Black hole horizons and quantum information

Discreteness and determinism

in

superstring theory

Gerard 't Hooft

Institute for Theoretical Physics
Spinoza Institute
Utrecht University, the Netherlands

minitalk:

The Conformal Black Hole

minitalk:

The Conformal Black Hole

The black hole horizon was recognized to be a major problem in quantum gravity already some 30 years ago.

minitalk:

The Conformal Black Hole

The black hole horizon was recognized to be a major problem in quantum gravity already some 30 years ago. One cannot derive the quantum properties of a black hole using textbook calculational procedures regardless which of today's quantum gravity theories one adheres to.

minitalk:

The Conformal Black Hole

The black hole horizon was recognized to be a major problem in quantum gravity already some 30 years ago. One cannot derive the quantum properties of a black hole using textbook calculational procedures regardless which of today's quantum gravity theories one adheres to. This includes superstring theory.

minitalk:

The Conformal Black Hole

The black hole horizon was recognized to be a major problem in quantum gravity already some 30 years ago. One cannot derive the quantum properties of a black hole using textbook calculational procedures regardless which of today's quantum gravity theories one adheres to. This includes superstring theory.
The problem is not to identify what is wrong with the textbook procedures, and how one might cure the disease.

minitalk:

The Conformal Black Hole

The black hole horizon was recognized to be a major problem in quantum gravity already some 30 years ago. One cannot derive the quantum properties of a black hole using textbook calculational procedures regardless which of today's quantum gravity theories one adheres to. This includes superstring theory.

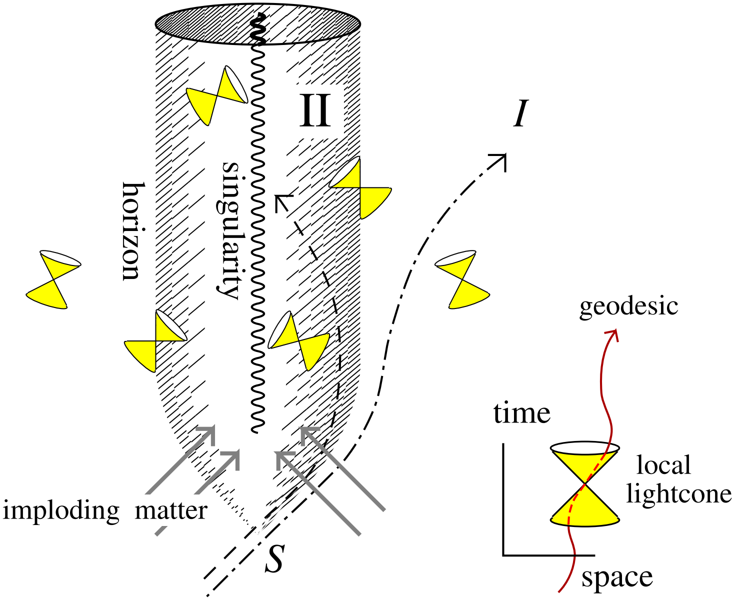
The problem is not to identify what is wrong with the textbook procedures, and how one might cure the disease. The problem is to find a solution that allows one to do detailed calculations and to understand what the rules are.

minitalk:

The Conformal Black Hole

The black hole horizon was recognized to be a major problem in quantum gravity already some 30 years ago. One cannot derive the quantum properties of a black hole using textbook calculational procedures regardless which of today's quantum gravity theories one adheres to. This includes superstring theory.
The problem is not to identify what is wrong with the textbook procedures, and how one might cure the disease. The problem is to find a solution that allows one to do detailed calculations and to understand what the rules are.

Quantum black hole physics today is in the same state of confusion as elementary particle physics before the advent of the Standard Model.


II
I
horizon
singularity
geodesic
time
local
lightcone
space
imploding matter
S

Hawking's result: what is perceived as a vacuum to an observer who goes through the horizon, is a state of entangled particles for an outside observer.
Since the outside observer does not see the particles that disappeared into the black hole, the states he does observe form a *quantum mixed state*, to be described by a *density matrix*.

A text book procedure should be found to replace that by a quantum mechanical *pure* state.
But whatever you do, you then modify the state described by the observer who went in.

Now, the observer who went in sees particles: a firewall.

Apparently, the *general coordinate transformation* that links the inside observer to the outside observer is more complex than previously thought. We now have a proposal:

Apparently, the *general coordinate transformation* that links the inside observer to the outside observer is more complex than previously thought. We now have a proposal:

Causality: the two observers agree about the causal ordering of any pair of space-time points (future, past, or spacelike separated).

