Following Lenny’s Lead

John Preskill

DanLennyFest

7 October 2022

PHYSICAL REVIEW D VOLUME 11, NUMBER 2 15 JANUARY 1975

Hamiltonian formulation of Wilson's lattice gauge theories

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(Received 9 July 1974)

Wilson's lattice gauge model is presented as a canonical Hamiltonian theory. The structure of the model is reduced to the interactions of an infinite collection of coupled rigid rotators. The gauge-invariant configuration space consists of a collection of strings with quarks at their ends. The strings are lines of non-Abelian electric flux. In the strong-coupling limit the dynamics is best described in terms of these strings. Quark confinement is a result of the inability to break a string without producing a pair.

Loeb Lectures at Harvard 1977
"Coarse-Grained Quantum Field Theory"

Provably accurate simulation of gauge theories and bosonic systems

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April 4th, 2022

arXiv:2110.06942v2 [quant-ph] 20 Sep 2022

Quantum many-body systems involving bosonic modes or gauge fields have infinite-dimensional local Hilbert spaces which must be truncated to perform simulations of real-time dynamics on classical or quantum computers. To analyze errors resulting from truncation, we develop methods for bounding the rate of growth of local quantum numbers such as the occupation number of a mode at a lattice site, or the electric field at a lattice link. Our approach applies to various models of bosons interacting with spins or fermions such as the Hubbard-Holstein, Fröhlich, and Dicke models, and also to both abelian and non-abelian gauge theories. We show that if states in these models are truncated by imposing an upper limit Λ on each local quantum number, and if the initial state has low local quantum numbers, then a truncation error no worse than ϵ can be achieved by choosing Λ to increase polylogarithmically with ϵ^{-1}, an exponential improvement over previous bounds based on energy conservation. For the Hubbard-Holstein model, we numerically compute a bound on Λ that achieves accuracy ϵ, obtaining significantly improved estimates in various parameter regimes. We also establish a criterion for truncating the Hamiltonian with a provable guarantee on the accuracy of time evolution. Building on that result, we formulate quantum algorithms for dynamical simulation of lattice gauge theories and of models with bosonic modes; the gate complexity depends almost linearly on spacetime volume in the former case, and almost quadratically on time in the latter case. We establish a lower bound showing that there are systems involving bosons for which this quadratic scaling with time cannot be improved. By applying our results on the truncation error in time evolution, we also prove that spectrally isolated energy eigenstates can be approximated with error at most ϵ by truncating local quantum numbers at $\Lambda = \mathrm{polylog}(\epsilon^{-1})$.

1 Introduction

Model physical systems are often formulated on spatial lattices, where the local Hilbert space residing on each site or link of the lattice is infinite dimensional. Examples include condensed-matter systems with bosonic degrees of freedom [21, 27, 43, 51, 52, 62, 64, 67, 76], lattice gauge

PHYSICAL REVIEW D VOLUME 16, NUMBER 10 15 NOVEMBER 1977

Lattice fermions

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and Belfer Graduate School of Science, Yeshiva University, New York, New York 10033†
(Received 9 February 1976)

The problem of formulating the field theory of Dirac particles on a spatial lattice is reviewed. In one dimension we construct free massless Dirac fields and Thirring fields and show their equivalence to the X-Y and asymmetric Heisenberg antiferromagnetic chains. In three dimensions we find that the simplest construction describes an isodoublet of massless Dirac fields. We discuss the incorporation of gauge degrees of freedom and illustrate how chiral symmetry is spontaneously broken by the interaction of gauge and fermion fields.

CHIRAL GAUGE THEORIES ON THE LATTICE*

Estia EICHTEN
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Received 5 November 1985

We propose a method for constructing lattice gauge theories in which fermions transform as a complex representation of the gauge group.

PHYSICAL REVIEW D VOLUME 18, NUMBER 12 15 DECEMBER 1978

Baryon number of the universe

Savas Dimopoulos*
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Leonard Susskind
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305

(Received 9 June 1978)

We consider the possibility that the observed particle-antiparticle imbalance in the universe is due to baryon-number, *C*, and *CP* nonconservation. We make general observations and describe a framework for making quantitative estimates.

VOLUME 43, NUMBER 19 PHYSICAL REVIEW LETTERS 5 NOVEMBER 1979

Cosmological Production of Superheavy Magnetic Monopoles

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(Received 21 June 1979)

Grand unified models of elementary particle interactions contain stable superheavy magnetic monopoles. The density of such monopoles in the early universe is estimated to be unacceptably large. Cosmological monopole production may be suppressed if the phase transition at the grand unification mass scale is strongly first order.

