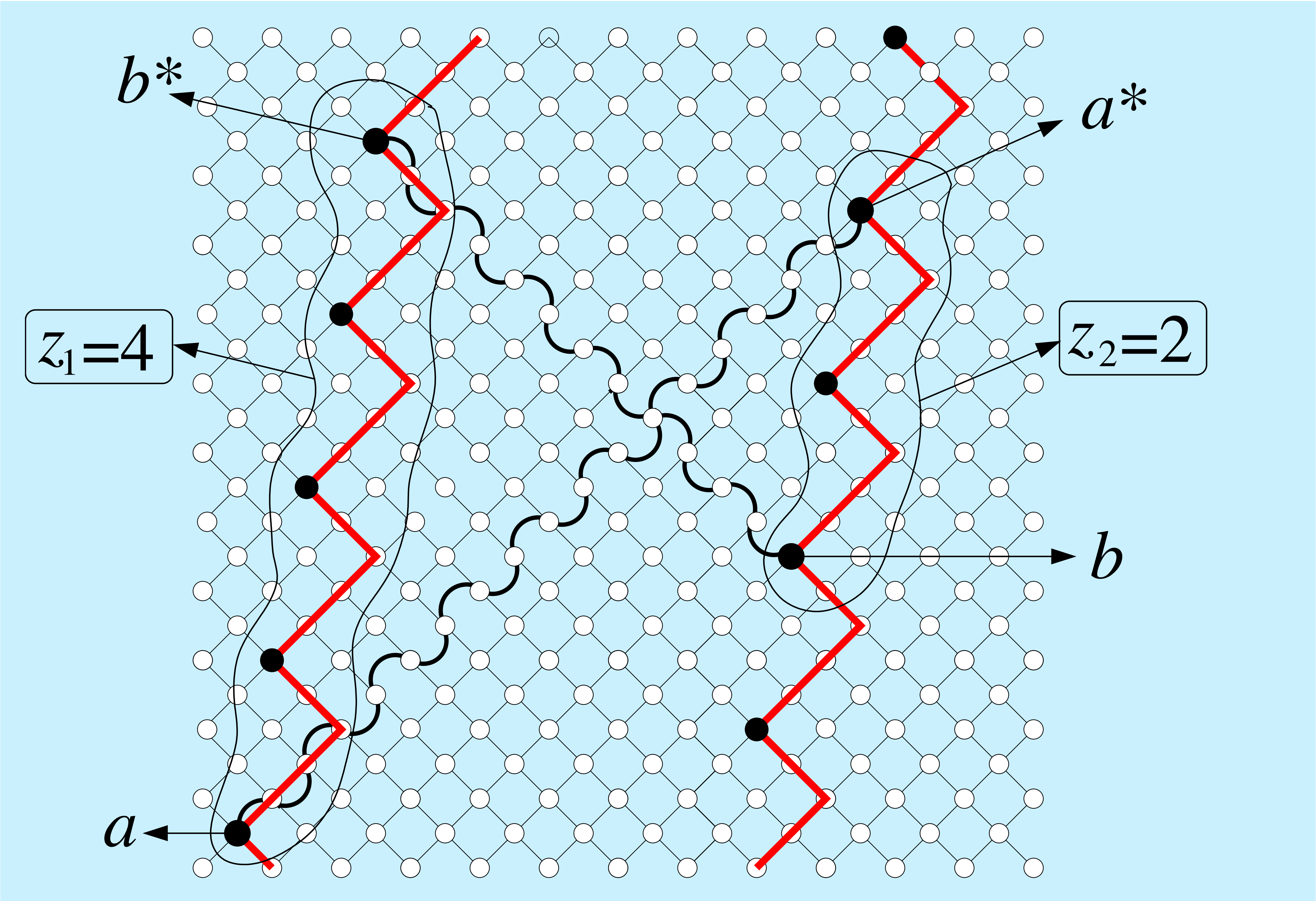
The collection of all leaves for all the events in O_a is the *foliation* $\mathsf{L}(\mathsf{O}_a)$ of N associated to the observer O_a

$$\mathsf{L}(\mathsf{O}_a) := \{\mathsf{L}_i(\mathsf{O}_a), \forall i \in \mathbb{Z}\}. \tag{4}$$

For a given foliation $\mathsf{L}(\mathsf{O}_a)$ we can now define a pair of coordinates $\mathbf{z}(b)$ for any event $b \in \mathsf{L}(\mathsf{O}_a)$ via the map

$$K_{\mathsf{O}_a} : \mathsf{N} \to \mathbb{Z}^2, \quad b \mapsto K_{\mathsf{O}_a}(b) := \mathbf{z}(b) = \begin{bmatrix} z_1(b) \\ z_2(b) \end{bmatrix},$$

$$z_1(b) := \inf_{b^* \in \mathsf{J}_b^+} |\mathsf{O}_a(a, b^*)|_\pm, \quad z_2(b) := \inf_{a^* \in \mathsf{J}_a^+} |\mathsf{O}_b(b, a^*)|_\pm.$$



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Coordinates

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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 $\mathsf{L}(\mathsf{O}_a)$.

Coordinates

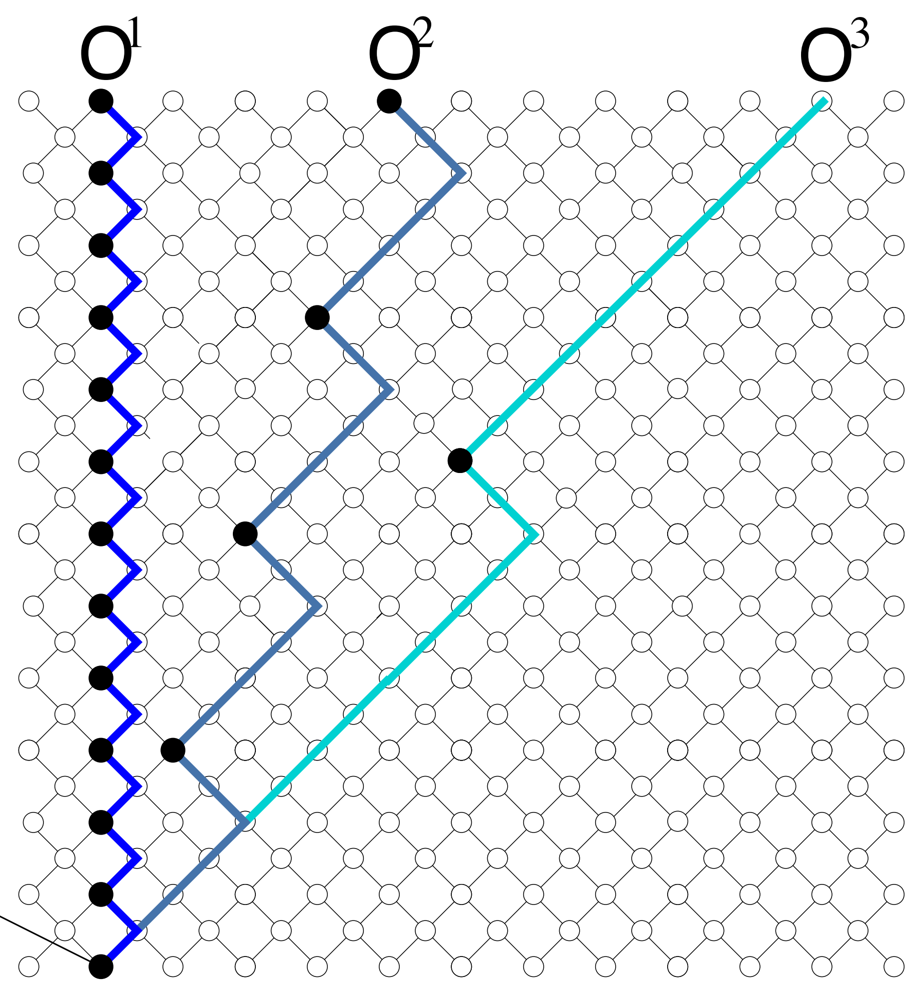
Frames in standard configuration (boosted). Consider now two observers $\mathsf{O}^1_a = \{o^1_i\}$ and $\mathsf{O}^2_a = \{o^2_j\}$ sharing the same origin (homogeneity guarantees the existence of observers sharing the origin). We will shortly denote the two frames as $\mathfrak{R}^1$ and $\mathfrak{R}^2$, 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 $\forall i \in \mathbb{Z}$

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

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

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

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



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

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Boosts

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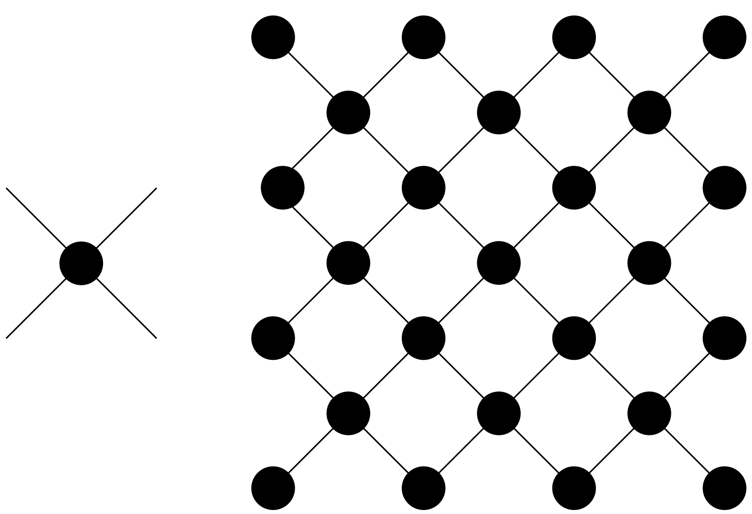
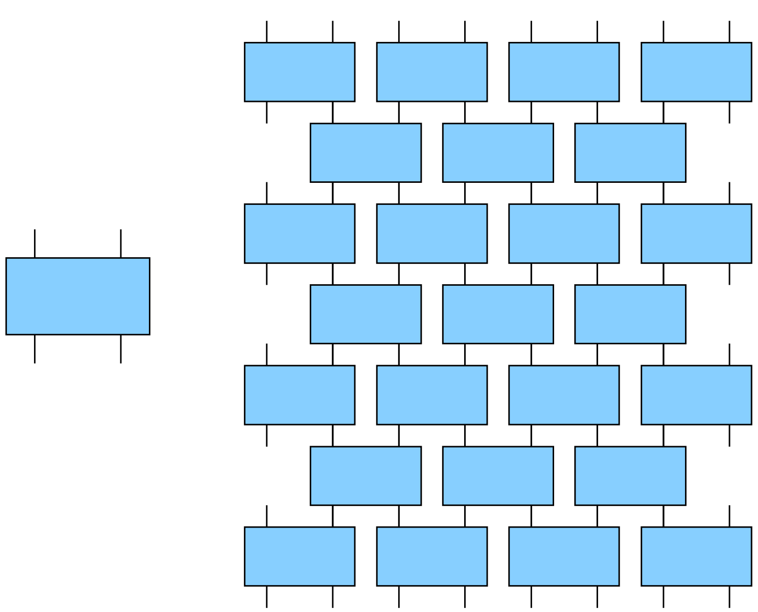
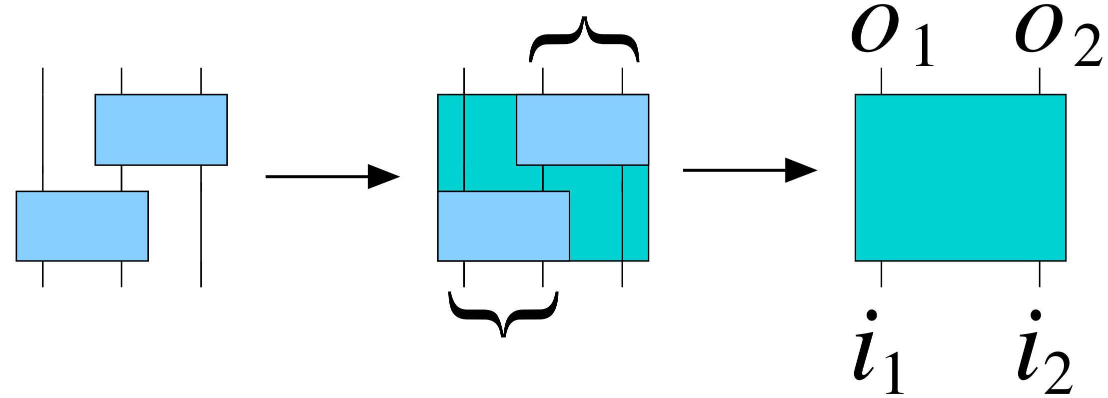
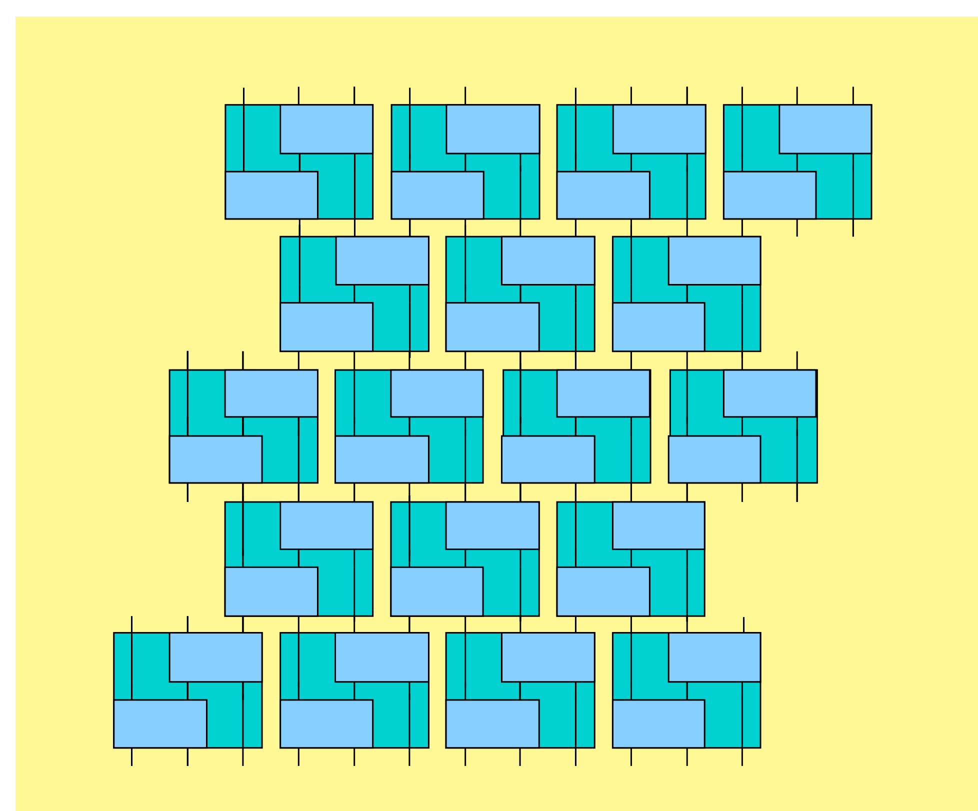
Coarse-graining









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

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

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

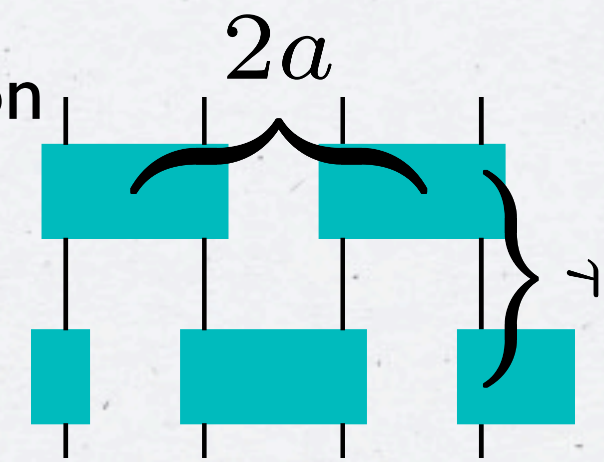
which differ from the Lorentz transformations only by the multiplicative factor χ_{12}. The factor χ_{12} can be removed by rescaling the coordinate map in Eq. (10) using the factor $(2\alpha\beta)^{\frac{1}{2}}$ in place of $2^{\frac{1}{2}}$, with the constants α and β

Coordinates

SIMULATING QFT

Simple scalar fields in 1 space dimension

★ ★ ★ ★ ★ ★ ★ ★



a ***topon*** space-granularity (minimal in principle discrimination between independent events);

τ ***chronon*** time-granularity;

$\phi(x)$: field, operator function of space (evolving in time); we will describe it by the set of operators $\phi_n := a^{\frac{1}{2}}\phi(na)$

ϕ_n generally nonlocal operators. In QFT they satisfy (anti)commutation relations

Microcausality (equal time)

$$[\phi_n^\dagger, \phi_m]_\pm = \delta_{nm}$$

+ : *Fermi*

- : *Bose* (Newton-Wigner)

CAUSAL SPEED

$$v_c := \frac{a}{\tau}$$

Quantum-computational simulation of QFT

PROBLEM with QFT: "violation" of Einstein causality

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

the simulation gives back exactly QFT in the limit $\tau, a \to 0$ and for infinite circuit, but ...

$$v_c = \infty!$$

Galileo!

Einstein causality only in average!

Lorentz-covariance is not a consequence of QM (causality)!

THE NEW QCFT

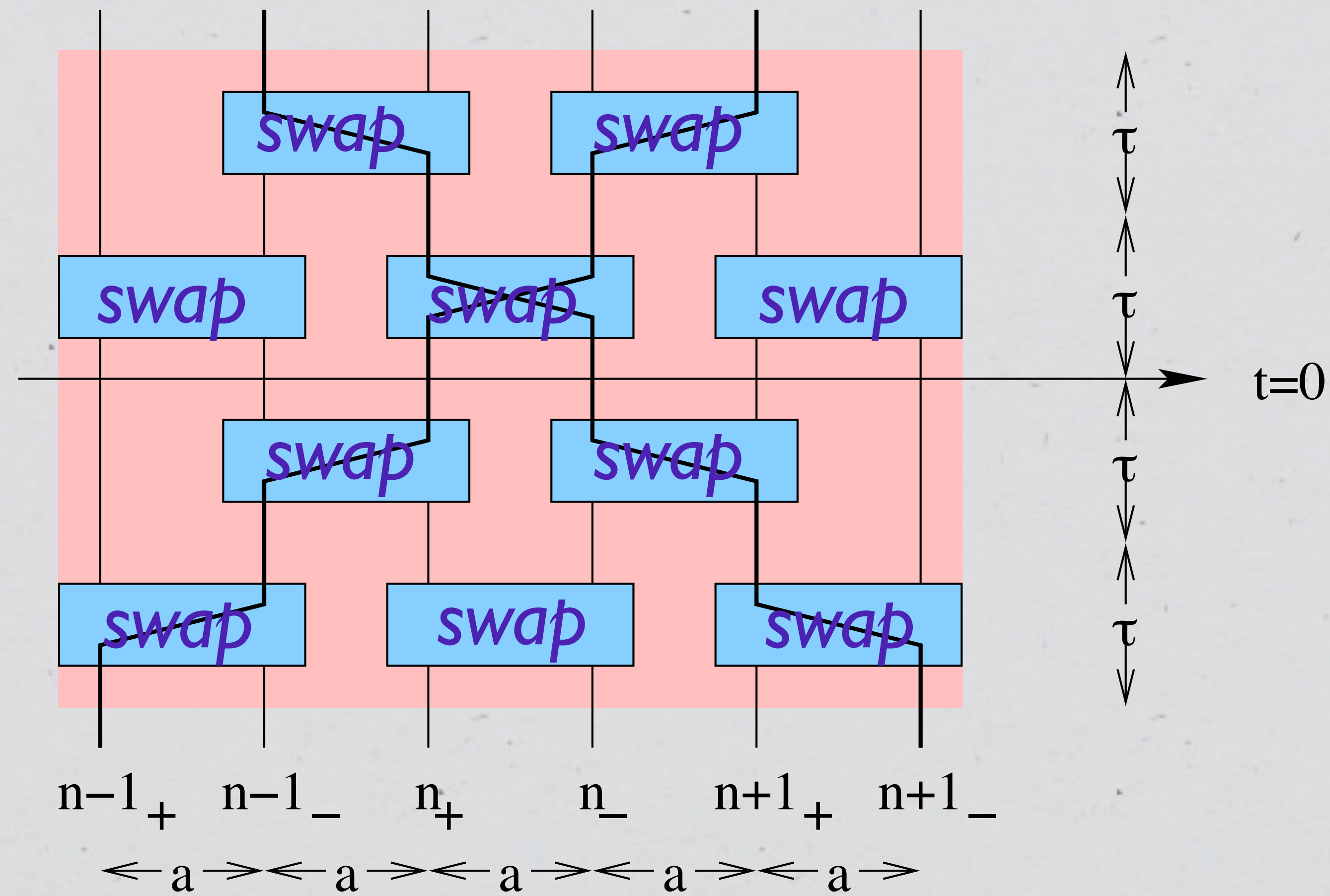
Finite gate-transformations (not infinitesimal!)

The causal speed v_c is finite!

Lorentz's transformations emerge from the causal network

Different QFT

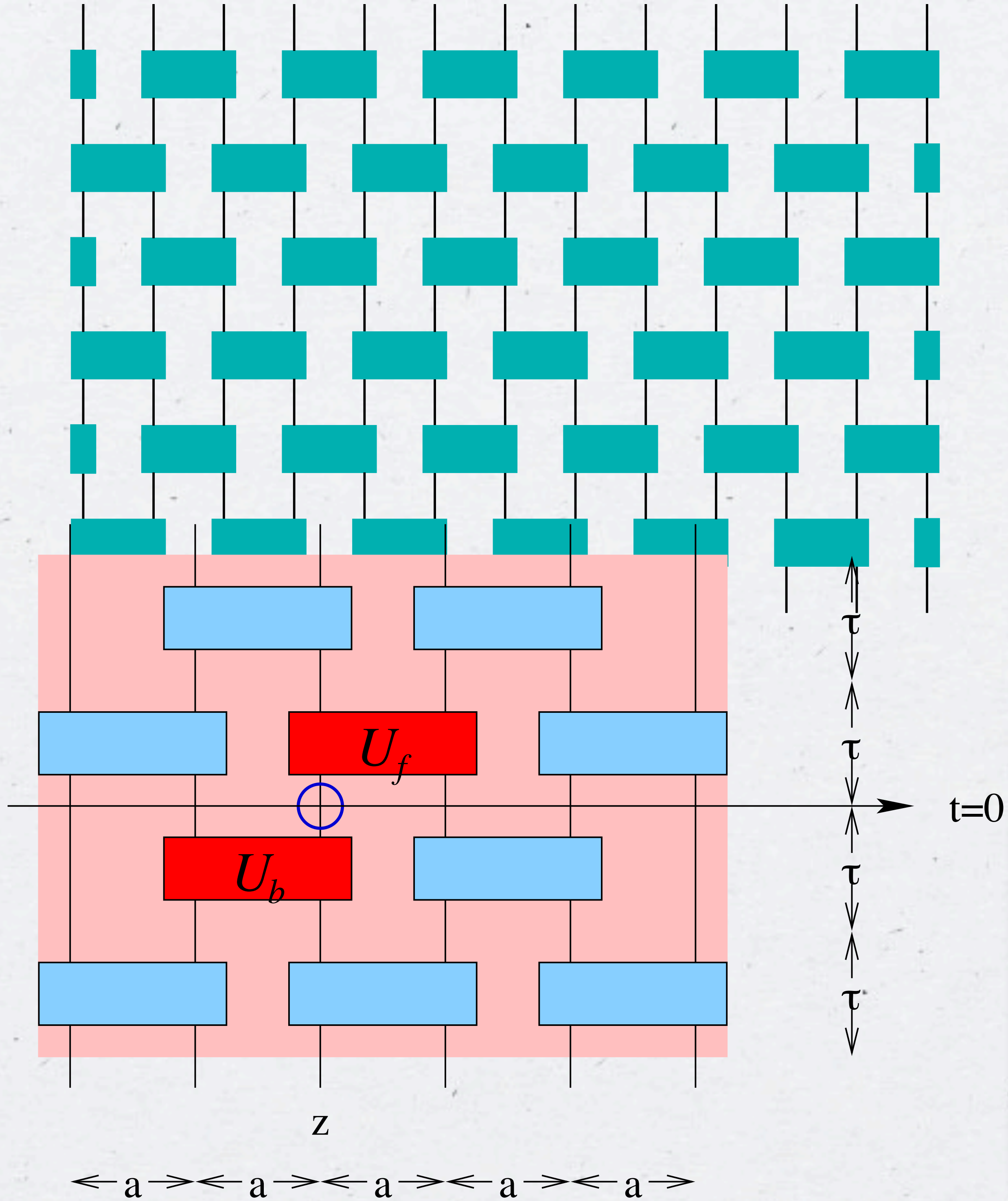
observational consequences!