Apparently, the *general coordinate transformation* that links the inside observer to the outside observer is more complex than previously thought. We now have a proposal:

Causality: the two observers agree about the causal ordering of any pair of space-time points (future, past, or spacelike separated).

Therefore, they agree about the location of all light cones.

Apparently, the *general coordinate transformation* that links the inside observer to the outside observer is more complex than previously thought. We now have a proposal:

Causality: the two observers agree about the causal ordering of any pair of space-time points (future, past, or spacelike separated).

Therefore, they agree about the location of all light cones.

In a given coordinate frame, the metric tensor $g_{\mu\nu}(\vec{x}, t)$ has 10 independent components. One of these is the overall factor ("conformal factor"): $g_{\mu\nu} = \omega^2 \, \hat{g}_{\mu\nu}$. The light cones only depend on $\hat{g}_{\mu\nu}$, not on ω. *Our two observers disagree about* ω *!!*

Apparently, the *general coordinate transformation* that links the inside observer to the outside observer is more complex than previously thought. We now have a proposal:

Causality: the two observers agree about the causal ordering of any pair of space-time points (future, past, or spacelike separated).

Therefore, they agree about the location of all light cones.

In a given coordinate frame, the metric tensor $g_{\mu\nu}(\vec{x}, t)$ has 10 independent components. One of these is the overall factor ("conformal factor"): $g_{\mu\nu} = \omega^2 \hat{g}_{\mu\nu}$. The light cones only depend on $\hat{g}_{\mu\nu}$, not on ω. *Our two observers disagree about* ω *!!*

Indeed they do! The outside observer sees that the hole shrinks to zero; the inside observer sees a whole whose mass did not change as he passed the $t = \infty$ line (the horizon). One can write the Schw. metric as

$$\mathrm{d}s^2 = M^2(t)\Big(-\mathrm{d}t^2(1-2/r) + \frac{\mathrm{d}r^2}{1-2/r} + r^2\mathrm{d}\Omega^2\Big)$$

We promote ω to a "local gauge field", *without modifying the physics!*. The field ω always was a dynamical variable in Einstein Hilbert gravity.

Now, splitting off the field ω, it appears to behave just as a scalar "Higgs" particle, *except that it has negative energy* (It sits at the wrong end in Einstein's gravity equation: $G_{\mu\nu} = 8\pi G\, T_{\mu\nu}$) .

Here, $G_{\mu\nu}$ is the ω contribution to the energy momentum tensor.

We promote ω to a "local gauge field", *without modifying the physics!*. The field ω always was a dynamical variable in Einstein Hilbert gravity.

Now, splitting off the field ω, it appears to behave just as a scalar "Higgs" particle, *except that it has negative energy* (It sits at the wrong end in Einstein's gravity equation: $G_{\mu\nu} = 8\pi G\, T_{\mu\nu}$) .

Here, $G_{\mu\nu}$ is the ω contribution to the energy momentum tensor.

ω has a "vacuum expectation value", $\langle\,\omega\,\rangle$. But the notion of 'vacuum' depends on how you choose your boundary at infinity. that's why our two observers disagree about $\langle\,\omega\,\rangle$.

We promote ω to a "local gauge field", *without modifying the physics!*. The field ω always was a dynamical variable in Einstein Hilbert gravity.

Now, splitting off the field ω, it appears to behave just as a scalar "Higgs" particle, *except that it has negative energy* (It sits at the wrong end in Einstein's gravity equation: $G_{\mu\nu} = 8\pi G\, T_{\mu\nu}$) .

Here, $G_{\mu\nu}$ is the ω contribution to the energy momentum tensor.

ω has a "vacuum expectation value", $\langle\, \omega \,\rangle$. But the notion of 'vacuum' depends on how you choose your boundary at infinity. that's why our two observers disagree about $\langle\, \omega \,\rangle$.

New observation: demand laws of nature to stay regular as $\omega \to 0$. This helps. This is great. But:

We promote ω to a "local gauge field", *without modifying the physics!*. The field ω always was a dynamical variable in Einstein Hilbert gravity.

Now, splitting off the field ω, it appears to behave just as a scalar "Higgs" particle, *except that it has negative energy* (It sits at the wrong end in Einstein's gravity equation: $G_{\mu\nu} = 8\pi G\, T_{\mu\nu}$) .

