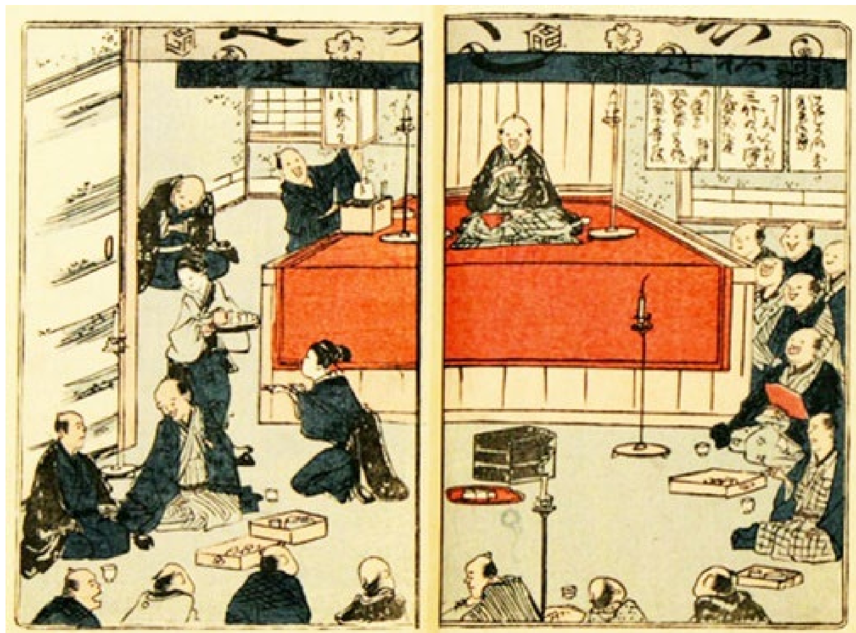
Strings 2024

The Future of String Theory

Hirosi Ooguri

6 – 10 June 2024, CERN

前座でございます



In traditional storytelling in Japan, an apprentice would give a casual talk to warm up the audience before the master comes in to give the main talk.

It is the **50th** anniversary of the **discovery of the gravity** in string theory.

- T. **Yoneya**, "Quantum Gravity and the Zero Slope Limit of the Generalized Virasoro Model," Lett. Nuovo Cim. 8 (1973) 951.
- J. **Scherk**, J. H. **Schwarz**, "Dual Models for Nonhadrons," Nucl. Phys. B81 (1974) 118.

hyperlinks

"Our analysis suggests that a dual model might perhaps provide a unified theory of electromagnetism, weak interactions, and gravitation."

It is the **40**$^{\text{th}}$ anniversary of the **first superstring revolution**.

- M. B. **Green**, J. H. **Schwarz**, “Anomaly Cancellation in Supersymmetric $D = 10$ Gauge Theory and Superstring Theory,” Phys. Lett. B149 (1984) 117.

- D. J. **Gross**, J. A. **Harvey**, E. J. **Martinec**, R. **Rohm**, “The Heterotic String,” Phys. Rev. Lett. 54 (1985) 502.

- P. **Candelas**, G. T. **Horowitz**, A. **Strominger**, E. **Witten**, “Vacuum Configurations for Superstrings,” Nucl. Phys. B258 (1985) 46.

It is the $(\mathbf{30} - 1)^{\text{th}}$ anniversary of the **second superstring revolution**.

E. **Witten**,

- "Some Comments on String Dynamics," Proceedings of Strings '95 at USC, 13 – 18 March 1995.
- "String Theory Dynamics in Various Dimensions," hep-th/9503124.

followed by **D-branes**, **black hole microstate counting**, **AdS/CFT**, and many more.

“Every generation needs a new revolution”