THE NEW QCFT

Simple scalar fields in 1 space dimension

★ ★ ★ ★ ★ ★ ★ ★



Coarse-grained discrete derivatives:

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

$$\widehat{\partial}_x = \frac{1}{2ka}(\delta_+^k - \delta_-^k)$$

"HAMILTONIAN"

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

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

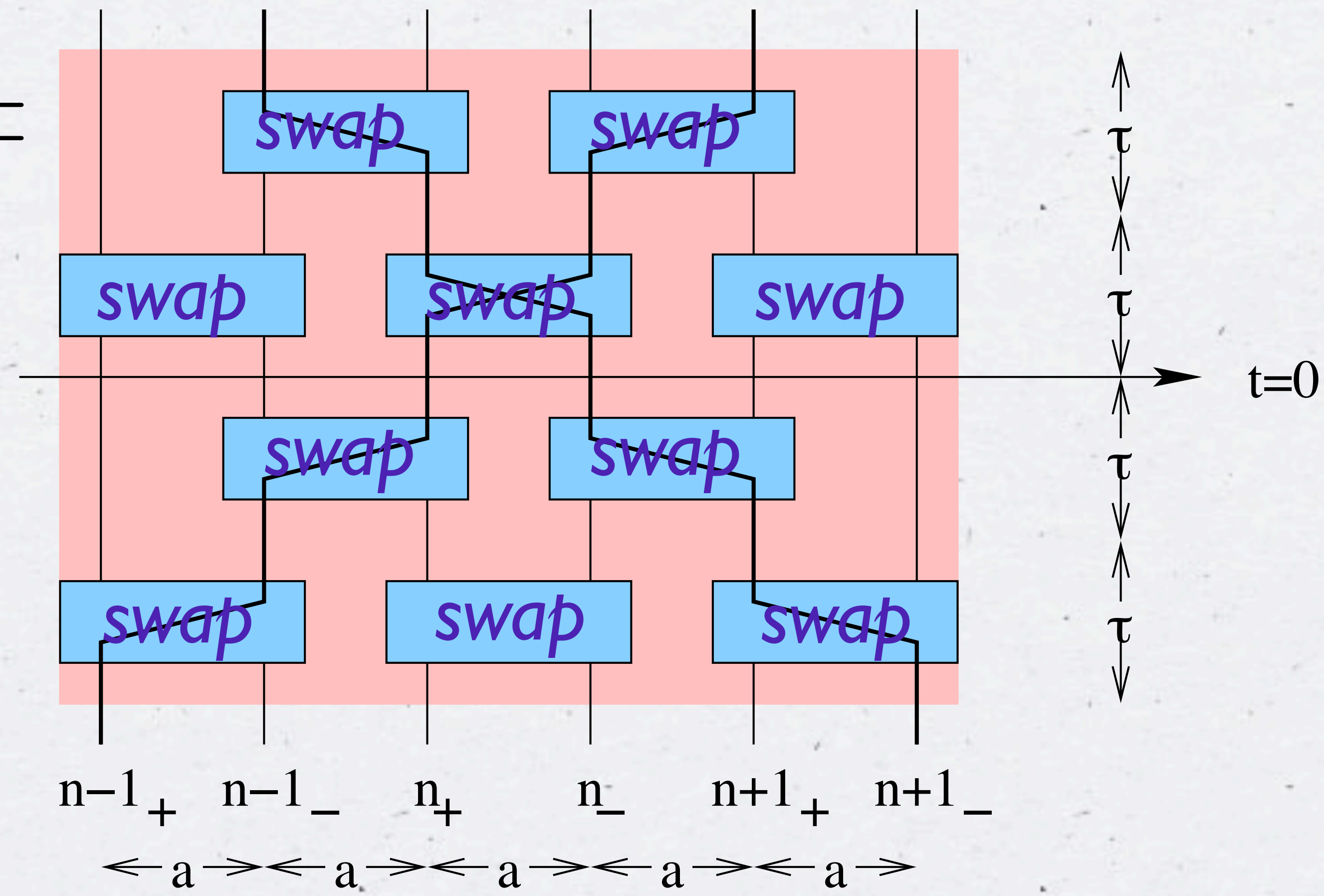
THE NEW QCFT

MASSLESS KLEIN GORDON FIELD

NEW QFT: *finite gate-transformations (not infinitesimal!)*

$$\phi_n^+(\pm 2\tau) = \phi_{n\pm 1}^+(0), \quad \phi_n^-(\pm 2\tau) = \phi_{n\mp 1}^-(0)$$

$$\mathrm{H}_{\mathrm{gate}}^{(4)}\phi_n^\alpha = i\alpha v_c \widehat{\partial}_x \phi_n^\alpha, \; \alpha = \pm$$



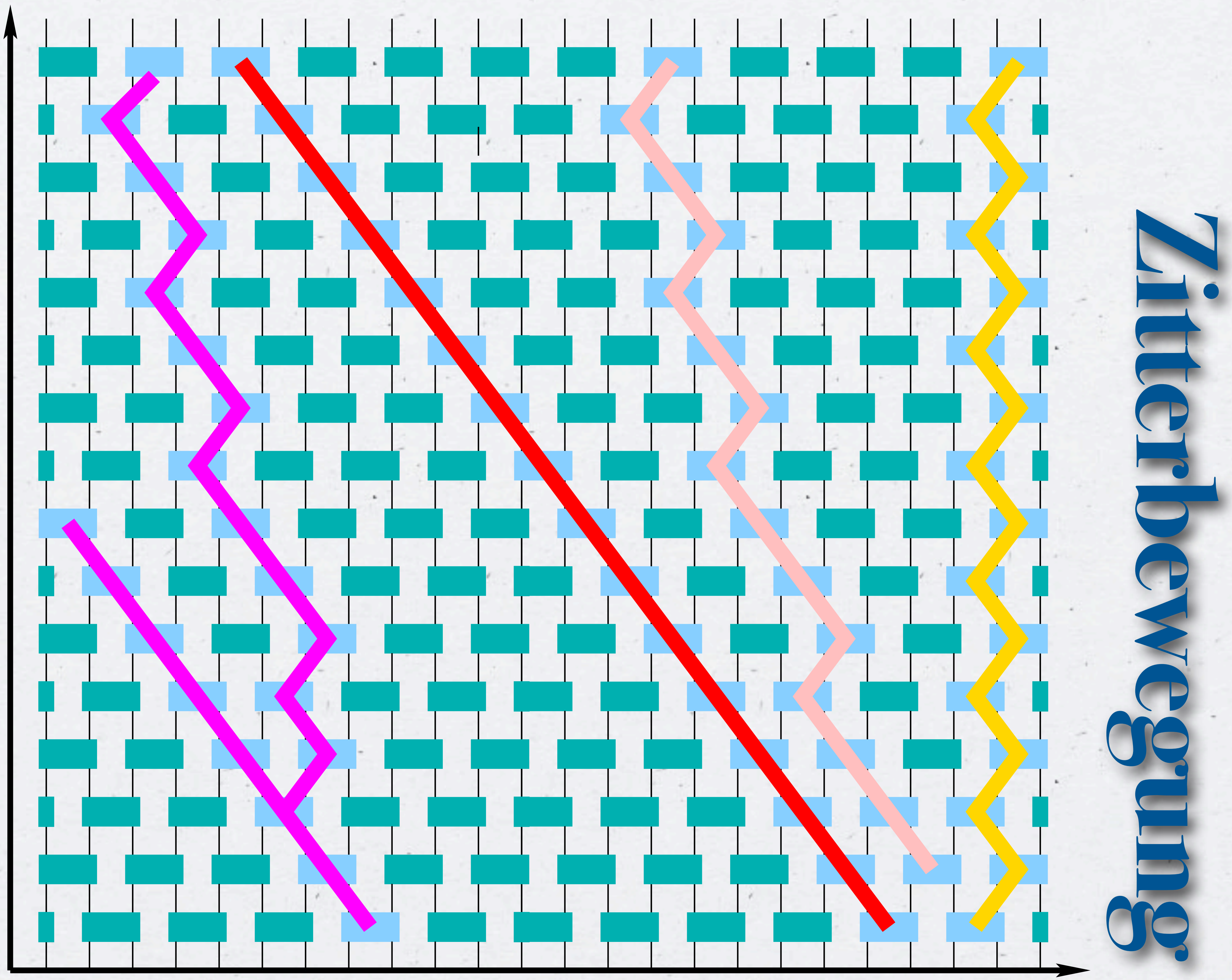
$$\mathrm{H}_{\mathrm{gate}}^{(4)}\boldsymbol{\phi}_n = i\sigma_z v_c \widehat{\partial}_x \boldsymbol{\phi}_n$$

$$\boxed{\widehat{\Box}\boldsymbol{\phi}_n = 0}$$

$$\widehat{\Box} = \widehat{\partial}_x^2 - \frac{1}{v_c^2}\widehat{\partial}_t^2$$

THE NEW QCFT

KLEIN GORDON WITH MASS



What is inertial mass?

THE NEW QCFT

KLEIN GORDON WITH MASS

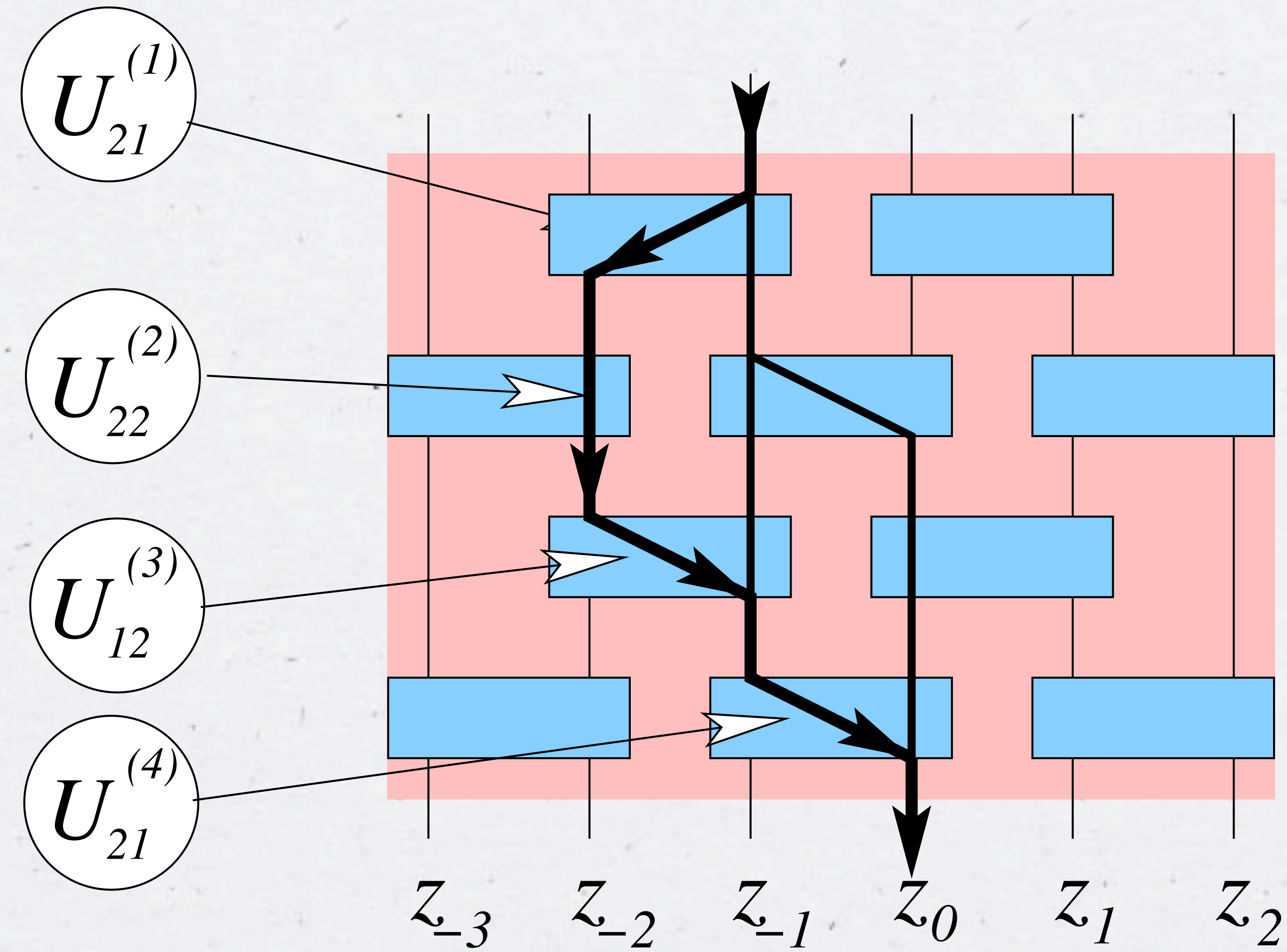
We need to develop a *path-sum calculus* over the circuit:

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



$$z_l(t) = \sum_{\mathbf{i}_{kl}} U^{(1)}_{i_1 i_2} U^{(2)}_{i_2 i_3} \dots U^{(n)}_{i_n i_{n+1}} z_k(0)$$

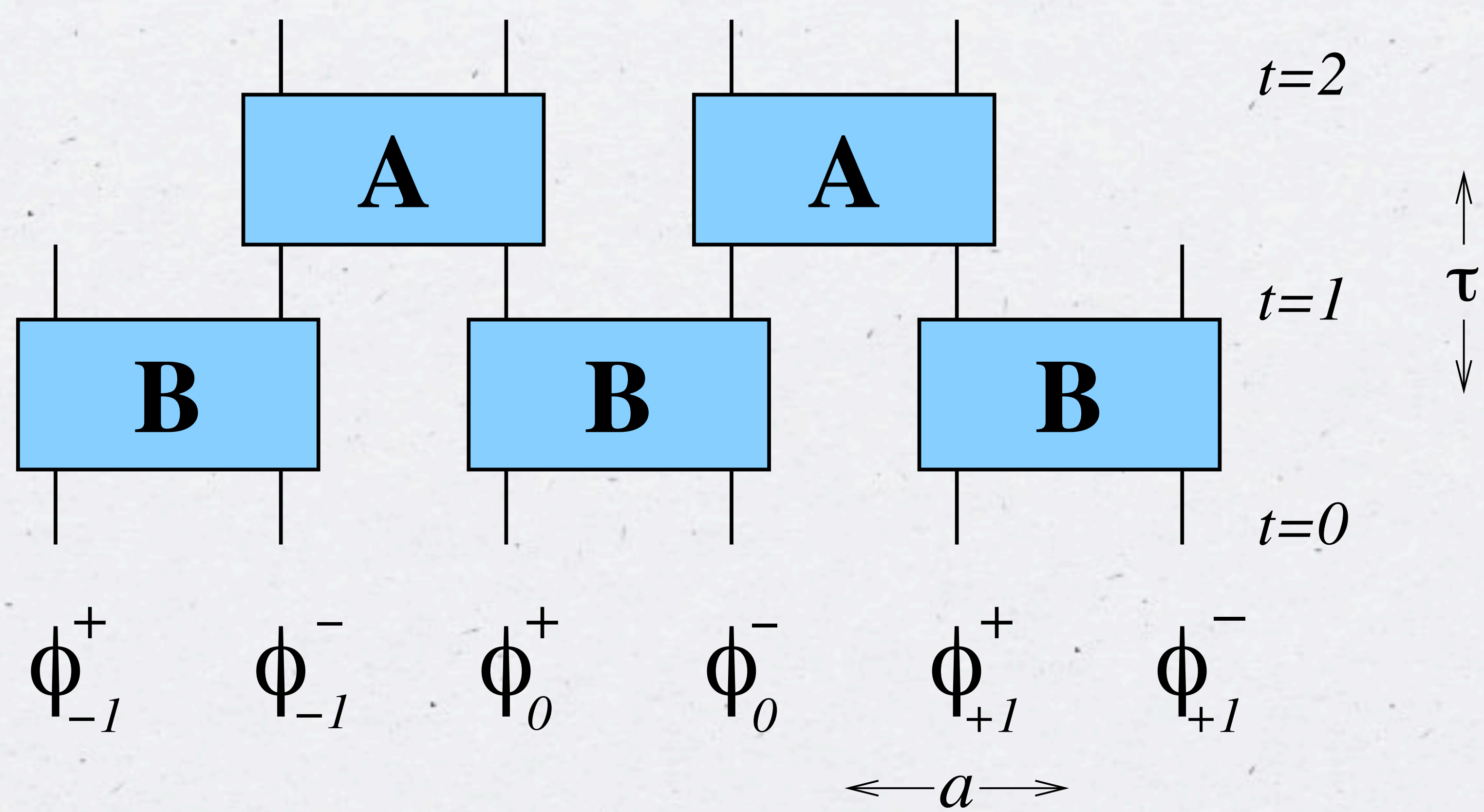
$\mathbf{i}_{kl} = (i_1 i_2 \dots i_n i_{n+1})$ with $i_1 = k,\ i_{n+1} = l,$

THE NEW QCFT

KLEIN GORDON WITH MASS

"Hamiltonian"

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



THE NEW QCFT

KLEIN GORDON WITH MASS

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Hermiticity is satisfied:

$$\begin{aligned}
\langle\phi^\pm_n|\mathrm{H}^{(4)}_{\mathrm{gate}}|\phi^\pm_n\rangle = \langle\phi^\pm_n|\mathrm{H}^{(4)}_{\mathrm{gate}}|\phi^\pm_n\rangle^* &\Longrightarrow i(A_{aa}B_{bb} - A^\dagger_{aa}B^\dagger_{bb}) \in \mathbb{R}, \\
\langle\phi^\pm_n|\mathrm{H}^{(4)}_{\mathrm{gate}}|\phi^\mp_n\rangle = \langle\phi^\mp_n|\mathrm{H}^{(4)}_{\mathrm{gate}}|\phi^\pm_n\rangle^* &\Longrightarrow (A_{22}B_{12} - A^\dagger_{11}B^\dagger_{12}) = -(A_{11}B_{21} - A^\dagger_{22}B^\dagger_{21})^*, \\
\langle\phi^\pm_{n+1}|\mathrm{H}^{(4)}_{\mathrm{gate}}|\phi^\pm_n\rangle = \langle\phi^\pm_n|\mathrm{H}^{(4)}_{\mathrm{gate}}|\phi^\pm_{n+1}\rangle^* &\Longrightarrow A^\dagger_{ab}B^\dagger_{ab} = A^*_{ba}B^*_{ba}, \\
\langle\phi^+_n|\mathrm{H}^{(4)}_{\mathrm{gate}}|\phi^-_{n-1}\rangle = \langle\phi^-_n|\mathrm{H}^{(4)}_{\mathrm{gate}}|\phi^+_{n+1}\rangle^* &\Longrightarrow A_{21}B_{22} - A^\dagger_{21}B^\dagger_{11} = -(A_{12}B_{11} - A^\dagger_{12}B^\dagger_{22})^*.
\end{aligned}$$

THE NEW QCFT

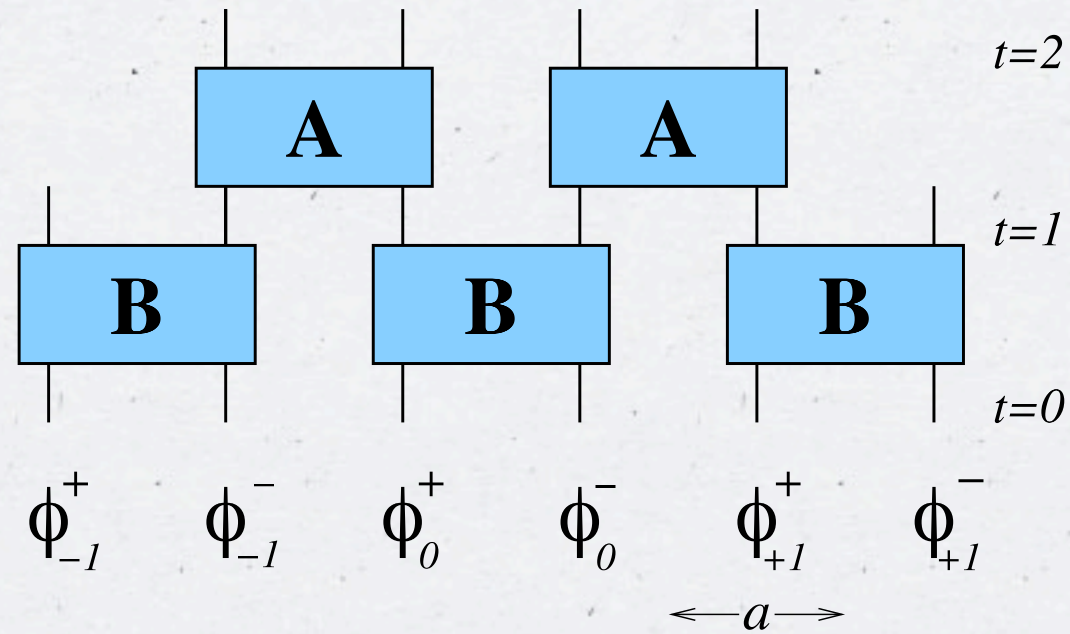
KLEIN GORDON WITH MASS (SPINLESS DIRAC)

Write the "Hamiltonian" as follows:

(inverse) refraction index

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

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



THE NEW QCFT

KLEIN GORDON WITH MASS (SPINLESS DIRAC)

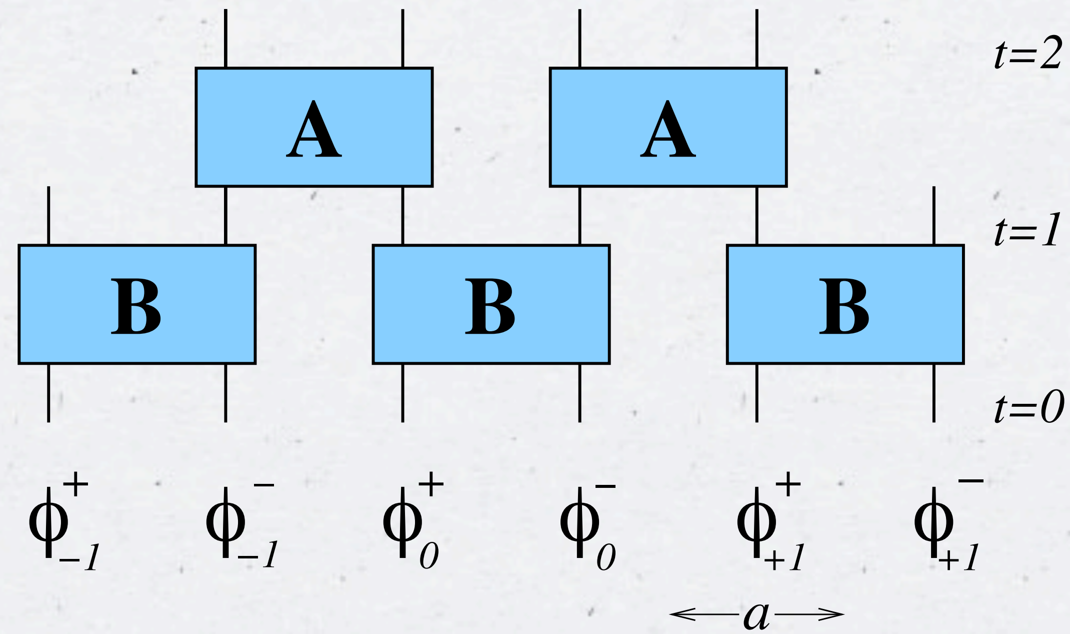
★ ★ ★ ★ ★ ★ ★ ★

Write the “Hamiltonian” as follows:

(inverse) refraction index

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

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



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

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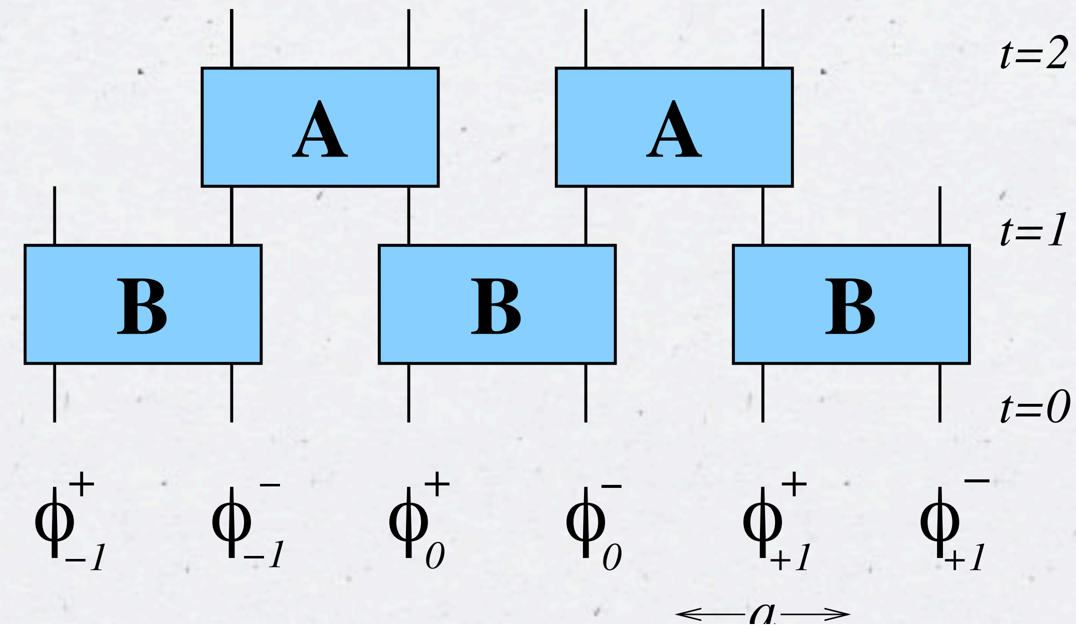

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$$\sin\theta = \zeta = \sqrt{1 - \left(\frac{2a}{\lambda}\right)^2}$$

MASS-DEPENDENT REFRACTION INDEX OF VACUUM

General phenomenon due to unitariety

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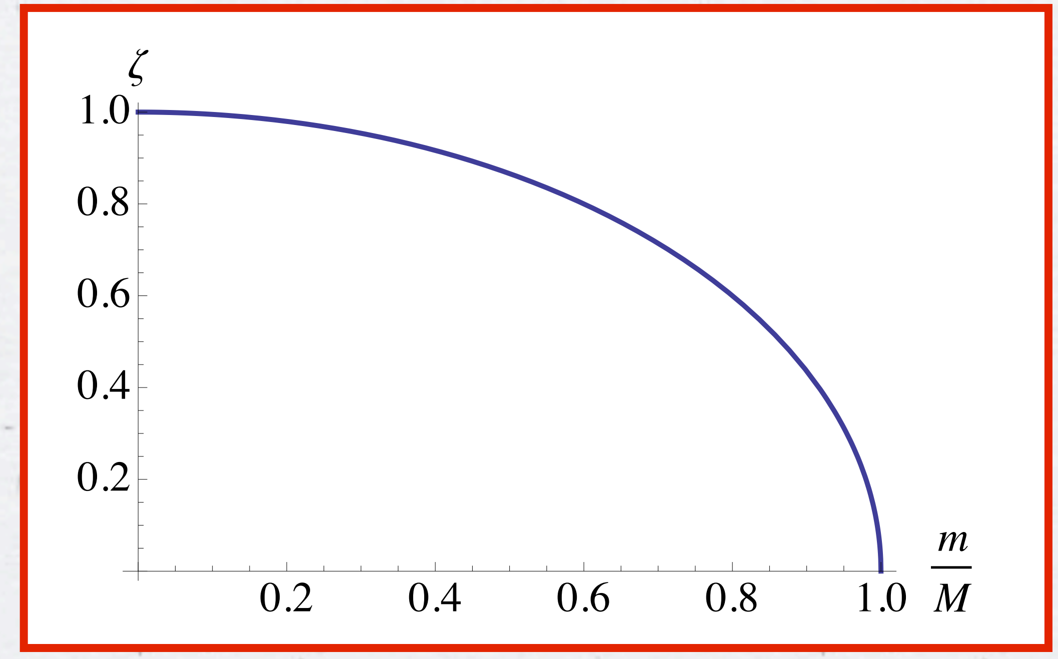

MASS-DEPENDENT REFRACTION INDEX OF VACUUM

General phenomenon due to unitariety

Proof. We need the gate-Hamiltonian:

$$\mathrm{H}^{(2\mathrm{n})}_{\mathrm{gate}} = ic\zeta\sigma_3\widehat{\partial}_x + \omega\sigma_1$$

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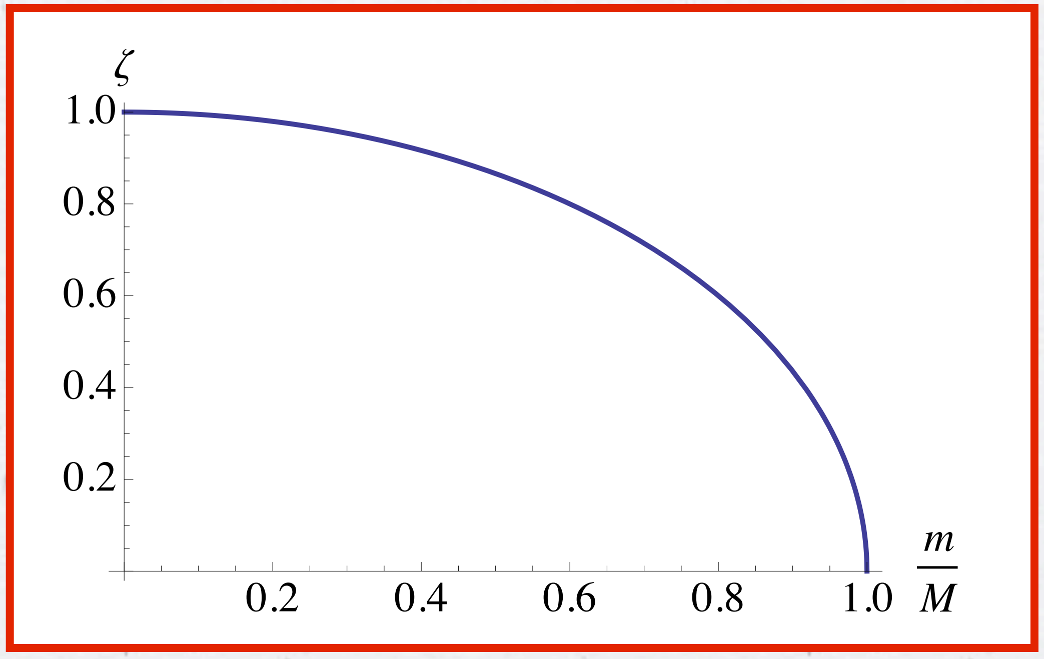

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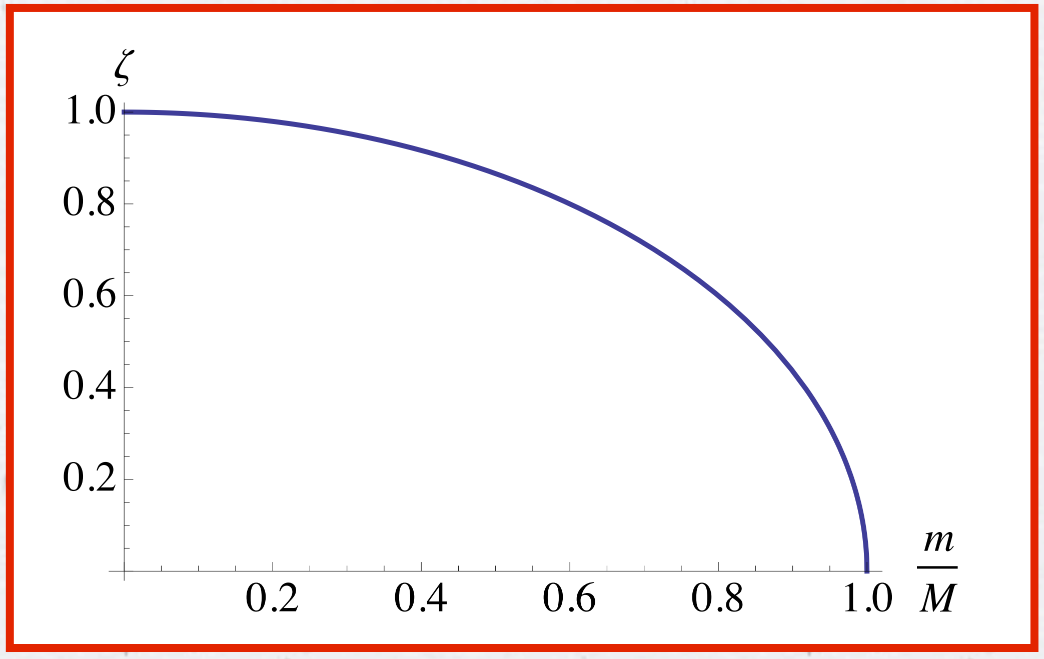

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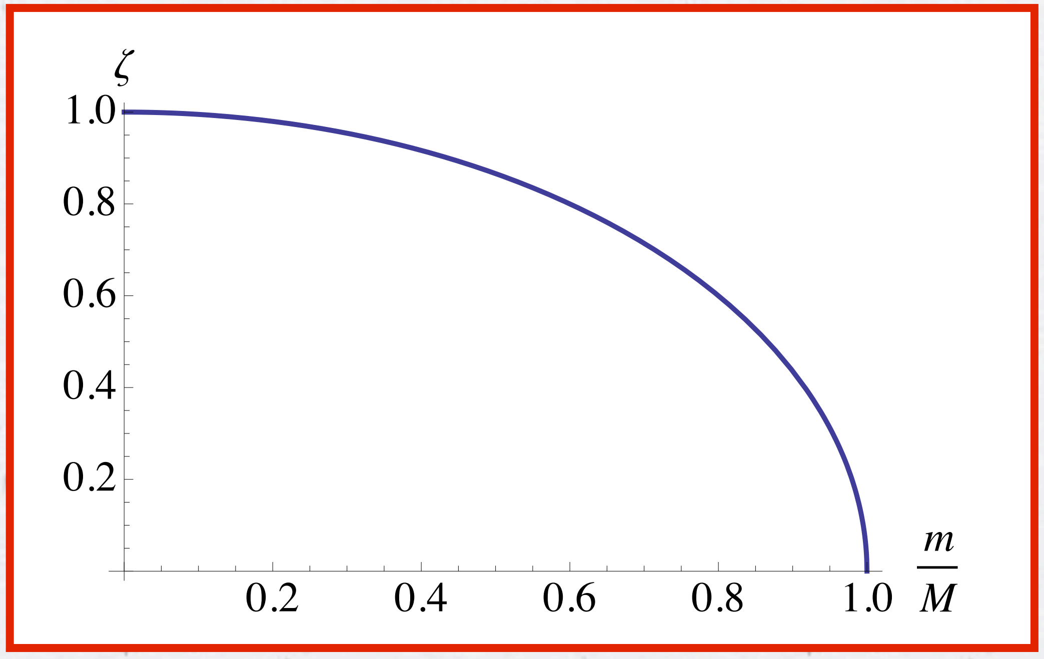

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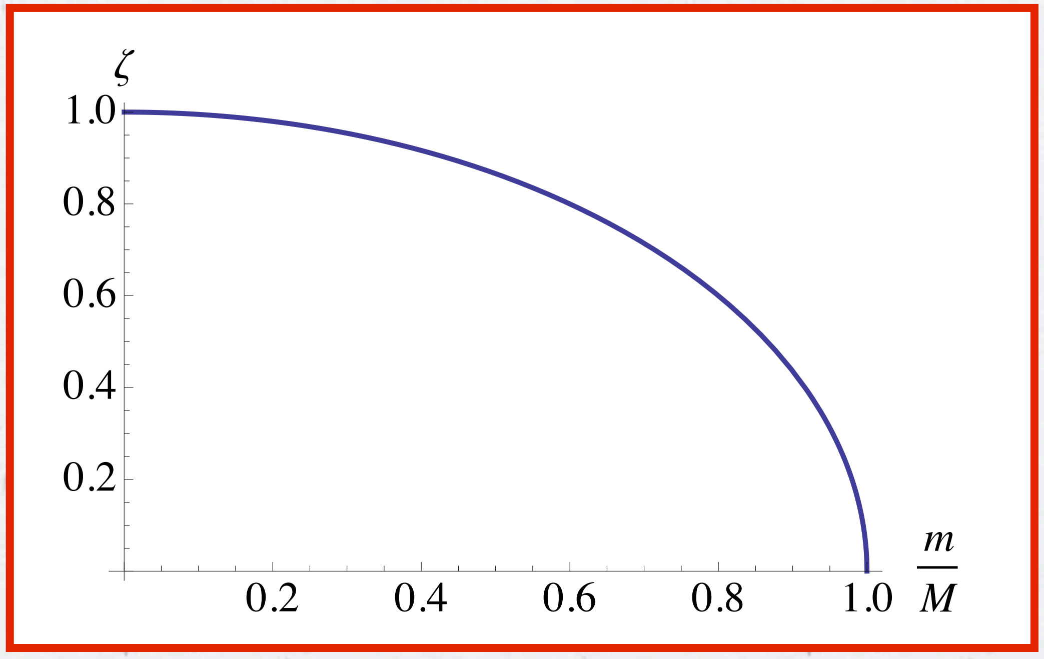
$$\mathrm{H}^{(4)}_{\mathrm{gate}} = \frac{i}{4\tau}(U_f - U_f^\dagger) \quad \Rightarrow \quad \|\mathrm{H}^{(4)}_{\mathrm{gate}}\| \leqslant \frac{1}{2\tau}$$

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



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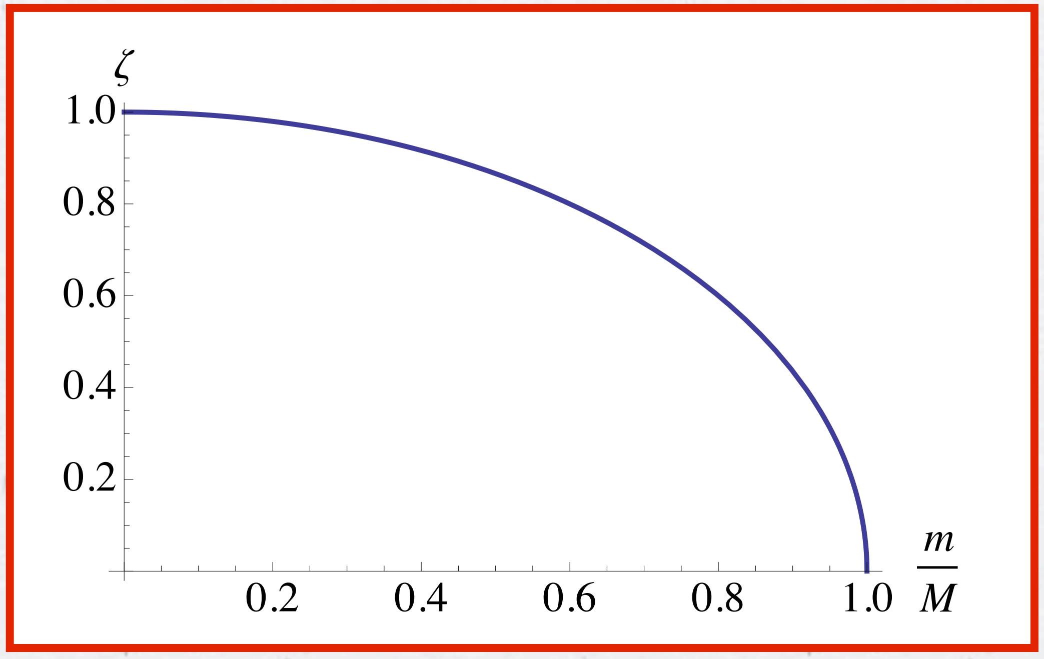

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The norm is obtained by FT at $k = \frac{\pi}{2a}$

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

MASS-DEPENDENT REFRACTION INDEX OF VACUUM

General phenomenon due to unitariety

Proof. We need the gate-Hamiltonian:

$$\mathrm{H}^{(2\mathrm{n})}_{\mathrm{gate}} = ic\zeta\sigma_3\widehat{\partial}_x + \omega\sigma_1$$

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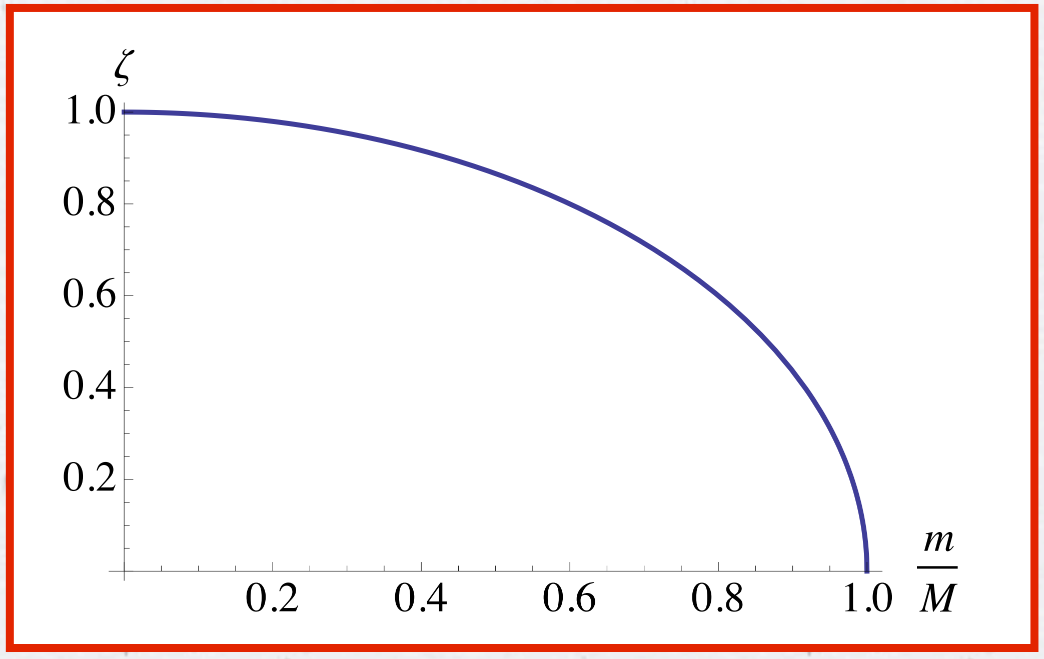
namely for $\omega = c\lambda^{-1}$ one has: $\Rightarrow$

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



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

THE NEW QCFT

KLEIN GORDON WITH MASS (SPINLESS DIRAC)

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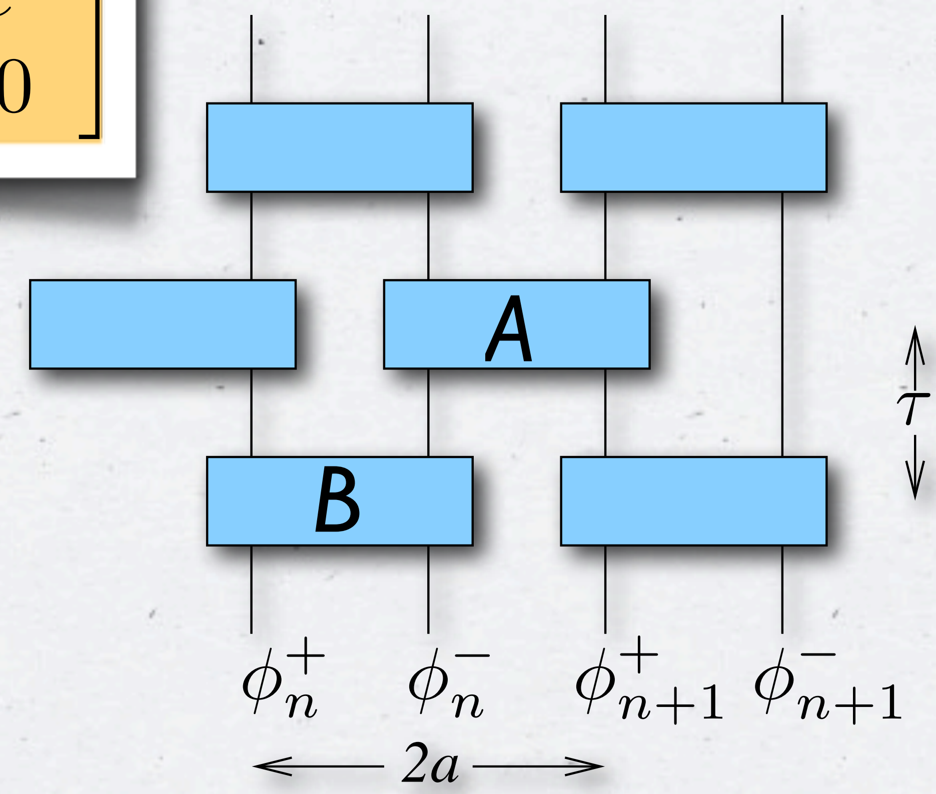

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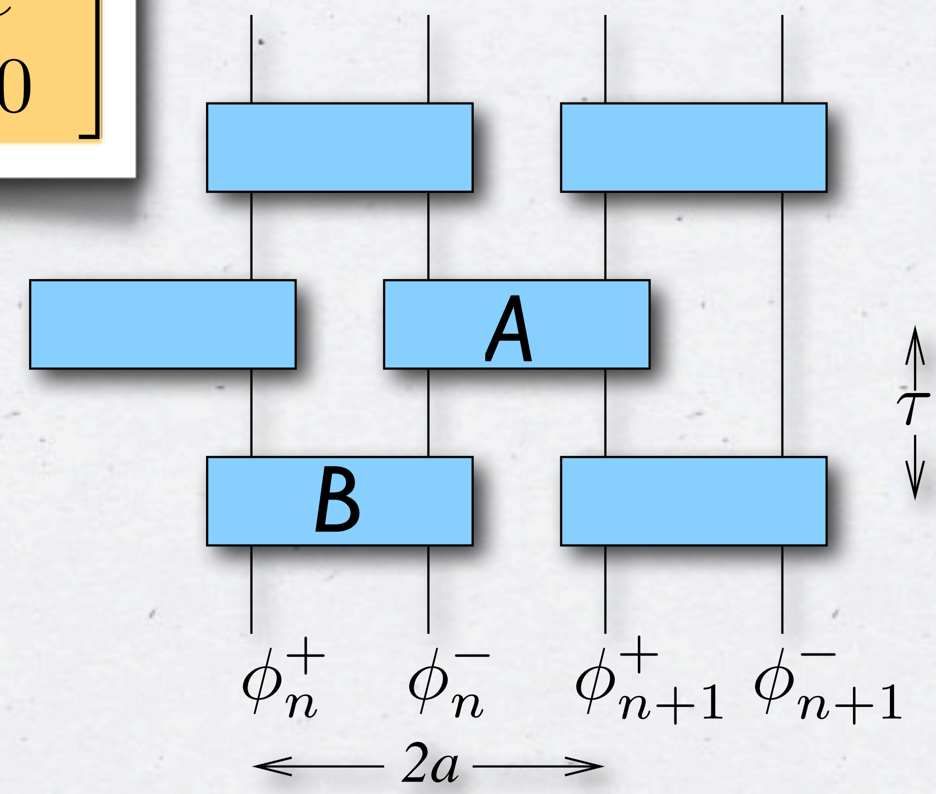