Here, $G_{\mu\nu}$ is the ω contribution to the energy momentum tensor.

ω has a "vacuum expectation value", $\langle\,\omega\,\rangle$. But the notion of 'vacuum' depends on how you choose your boundary at infinity. that's why our two observers disagree about $\langle\,\omega\,\rangle$.

New observation: demand laws of nature to stay regular as $\omega \to 0$. This helps. This is great. But:

. . . it gives too strong constraints on the physics (all anomalies have to cancel, which gives too many equations for Nature's constants, and they appear to be in conflict.

End of minitalk on black holes

The Cellular Automaton Interpretation of QM

Axioms:

The Cellular Automaton Interpretation of QM

Axioms:

i CA-States evolve classically:
$t = t_1 \to t_2, \to \cdots , \quad \vec{Q}_1 \to \vec{Q}_2 \to \cdots$
Write these states as a *basis* for a *Hilbert space*.

ii Write evolution operator U : $\quad |\vec{Q}(t+\delta t)\rangle = U(\delta t)|\vec{Q}(t)\rangle$;

$$\text{Example: } U = \begin{pmatrix} 0 & 0 & \cdots & 1 \\ 1 & 0 & & 0 \\ 0 & 1 & & 0 \\ & & \cdots & \end{pmatrix}$$

iii Find operator H such that $\quad U = \exp(-iH\,\delta t)$.

The Cellular Automaton Interpretation of QM

Axioms:

i CA-States evolve classically:
$t = t_1 \to t_2, \to \cdots , \quad \vec{Q}_1 \to \vec{Q}_2 \to \cdots$
Write these states as a *basis* for a *Hilbert space*.

ii Write evolution operator U : $\quad |\vec{Q}(t+\delta t)\rangle = U(\delta t)|\vec{Q}(t)\rangle$;

$$\text{Example: } U = \begin{pmatrix} 0 & 0 & \cdots & 1 \\ 1 & 0 & & 0 \\ 0 & 1 & & 0 \\ & & \cdots & \end{pmatrix}$$

iii Find operator H such that $U = \exp(-iH\,\delta t)$.

iv Make unitary transformation to *any* other basis. One finds a "quantum mechanical" system, obeying Schrödinger equation
$\frac{\mathrm{d}}{\mathrm{d}t}|\psi(t)\rangle = -iH|\psi(t)\rangle$.

v Measurement: "classical" states are CA states: planets, people, indicators of detectors. Therefore, at the end of an experiment, all observed quantities are diagonal in $|\vec{Q}\rangle$.

This is nearly quantum mechanics, except:

This is nearly quantum mechanics, except:

the expectation value of an operator is not: $\langle\, \mathcal{O}\, \rangle \stackrel{?}{=} \langle\psi|\mathcal{O}|\psi\rangle$,
but:

$$\langle\, \mathcal{O}\, \rangle = \sum_{\vec{Q}} |\langle\vec{Q}|\psi\rangle|^2 \,\langle\vec{Q}|\, \mathcal{O}\, |\vec{Q}\rangle = \mathrm{Tr}\, \varrho\, \mathcal{O} \ \ ; \ \ \varrho = \sum_{\vec{Q}} \varrho_{\vec{Q}} |\vec{Q}\rangle\langle\vec{Q}| \ .$$

This is nearly quantum mechanics, except:

the expectation value of an operator is not: $\langle\, \mathcal{O}\,\rangle \stackrel{?}{=} \langle\psi|\mathcal{O}|\psi\rangle$,
but:

$$\langle\, \mathcal{O}\,\rangle = \sum_{\vec{Q}} |\langle\vec{Q}|\psi\rangle|^2 \,\langle\vec{Q}|\,\mathcal{O}\,|\vec{Q}\rangle = \mathrm{Tr}\,\varrho\,\mathcal{O}\ \ ;\ \ \varrho = \sum_{\vec{Q}} \varrho_{\vec{Q}}|\vec{Q}\rangle\langle\vec{Q}|\ .$$

This means that we have to restrict ourselves to density matrices diagonal in the CA basis.

"Collapse" of the wave function explained (axiom *v*): classical states are diagonal in $|\vec{Q}\rangle$.

Work was motivated when attempting to formulate the quantum rules of compact universes.

*) SUPERSTRINGS may provide for the best scenario for
Cellular Automaton - determinism!

**) But one has to address *NO* - *GO* theorems !

Can one escape no-go theorems (Bell's inequalities)?