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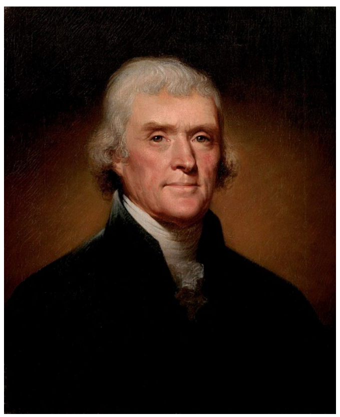
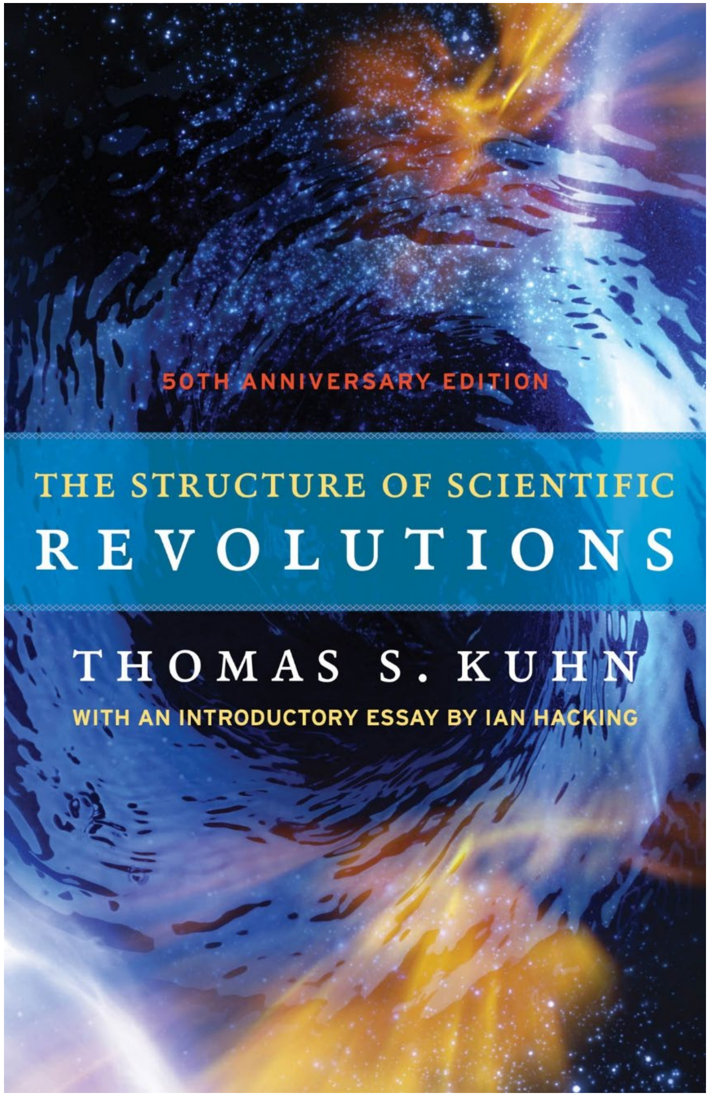
is a **misquote** of Thomas Jefferson, who actually wrote,

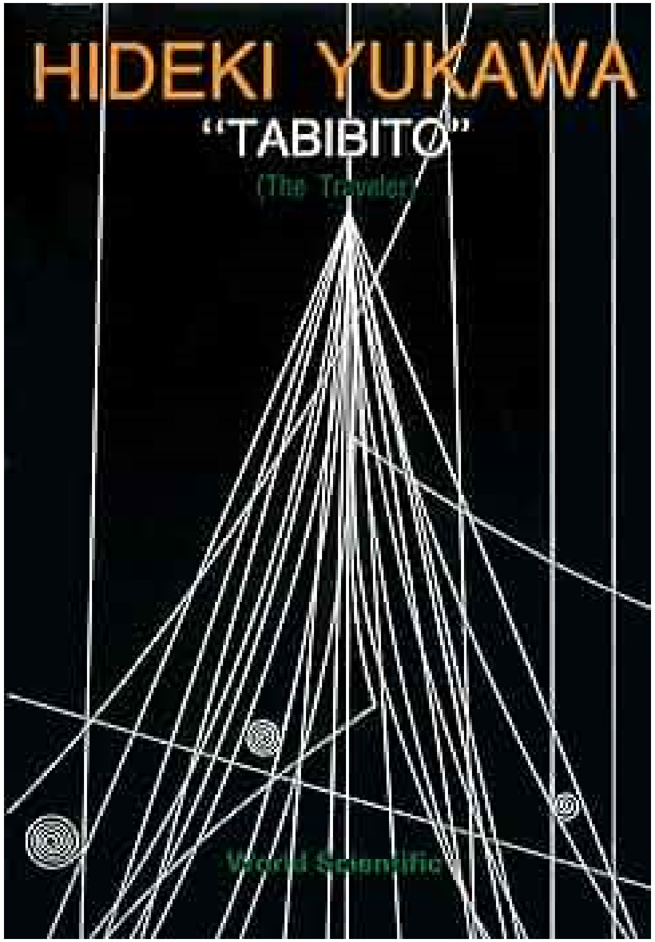


“The tree of liberty must be refreshed from time to time with the blood of patriots and tyrants.”

Letter to William Stephen Smith
Paris, Nov. 13, 1787



Or are we in the normal science phase, setting up the stage for the next revolution?



