String Theory Circa 2022

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Goal of this talk

- In this talk I will attempt to summarize (my opinion of) the highlights of research conducted by the global community of string theorists over the last decade or so.
- I will give no references in this talk. However, anyone interested will be able to track down all relevant references, starting with the 'Snowmass White paper' TF1 Snowmass Report: Quantum gravity, string theory, and black holes, https://arxiv.org/abs/2210.01737
- This brief and readable document, which has a mandate similar to the goal of this talk, refers to several other more specialized white papers, which, in turn, contain extensive references to the original papers.

What is string theory?

- As will be clear from my talk, string theorists interests are wide ranging. They extend over all of the structures of theoretical physics, especially those that are 'UV complete' and have a natural interplay with geometry (often with gravity).
- In order to give my talk some structure, however, I begin with a 2 slide description of one of the (many) organizing goals of research in this area.

Continuum QFT

- At the level of formalism, the development of the theoretical framework of quantum field theories over, say, the last 80 years, has been one of the great accomplishments of theoretical physics.
- According to our current understanding, continuum QFTs always reduce to a scale invariant structure at sufficiently high energies. At these energies QFTs are always either CFTs or effectively massless free theories.
- QFTs are defined as RG flows away from CFTs. Inequivalent RG flows are parameterized by relevant deformations away from CFTs. QFTs may then be classified by ennumerating all CFTs and all their relevant deformations.
- There is continuous progress towards such a (still distant) classification. Does not seem unreasonable to me to hope it can be achieved over decadal time scales. Would mark huge progress in theoretical physics.

String Theory

- The framework of QFT is key to the study of high energy physics, statistical physics (phase transitions) and condensed matter physics (e.g. superconductivity, quantum hall effect).
- Except in a holographic sense (see below), however, QFT does not appear to be the appropriate framework for gravitational physics in a quantum setting.
- In part, String theory may be thought of as a research programme that aims to unearth the gravitational analogue of the space of QFTs spelt out above. Also, ofcourse, to understand the physics of the theories so obtained.
- The AdS/CFT correspondence reveals a holographic relation between field theory and gravity, so understanding the space of gravitational theories in D dimensions is related to the programme of understanding the space of *QFTs* in dimensions less than D.

Highlights of String Theory Research over $\sim$ 1 decade

- In the rest of this talk I will summarize the most interesting results that have come out of string theory research, over the last decade or so.
- Of course the word ‘interesting’, by its very nature is subjective. In this talk I will, of course, only give you my opinion for the answer to this question.
- However I have been careful to calliberate my views against those expressed in the community written Snowmass papers listed above, and so feel confident that my assessements do not lie too many standard deviations away from the community consensus.
- The progress I review falls into three categoreies: 1) Emergent Spacetime and black holes. 2) Better understanding of QFT. 3) Perturbative String theory and String Compactifications.

Emergence of Spacetime

- Bulk Dynamical Spacetime is an emergent phenomenon in the AdS/CFT correspondence. This phenomenon appears to have a fair degree of universality. QFTs that are very different on the boundary have holographic descriptions in terms of the same (or very similar) local physics. It thus seems that the (still mysterious) emergence of spacetime must occur via a mechanism that makes no crucial use of the dynamical details of any particular QFT.
- One hint to how this might work comes from (generalizations of) the Ryu Takayanagi formula, which expresses the entanglement entropy of a boundary region in terms of the area of the (generalized) bulk soap bubble that ends on the (boundary of) the boundary region.
- General arguments from quantum information theory then tell us that the map between boundary and bulk must occur in a 'subregion-subregion' manner.

Emergence of Spacetime: Quantum Information

- Subregion-subregion duality gives rise to an apparent puzzle. The same bulk region can be encoded for by several distinct boundary regions. This feature is strongly reminiscent of ‘Quantum Error Correcting Codes’, which encode information in a redundant manner, designed to protect against erasure of parts of the encoding system.
- About 8 years ago, this observation motivated the suggestion that spacetime is a sophisticated ‘error correcting code’. Some cartoon models for how this might work have been constructed.
- Motivated by these observations, the IT from QBIT programme hopes to use ideas from condensed matter (e.g. tensor networks), and Information Theory (entanglement entropies, error correcting codes, modular Hamiltonians ($\rho = e^{-H}$) etc) to quantitatively understand emergent spacetime.