Theorem (Bell):
In any deterministic theory intended to reproduce quantum behavior, (for instance when Einstein-Podolsky-Rosen photons are observed through two spacelike separated filters, $\vec{a}$ and $\vec{b}$), one will have to allow superluminal signals between $\vec{a}$ and $\vec{b}$.

... since we should be allowed to modify the settings $\vec{a}$ and/or $\vec{b}$ any time, at free will...

Can one escape no-go theorems (Bell's inequalities)?

Theorem (Bell):
In any deterministic theory intended to reproduce quantum behavior, (for instance when Einstein-Podolsky-Rosen photons are observed through two spacelike separated filters, $\vec{a}$ and $\vec{b}$), one will have to allow superluminal signals between $\vec{a}$ and $\vec{b}$.

... since we should be allowed to modify the settings $\vec{a}$ and/or $\vec{b}$ any time, at free will...

But there is no "free will" in a deterministic theory (Super-determinism).

Superdeterminism?

Superdeterminism?

Theorem: even so, you cannot avoid Bell's inequalities!

unless you accept "ridiculous fine-tuning", or "conspiracy"

Superdeterminism?

Theorem: even so, you cannot avoid Bell's inequalities!

unless you accept "ridiculous fine-tuning", or "conspiracy"

Today's claim: we never need actual signals going backwards in time or faster than light. All we need is non-locally correlated vacuum fluctuations.

Vacuum fluctuations with spacelike separated correlations are ubiquitous in QFT vacua.

This does *still not* invalidate Bell's theorem completely: the correlations at any given Cauchy surface must "anticipate" what Aice and Bob are going to decide.

This does *still not* invalidate Bell's theorem completely: the correlations at any given Cauchy surface must "anticipate" what Aice and Bob are going to decide.

This form of superdeterminism requires: *conspiracy*.
"That's disgusting".

But:

This does *still not* invalidate Bell's theorem completely: the correlations at any given Cauchy surface must "anticipate" what Aice and Bob are going to decide.

This form of superdeterminism requires: *conspiracy*.
"That's disgusting".

But:
is "disgusting" a sound mathematical argument?

Now introduce the Superstring

Superstring theory appears to be complicated and counter intuitive. Some physicists insist that physics at smaller distance scales will be strange and counter intuitive.

"*stranger even than quantum mechanics*" (D. Gross) .

should we believe this ?

Now introduce the Superstring

Superstring theory appears to be complicated and counter intuitive. Some physicists insist that physics at smaller distance scales will be strange and counter intuitive.

"*stranger even than quantum mechanics*" (D. Gross) .

should we believe this ?

Gell-Mann: the world seems to become more and more complex, *until you reach new understanding.* Then things are simple again.

I now want to present my theory:

Now introduce the Superstring

Superstring theory appears to be complicated and counter intuitive. Some physicists insist that physics at smaller distance scales will be strange and counter intuitive.

"*stranger even than quantum mechanics*" (D. Gross) .

should we believe this ?

Gell-Mann: the world seems to become more and more complex, *until you reach new understanding.* Then things are simple again.

I now want to present my theory:

Superstring theory is even simpler than classical mechanics!

(because there is not even chaos. . .)

If you understand what String Theory really is ...

this idea is conceptually simple, but mathematically hard . . .

The Superstring can be mapped onto a CA

QFT works with operator fields whose eigenvalues are real numbers
CA works with observables that are discrete, or integers
(and they all commute . . .)

Theorem:

The Superstring can be mapped onto a CA

QFT works with operator fields whose eigenvalues are real numbers
CA works with observables that are discrete, or integers
(and they all commute . . .)

Theorem:

There are unitary transformations between

- Hilbert spaces spanned by the eigenstates of real number operators

and

- those spanned by pairs of integer valued operators.

The Superstring can be mapped onto a CA

QFT works with operator fields whose eigenvalues are real numbers
CA works with observables that are discrete, or integers
(and they all commute . . .)