"People who explore the unknown are travelers without maps."

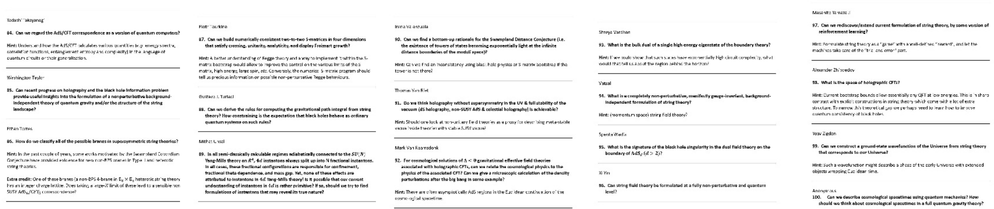
Autobiography of Hideki Yukawa

Ask good questions.

Curiosity-driven research often leads to unexpected discoveries and applications.

100 Questions

plausibly be answered in the next ten years



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Nonperturbative Methods

String Field Theory

Xi Yin

96. Can string field theory be formulated at a fully non-perturbative and quantum level?

Discussion Session led by Ted Erler and Xi Yin

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String field theory turned out to have many practical applications:

- First-principle calculation of D-instanton effects,
- Time-dependent solutions,
- Quantum string vacua,
- Conformal perturbation,
- RR flux backgrounds,
- and more.

String field theory resolves ambiguities.

Lefschetz Thimbles

Ashoke Sen

72. Can non-perturbative string theory be defined as the sum of the contributions from its saddle points?

Hint: For generic complex values of the coupling constant, the Borel resummation of the perturbation expansion around a saddle point is expected to generate the result of the path integral over the Lefschetz thimble associated to that saddle point. So, **if we knew how to generate perturbation expansion around all the saddle points and also how the desired integration contour is expressed as a sum of the Lefschetz thimbles, we have in principle a non-perturbative definition of the theory**. In string theory, we have a systematic procedure for generating perturbation expansion around the perturbative saddle and the Euclidean D-brane saddles. Can we develop such expansions around other saddle points (*e.g.* the NS 5-brane saddles, wormholes *etc*) and in parallel explore how the desired integration contour might be expressed as a union of the Lefschetz thimbles of different saddles?

Non-unitary CFTs as Complex Saddles?

Nikita Nekrasov

53. Do non-unitary $2d$ CFTs and RG flows around them represent Lefschetz thimbles for non-perturbative definition of string theory?

Hint: Liouville theory at complex values of the b parameter, WZW model for complex k, to some extent, can be defined through unitary $d = 4, N = 2$ theory.

Topological Strings

Ricardo Schiappa

71. Can we use resurgence to compute transseries – including all nonperturbative transmonomial contributions - for (large classes of) observables/correlation functions in generic string theoretic backgrounds?

Hint: This is likely **reachable within matrix models, minimal, and topological string theories**. Will those results serve as a clue towards generic string theoretic backgrounds or will something else be required?

Strings 2024 Talk by Raghu Mahajan

Topological Strings

The recent progress (*e.g.*, Strings 2023 Talk by Marcos Mariño) gives us the hope that we could plausibly,

- determine the large genus behavior of the topological string partition function for a **compact** Calabi-Yau manifold,
- match it with the black hole entropy counting,
- give the unique non-perturbative completion of the topological string partition function,

within the next ten years.

Space of Theories

ANNALS OF PHYSICS **163**, 318–419 (1985)

Nonlinear Models in $2+\varepsilon$ Dimensions*

DANIEL HARRY FRIEDAN[†]

Lawrence Berkeley Laboratory, University of California, Berkeley, California 94720

Received February 10, 1984

The general nonlinear scalar model is studied at asymptotically low temperature near two dimensions. The low temperature expansion is renormalized and effective algorithms are derived for calculation to all orders in the renormalized expansion. The renormalization group coefficients are calculated in the two loop approximation and topological properties of the renormalization group equations are investigated. Special attention is paid to the infrared instabilities of the fixed points, since they provide the continuum limits of the model.

The model consists of a scalar field ϕ on Euclidean $2+\varepsilon$ space whose values $\phi(x)$ lie in a finite dimensional differentiable manifold M. The action is $S(\phi)=\Lambda^{\varepsilon}\int dx\,\frac{1}{2}T^{-1}g_{ij}(\phi(x))\,\partial_\mu\phi^i(x)\,\partial_\mu\phi^j(x)$, where Λ^{-1} is the short distance cutoff and $T^{-1}g_{ij}$ is a (positive definite) Riemannian metric on M, called the metric coupling.