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For both Bose and Fermi fields one has:

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

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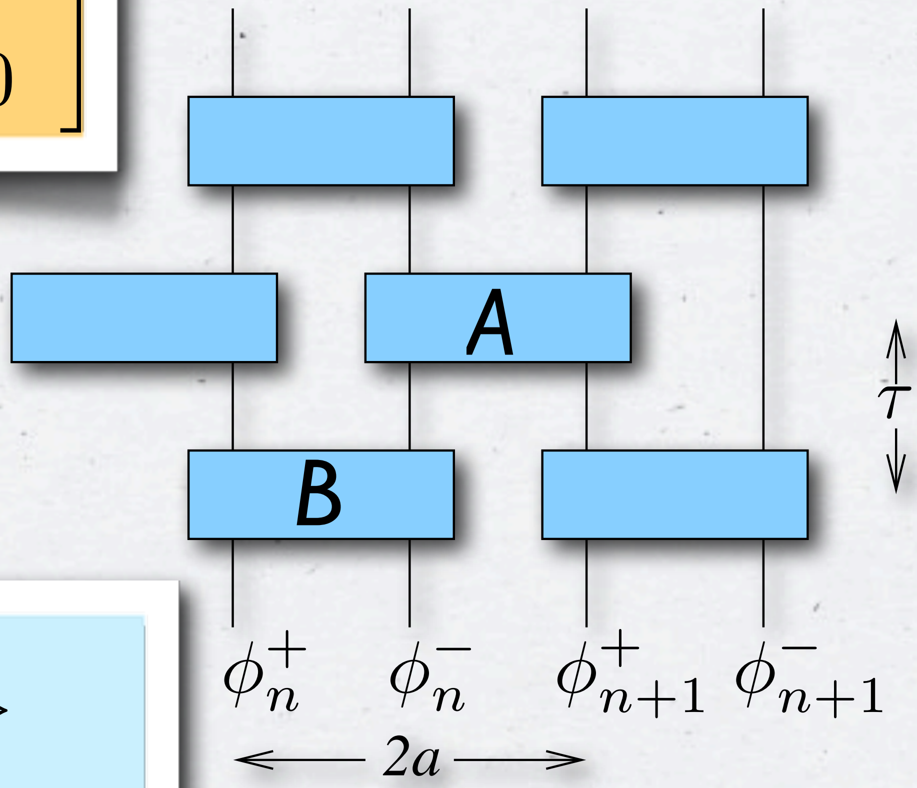

THE NEW QCFT

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★ ★ ★ ★ ★ ★ ★ ★

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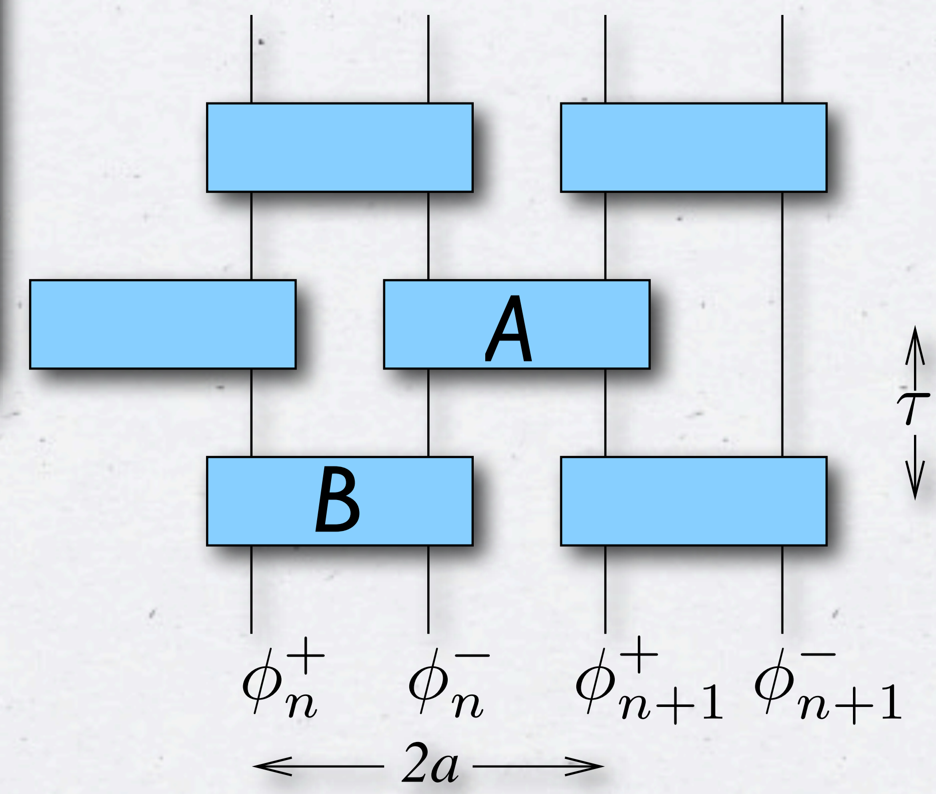

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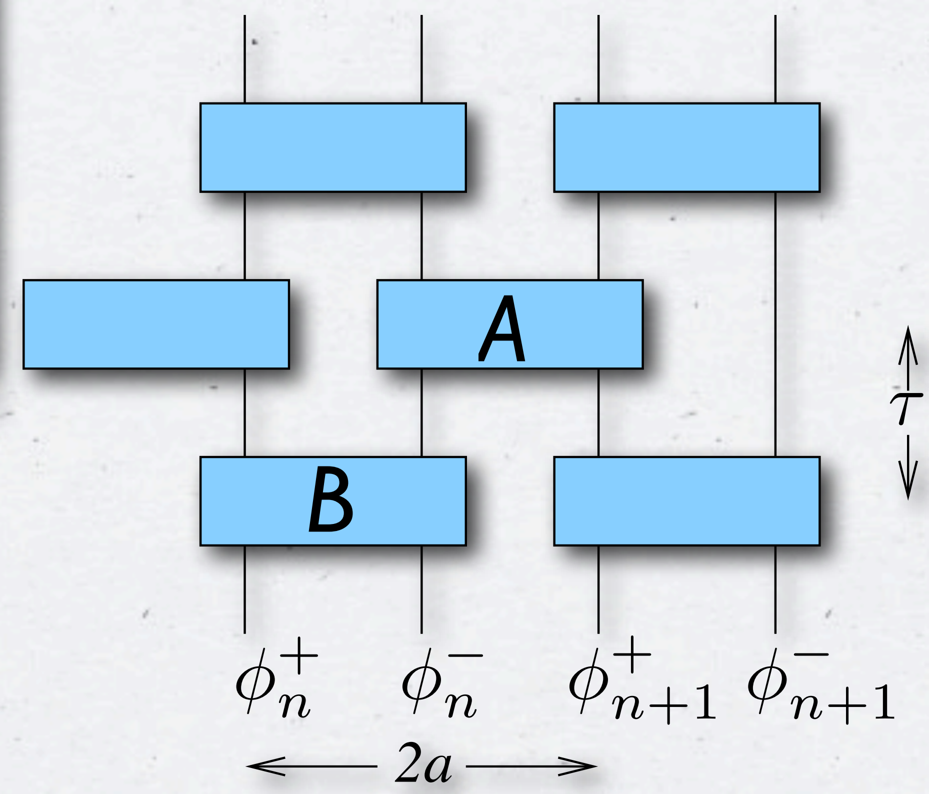

Commuting	Anticommuting
Harmonic oscillator	*Clifford algebra*
$[a_l, a_k^\dagger] = \delta_{lk}$	$\phi_n^+ = \sigma_{2n}^- \prod_{k=-\infty}^{n-1} \sigma_{2k+1}^z \sigma_{2k}^z$
$\phi_n^+ = a_{2n} \quad \phi_n^- = a_{2n+1}$	$\phi_n^- = \sigma_{2n+1}^- \sigma_{2n}^z \prod_{k=-\infty}^{n-1} \sigma_k^z$

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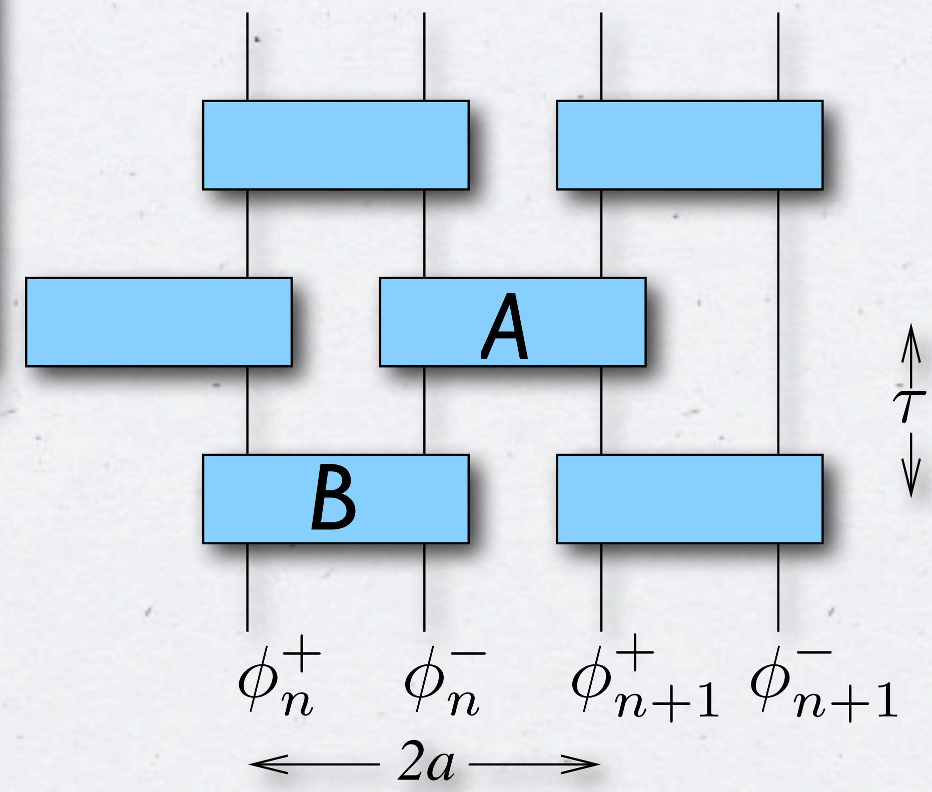

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$$A = \exp\left[-i\theta \left(\sigma_{2n-1}^- \sigma_{2n}^+ + \sigma_{2n-1}^+ \sigma_{2n}^- \right) \right]$$

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Gates act on local algebras only!

THE NEW QCFT

CONNECTION WITH THE USUAL QFT

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

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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")

$$\boxed{N = \sum_n \phi_n^\dagger \phi_n = \sum_n \sigma_n^3}$$

or $N = \sum_n a_n^\dagger a_n$

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$$P^\alpha = -i\hbar \sum_n |\phi_n^\alpha\rangle \widehat{\partial}_x \langle \phi_n^\alpha|, \quad X^\alpha = 2a \sum_n |\phi_n^\alpha\rangle n \langle \phi_n^\alpha|.$$

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

FIRST QUANTIZATION

Single-”particle” Schrödinger equation in ppm representation:

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

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

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

SIMULATING QFT

GAUGE INVARIANCE

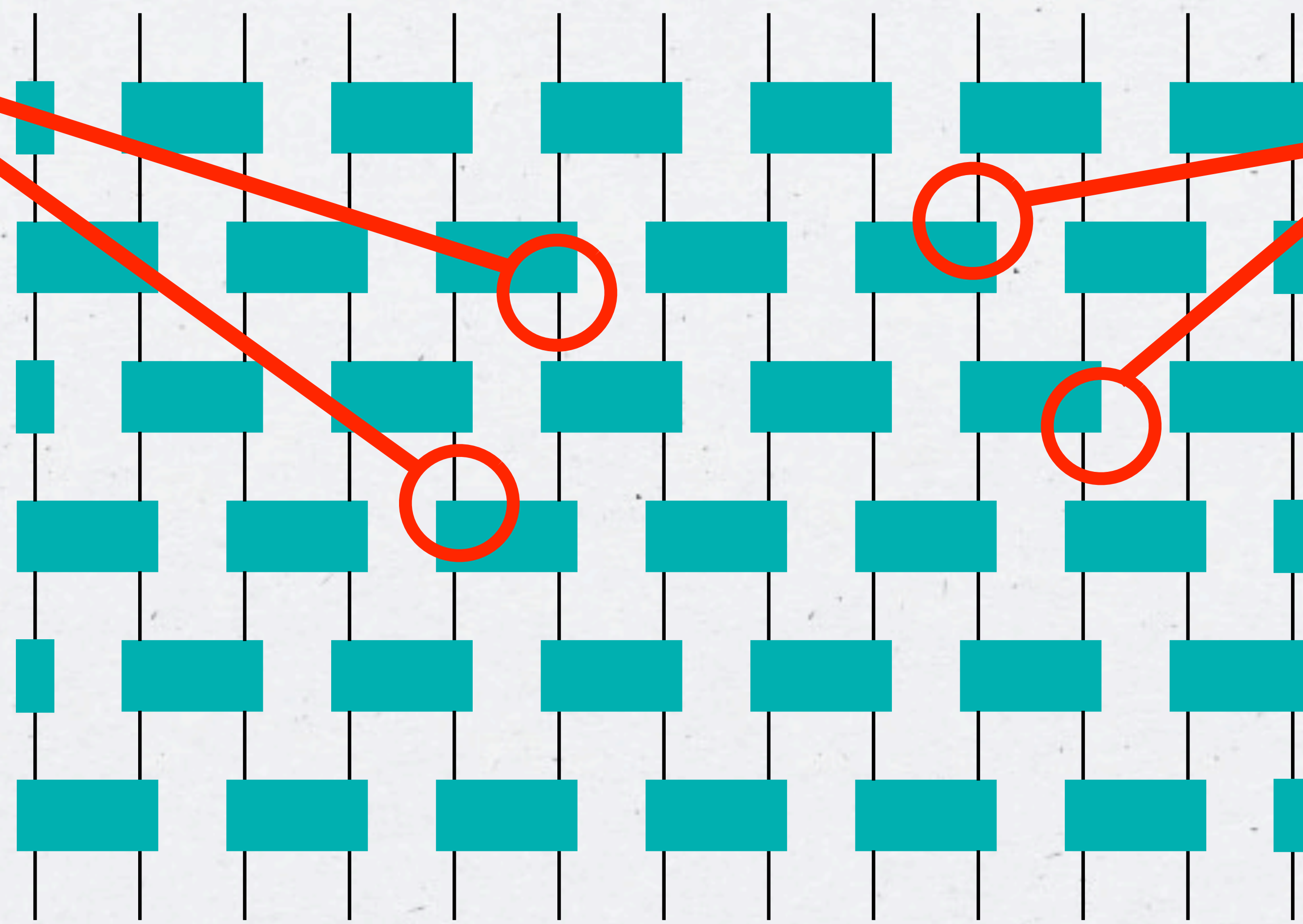
★ ★ ★ ★

Jordan realization of the matrix algebra

NONABELIAN **_ABELIAN_**

$U(x)$ $e^{i\phi(x)}$

2nd quantization



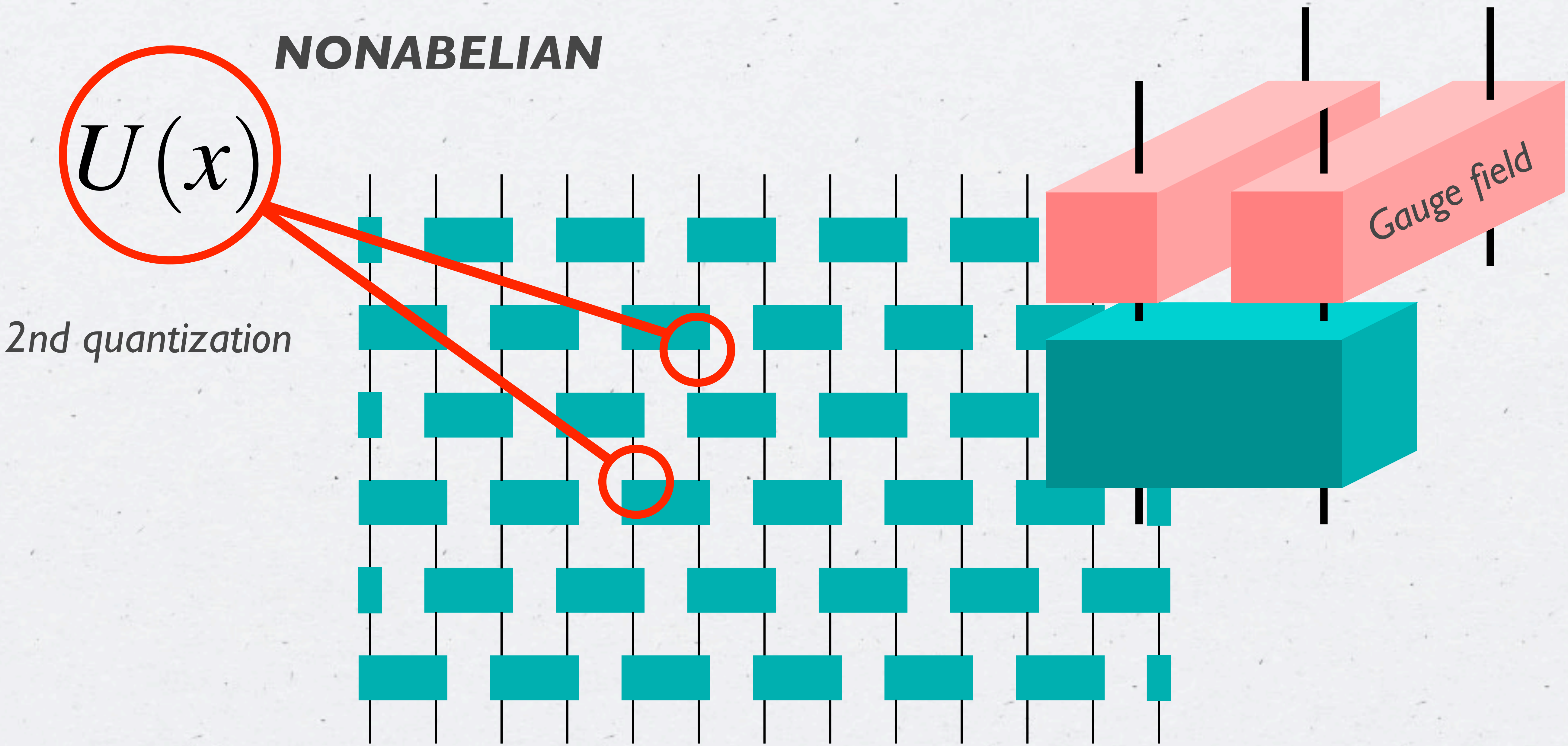
1st quantization

SIMULATING QFT

GAUGE INVARIANCE

★ ★ ★ ★ ★ ★ ★ ★

NONABELIAN



SIMULATING QFT

GAUGE INVARIANCE

★ ★ ★ ★ ★ ★ ★ ★

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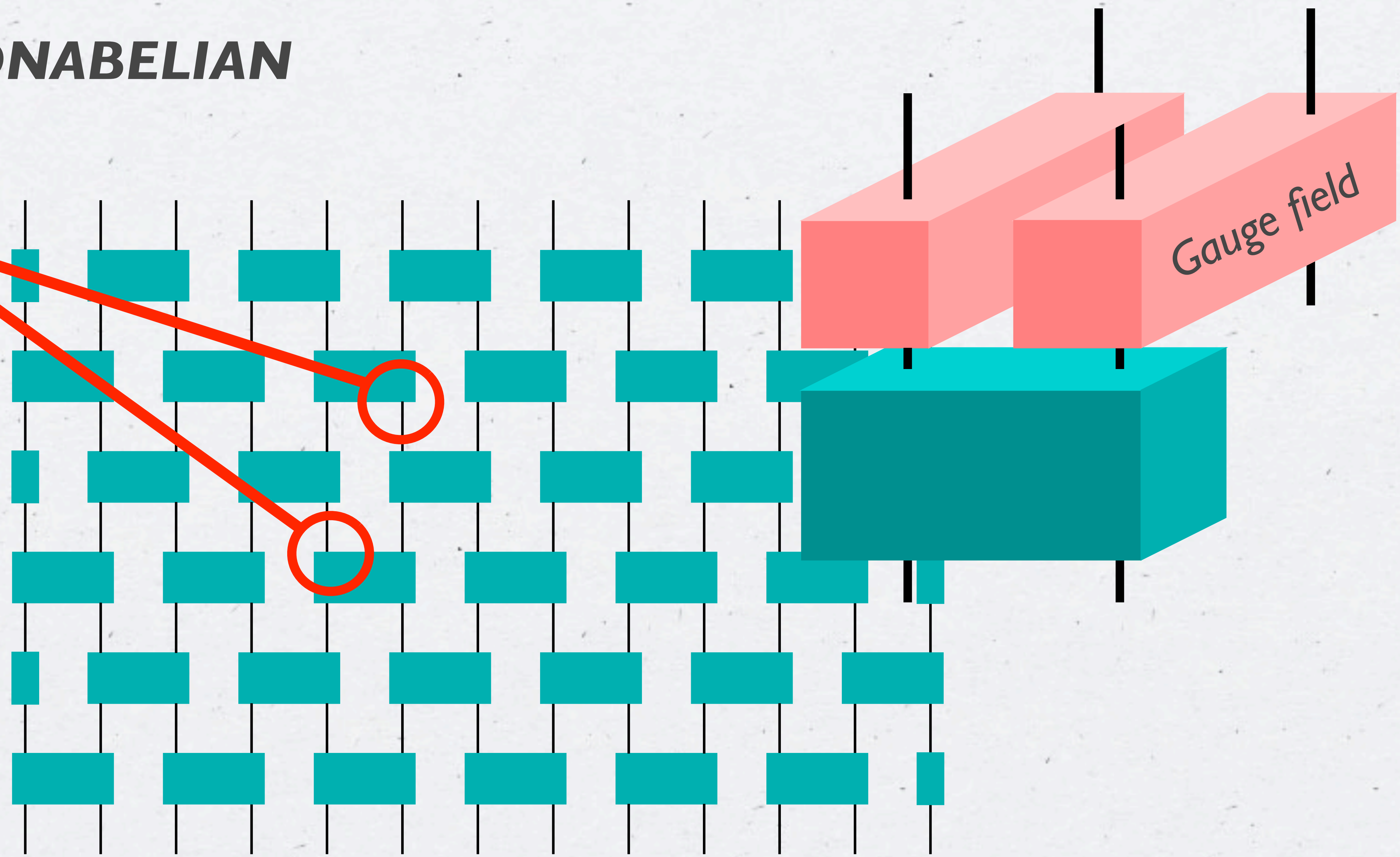