Theorem:

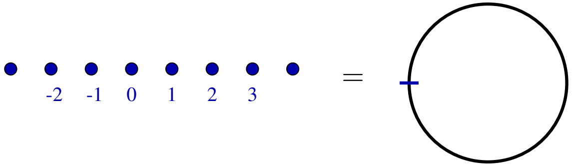
There are unitary transformations between

- Hilbert spaces spanned by the eigenstates of real number operators

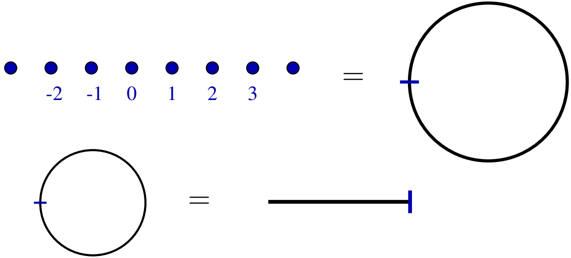
and

- those spanned by pairs of integer valued operators.

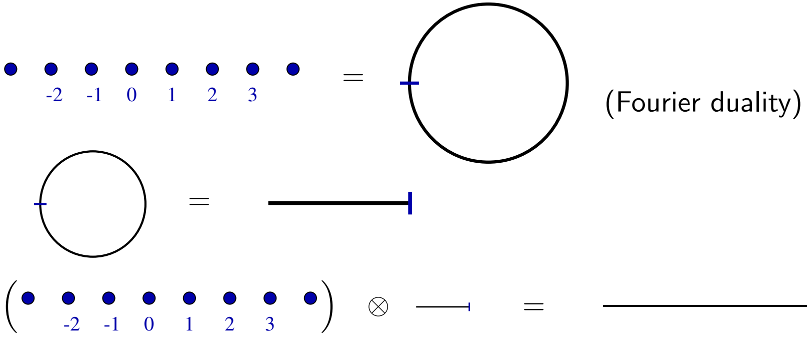
And indeed, in some special cases, the integers may evolve *classically* while the real number operators can only evolve *quantum mechanically*.



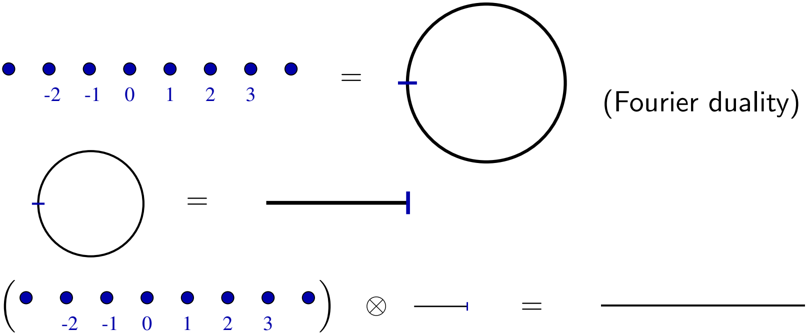
(Fourier duality)



(Fourier duality)

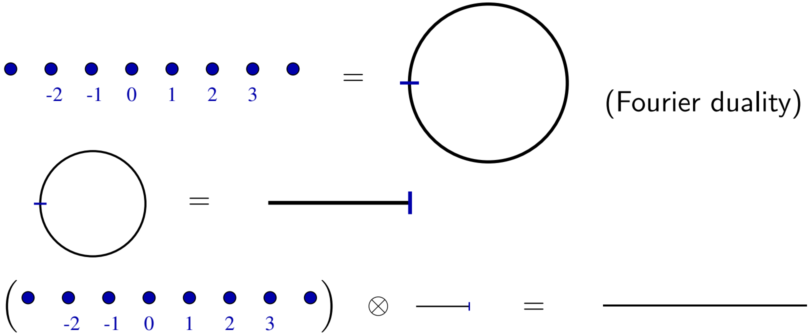


Make real number operators $-\infty < q < \infty$ as follows:



Make real number operators $-\infty < q < \infty$ as follows: $q = Q + \eta_P$

There is a unitary transformation of states from one basis to another: $\langle Q,\, \eta_P | \psi \rangle \;=\; \langle q | \psi \rangle$. $\qquad \epsilon \equiv e^{2\pi} = 535.5$



Make real number operators $-\infty < q < \infty$ as follows: $q = Q + \eta_P$

There is a unitary transformation of states from one basis to another: $\langle Q,\, \eta_P | \psi \rangle \;=\; \langle q | \psi \rangle$. $\epsilon \equiv e^{2\pi} = 535.5$

Then transform $\langle Q,\, \eta_P | \psi \rangle = \sum_{P=-\infty}^{\infty} \epsilon^{-iP\eta_P} \langle Q,\, P | \psi \rangle \;=\; \langle q | \psi \rangle$

Alternatively, find the p basis: $\langle q | p \rangle = \epsilon^{\,ipq}$

How does this work in QFT?