The standard nonlinear models are the special cases in which M is a homogeneous space (the quotient G/H of a Lie group G by a compact subgroup H) and g_{ij} is some G-invariant Riemannian metric on M. G acts as a global internal symmetry group.

The renormalization of the model is divided into two parts: showing that the action retains its form under renormalization and showing that renormalization respects the action of the diffeomorphisms (i.e., the reparametrizations or transformations) of M. The techniques used are the standard power counting arguments combined with generalizations of the BRS transformation and the method of quadratic identities.

The second part of the renormalization is crucial for renormalizing the standard models, since it implies the renormalization of internal symmetry. It is carried out to the point of identifying the finite dimensional cohomology spaces containing possible obstructions to the renormalization of the transformation laws, and of noting the absence of obstructions when M has finite fundamental group and nonabelian semisimple isometry group.

The renormalization group equation for the metric coupling is $\Lambda^{-1}(\partial/\partial\Lambda^{-1})\,g_{ij}=-\beta_{ij}(g)$, $\beta_{ij}(T^{-1}g)=-\varepsilon T^{-1}g_{ij}+R_{ij}+\frac{1}{2}TR_{ipqr}R_{jpqr}+O(T^2)$. R_{ipqr} is the curvature tensor and $R_{ij}=R_{ipjp}$ the Ricci tensor of the metric g_{ij}. The β-function $\beta_{ij}(g)$ is a vector field on the infinite dimensional space of Riemannian metrics on M. Two results on global properties of β are obtained. When M is a homogeneous space G/H, the β-function is shown to be a gradient on the finite dimensional space of G-invariant metric couplings on M. And, when M is a two dimensional compact manifold, the β-function is shown to be a gradient on the infinite dimensional space of metrics on M. The rest of the results are concerned with fixed points. The fixed points are shown to correspond to the metrics satisfying a generalized Einstein equation, $R_{ij}-ag_{ij}=\nabla_i v_j+\nabla_j v_i$, $a=\pm 1$ or 0, for v^i some vector field on M. Known solutions to these

* Ph.D. thesis submitted to the Department of Physics, University of California at Berkeley, August 1980. Distributed as LBL publication LBL-11517. Prepared for the U.S. Department of Energy under Contract W-7405-ENG-48.

In his 1984 Ph.D. thesis, Dan Friedan suggested the analogy between the classification of QFTs and the classification of Riemannian manifolds.

- Space of SQFTs
- Space of CFTs
- Space of Holographic CFTs
  $\Leftrightarrow$ Space of weakly coupled gravitational theories in AdS
- Space of S-matrices
- Classification of Branes

Space of Holographic CFTs

Alexander Zhiboedov

98. What is the space of holographic CFTs?

Hint: Current bootstrap bounds allow essentially any QFT at low energies. This is in sharp contrast with explicit constructions in string theory which come with a lot of extra structure. To narrow this theoretical gap we perhaps need to learn how to impose quantum consistency of black holes.

For example, in the bulk **we can write a free scalar minimally coupled to GR and we do not know how to exclude such a theory** from first principles yet.

Space of Holographic CFTs

Alexander Zhiboedov

98. What is the space of holographic CFTs?

Hint: Current bootstrap bounds allow essentially any QFT at low energies.

There are other constraints:

For example, Åsmund Folkestad (2209.00013) found that **some scalar potentials violate the Penrose inequality** and are incompatible with the AdS/CFT correspondence.

Space of S-matrices

Grant Remmen

68. Can we prove that string theory is the only consistent perturbative ultraviolet completion of gravity?

Hint: Can we cast the question in terms of the S-matrix at weak coupling and **identify a set of constraints that uniquely bootstrap the amplitudes of string theory**, including crossing, dual resonance, n-point factorization, *etc.*?

Strings 2024 Talk by Andrea Guerrieri

Discrete Families of CFTs

Eric Perlmutter

66. Can we quantitatively describe large scale structures in the space of unitary, generic CFTs?

For example, how CFTs are distributed as a function of c.

H.O.

56. Can we define a distance between any pair of conformal field theories that are not necessarily related by marginal perturbations?

Hint: Can we use a domain wall between such a pair?

Classification of Branes

Ethan Torres

86. How do we classify all of the possible branes in supersymmetric string theories?

Hint: In the past couple of years, some works motivated by the **Swampland Cobordism Conjecture** have provided evidence for new non-BPS branes in Type II and heterotic string theories.

Strings 2024 Talk by Kazuya Yonekura

Swampland

Constraints on Effective Theories of Gravitational Systems

Strings 2024 Talk by Miguel Montero

Gravity is different.

