A pragmatic approach to formal fundamental physics

Daniel Friedan

Rutgers University and the University of Iceland

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Abstract

I discuss a long-running project to construct a mechanism to produce the fundamental laws of physics.

These slides and related writings can be found at

`http://www.physics.rutgers.edu/~friedan/#munich`

I was honored to receive a wonderfully open invitation from the MPP:

> *We would like to invite you to give a Colloquium talk on your research . . .*

I work on three exploratory projects with long-range prospects:

1. A project in formal fundamental physics (today's talk)
2. A project in quantum field theory

   opening a new territory of constructable qfts of $n-1$ *dimensional extended objects (defects) in* $2n$ *dimensions*

3. A project in quantum computing

   laying the foundations for a physical theory of asymptotically large-scale quantum computers

For more on these projects, see my web page (linked in the abstract).

I'm always happy to talk about these projects, hoping to enlist adventurous young theorists.

But that sort of technical exposition directed at theorists does not seem appropriate for a general physics colloquium.

So I am going to talk today about philosophy — about the philosophy underlying my project in formal fundamental physics. I use 'philosophy' as shorthand for 'intellectual strategy'.

I've interpreted your generous invitation as encouragement to express my thoughts on fundamental theoretical physics at this important time of soul searching.

It is especially appropriate here at the MPP because there are several connections to ideas of Heisenberg.

I hope you will find the talk provoking.

For 45 years, our most fundamental theory of physics has been the Standard Model combined with General Relativity. It describes almost everything we know at distances larger than about $1\,\mathrm{TeV}^{-1}$.

Dark matter, neutrino mixing, and some CP violation are the only observed phenomena not accounted for.

Fundamental physics now finds itself in a wonderful state of uncertainty about the future.

Experiment has again and again showed the way towards this remarkably successful theory.

We need to push on every frontier of fundamental experimental physics.

Who knows what waits to be discovered?

But I've never had the talent for experimental physics. So I explore the possibility of doing formal fundamental physics:

1. hypothesize a more comprehensive formal theoretical machinery
2. predict consequences beyond the SM+GR that can be checked experimentally

Prototypes are Grand Unification with proton decay and
GR with Mercury's precession and light bending around the sun.

No attempt at formal fundamental physics has worked in the 45 years since the SM was verified (in the strict sense of 'work' — making predictions that check successfully against experiment).

One reaction is to give up on the project. But maybe the project simply has not been done properly. It might be useful to reexamine the popular assumptions that have guided the formal fundamental physics enterprise over these past 45 years and perhaps reconsider paths not taken.

The SM+GR is an *effective* QFT with UV cutoff distance $\sim 1\,\text{TeV}^{-1}$.

Classical GR can be thought of as an effective QFT because quantum effects in GR are completely negligible at $1\,\text{TeV}^{-1} = 10^{16}\ell_P$.

$$\hbar = c = 1 \qquad \ell_P = \sqrt{G} = 1.6 \times 10^{-35}\mathrm{m} = 0.8 \times 10^{-16}\,\text{TeV}^{-1}$$

Physics at every distance scale $L > 1\,\text{TeV}^{-1}$ is described by an effective QFT(L) with UV cutoff distance $\sim L$.

QFT(L) at larger distance L derives from QFT(L') at smaller L' by integrating out short distance degrees of freedom in QFT(L').

This is the Kadanoff-Wilson version of the renormalization group.

There is a huge amount of evidence that this form of atomism (reductionism) works at distances $> 1\,\text{TeV}^{-1}$.

Future experimental results will most likely refine the SM+GR, improving QFT(L) and pushing L somewhat below $1\,\text{TeV}^{-1}$.

But the renormalization group cannot be run backwards to smaller distances.

There are too many effective QFTs.

Can we come up with a formal structure that is more useful for fundamental theoretical physics?

Maybe the present theoretical situation is partly due to a lack of philosophy.

'Philosophy' is a shorthand for intellectual strategy. Philosophical considerations have been useful for fundamental physics in the past.

I am thinking especially about the idea that physical theory should be shaped by what is actually observable, that fundamental physics should be expressed in terms of what can actually be observed (Mach, Einstein, Bohr, Heisenberg).

The route Bohr & Heisenberg took to Matrix Mechanics was guided by a focus on observable transitions. However, the world was described in the end by quantum states and transition amplitudes which are not observable. Only their absolute squares are observable.

A pragmatic version of the principle might be: *use the minimal formal machinery needed to produce the observable quantities of physics.*

Pursuing Quantum Gravity has been a popular strategy.