Black Hole Information Paradox

- The ideas above have led to sharp recent progress on the Black Hole Information in the following manner. The Ryu Takayanagi formula - originally a conjecture - was derived in the context of the AdS/CFT via a semiclassical study of quantum gravity path integrals.
- The same semiclassical techniques were applied to compute the entanglement entropy of Hawking radiation. It was discovered that, after the Page time, a new 'quantum extremal surface' dominates the computation. This surface roughly tracks the local event horizon, and so describes decreasing entanglement entropy, in agreement with the expectations of unitarity.
- Subregion-subregion duality then implies that, after the Page time, the old Hawking radiation makes up the underlying degrees of freedom that encode the local degrees of freedom inside the black hole. Implies an unprecedented fundamental nonlocality in gravity

Black Hole Information: Assessment

- Semi classical gravity is surprisingly potent. It knows about the entanglement properties of the underlying degrees of freedom. Like Fluid dynamics on steroids.
- Nonlocal complimentarity presumably consistent with causality only because spacetime itself is emergent. The highly complex manipulations that ‘create’ a truck inside the black hole’ also, presumably, alter the spacetime itself.
- All progress at the level of semiclassical gravity. Essentially no role yet for string theory. No detailed understanding of how information is carried out. No in principle computation of black hole S matrices. No clear bulk description of black hole microstates. No clear conclusion on the existence, or otherwise, of firewalls, especially in very old black holes. No understanding at all about black hole singularities. No mathematical theory (or framework) for the nonlocal encoding of spacetime. Lots to understand.

SYK, JT, Black Holes

- Much of the progress on the black hole information paradox was facilitated by the study of the SYK model. It was discovered that the low energy dynamics of this model is governed a very simple (and quantum mechanically exactly solvable) theory of 2D gravity called JT gravity.
- Interestingly, 2d JT gravity also dominates the low energy dynamics of near extremal black holes in higher dimensions. This fact has been used to improve our understanding of the density of states of near extremal black holes. In particular, it has been established that susy black holes (which have a large exact macroscopic groud state degeneracy) also always have universal and precisely computable mass (to the first nonsusy state). Furthermore, in examples, the number of susy states has now been computed exactly, yielding an integer (and the correct integer) as an answer.

Black Holes and the Bound on Chaos

- Another recent result involving black holes, which is somehow intimately connected to the previous discussion, involves the precise definition of a Lyapanov index in quantum mechanical theories, a theorem that this index is bounded from above, and the demonstration that AdS/CFT systems dual to black holes in two derivative gravity saturate this bound.
- This remarkable result has many unexpected ramifications. In particular it bounds the growth of classical gravitational amplitudes with energy in a surprising way. This so called CRG conjecture, has more or less been proved now.

- Quantum Information methods have also been useful in the direct study of quantum field theory.
- The monotonicity of relative entropy has been used to prove a ‘c theorem’ for 3 dimensional field theories.
- Quantum information techniques have also been used to prove integrated null energy theorems (ANEC and QNEC) in general quantum field theories.

Black Holes and thermalization

- The AdS/CFT turns questions about non equilibrium dynamics in large N strongly coupled field theories into questions about black hole physics.
- The fluid gravity correspondence, which was developed largely in India 14 years ago, continues to be further developed. Recent progress includes a prescription for the computation of arbitrary Schwinger Keldysh correlators in thermal equilibrium (as well as in other states). Reviewed in Loga's talk yesterday. Unlike the original fluid gravity construction, the recent progress has been perturbative in amplitudes .... so far. Perhaps an opportunity for further progress.

Progress in QFT

- We are used to following RG flows from the UV to the IR. One might ask if it is possible to follow flows the other way around. One obstruction to this idea is that an infinite number of coefficients grow exponentially towards the UV, so the direction of the initial deviation has to be defined with perfect precision in order to make sense of the flow.
- A related worry is that flows that would lead to sensible UV theories are must be infinitely finely tuned: generic flows should be overwhelmingly likely to land up in garbage.

- However recent studies in a particular example have led to a surprise. A very particular RG flow up to the UV, starting in a generic 2d CFT, appears to lead to sensible UV behaviour. In some examples the UV theory is 2d gravity coupled to conformal matter, and not a QFT!
- The results here are very beautiful and quite surprising. The obvious question here is whether this is the tip of the iceberg. Are there more such tractable and interesting RG flows towards the UV waiting to be discovered. Potentially very interesting.

The Space of Susy QFTs

- Over the last decade or so there has been a steady and continuous development in understanding various aspects of quantum field theory.
- The study of protected quantities (e.g. indices) and dualities supersymmetric quantum field theories has proceeded with increasing sophistication. There now exists a conjecture for a relatively simple classification of 6 dimensional CFTs with 8 supercharges. Moreover very large classes of QFTs in 5, 4 and 3 dimensions can be identified as arising out of compactifications of these 6 dimensional theories on appropriate manifolds.
- Overall, we seem to be steadily moving towards the goal of classifying all supersymmetric CFTs, the first step towards classifying all QFTs.

Generalized Symmetries

- The progress above has been facilitated by the following structural development. It has been realized the the notion of symmetry can be generalized in a useful way.
- Familiar symmetries are now sometimes called 0 form symmetries. Charged operators live at points. Conserved charges are integrals over a $D-1$ dimensional manifold.
- In contrast, the conserved charges associated with p form symmetries are integrals over $D-p-1$ surfaces. Operators charged under these symmetries live on p dimensional surfaces.
- The symmetry groups associated with p form symmetries are always Abelian. They are useful in part because anomalies involving p form symmetries are preserved under RG flow, as in the case of 0 form symmetries, so anomaly cancelation helps constrain IR behaviour and check dualities.