PHYSICAL REVIEW D VOLUME 20, NUMBER 10 15 NOVEMBER 1979

Dynamics of spontaneous symmetry breaking in the Weinberg-Salam theory

Leonard Susskind*
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(Received 5 July 1978)

We argue that the existence of fundamental scalar fields constitutes a serious flaw of the Weinberg-Salam theory. A possible scheme without such fields is described. The symmetry breaking is induced by a new strongly interacting sector whose natural scale is of the order of a few TeV.

ACKNOWLEDGMENT

I would like to thank K. Wilson for explaining the reasons why scalar fields require unnatural adjustments of bare constants.

UNIFIED GAUGE THEORIES
WITHOUT ELEMENTARY SCALAR FIELDS

A thesis presented

by

John Phillip Preskill

to

The Department of Physics
in partial fulfillment of the requirements
for the degree of
Doctor of Philosophy
in the subject of
Physics

Harvard University
Cambridge, Massachusetts
May, 1980

Yet by the summer of 1980, Lenny, his T-shirt still soaked from a just-completed jog, stood in my office at Harvard loudly insisting that his earlier ideas about technicolor were deeply flawed and should be rejected. I resisted for many months before concluding that Susskind was probably right about having been wrong. It was an unforgettable lesson in scientific integrity.

Review of The Black Hole Wars, Physics World, December 2008.

“Quantum Aspects of Black Holes”

Aspen Workshop
August 3 to September 4, 1992

Among the participants:
Tom Banks, Sidney Coleman, Steve Giddings, Stephen Hawking,
Gary Horowitz, Don Page, Malcolm Perry, John Preskill,
Andy Strominger, Lenny Susskind, Kip Thorne, Erik and Herman Verlinde

L. Susskind "The Puzzle of BH Evaporation" 14 Aug. 92

Little learned about grav and qm
- No guidance from exp
- No remote

History - Gedanken exp
- Mismatch of Newton + Maxwell - Einstein running along light ray

Not spectral line [• Thermo + equipartition of radiation

- Elevator in case of GR

Now [$\Lambda = 0$, Black Holes] May be out for 20 yrs

Glimpse of the next revolution

Monopoles - viol of B cons
BHs - viol of QM itself !?

Heros - Bekenstein, Hawking

History: Beginning: Area theorem
Bekenstein: Generalized 2nd Law

Count # of ways to make BH ◯ r = M
use photons with $\lambda \sim r$

$\frac{M}{\omega} \sim r^2$ $dE = TdS \Rightarrow T \sim \frac{1}{M}$

$\Rightarrow L \sim \frac{1}{M^2} \Rightarrow t \sim M^3$

1+1 dim models confirm this picture in back reaction calc

Featureless radiation (?)

S-matrix? orthogonal initial ⇒ orthogonal final

Real honest dilemma

Another way out?

horizon is innocuous
sing is terrible / we don't know what happens

Can info propagate along this spacelike curve
then finally comes out

But only ~ M_{pl} left for google-plex of info
⇒ Info takes a very long time to come out (sketch radiation)
⇒ "stable remnant"

Solutions:

Go beyond semiclassical fluctuations in sing and horizon

- Info lost: Can't stop there ... becomes cumulatory
  Sym + Cons laws no longer connected
  ⇒ energy not conserved
  cf - Noise quenched randomness heats a system up

  What small parameter makes info loss small? Energy density?
  But energy of vac ~ Λ at planck scale
  ⇒ O(1) violation of energy at this scale

Cosmo superselect sectors (from string theory)

no of conserved quantities ⇒ trivial S matrix

- Stable Remnants:
  Carry the info ⇒ enormous level density near planck scale
  Dangerous in QFT - e.g. enormous from a big BH

- Hawking - info lost
- 't Hooft - unitary S matrix for profound reasons
- Polchinski - info lost. No way to retrieve it
- Strominger - remnant
- Coleman - lump of coal
- Wilczek - Technical problem - till soon have it solved
- Witten - Problem not interesting

- Hawking – info lost
- 't Hooft – unitary S matrix for profound reasons
- Polchinski – info lost. No way to retrieve it
- Aharonov – remnant
- Coleman – lumps of coal
- Wilczek – Technical problem – I'll soon have it solved
- Witten – Problem not interesting

There is an emerging consensus among the participants that Hawking is essentially right—that the information loss paradox portends a true revolution in fundamental physics. If so, then one must go further, and develop a sensible "phenomenological" theory of information loss. One must reconcile the fact of information loss with established principles of physics, such as locality and energy conservation. We expect that many people, stimulated by their participation in the workshop, will now focus attention on this challenge.