- Quantum Gravity effects would become detectable near ℓ_P.
- But General Relativity as an effective QFT breaks down theoretically near ℓ_P (because it is not renormalizable).
- *GR is inconsistent with Quantum Mechanics.*
  GR and Quantum Mechanics must be reconciled.
  We need to find a theory of Quantum Gravity.

On the contrary, it is clear that pursuing Quantum Gravity is not going to be useful for fundamental physics.

energy in TeV	10^{15}	10^{12}	10^{9}	10^{6}	10^{3}	10^{0}	10^{-3}	10^{-6}	10^{-9}	10^{-12}	10^{-15}	$\cdots$
distance in ℓ_P	10^{1}	10^{4}	10^{7}	10^{10}	10^{13}	10^{16}	10^{19}	10^{22}	10^{25}	10^{28}	10^{31}	
						L_{exp}					1mm	

???? ??? ?? ? Quantum Mechanics

- No theory of Quantum Gravity can be checked experimentally given that $10^{16}\ell_P$ is the smallest distance now accessible.

- We know nothing about physics below $10^{16}\ell_P$.

  What use is a contradiction that only arises if we extrapolate over 16 orders of magnitude in distance beyond all the evidence?

Consider the form of observation in high energy physics.

A scattering experiment at a distance scale L probes our ignorance about physics at distances $< L$.

We have an effective QFT(L) for physics at distances $> L$.

QFT(L) describes the experimental apparatus.

The incoming and outgoing scattering states are states in QFT(L).

Their scattering amplitudes capture the physics at distances $< L$.

A minimal practical formalism would be:

- an effective QFT(L) with UV cutoff L for distances $> L$
- an effective S-matrix(L) with IR cutoff L for distances $< L$

Heisenberg proposed using the S-matrix instead of QFT as fundamental formalism, on the principle that fundamental physics should be expressed in terms of what is actually observed.

This was the asymptotic S-matrix which supposes ingoing scattering states produced infinitely early in time and infinitely far from the scattering region and outgoing scattering states detected infinitely later in time and infinitely far away in space.

The asymptotic S-matrix is a mathematical idealization. Actual scattering experiments take place in a finite region of space over a finite period of time, described by an *effective* S-matrix with an IR cutoff.

Continuum QFT is also a mathematical idealization. A quantum field theory is used in physics as an *effective* theory which describes physics at distances greater than some UV cutoff at the short distance limit of observation. Effective QFT does not even suppose the existence of a space-time continuum.

Mathematical idealization is useful for mathematics. In physics, mathematical idealization is self deception: assuming that we know more than we know.

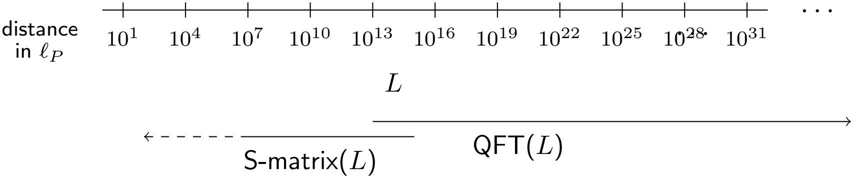
The idealized asymptotic S-matrix is not a practical formalism for all of physics.

The useful work of physics at distances much larger than $1\,\mathrm{TeV}^{-1}$ employs QFT or an effective approximation as Hamiltonian Quantum Mechanics or Classical Mechanics. Is it feasible to use an asymptotic S-matrix to describe the behavior of a galaxy?

An S-matrix can be derived from a hamiltonian, but not vice versa. There is no derivation from an idealized asymptotic S-matrix of an effective QFT or effective Hamiltonian Quantum Mechanics or effective Classical Mechanics.

On the other hand, a pragmatic version of the S-matrix philosophy is reasonable. An effective S-matrix(L) with IR cutoff distance L is a practical formulation of what we can actually observe at short distance, where 'short' is relative to the scale L of the observer.

The minimal practical formalism: an effective QFT(L) and an effective S-matrix(L) for observers at every distance scale $L \gg \ell_P$.



For $L' < L$, consistency conditions have to hold:

(1) The renormalization group makes QFT(L) from QFT(L').

(2) The "S-matrix RG" makes S-matrix(L') from S-matrix(L), using the scattering states at the larger L to make those at smaller L'.

(3) S-matrix(L) agrees with the scattering amplitudes derived from QFT(L') where both apply, i.e. between L' and L.

There is no presumption of QFT or Hamiltonian Quantum Mechanics all the way down to ℓ_P.

At every scale L, there is only S-matrix(L) for short distance physics. We send things in and measure what comes out.

Next: a mechanism that produces this formal structure.

I saw the best minds of my generation destroyed by madness . . . burning for the ancient heavenly connection to the starry dynamo in the machinery of night.