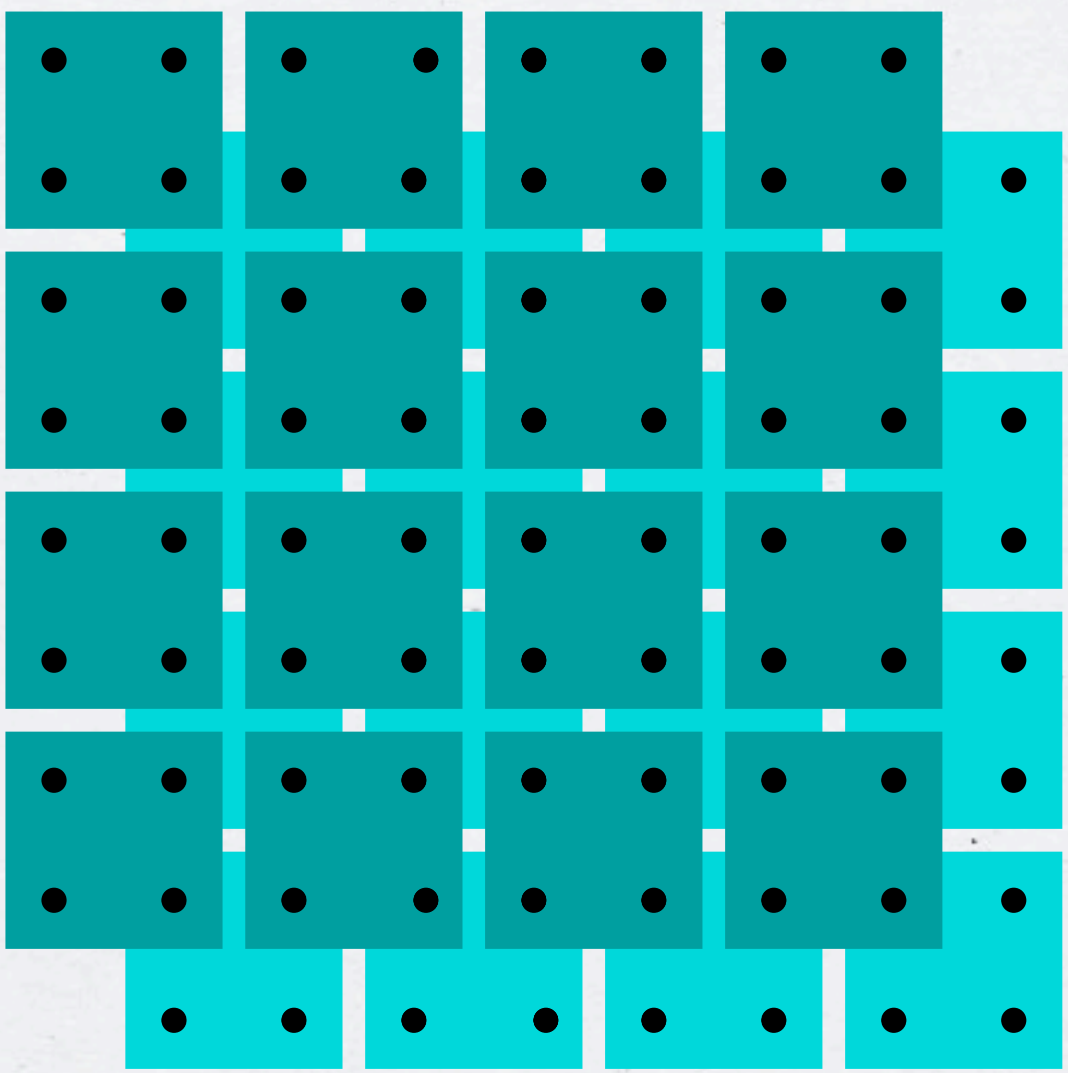
Natively nonabelian Gauge theory!
and on … foliation !!!

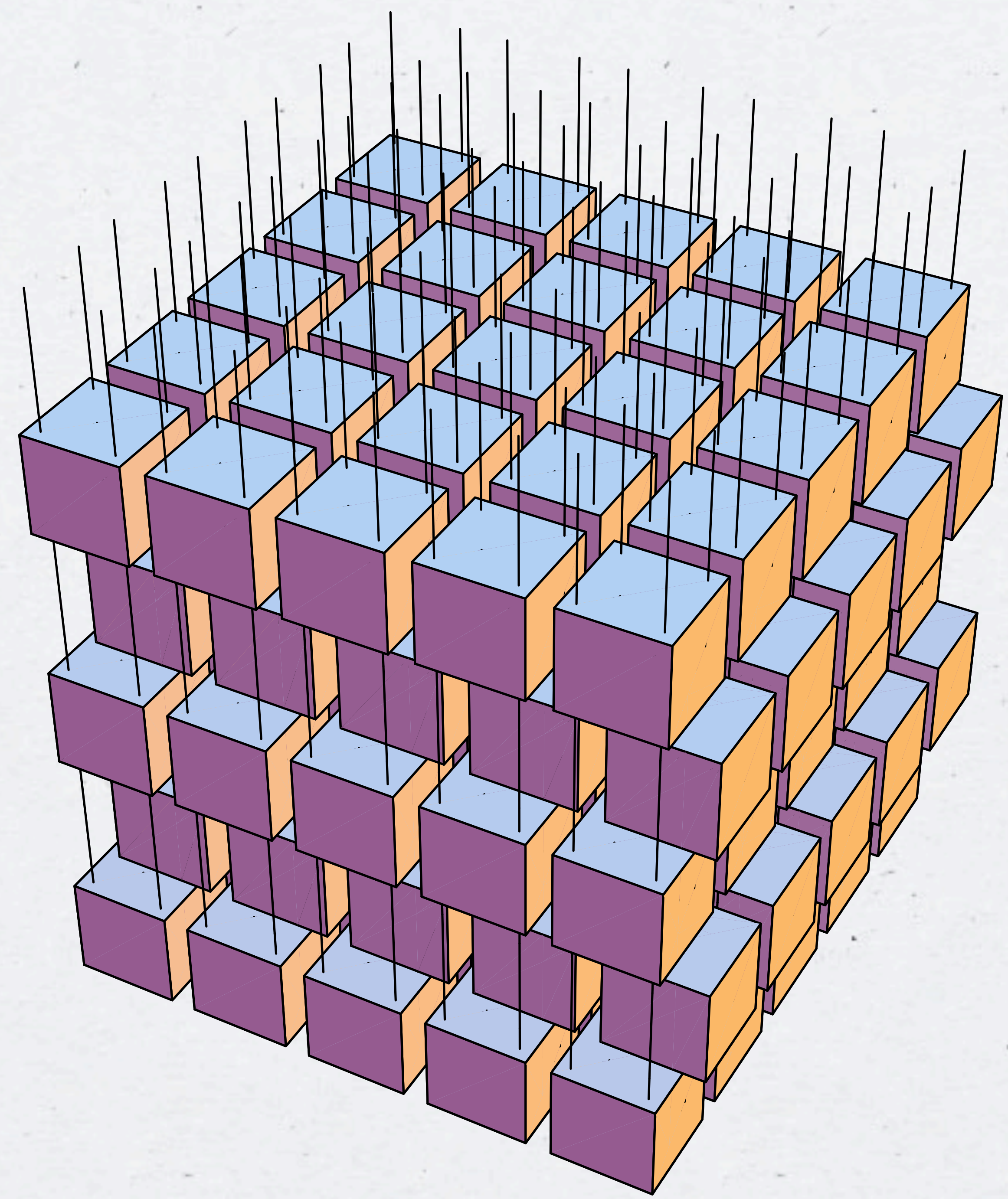
Good for Gravity!

THE NEW QCFT

QCFT in 3 space dimensions?

★ ★ ★ ★ ★ ★ ★ ★



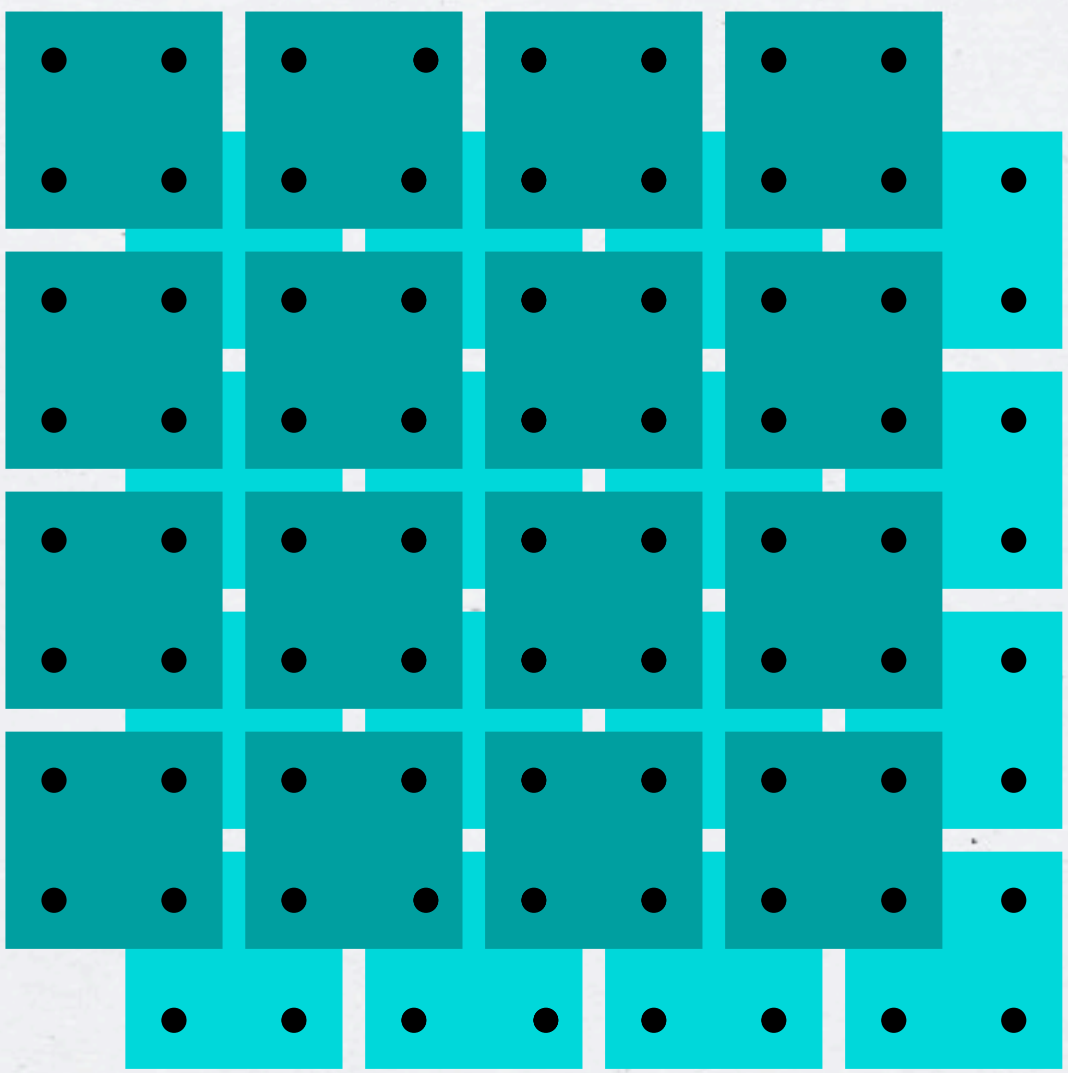


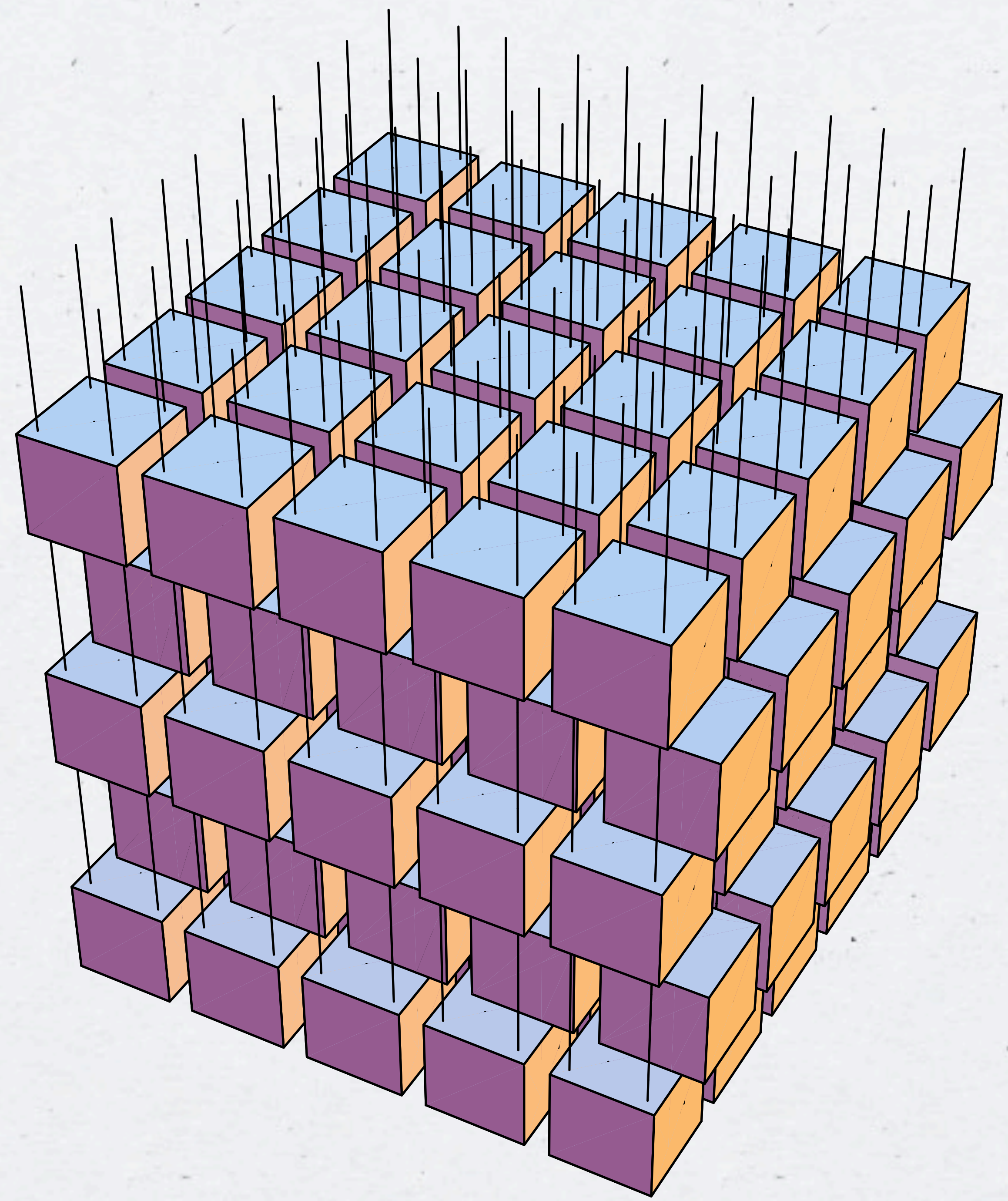
THE NEW QCFT

QCFT in 3 space dimensions?

★ ★ ★ ★ ★ ★ ★ ★

No anticommuting fields in more than one space dimension!





THE NEW QCFT

QCFT in 3 space dimensions?

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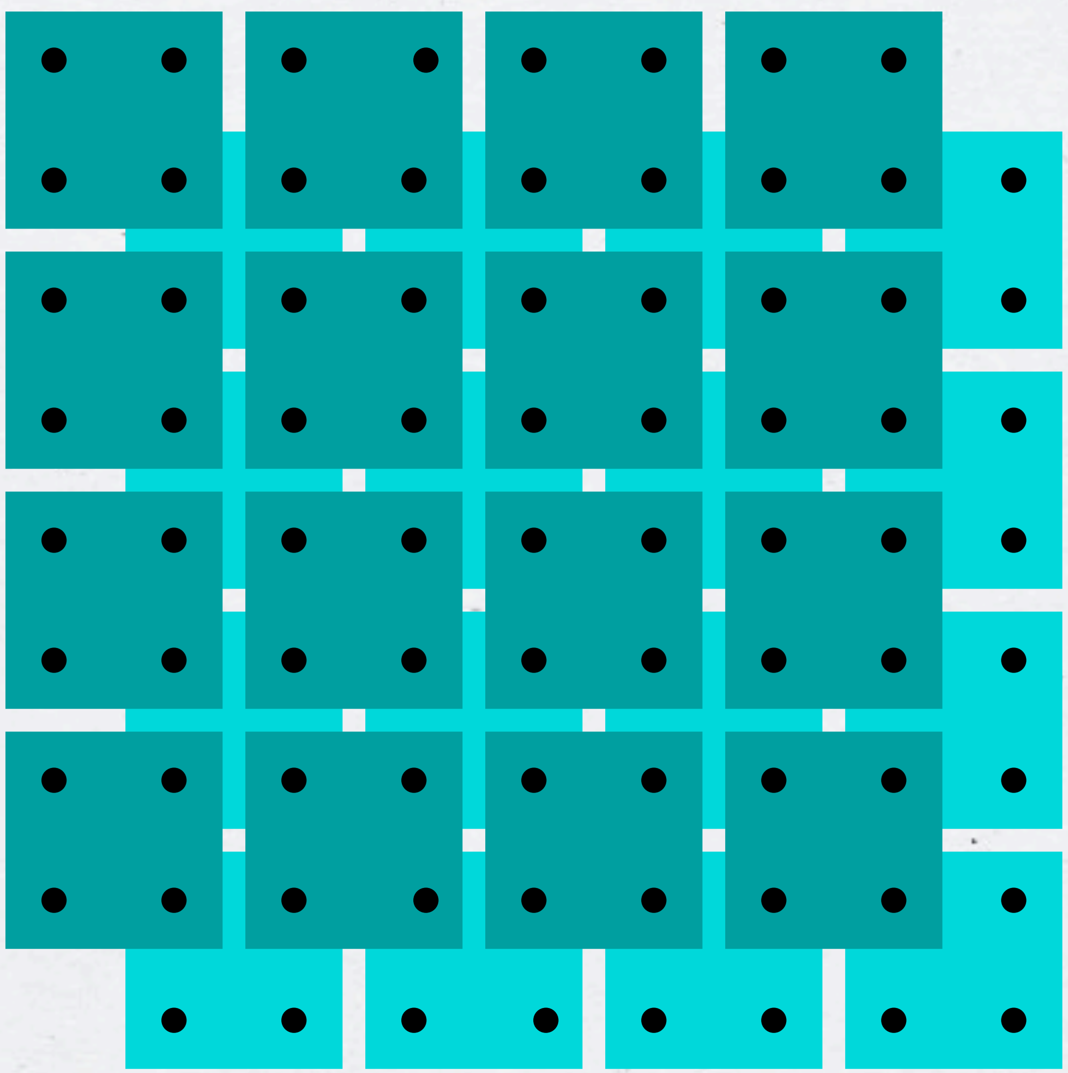
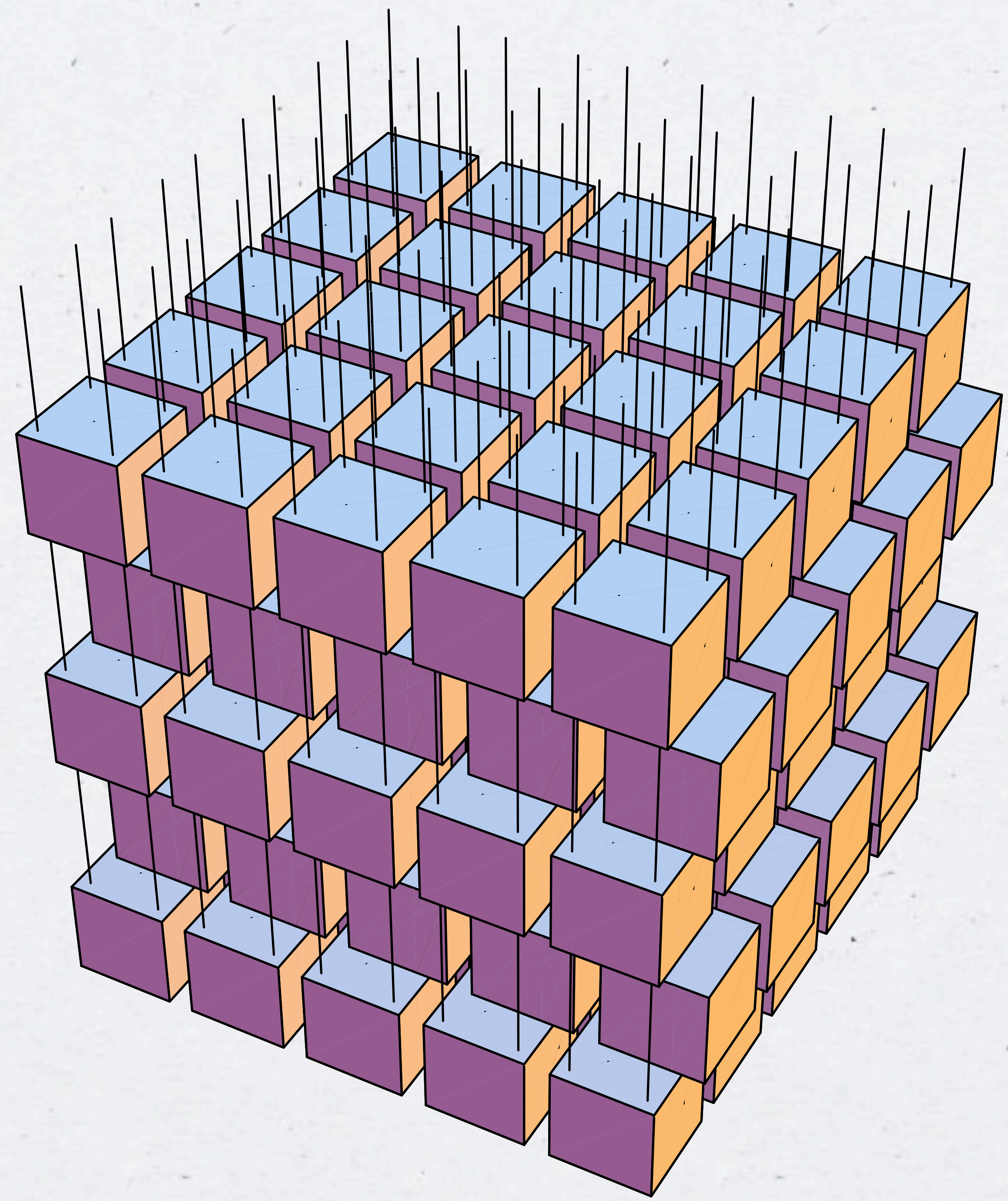
Do we really need anticommuting fields?

Grassman variables?