John Preskill and Andy Strominger

hep-th/9209058

Do Black Holes Destroy Information?*

John Preskill

California Institute of Technology, Pasadena, CA 91125

I review the information loss paradox that was first formulated by Hawking, and discuss possible ways of resolving it. All proposed solutions have serious drawbacks. I conclude that the information loss paradox may well presage a revolution in fundamental physics.

DIFFICULTIES FOR THE EVOLUTION OF PURE STATES INTO MIXED STATES

Thomas BANKS* and Leonard SUSSKIND**

Department of Physics, Stanford University, Stanford, California 94305, USA

Michael E. PESKIN†

Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305, USA

Received 5 January 1984

Motivated by Hawking's proposal that the quantum-mechanical density matrix ρ obeys an equation more general than the Schrödinger equation, we study the general properties of evolution equations for ρ. We argue that any more general equation for ρ violates either locality or energy-momentum conservation.

"Quantum Aspects of Black Holes"

ITP Conference, UCSB
June 21-25, 1993

Among the participants:
Gary Gibbons, Gerard 't Hooft, Joe Polchinski, John Preskill,
Lenny Susskind, Kip Thorne, Herman Verlinde, Bob Wald, …

Polchinski's Poll

1. Information is lost (unitarity violated)
2. Information escapes (causality violated)
3. Planck-scale black hole remnants
4. None of the above.

The vote favored "escape" over "loss" by a 60-40 margin.

The audience was 60% HEP theorists, 40% GR.

LS: Why is this meeting so much better than the one you organized last year?

JP: Because now you think you know the answer.

PHYSICAL REVIEW D VOLUME 48, NUMBER 8 15 OCTOBER 1993

The stretched horizon and black hole complementarity

Leonard Susskind,* Lárus Thorlacius,† and John Uglum‡
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(Received 21 June 1993)

Three postulates asserting the validity of conventional quantum theory, semiclassical general relativity, and the statistical basis for thermodynamics are introduced as a foundation for the study of black-hole evolution. We explain how these postulates may be implemented in a "stretched horizon" or membrane description of the black hole, appropriate to a distant observer. The technical analysis is illustrated in the simplified context of $(1+1)$-dimensional dilaton gravity. Our postulates imply that the dissipative properties of the stretched horizon arise from a course graining of microphysical degrees of freedom that the horizon must possess. A principle of black-hole complementarity is advocated. The overall viewpiont is similar to that poineered by 't Hooft but the detailed implementation is different.

PHYSICAL REVIEW D VOLUME 49, NUMBER 2 15 JANUARY 1994

Gedanken experiments involving black holes

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(Received 25 August 1993)

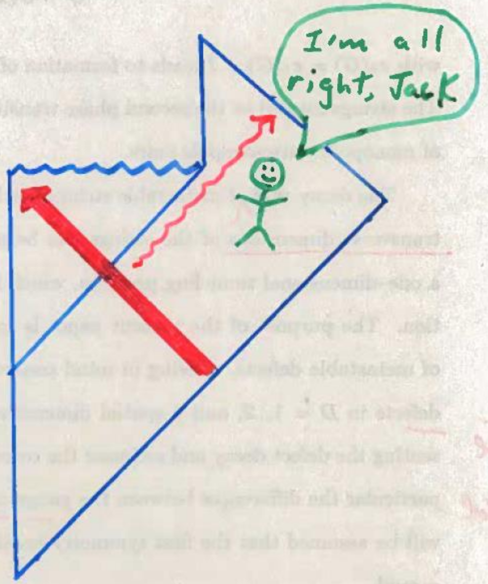
Analysis of several gedanken experiments indicates that black hole complementarity cannot be ruled out on the basis of known physical principles. Experiments designed by outside observers to disprove the existence of a quantum-mechanical stretched horizon require knowledge of Planck-scale effects for their analysis. Observers who fall through the event horizon after sampling the Hawking radiation cannot discover duplicate information inside the black hole before hitting the singularity. Experiments by outside observers to detect baryon number violation will yield significant effects well outside the stretched horizon.

In many respects, the situation seems comparable to that of the early part of the century. The contradictions between the wave and particle theories of light seemed irreconcilable, but careful thought could not reveal any logical contradiction. Experiments of one kind or the other revealed either particle or wave behavior, but not both. We suspect that the present situation is similar. An experiment of one kind will detect a quantum membrane, while an experiment of another kind will not. However, no possibility exists for any observer to know the results of both. Information involving the results of these two kinds of experiments should be viewed as *complementary* in the sense of Bohr.