Cindy Keeler

32. Can we develop a mathematically precise measure as to when effective field theory will break down in the context of quantum gravity?

Quantify and Prove/Falsify Swampland Bounds

Miguel Montero

47. Can we precisely quantify or prove a bound on the amount of breaking of global symmetries in quantum gravity? (*e.g.*, scale/coefficient of symmetry breaking operators)

Irene Valenzuela

90. Can we find a bottom-up rationale for the Swampland Distance Conjecture (*i.e.,* the existence of towers of states becoming exponentially light at the infinite distance boundaries of the moduli space)?

Quantify and Prove/Falsify Swampland Bounds

Julio Parra Martinez

62. Given a low-energy EFT with a large spectral gap and a global symmetry which appears to forbid a scattering process: is there a lower bound on the corresponding cross section implied by "no global symmetries in quantum gravity"? *e.g.*, is there a minimum value of the cross section for proton decay implied by QG?

Quantify and Prove/Falsify Swampland Bounds

Wang + H.O.: 2405.00674

In $2d$ unitary CFT, if the conformal weight Δ of a primary field vanishes in a limit on the conformal manifold,

$$\Delta = \exp(-\,\alpha\, t + O(1)),$$

with the Zamolodchikov distance $t \to \infty$.

$$c^{-1/2} \le \alpha \le 1$$

In the AdS units, these bounds translate to

$$\left(\frac{2}{3} L_{\mathrm{Planck}}\right)^{1/2} \le \alpha_{\mathrm{AdS}} \le (8\pi L_{\mathrm{AdS}})^{1/2}$$

de Sitter space?

I remain agnostic about whether string theory allows a semi-stable solution with a positive cosmological constant and with all the moduli fixed.

I hope we will have a definite answer in the next ten years.

Strings 2024 Talk by Jakob Moritz

H.O.

58. Can we settle the question of whether the KKLT construction can be realized in string theory?

Hint: Develop a method to calculate α' corrections in Ramond-Ramond backgrounds.

de Sitter space?

A successful and explicit construction in string theory will enable us to address many interesting questions,

such as:

Jakob Moritz

52. Can we use microscopic constructions of de Sitter cosmologies in string theory, such as KKLT, in order to find a notion of microstates that can account for the de Sitter entropy?

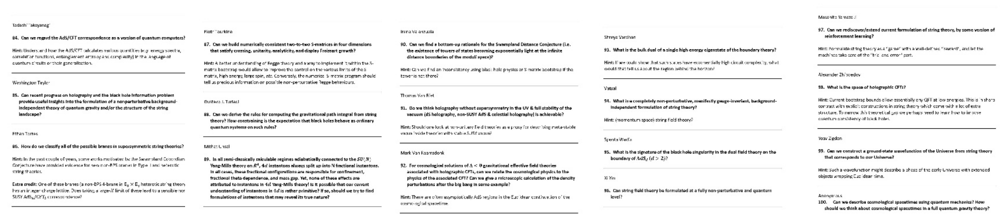
I have one more wish:

Gregory Moore

49. Is there a conceptual explanation of Mathieu (and Umbral) Moonshine, including the genus zero phenomena?

Hint: Good people have tried hard for the past 14 years, and we are still waiting for the "Ah Ha!" moment. So if the answer is yes, probably a new idea is required.

Many more interesting questions and helpful hints



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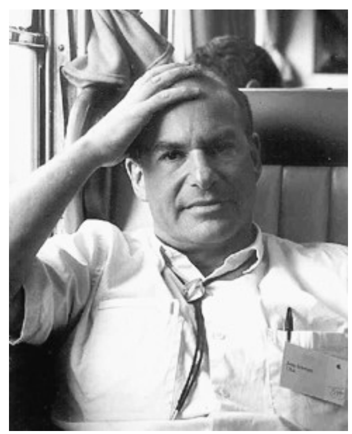
John Schwarz:

“I am pleased that 50 years later it is still plausible that string theory can provide a realistic quantum theory of gravity and the other forces.”



String theory:

- is a **consistent quantum theory of gravity** and provides a basis for theoretical speculation about quantum gravity.
- contains **all the ingredients** to construct the **Standard Model of Particle Physics**, such as generations of quarks and leptons, gauge interactions, and spontaneous symmetry breaking.
- contains promising candidates for the **dark matter** and may be able to explain the **dark energy**.
- provides guidance for future experiments and observations as an **alternative to Naturalness**.
- provides new insights and powerful tools for studying **quantum field theory**.
- inspires progress in **mathematics**.

Bon voyage!