Allen Ginsberg, "Howl" (1956)

My path started in 1977 studying a 2d QFT called the 2d Nonlinear Model (a descendent of Heisenberg's model for magnetism).

$$\text{path integral:} \qquad \int \mathcal{D}X \; e^{-\int d^2x \; g_{\mu\nu}(X)\partial X^\mu \partial X^\nu}$$

$$\begin{aligned} X(x^1, x^2) \quad &= \quad \text{a local 2d field with values in a manifold } M \\ &\qquad \text{(e.g., } M = \text{the 2-sphere of magnetizations)} \\ g_{\mu\nu}(X) \quad &= \quad \text{a riemannian metric on } M \end{aligned}$$

Many coupling constants — all the modes of the metric $g_{\mu\nu}(X)$.

All renormalizable !

The 2d couplings evolve with increasing 2d distance scale Λ^{-1}

the 2d RG: $$-\Lambda\frac{\partial}{\partial\Lambda}\,g_{\mu\nu}(X) = R_{\mu\nu}(X) + O(R^2)$$

driving the 2d-NLM to a solution of $R_{\mu\nu} = 0$, Einstein's equation.

This was extremely exciting (at least for me). The 2d RG appeared as a *mechanism* that *produces* solutions of the GR-like field theory equation $R_{\mu\nu} = 0$. It suggested the possibility of actually answering the question *Where does space-time field theory come from?* or even *Where do the laws of physics come from?* with a quite unexpected mechanism, the 2d RG.

Fundamental physics is about the machinery of nature. Why not a mechanism to produce the laws of physics? Such a mechanism might be useful as a source of explanations for puzzling features of the laws of physics.

Further developments (omitting technical details)

1. The 2d-NLM is interpreted as the string worldsheet in a classical background space-time metric $g_{\mu\nu}(X)$. The 2d RG fixed point equation $R_{\mu\nu} = 0$ is a consistency condition for constructing the asymptotic string S-matrix from the 2d QFT.
2. But an idealized asymptotic string S-matrix is not useful.
3. An effective string S-matrix(L) is given by an effective 2d QFT(Λ^{-1}) with space-time distance scale L and 2d distance scale Λ^{-1} inversely related by $L^2 = \ln \Lambda$ (in dimensionless units).
4. Introduce a new 2d QFT, the λ-model, acting at short 2d distances $< \Lambda^{-1}$, designed precisely so that the 2d RG of the λ-model implements the string S-matrix RG.
5. The λ-model also produces an effective QFT(L) which is the *quantum* string background.
6. The combination of this effective QFT(L) and the effective string S-matrix(L) is a realization of the minimal formal structure outlined above.

The λ-model is designed so that the λ-fluctuations at short 2d distance replicate the froth of small handles, thus implementing the S-matrix RG on the effective string S-matrix.

$$\int \mathcal{D}\lambda \ e^{-\int d^2x \, g_{\mathrm{str}}^{-2} G_{ij}(\lambda)\partial\lambda^i\partial\lambda^j} \ e^{\int d^2x \, \lambda^i(x)\phi_i(x)}$$

λ^i = the worldsheet 2d coupling constants,
the modes of the classical space-time fields

$\phi_i(x)$ = the worldsheet 2d quantum field that couples to λ^i

$\lambda^i(x)$ = a new 2d field for each space-time field mode

$G_{ij}(\lambda)$ = the natural metric on the manifold of 2d QFTs

g_{str} = the string coupling constant

At 2d scale Λ^{-1}, a point x represents a 2d block $\Lambda^{-1} \times \Lambda^{-1}$.

$$\mathcal{D}\lambda = \prod_x d\lambda(x)\,\rho(\lambda(x))$$

The measure $d\lambda\,\rho(\lambda)$, called the *a priori* measure, summarizes the fluctuations inside a block.

The λ^i are the modes of the classical space-time fields, so $d\lambda\,\rho(\lambda)$ is a functional integral over the space-time fields. This is the effective QFT(L).

The 2d RG of the λ-model produces $d\lambda\,\rho(\lambda) =$ QFT(L) by a 2d analog of stochastic quantization (which is a 1d process).

		λ-model		effective 2d QFT of the worldsheet
2d distance	0		Λ^{-1}	
space-time distance	∞	$\longrightarrow$	L	
		QFT(L)		effective string S-matrix(L)

$$L^2 = \ln \Lambda \gg 1$$

The 2d RG: $\Lambda^{-1} \uparrow$ so $L \downarrow$

Integrating out the λ-fluctuations up to 2d distance Λ^{-1} produces

- an effective 2d QFT of the worldsheet with 2d UV cutoff Λ^{-1} which gives an effective string S-matrix(L) with IR cutoff L,
- the *a priori* measure $d\lambda\, \rho(\lambda) =$ QFT(L) which is the *quantum* string background.