In this paper we shall illustrate the concept of black hole complementarity by considering a number of gedanken experiments where one might expect contradictions to arise. The basic argument we apply was formulated most clearly by Preskill [3]. It says that apparent contradictions can always be traced to unsubstantiated assumptions about physics at or beyond the Planck scale.

't Hooft / Susskind credo:

It is all right to do bad things, as long as no one can ever find out!



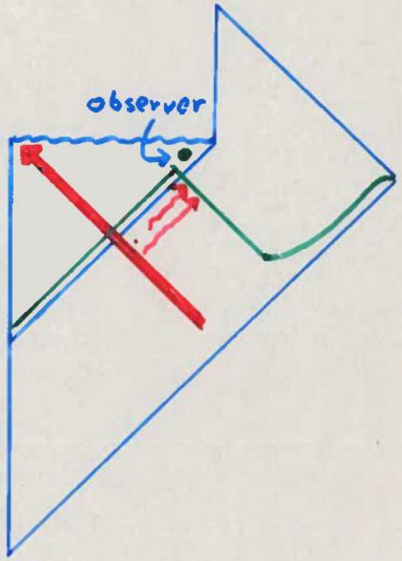
"Causality violation" that no conceivable observer can detect.

To the outside observer, information <u>might as well have been destroyed</u> at the global horizon, so it <u>can</u> be copied at the (stretched) horizon.

What about <u>inside</u>?

Observer behind global horizon has rights, too! Can he infer that information has escaped from behind the horizon?

Assume black hole S-Matrix is known:



- Highly blue-shifted message?
- Horizon fluctuations?

“Geometry and Gravity”

Newton Institute, Cambridge
June 1-30, 1994

Among the participants:
Gary Gibbons, Jeff Harvey, Stephen Hawking, John Preskill,
Rafael Sorkin, Andy Strominger, Lenny Susskind, Herman Verlinde, …

arXiv:hep-th/9409089v2 28 Sep 1994

The World as a Hologram

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ABSTRACT

According to 't Hooft the combination of quantum mechanics and gravity requires the three dimensional world to be an image of data that can be stored on a two dimensional projection much like a holographic image.

The two dimensional description only requires one discrete degree of freedom per Planck area and yet it is rich enough to describe all three dimensional phenomena. After outlining 't Hooft's proposal I give a preliminary informal description of how it may be implemented. One finds a basic requirement that particles must grow in size as their momenta are increased far above the Planck scale. The consequences for high energy particle collisions are described.

The phenomena of particle growth with momentum was previously discussed in the context of string theory and was related to information spreading near black hole horizons. The considerations of this paper indicate that the effect is much more rapid at all but the earliest times. In fact the rate of spreading is found to saturate the bound from causality. Finally we consider string theory as a possible realization of 't Hooft's idea. The light front lattice string model of Klebanov and Susskind is reviewed and its similarities with the holographic theory are demonstrated. The agreement between the two requires unproven but plausible assumptions about the nonperturbative behavior of string theory. Very similar ideas to those in this paper have long been held by Charles Thorn.

Acknowledgements:

During the month of July of this year I visited Gerard 't Hooft in Utrecht. Much of my thinking about these problems was stimulated by our discussions during this time. The idea that the world is in a sense two dimensional is 't Hooft's but it resonated very closely with my own thinking about horizons and strings. The way of implementing the idea, and its possible connections with string theory, is mine but it was very heavily influenced by our conversations.

I would like to thank both 't Hooft and John Preskill for emphasizing that information can and should spread at the causal limit as matter approaches a horizon.

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Fast scramblers

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Abstract: We consider the problem of how fast a quantum system can scramble (thermalize) information, given that the interactions are between bounded clusters of degrees of freedom; pairwise interactions would be an example. Based on previous work, we conjecture:

1) The most rapid scramblers take a time logarithmic in the number of degrees of freedom.

2) Matrix quantum mechanics (systems whose degrees of freedom are n by n matrices) saturate the bound.

3) Black holes are the fastest scramblers in nature.

The conjectures are based on two sources, one from quantum information theory, and the other from the study of black holes in String Theory.

JHEP10(2008)065

Acknowledgments

This paper was inspired by conversations with Patrick Hayden. We are very grateful to him for explaining the subtleties of quantum information theory that went into [4]. We are also indebted to Steve Shenker, Joe Polchinski, Debbie Leung, Daniel Gottesman, and John Preskill for helpful insights and comments.

Fortschr. Phys. **61**, No. 9, 781 – 811 (2013) / **DOI** 10.1002/prop.201300020

Cool horizons for entangled black holes

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General relativity contains solutions in which two distant black holes are connected through the interior via a wormhole, or Einstein-Rosen bridge. These solutions can be interpreted as maximally entangled states of two black holes that form a complex EPR pair. We suggest that similar bridges might be present for more general entangled states.