Not so well! If you have field equations relating real-number fields, it is hard to do the book keeping "integral part" vs "fractional part".

How does this work in QFT?

Not so well! If you have field equations relating real-number fields, it is hard to do the book keeping "integral part" vs "fractional part".

It *does* work in 1 space, 1 time dimension

(exactly what's needed in string theory)

why?

Free massless bosons in $1+1$ dimensions

$$(\partial_x^2 - \partial_t^2)\phi(x,t) = 0 \qquad \to \qquad \phi(x,t) = \phi_L(x+t) + \phi_R(x-t) \ .$$

$$[\phi(x,t), p(y,t)] = \tfrac{i}{2\pi}\delta(x-y) \ ; \qquad H = \pi \int \mathrm{d}x (p(x)^2 + (\partial_x\phi)^2) \ .$$

Temporary: put x and t on a lattice.

Discrete $\ p_x, \phi_x \ : \quad \phi_{x,t} \equiv \phi(x,t)\ ; \qquad [\phi_{x,t},\ p_{x',t}] = \tfrac{i}{2\pi}\delta_{x,x'}$.

We have: $\phi(x, t+a) + \phi(x, t-a) = \phi(x-a, t) + \phi(x+a, t)$.

We can *map* this model one-to-one on the cellular automaton:

$$Q(x, t+a) + Q(x, t-a) = Q(x-a, t) + Q(x+a, t) \ ,$$

where Q are integers.

In 1+1 dimensions, both in *field theory* and in *cellular automata*, we have *left movers* and *right movers*:

$$\phi(x,t)=\phi^L(x+t)+\phi^R(x-t)\ ;\ p(x,t)=\tfrac{1}{2}a^L(x+t)+\tfrac{1}{2}a^R(x-t)\ .$$

$$a^L=p+\partial_x\phi\ ;\quad a^R=p-\partial_x\phi\ .$$

In 1+1 dimensions, both in *field theory* and in *cellular automata*, we have *left movers* and *right movers*:

$$\phi(x,t)=\phi^L(x+t)+\phi^R(x-t)\ ;\ p(x,t)=\tfrac{1}{2}a^L(x+t)+\tfrac{1}{2}a^R(x-t)\ .$$

$$a^L=p+\partial_x\phi\ ;\quad a^R=p-\partial_x\phi\ .$$

$$\text{Now,}\qquad H\ =\ \pi(p^2+(\partial_x\phi)^2)\ =\ \tfrac{1}{2}\pi({a^L}^2+{a^R}^2)\ ,$$

$$[a^L,\,a^R]=0\ ;\quad [a^L(x),\,a^L(y)]=\tfrac{i}{\pi}\partial_x\delta(x-y)\quad ;$$

In 1+1 dimensions, both in *field theory* and in *cellular automata*, we have *left movers* and *right movers*:

$$\phi(x,t)=\phi^L(x+t)+\phi^R(x-t)\ ;\ p(x,t)=\tfrac12 a^L(x+t)+\tfrac12 a^R(x-t)\ .$$

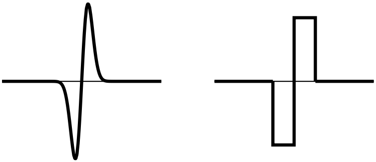
$$a^L=p+\partial_x\phi\ ;\quad a^R=p-\partial_x\phi\ .$$

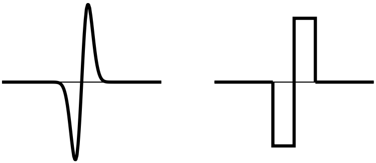
Now, $\quad H\ =\ \pi(p^2+(\partial_x\phi)^2)\ =\ \tfrac12\pi({a^L}^2+{a^R}^2)\ ,$

$$[a^L,\,a^R]=0\ ;\quad [a^L(x),\,a^L(y)]=\tfrac{i}{\pi}\partial_x\delta(x-y)\quad ;$$

Our cellular automaton will be on a lattice: $(x,t)\in\mathbb{Z}$. Therefore, replace commutator by

$$[\phi(x),\,p(y)]=\tfrac{i}{2\pi}\delta_{x,y}\quad\to\quad [a^L(x),\,a^L(y)]=\pm\tfrac{i}{2\pi}\ \text{ if }\ y=x\pm1\ .$$





Demanding $[a^L(x),\ a^L(y)] = \pm\frac{i}{2\pi}$ if $y = x \pm 1$

Disregarding periodicity:

$$a^L(x) = A^L(x) + \eta_A^L(x-1)\ .$$

This gives the mapping.