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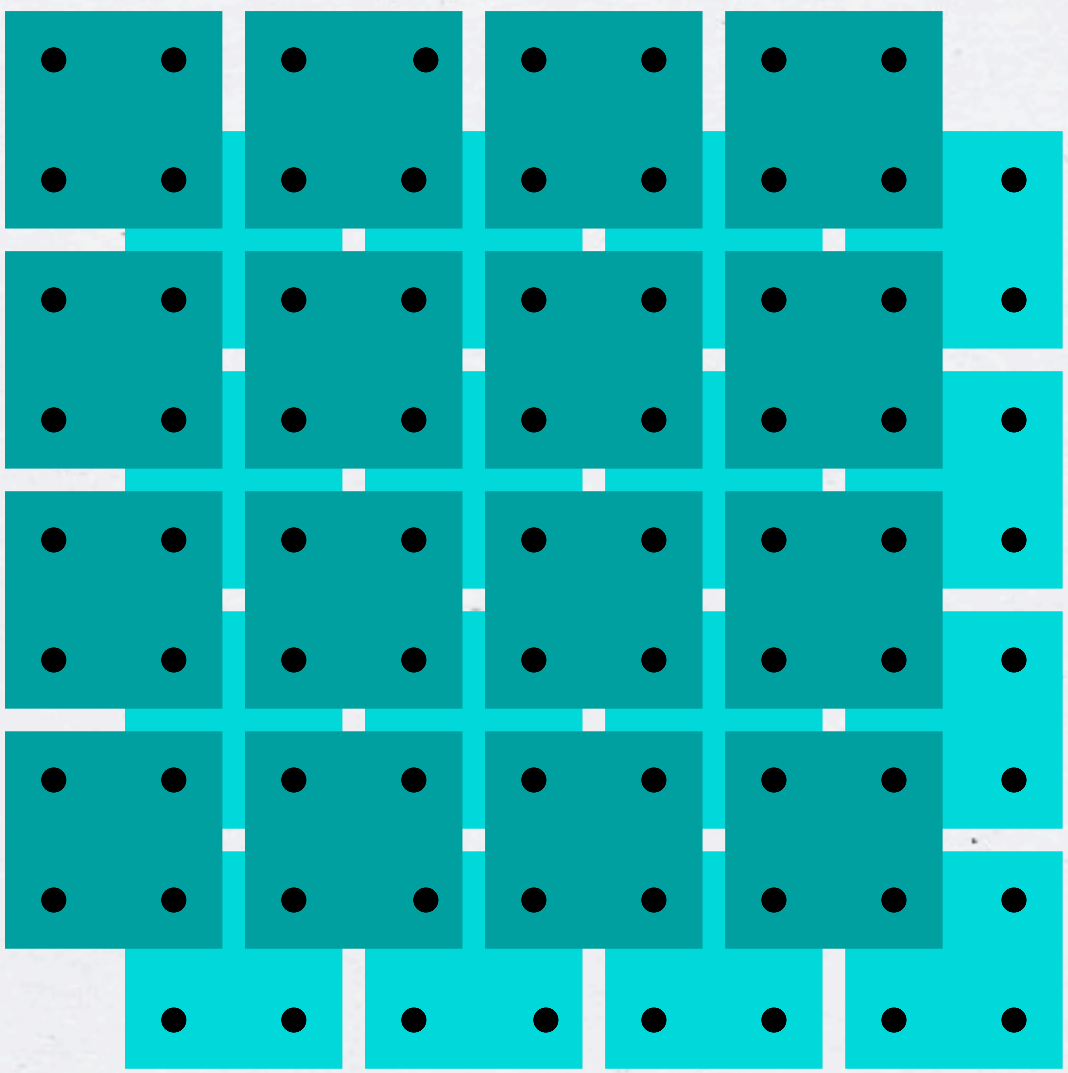
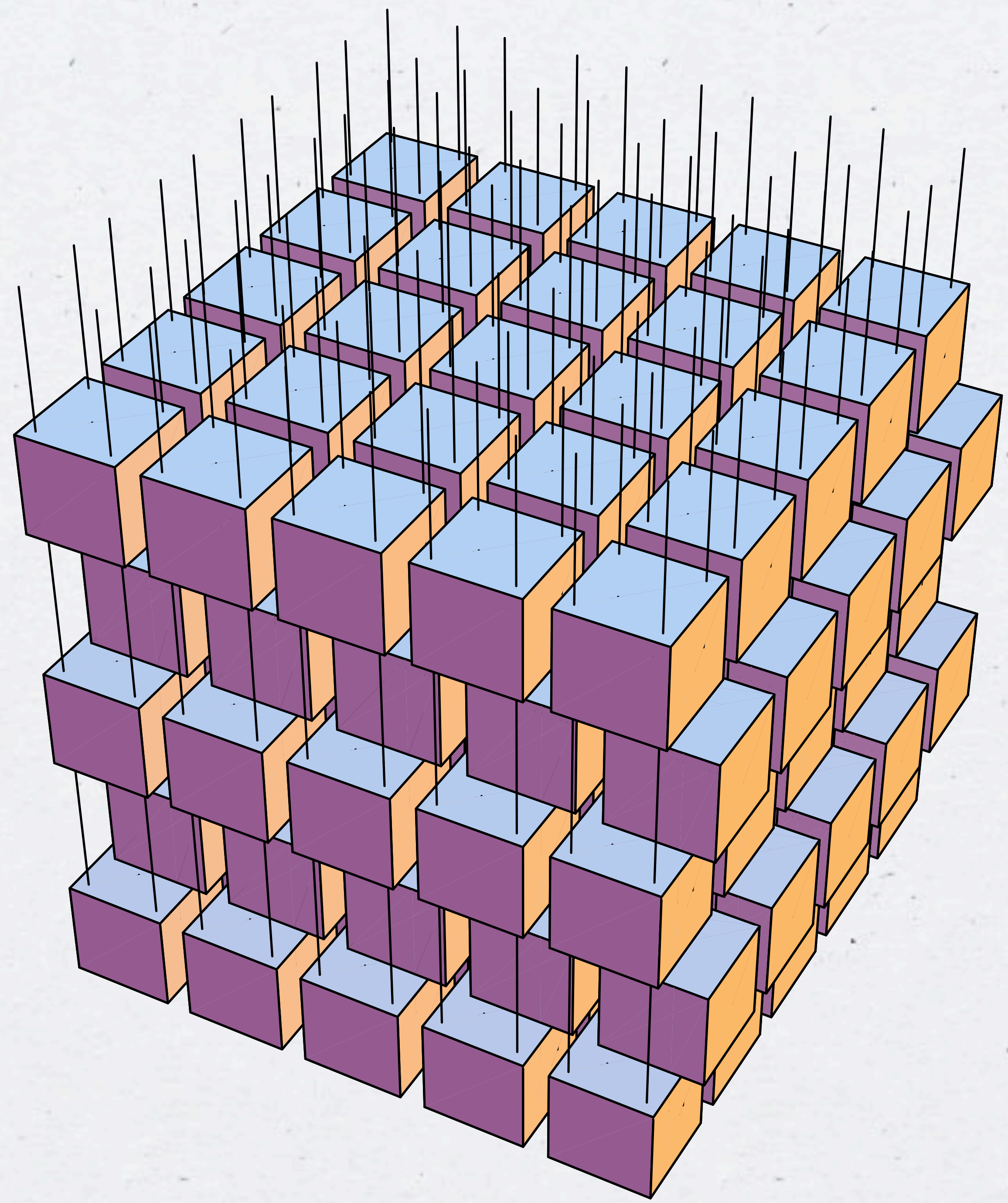


Microcausality and parastatistics



Advantages of QCFT versus QFT

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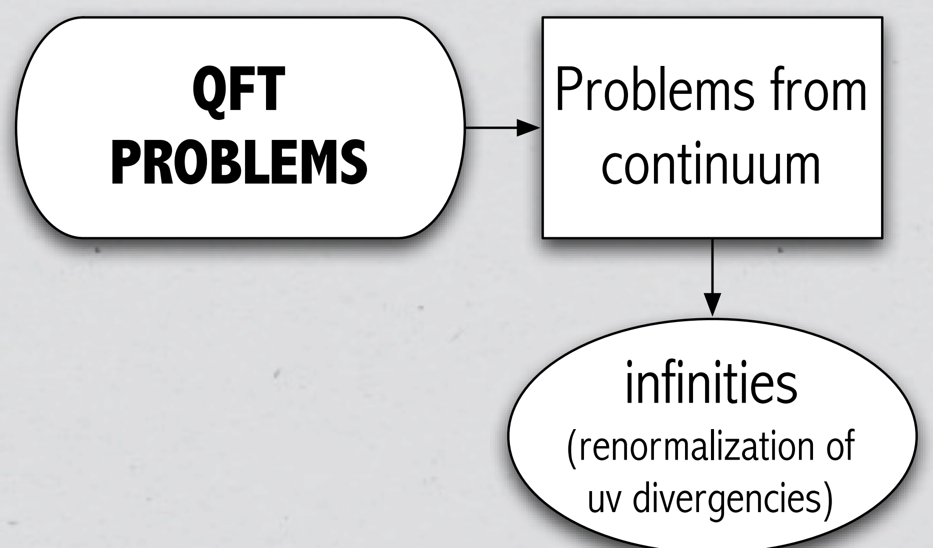

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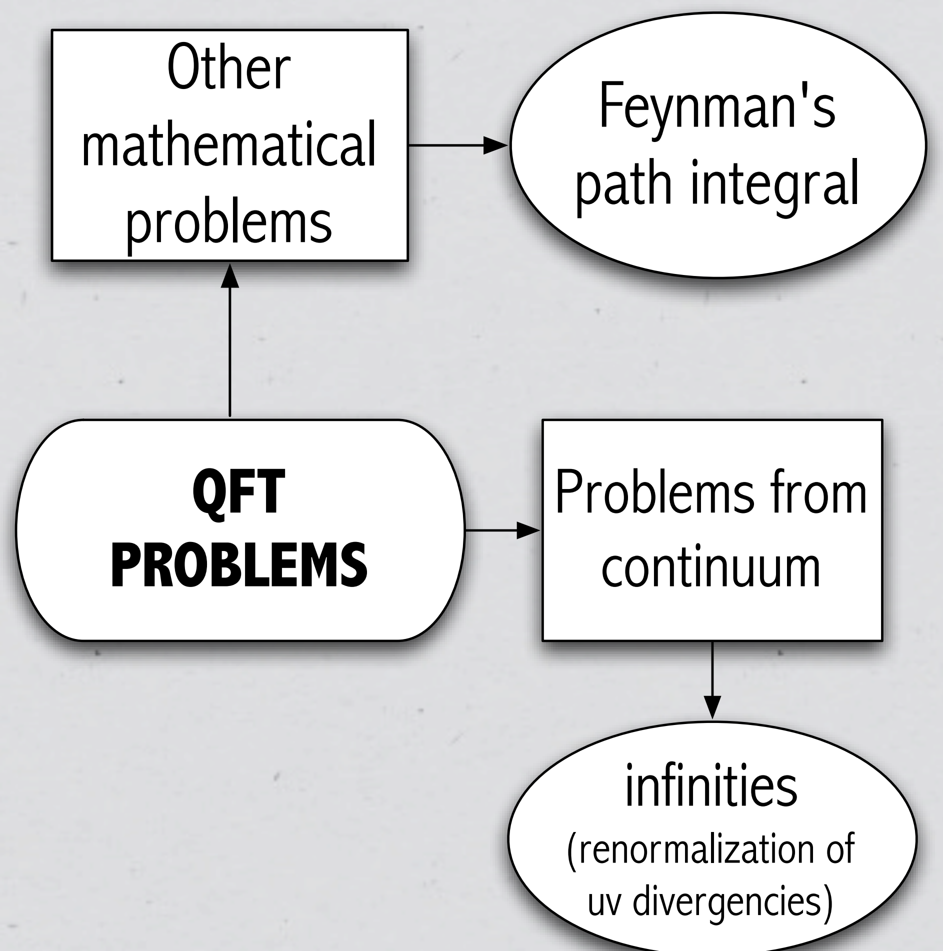

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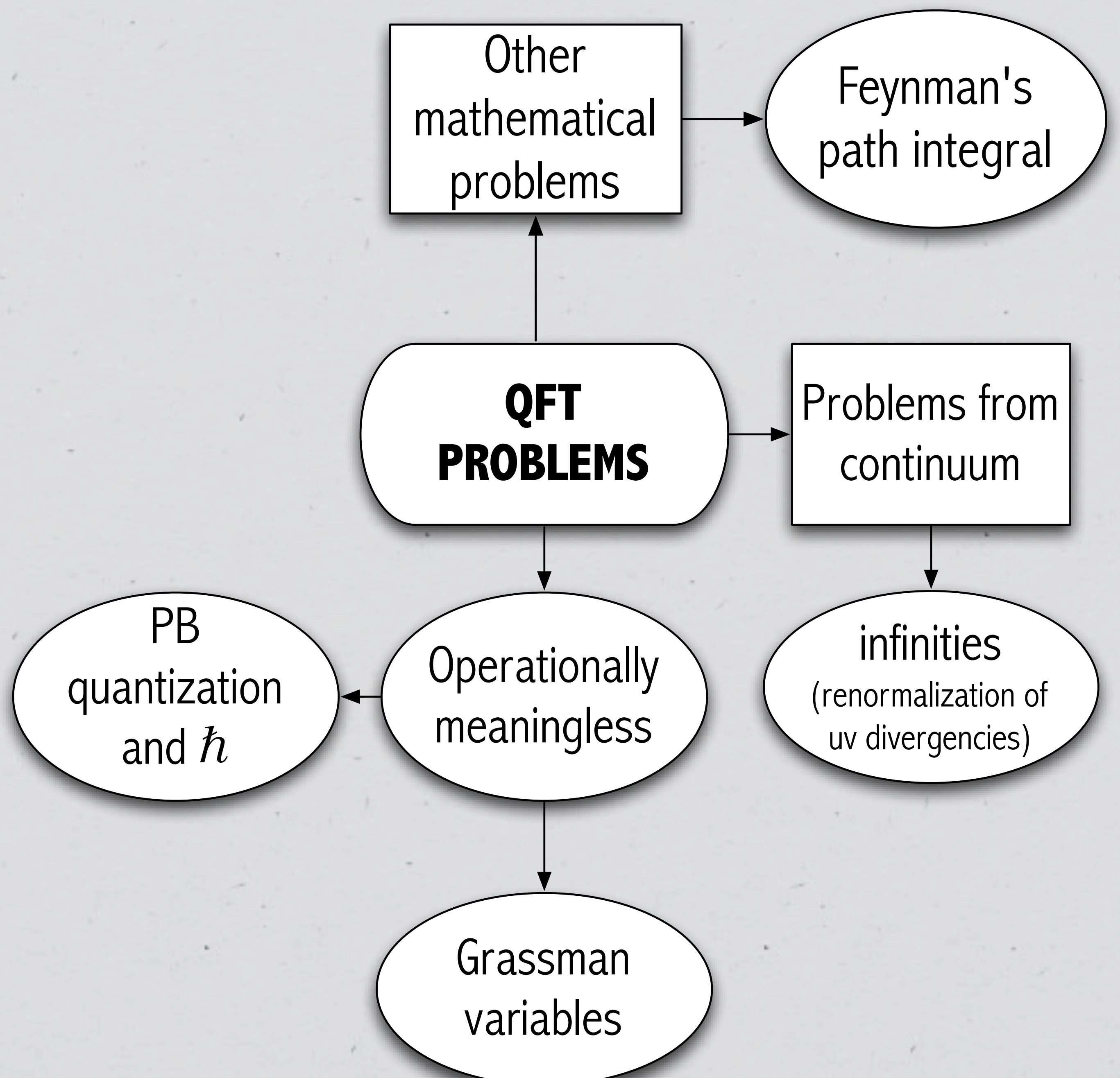

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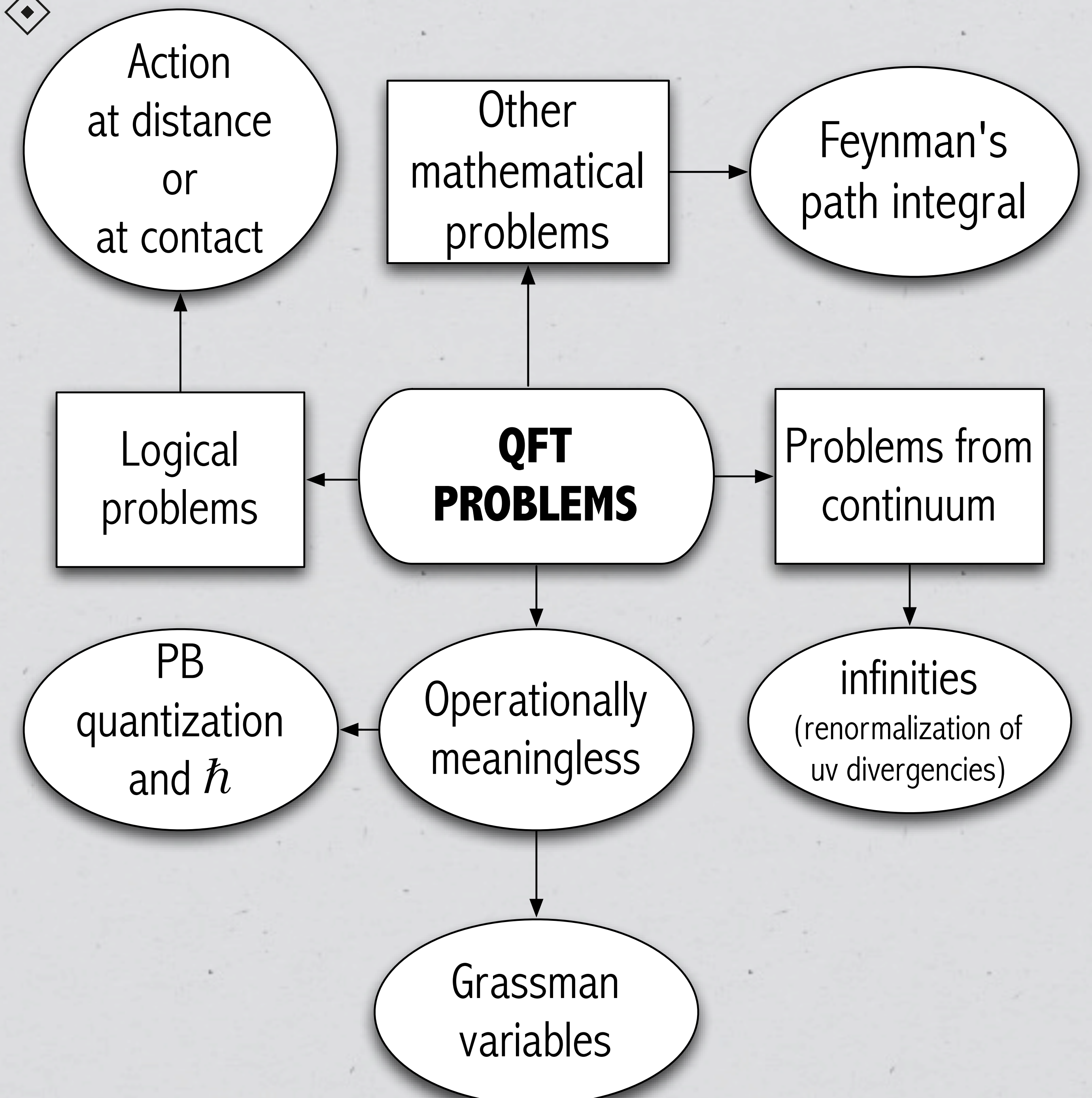

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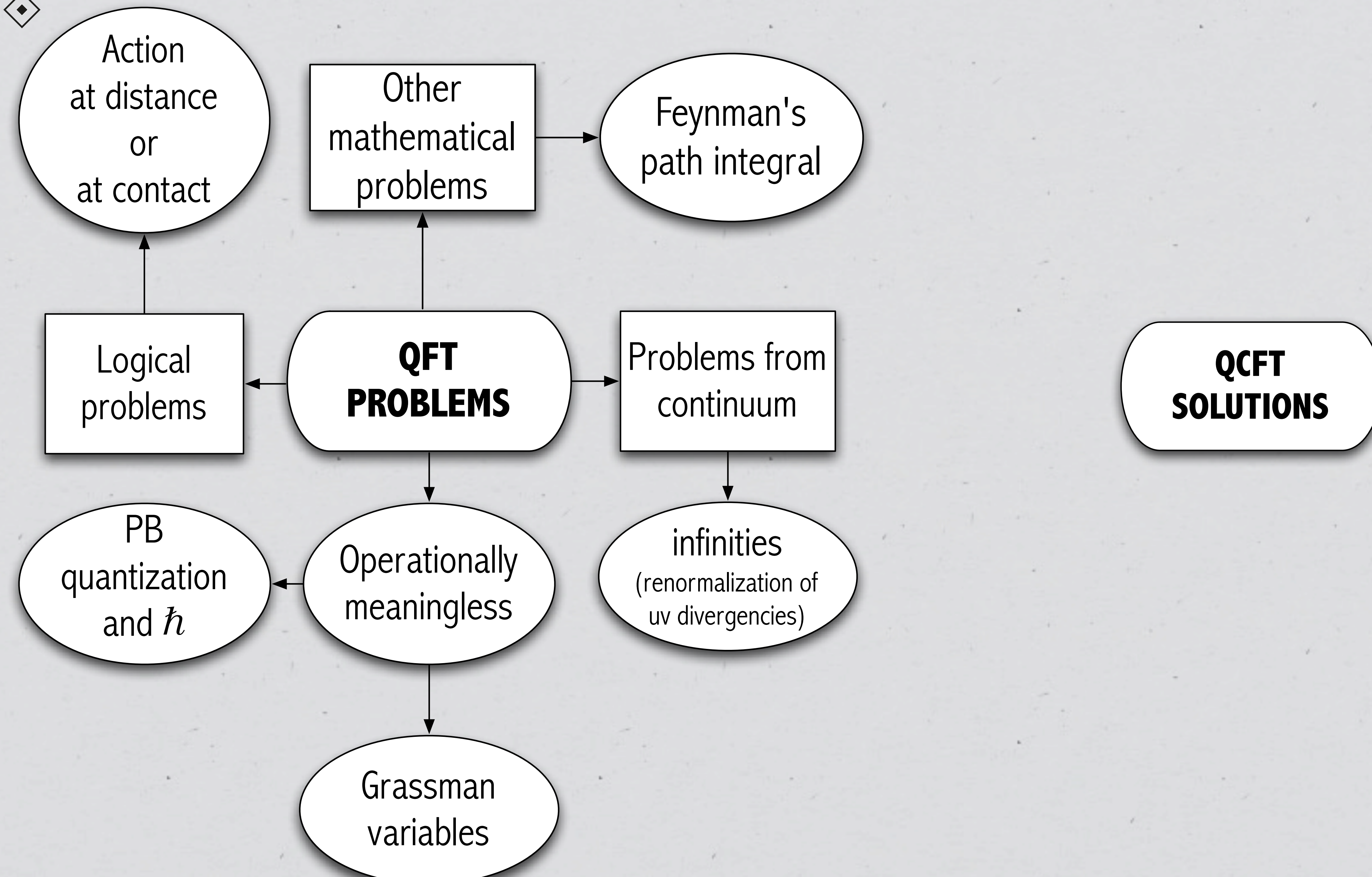