In the case of entangled black holes one can formulate versions of the AMPS(S) paradoxes and resolve them. This suggests possible resolutions of the firewall paradoxes for more general situations.

"The ER = EPR conjecture seems to allow us to view the early radiation with which the black hole is entangled as a complementary description of the black hole interior."

"Entanglement = Wormholes," Quantum Frontiers, 7 June 2013

Selected for a Viewpoint in *Physics*
PRL **116,** 191301 (2016) PHYSICAL REVIEW LETTERS week ending 13 MAY 2016

Holographic Complexity Equals Bulk Action?

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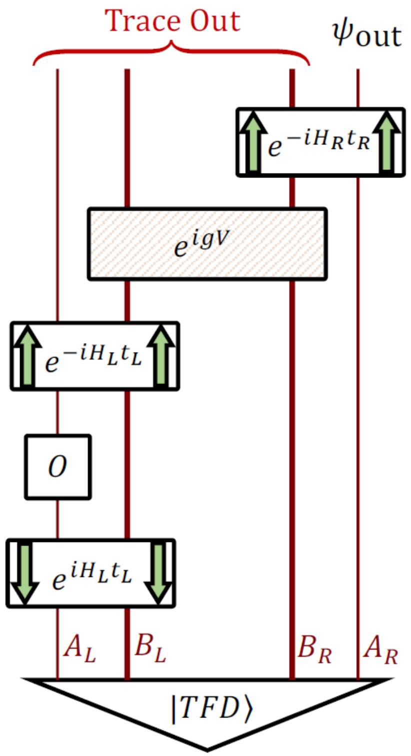
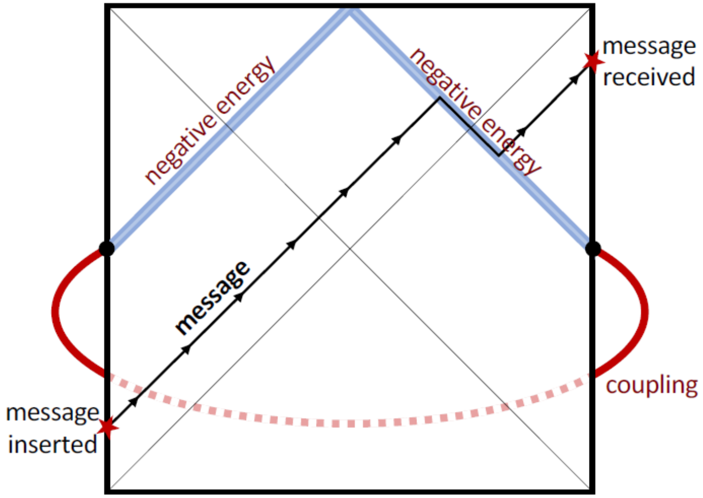
(Received 30 January 2016; published 9 May 2016)

We conjecture that the quantum complexity of a holographic state is dual to the action of a certain spacetime region that we call a Wheeler-DeWitt patch. We illustrate and test the conjecture in the context of neutral, charged, and rotating black holes in anti–de Sitter spacetime, as well as black holes perturbed with static shells and with shock waves. This conjecture evolved from a previous conjecture that complexity is dual to spatial volume, but appears to be a major improvement over the original. In light of our results, we discuss the hypothesis that black holes are the fastest computers in nature.

Quantum gravity in the lab

Brown, Gharibyan, Leichenauer, Lin, Nezami, Salton, Susskind, Swingle, Walter 1911.06314





Use gravitational intuition to understand complex emergent quantum phenomena?

Measure features of quantum gravity that are hard to analyze classically?

What quantum systems have useful gravitational duals?


John
Leonard

From JP to LS, 26 Oct 2001

One of my co-authors is Alexei Kitaev, and he is one of the most brilliant guys I’ve known. A week or two ago, he went to UCLA to hear your talk, as he’s very interested in the quantum Hall effect.

The next day we had this conversation:
==
AK: I heard a talk about how string theory explains the quantum Hall effect, but I did not understand anything.

JP: Who gave the talk?

AK: I don’t know. Someone from Stanford. (AK is one of these Russians who is not interested in who people are …)

JP: Was it Lenny Susskind? He’s my favorite physicist!

AK: I don’t know. I will have to look at the program.

JP: Well, was he an old guy with a beard?

AK: No. He had a beard, but he was not old.
==
And of course he’s right. You’re not.