There are some mathematical complications. A set of states with measure zero cannot be mapped. These are the states that span the whole universe, and all (unbounded) values of the fields. This can partly be cured using elliptic functions, but not completely.

The (super) string is a 1+1 dimensional theory.

Here, the quantized field is the set of (super) string coordinates.

The (super) string is a 1+1 dimensional theory.

Here, the quantized field is the set of (super) string coordinates. They are now replaced by the integer valued left- and right-movers $A^{L,R}(x \pm t)$.

The (super) string is a 1+1 dimensional theory.

Here, the quantized field is the set of (super) string coordinates. They are now replaced by the integer valued left- and right-movers $A^{L,R}(x \pm t)$.

Re-inserting the units gives a surprise: these coordinates form a discrete lattice with lattice length a that is independent of the lattice chosen on the world sheet. Even if you send the world sheet to a continuum, the space-time lattice length a is

The (super) string is a 1+1 dimensional theory.

Here, the quantized field is the set of (super) string coordinates. They are now replaced by the integer valued left- and right-movers $A^{L,R}(x \pm t)$.

Re-inserting the units gives a surprise: these coordinates form a discrete lattice with lattice length a that is independent of the lattice chosen on the world sheet. Even if you send the world sheet to a continuum, the space-time lattice length a is

$$a = 2\pi\sqrt{\alpha'} \ .$$

The (super) string is a 1+1 dimensional theory.

Here, the quantized field is the set of (super) string coordinates. They are now replaced by the integer valued left- and right-movers $A^{L,R}(x \pm t)$.

Re-inserting the units gives a surprise: these coordinates form a discrete lattice with lattice length a that is independent of the lattice chosen on the world sheet. Even if you send the world sheet to a continuum, the space-time lattice length a is

$$a = 2\pi\sqrt{\alpha'} \ .$$

Furthermore, as we will see later, the string constant ρ is not freely adjustable.

Fermions

A fermionic system can be handled the same way.

Fermions

A fermionic system can be handled the same way. Assume a Majorana fermionic field ψ_A with $\psi_A = \psi_A^\dagger$, $A = 1, 2$ (or, $A = L, R$). Dirac equation: $(\gamma_+ \partial_- + \gamma_- \partial_+)\psi = 0$.

Fermions

A fermionic system can be handled the same way. Assume a Majorana fermionic field ψ_A with $\psi_A = \psi_A^\dagger$, $A = 1, 2$ (or, $A = L, R$). Dirac equation: $(\gamma_+ \partial_- + \gamma_- \partial_+)\psi = 0$.

One finds that $\psi_A^\mu(x,t) = \begin{pmatrix} \psi_L^\mu(x+t) \\ \psi_R^\mu(x-t) \end{pmatrix}$.

Fermions

A fermionic system can be handled the same way. Assume a Majorana fermionic field ψ_A with $\psi_A = \psi_A^\dagger$, $A = 1, 2$ (or, $A = L, R$). Dirac equation: $(\gamma_+\partial_- + \gamma_-\partial_+)\psi = 0$.

$$\text{One finds that} \quad \psi_A^\mu(x,t) = \begin{pmatrix} \psi_L^\mu(x+t) \\ \psi_R^\mu(x-t) \end{pmatrix} \ .$$

The corresponding classical theory now has Boolean degrees of freedom, $\sigma(x,t) = \pm 1$, obeying the equations:

$$\sigma(x,\ t+1) = \sigma(x-1,\ t)\ \sigma(x-1,\ t)\ \sigma(x,\ t-1)\ .$$

This also splits up into left- and right-movers:

$$\sigma(x,t) = \sigma_L(x+t)\ \sigma_R(x-t)\ .$$

Superstring theories contain $D-2$ independent bosonic fields (coordinates) and $D-2$ Majorana fermion species. All these can be mapped onto deterministic models processing integers classically.

Superstring theories contain $D - 2$ independent bosonic fields (coordinates) and $D - 2$ Majorana fermion species. All these can be mapped onto deterministic models processing integers classically.

So-far, we only handled strings of infinite length. We need to add: (periodic) boundary conditions, interactions, and *constraints.* The constraints give us the remaining two *longitudunal* coordinates, needed to investigate *Lorentz invariance*.

Superstring theories contain $D - 2$ independent bosonic fields (coordinates) and $D - 2$ Majorana fermion species. All these can be mapped onto deterministic models processing integers classically.