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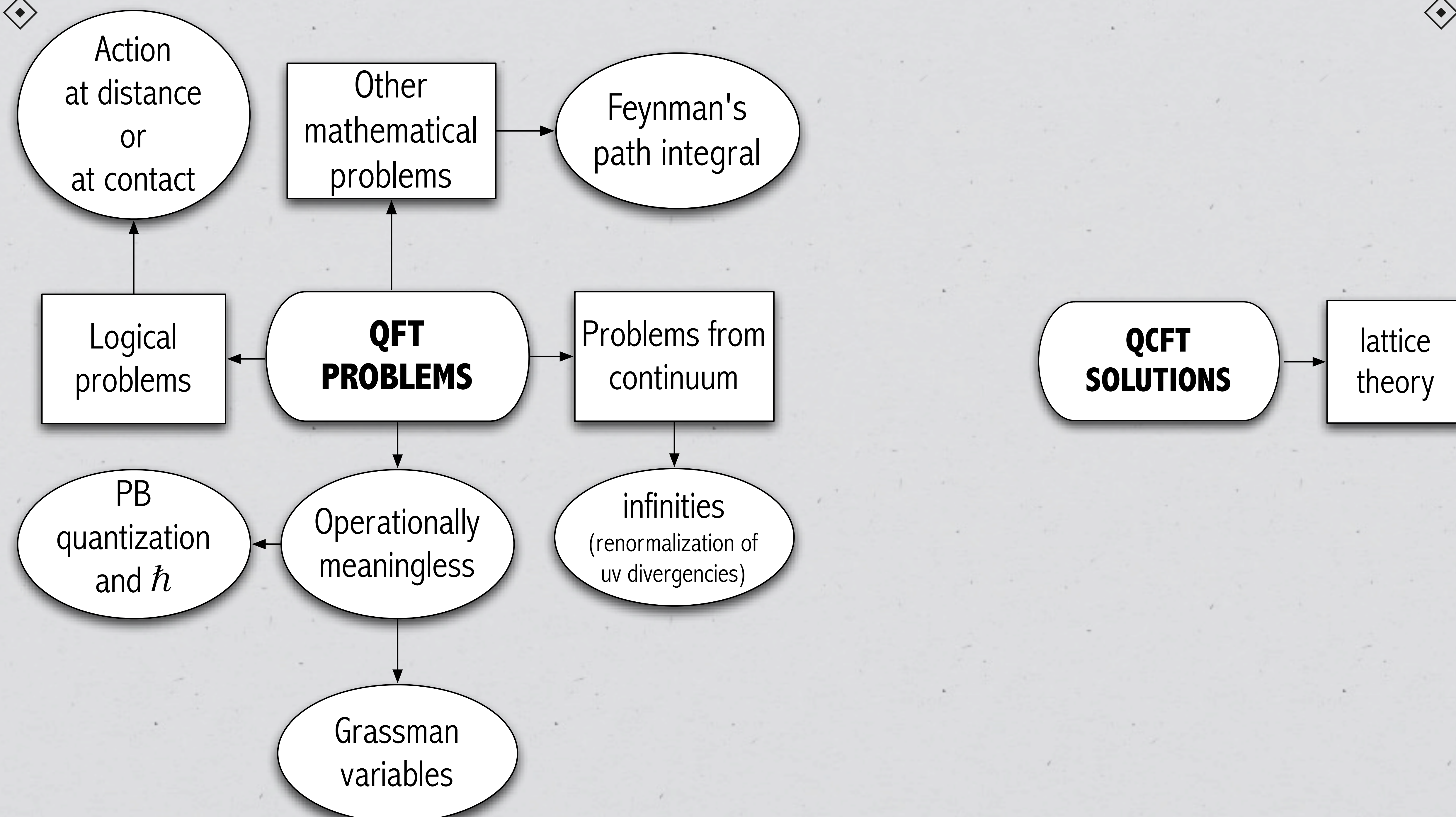

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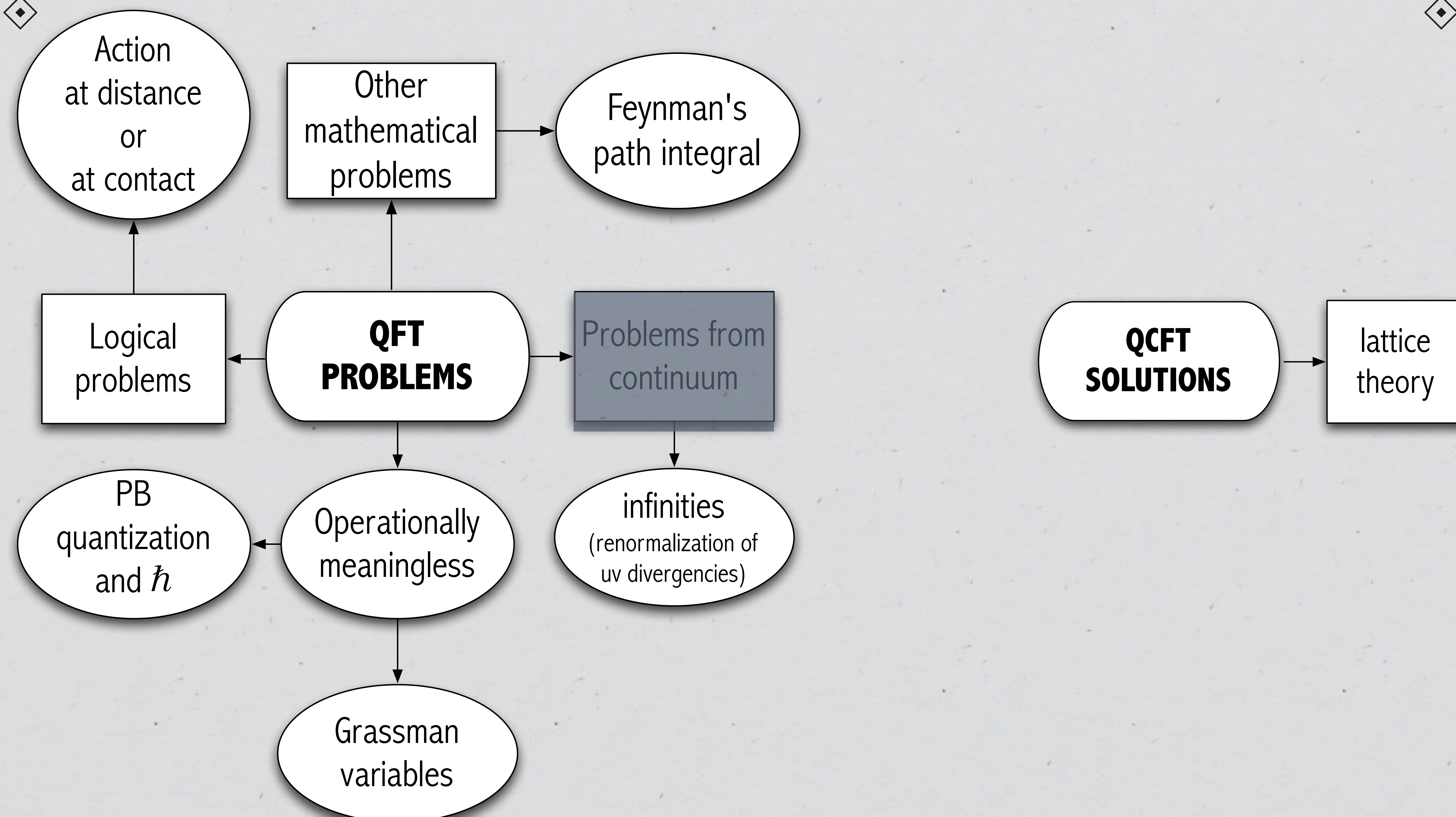

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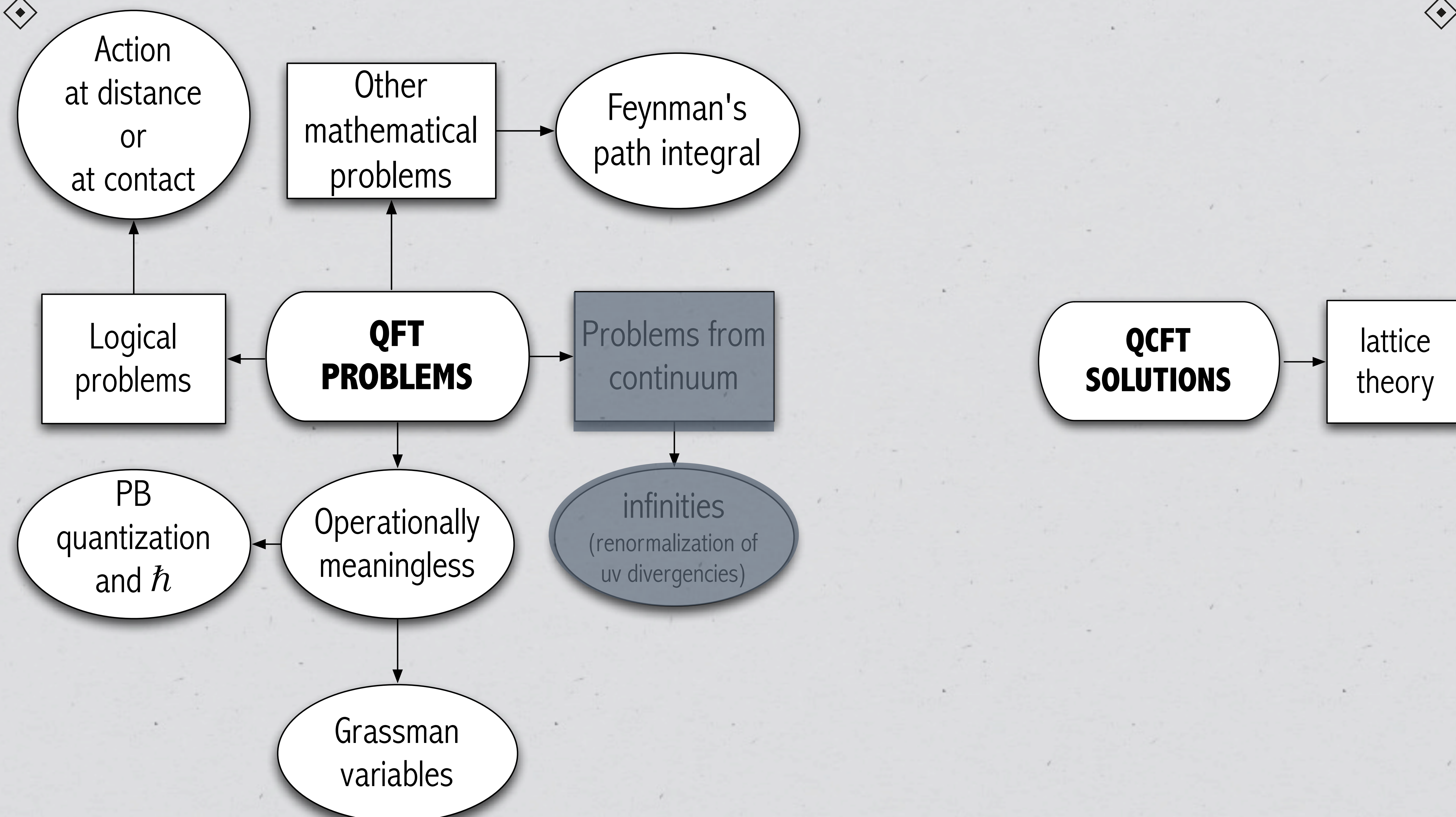

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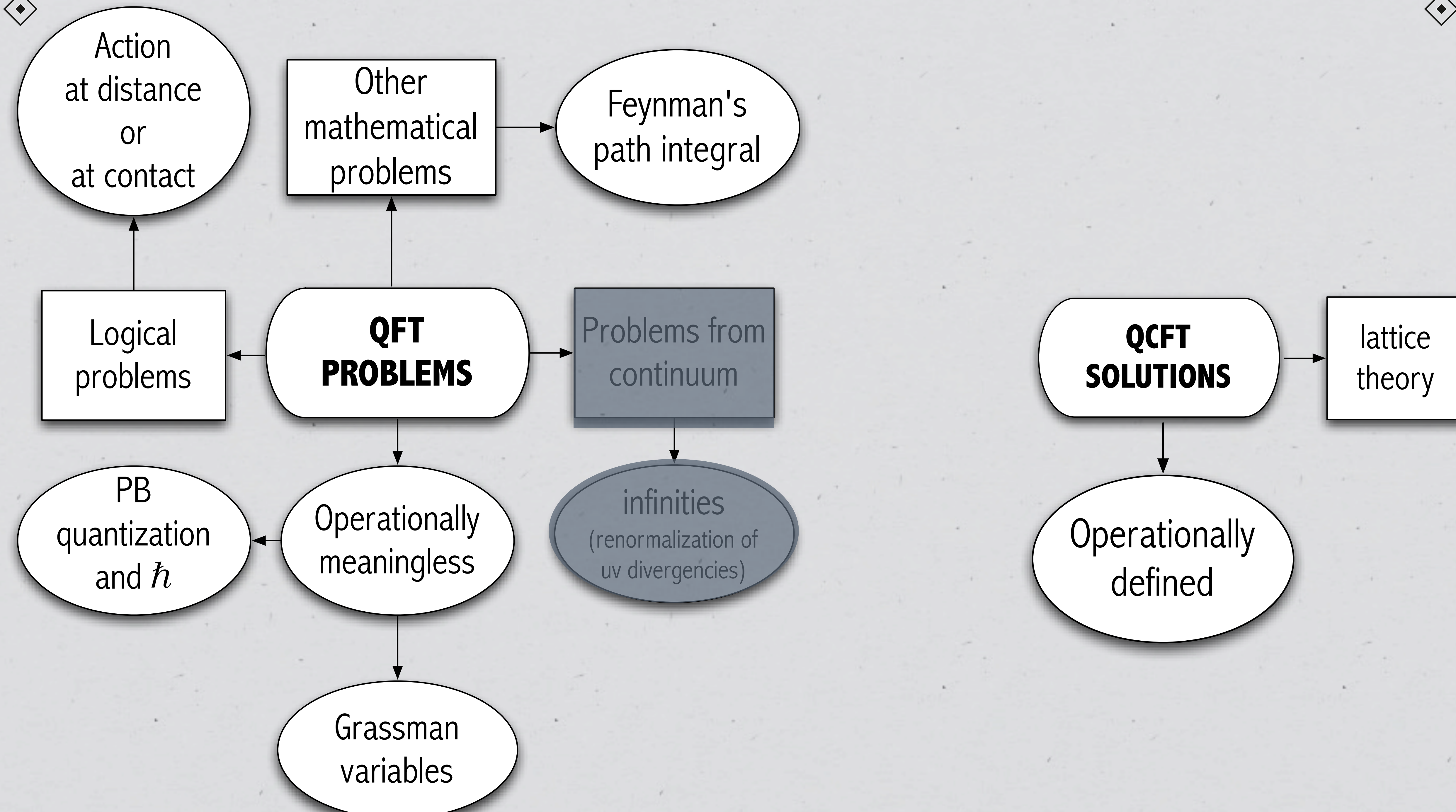

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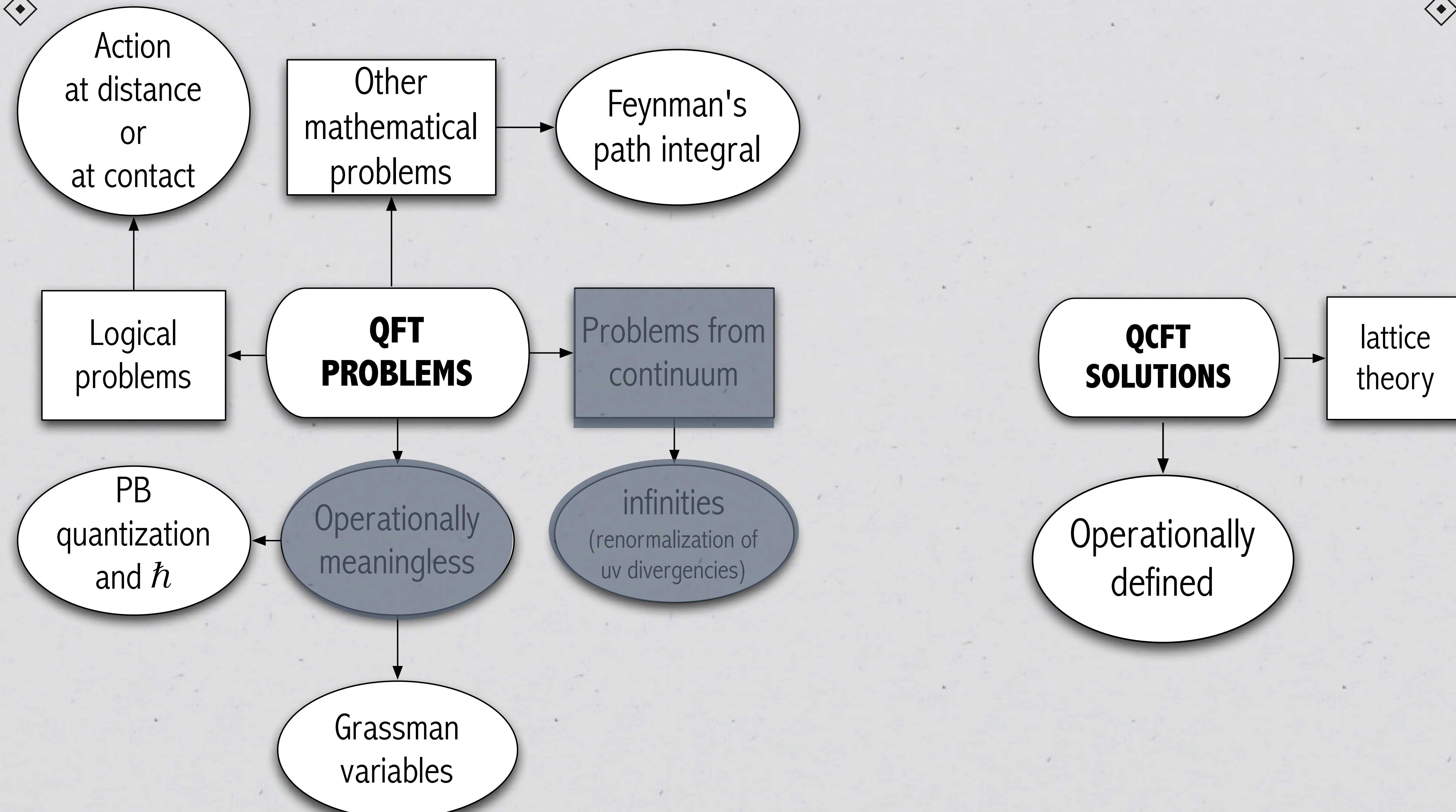

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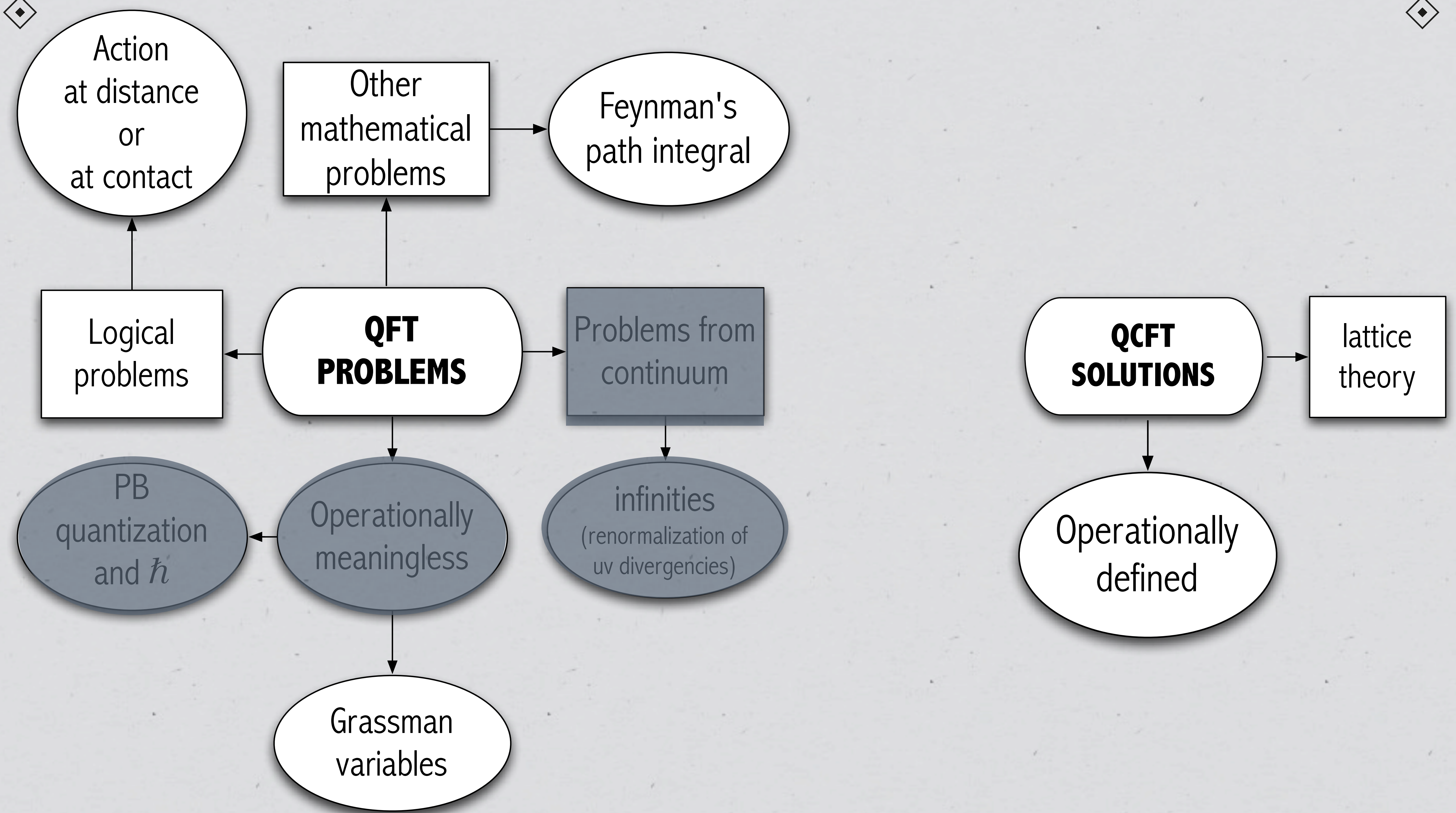

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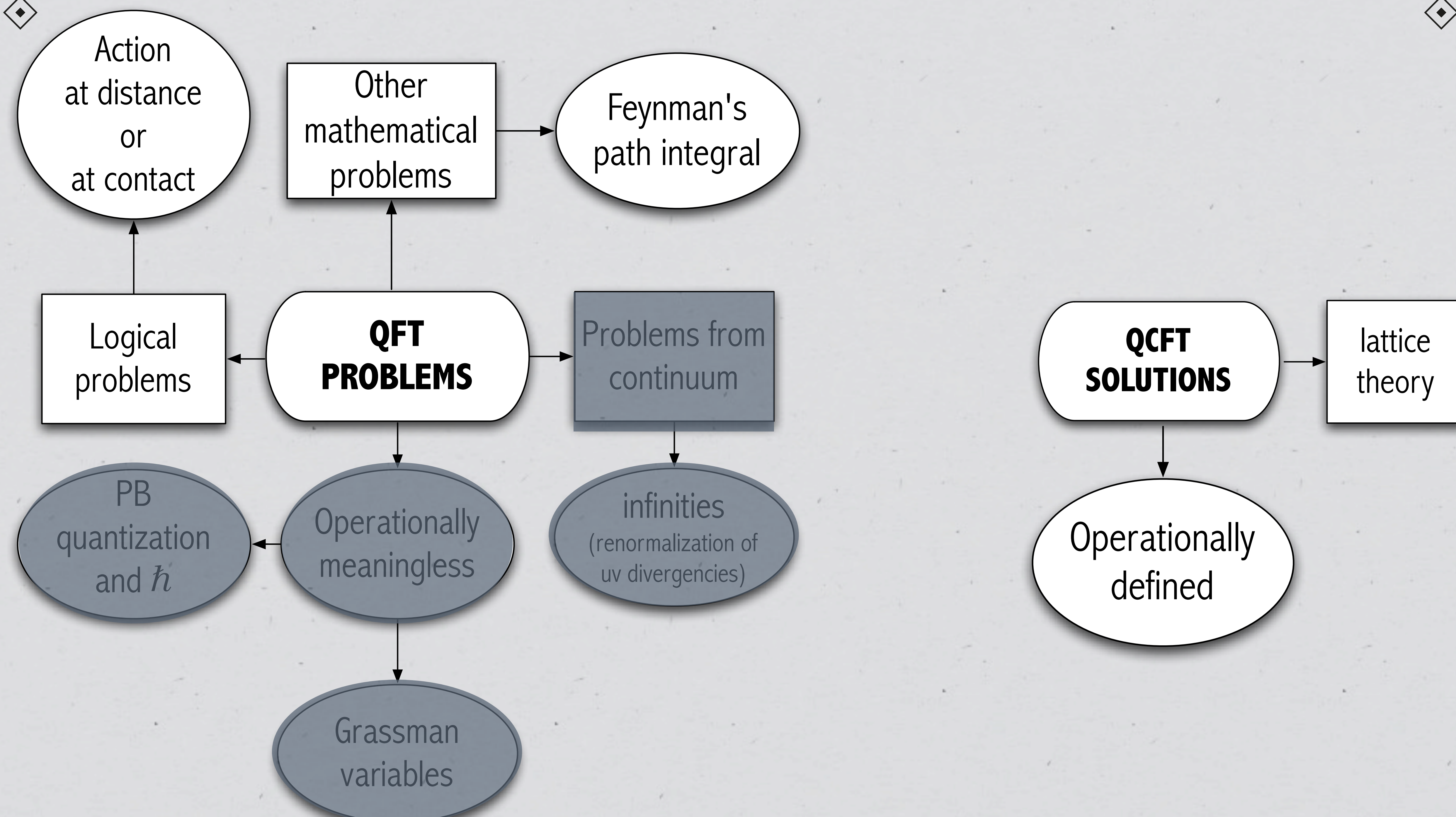