Philosophically, the situation is satisfactory. We have a mathematically natural mechanism which produces the minimal formal structure needed for fundamental physics. The machinery is effective but perhaps not particularly beautiful or elegant.

I've been influenced by the pragmatist philospher C. S. Peirce who proposed that the symbolic tools of science should take their significance from the work that they do. A pragmatic strategy is to shape the formalism of fundamental physics for the work it needs to perform.

The pragmatic view argues against pursuing beautiful fundamental principles, against trying to extrapolate to an absolutely fundamental theory. There is no telling how far away that might be or in what direction. There is no telling in advance which mathematically beautiful forms will prove useful for fundamental physics.

Meanwhile, a practical strategy is to try to build a formalism that can actually do useful work in describing the fundamental physics of the real world.

But philosophy is not physics. There must be a practical way to test the theory in the real world.

The effective QFT(L) is produced by a 2d mechanism that might not give exactly the same result as the usual canonical quantization of classical field theory.

There are concrete possibilities of semi-classical non-perturbative 2d effects in the λ-model when the space-time fields include SU(2) and SU(3) gauge fields, as in the Standard Model.

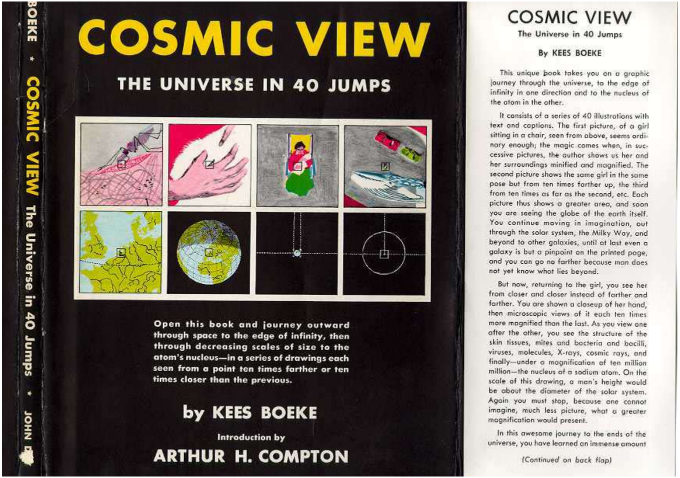
The most striking possibility is a non-canonical vacuum condensate of SU(2) gauge fields. I'm working now on calculating its properties.

If this can be done and if the predicted vacuum condensate matches something in the real world, then perhaps I can come back here to talk physics instead of philosophy.

Extra slides

- The universe on a log distance scale
- Unifying Newtonian Gravity and Special Relativity as a prototype for formal fundamental physics
- Timeline of Formal Fundamental Physics
- What is String Theory good for?

The universe on a log distance scale



a book for children published in 1957

Scans at `http://www.vendian.org/mncharity/cosmicview/`

Unifying Newtonian Gravity and Special Relativity as a prototype for formal fundamental physics

The strategy of unifying Newtonian Gravity with Special Relativity was a great success.

But compare:

Newtonian Gravity + SR	GR + Quantum Mechanics
$\frac{M_{\mathsf{sun}}}{R_{\mathsf{Merc\ orbit}}} = 2.5 \times 10^{-8} \, \frac{c^2}{G}$	$1 \, \mathsf{TeV} = 10^{-16} \, \ell_P^{-1}$
thought experiments in elevators	thought experiments deep in black holes

Timeline of Formal Fundamental Physics 1819 – 2019

1820	
1830	Electric and magnetic fields
1840	
1850	
1860	Field theory of E&M
1870	
1880	
1890	
1900	Special Relativity
1910	Old Quantum Theory General Relativity
1920	Quantum Mechanics Quantum Field Theory
1930	
1940	
1950	Renormalized QED The Renormalizaton Group Nonabelian Gauge Theory
1960	
1970	Standard Model
1980	
1990	
2000	
2010	
2020	

What is String Theory good for?

String theory is useful not as "theory of everything", but as a tool to construct a self-consistent effective S- matrix for short distance physics without requiring a short distance QFT.

Before string theory, the only way to construct an S-matrix was to derive it from a Hamiltonian Quantum Mechanics (e.g., a QFT).

What are popularly considered the string backgrounds are the scale-invariant 2d-NLMs of the world-sheet, the solutions of $R_{\mu\nu} = 0$ (Calabi-Yau manifolds) and generalizations.

These are the backgrounds for idealized asymptotic string scattering. But the asymptotic string S-matrix is not useful.

The potentially physical string backgrounds are the effective QFT(L) with IR cutoff L which are the quantum backgrounds for the effective string S-matrix.