So-far, we only handled strings of infinite length. We need to add: (periodic) boundary conditions, interactions, and *constraints.*
The constraints give us the remaining two *longitudunal* coordinates, needed to investigate *Lorentz invariance*.

The constraints only need to be imposed on the quantum side of the theory, as is done in superstrings.
As is standard in Superstring theory, this restricts us to $D = 10$.

Superstring theories contain $D-2$ independent bosonic fields (coordinates) and $D-2$ Majorana fermion species. All these can be mapped onto deterministic models processing integers classically.

So-far, we only handled strings of infinite length. We need to add: (periodic) boundary conditions, interactions, and *constraints*. The constraints give us the remaining two *longitudunal* coordinates, needed to investigate *Lorentz invariance*.

The constraints only need to be imposed on the quantum side of the theory, as is done in superstrings.
As is standard in Superstring theory, this restricts us to $D=10$.

In Superstring Theory, both bosons and fermions obey gauge conditions and constraints, which should determine $\psi_A^\pm$ in terms of $a_{L,R}^{\mathrm{tr}}$, and so also $\sigma_{L,R}^0$ and $\sigma_{L,R}^{D-1}$ should be determined by the transverse $\sigma_{L,R}^a$

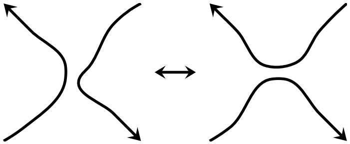
String Interactions

String Interactions

One can write down a *classical and unique* interaction among these classical strings: if two strings hit the same spacetime point Q^μ,

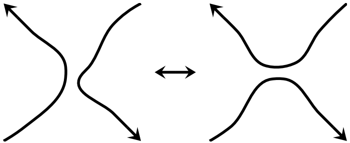
String Interactions

One can write down a *classical and unique* interaction among these classical strings: if two strings hit the same spacetime point Q^μ, two arms are exchanged:



String Interactions

One can write down a *classical and unique* interaction among these classical strings: if two strings hit the same spacetime point Q^μ, two arms are exchanged:

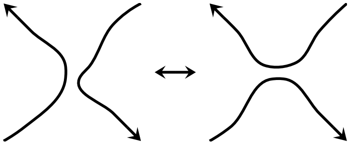


This is also deterministic if the string coupling constant g_s is fixed to $g_s = 1$, and the strings must be oriented.

This generates closed, interacting, oriented strings.

String Interactions

One can write down a *classical and unique* interaction among these classical strings: if two strings hit the same spacetime point Q^μ, two arms are exchanged:



This is also deterministic if the string coupling constant g_s is fixed to $g_s = 1$, and the strings must be oriented.

This generates closed, interacting, oriented strings.
We automatically have exact invariance under $O(D-2, \mathbb{Z})$.

After the mapping to QM in $D - 2 = 8$, the constraints confirm that we have 10-dimensional Lorentz invariance.

Conclusions

Conclusions

Superstring theory is a quantum theory that can be mapped onto a cellular automaton. The automaton puts the system on a space-time lattice with lattice length $a = 2\pi\sqrt{\alpha'}$. Obviously, this is finite.

Conclusions

Superstring theory is a quantum theory that can be mapped onto a cellular automaton. The automaton puts the system on a space-time lattice with lattice length $a = 2\pi\sqrt{\alpha'}$. Obviously, this is finite.

We do have to caution that the lattice on the *world sheet* was not yet sent to zero, but this seems to be a question of gauge-fixing rather than a physical limit, since we should have conformal invariance on the world sheet.

Conclusions

Superstring theory is a quantum theory that can be mapped onto a cellular automaton. The automaton puts the system on a space-time lattice with lattice length $a = 2\pi\sqrt{\alpha'}$. Obviously, this is finite.

We do have to caution that the lattice on the *world sheet* was not yet sent to zero, but this seems to be a question of gauge-fixing rather than a physical limit, since we should have conformal invariance on the world sheet.

What would John Bell say about this? There is "conspiracy" but it is only visible by observers who can see the space-time lattice. One can also object that this theory is far from complete.

THE END

arXiv: 1204.4926
arXiv: 1205.4107
arXiv: 1207.3612
and to be published.

On black holes:
arXiv:9607022[gr-qc]
arXiv:0909.3426
arXiv:1009.0669[gr-qc]
arXiv:1011.0061[gr-qc].