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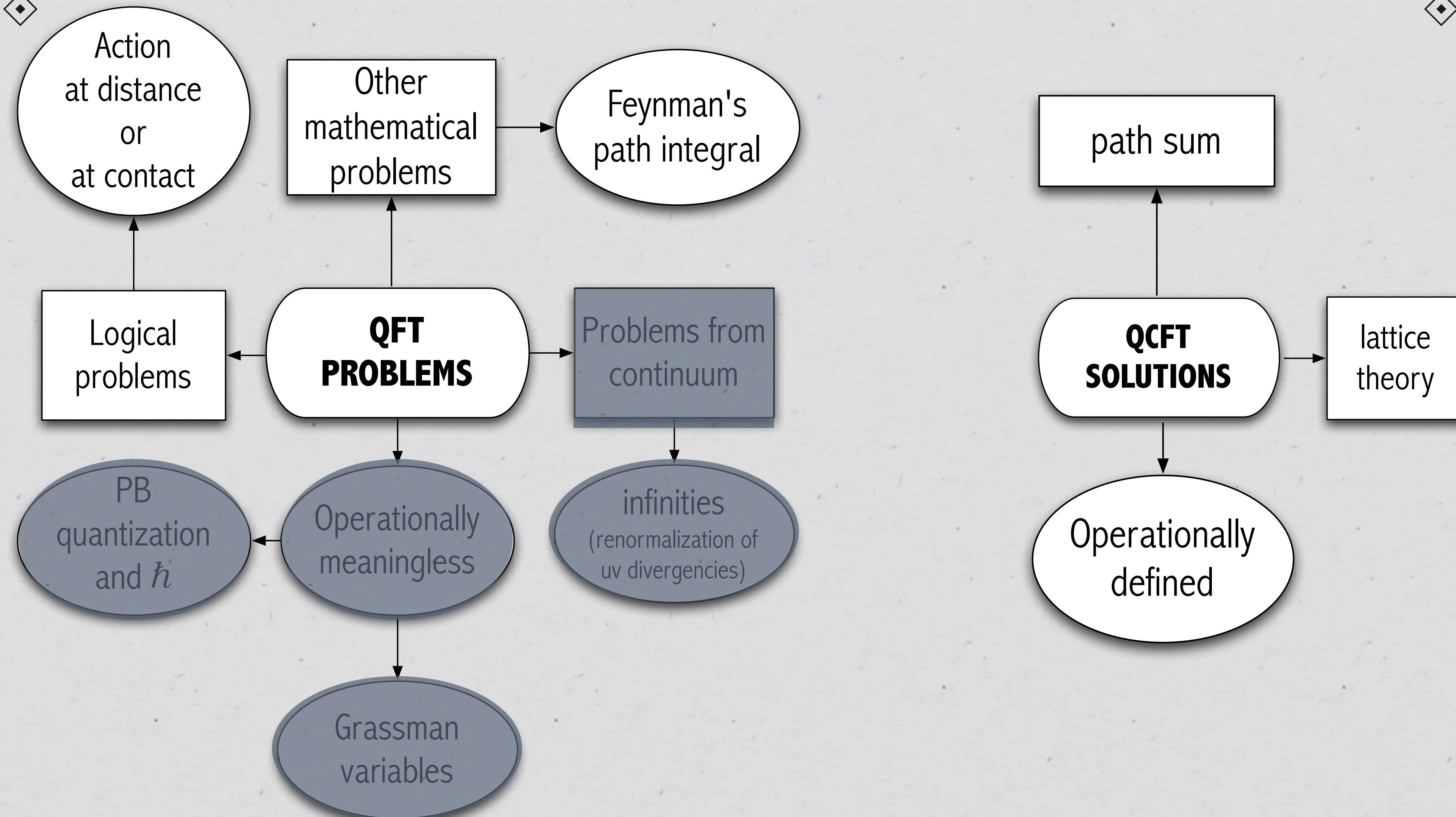

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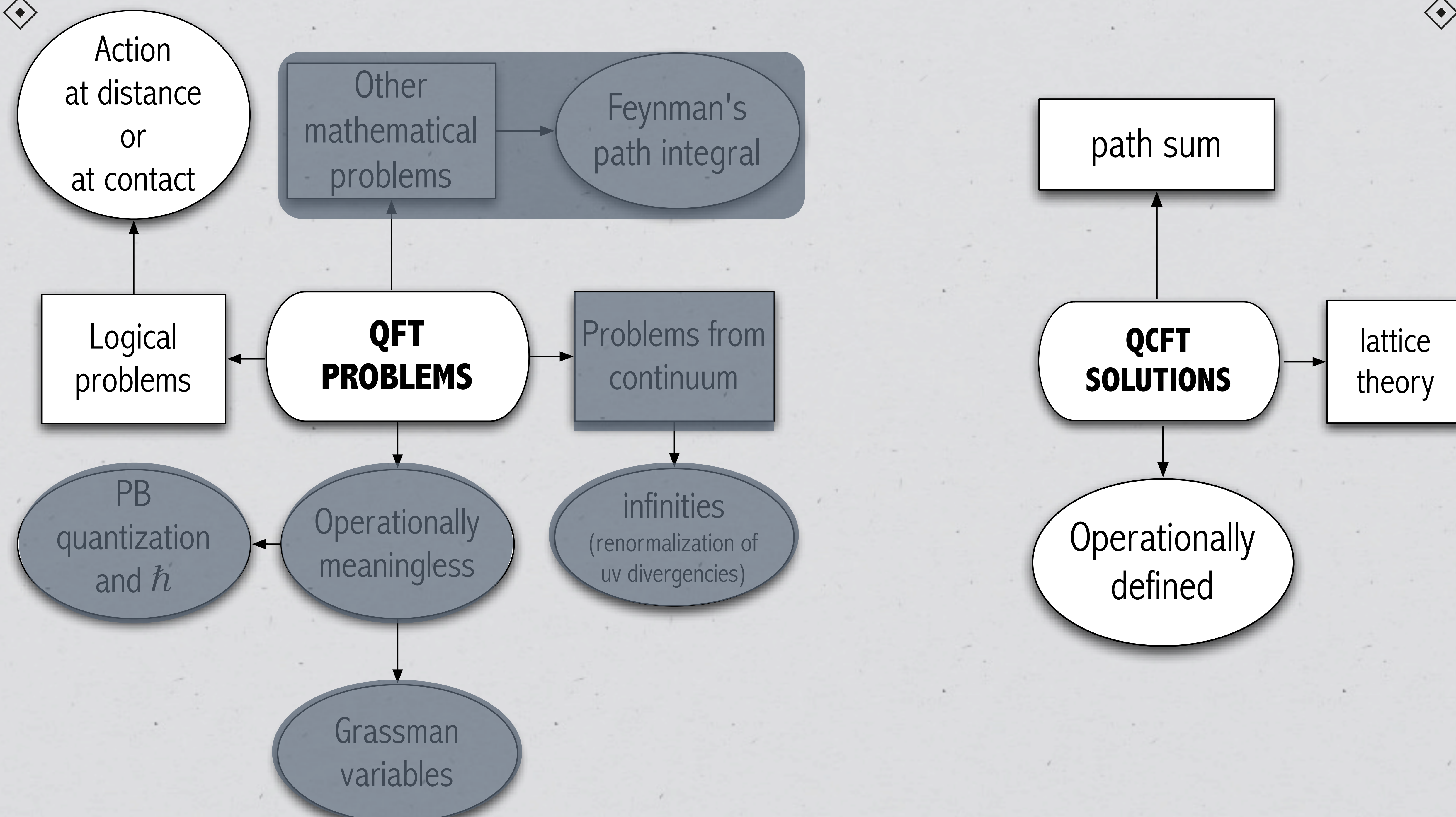

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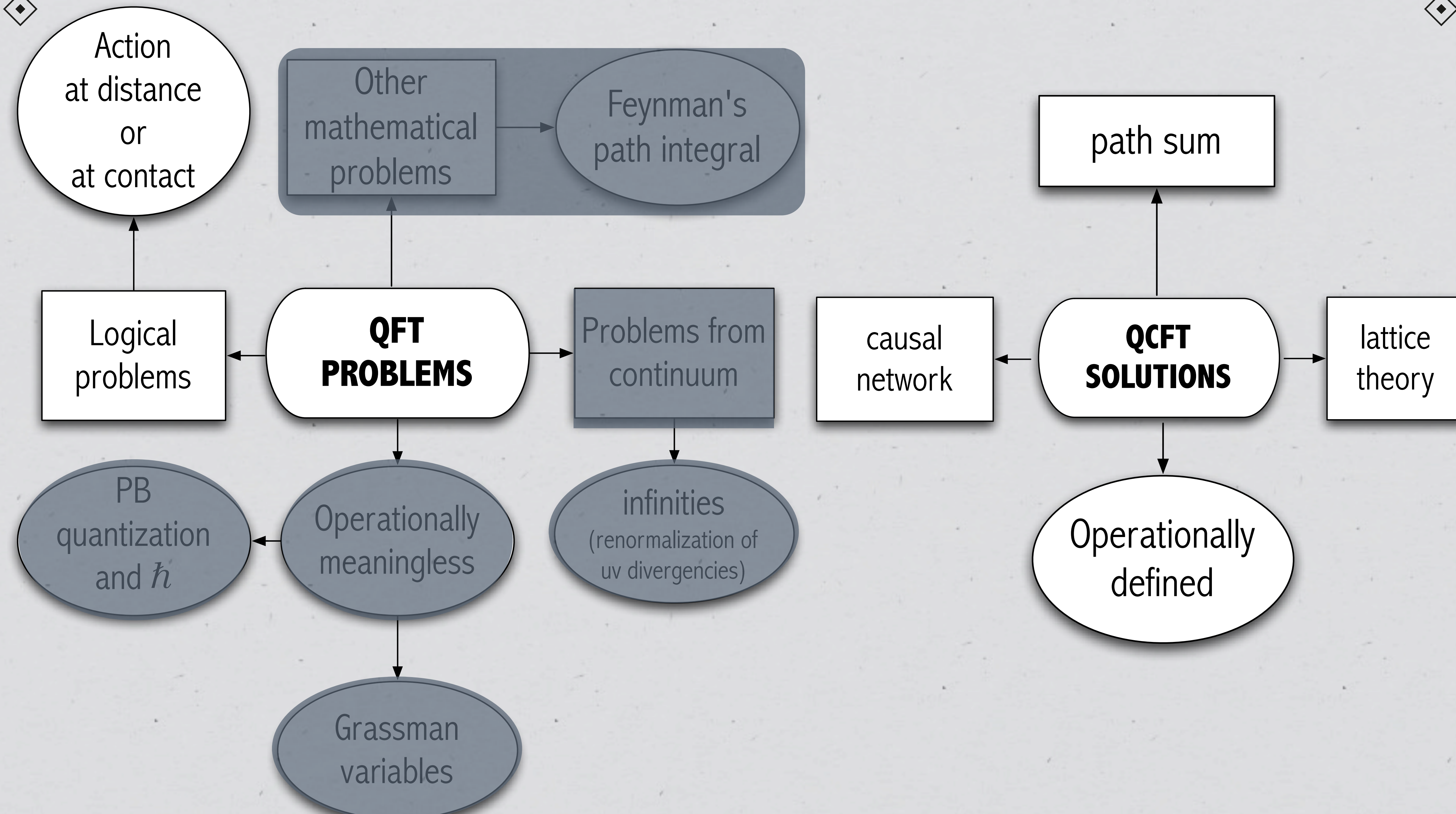

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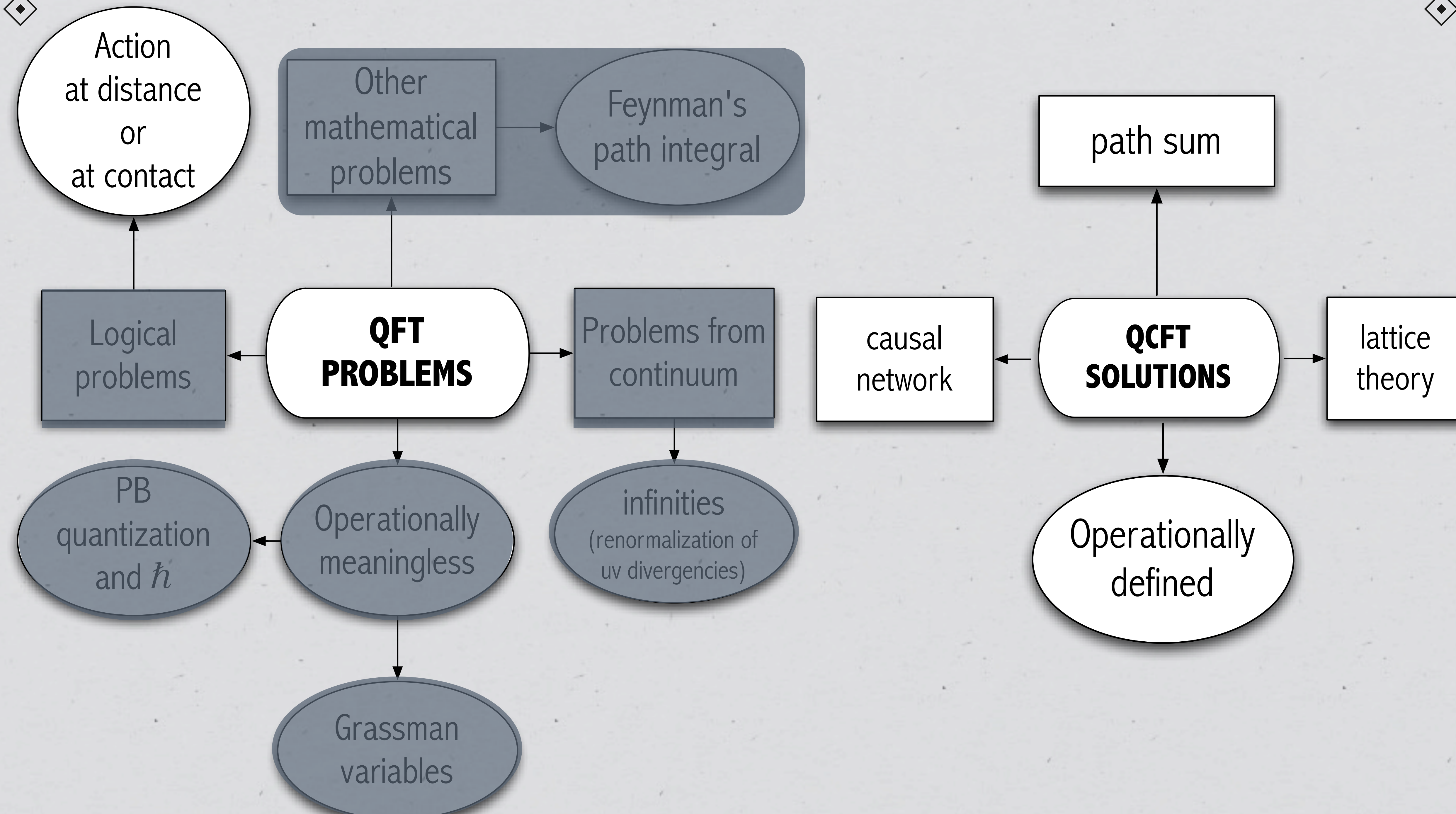

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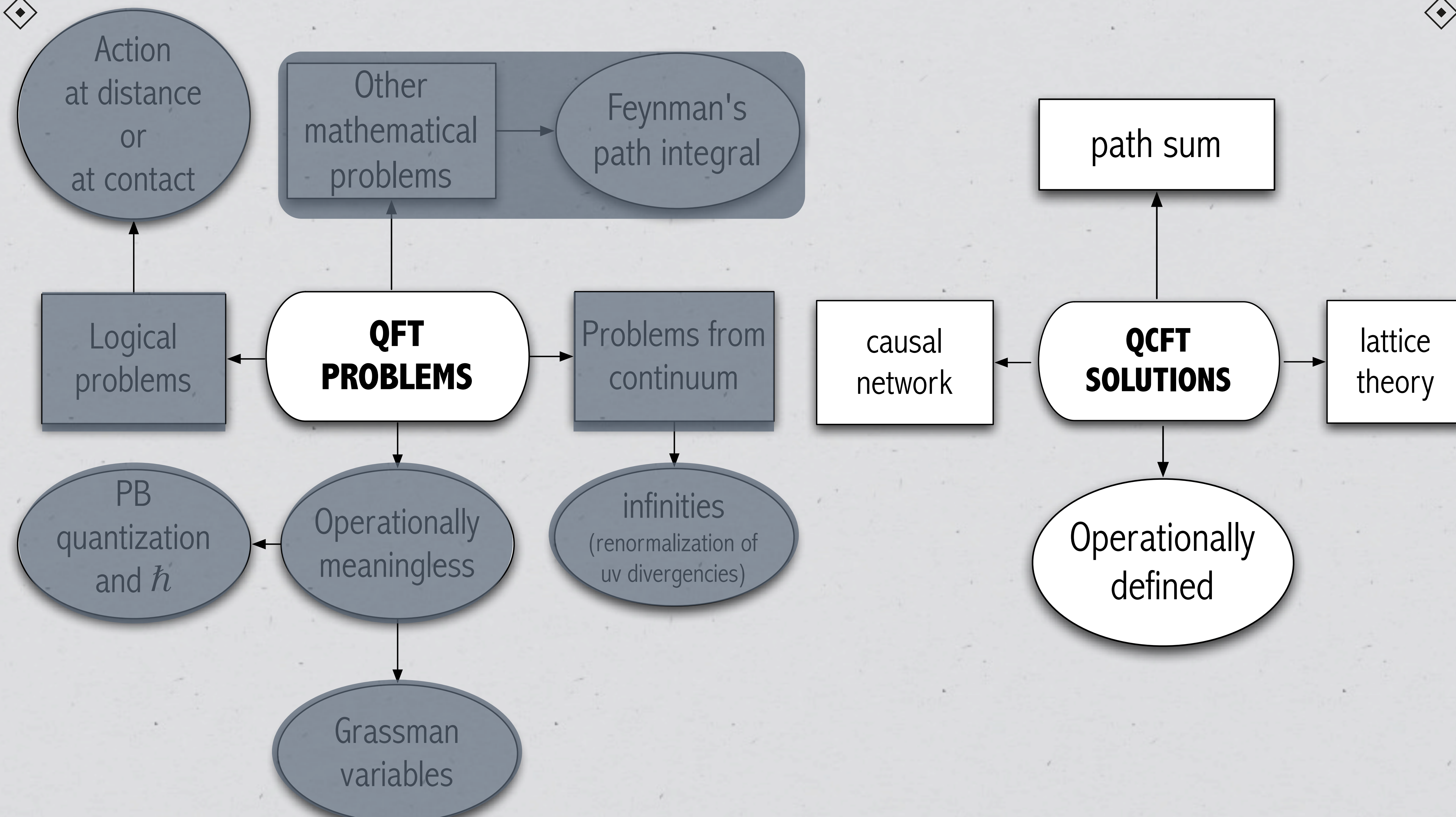

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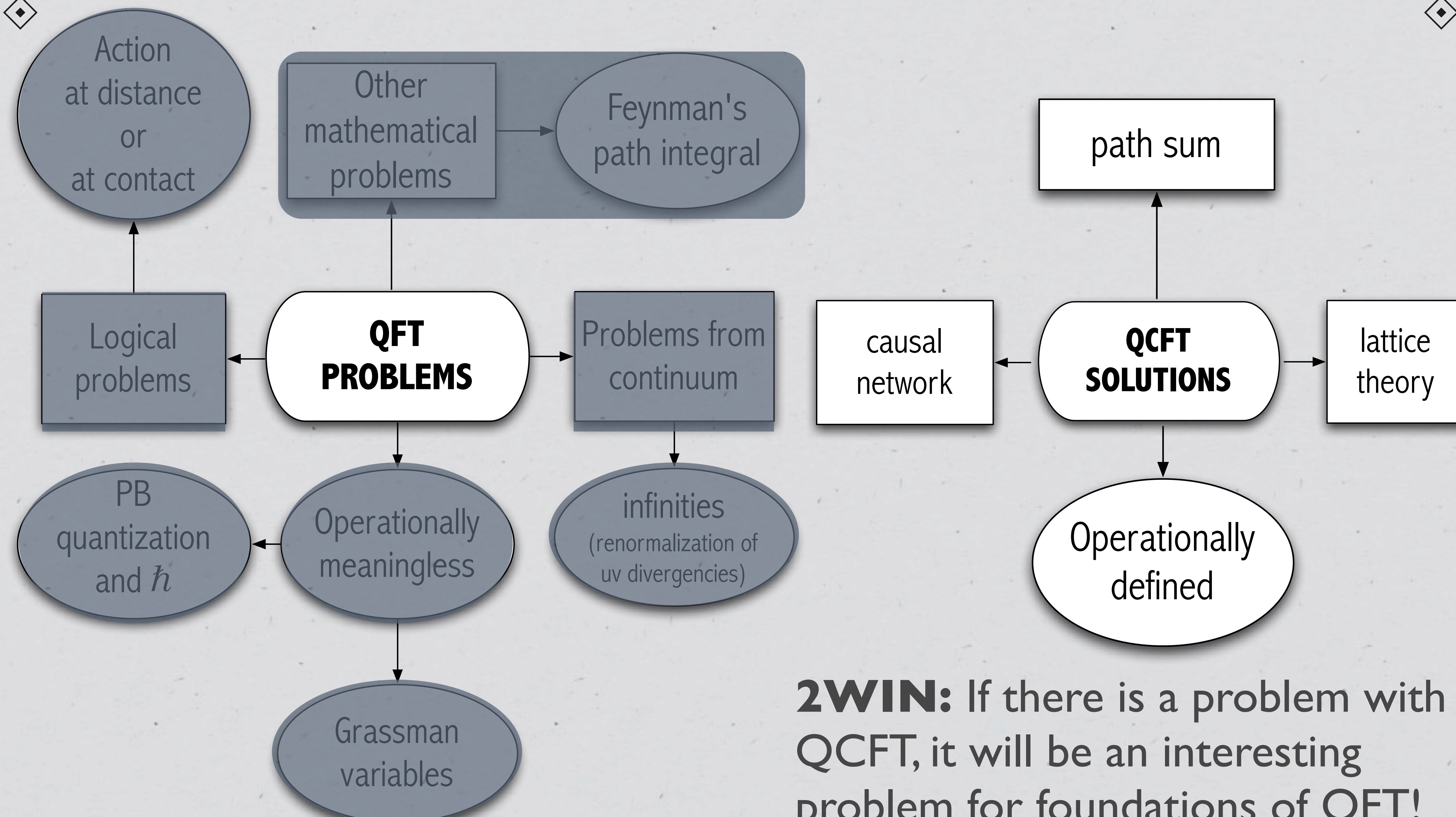

2WIN: If there is a problem with QCFT, it will be an interesting problem for foundations of QFT!

CONCLUSIONS

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- is QG-ready (no presupposed space-time backround)
- is fun! (good excuse for QI people to come back to physics)