CFT Bootstrap

- The last decade has seeen major effort invested into the so called CFT bootstrap programme
- Recall that all correlators of a CFT in flat space are determined by the spectrum of operators and 3 point functions by the OPE expansion. Performing the OPE in different fusion channels must give the same correlation functions. This requirement imposes significant contraints on CFT data. It seems plausible that the imposed constraints are so severe that their solutions are generically discrete. A classification of these solutions could go a long way towards classifying conformal field theories.
- The last decade or so has seen some progress taking this grand goal and making it concrete. I list three concrete accomplishments below

- First, the CFT crossing equations, employed in the so called light cone limit, have been used to show that the operator spectrum of a CFT becomes almost free in an appropriate high spin limit, and to systematically parameterize deviations from this free behaviour.
- Second, the so called ‘inversion formula’ - which allows one to unambiguously isolate the contribution of any particular block to a correlator - has been understood.
- Third, and most surprisingly, it has been understood that the constraints of positivity (that follow from unitarity) are surprisingly powerful. These constraints (implimented via a numerical technique called linear programming) have been used to prove several theorems ruling out the existence of CFTs with certain properties, for example the property of having no scalar operators, of a certian sort, below a critical dimension.

CFT Bootstrap

- The concrete output from the last point often proceeds via numerical implementation of the constraints of positivity. This approach has led, for instance, to the most accurate current determination of the anomalous dimensions of the 3d Ising model. Aspects of this story are still not understood as well as they should be (why do theories appear to live at kinks?). Perhaps understanding this better is one key to further progress.
- To my mind, however, the real potential of this programme lies in its analytic implementation, using equations rather than inequalities. This approach has already had some successs (points 1 and 2 above) - and feels to me like it is bristling with promise for the future.

S matrix Bootstrap

- Motivated by the success of the CFT bootstrap programme, many people have attempted to use the same methods to constrain S matrices (marking a return to the 60s, a full circle in string theory research)
- As with the CFT bootstrap, the key element in current work is the emphasis on the positivity constraints from unitarity. Also proper exploitation of the simple explicit forms of the S matrix analogues of conformal blocks, namely (generalized) Legendre polynomials.
- A concrete result goes as follows. Consider a theory of massive scalars that is weakly coupled in the IR. At low energies the amplitude of this theory can be expanded in terms of the tree level contributions of various local effective operaors. In particular the amplitude is analytic at low energies.

S Matrix Bootstrap

- Let us suppose that amplitude above becomes more complicated at high energies, and in particular develops its first non analyticity at $s = M^2$.
- In this context, the S matrix bootstrap has been used to obtain sharp two sided bounds on the coefficients of effective low energy operators. For example these bounds tell us that the modulus of a particular dimension 6 Wilson coefficient cannot be larger than, say, $2/M^2$. The power of M follows on dimensional grounds (i.e. is just an RG estimate). The new thing here is the sharp number. In the context described above, the CFT bootstrap turns approximate RG intuition into a theorem with a precise number.

QFTs built on nontrivial TFTs

- QFTs with massless particles are obviously ungapped. While there is a sense in which QFTs with only massive particles are 'gapped', not all gapped theories are equal.
- Trivially gapped QFTs are completely trivial in the IR. These theories have a unique vacuum when quantized on any manifold. When studied on a manifold with a boundary, they have no degrees of freedom.
- On the other hand theories without massless particles can also reduce to TFTs in the IR. Such theories have multiple vacuua when quantized on complicated manifolds (like Torii). They also have boundary degrees of freedom when studied in manifolds with a boundary. TFTs have recently been much studied by condensed matter physicists. I believe they have been classified. A simple example of a TFT is Chern Simons theory in $2+1$ dimensions.

QFTs built on nontrivial TFTs

- TFTs are exactly solvable, and very well understood.
- In physical problems, however, we are often interested not in the TFT itself, but in the dynamics of massive degrees of freedom coupled interacting with the TFT.
- Over the last 10 years or so this problem has been analysed in great detail in the context of the example of $2+1$ dimensional Chern Simons theory interacting with massive matter. The results are novel and quite surprising. The TFT modifies the properties of the massive matter in several ways. Crossing symmetry rules are modified. The rules of occupation statistics are modified. Fermions blur into bosons. Its a new world with new rules, and a lot remains to be understood.

Perturbative String Theory

- Perhaps surprisingly, there has been steady recent advances in the old subject of string perturbation theory. The measure for integrating over supermoduli space at two and three loop order has been unambiguously determined and checked. String field theory has been used as a crutch to complete the proof that string amplitudes are analytic, obey crossing symmetry and Cutkowski's rules.
- Recently, there has been a revival of interest in the duality between $0+1$ dimensional matrix models and exactly solvable $1+1$ dimensional string theories. The agreement between the two sides - which had been checked to all orders in perturbation theory in the early 90s - has now been checked in several nonperturbative computations involving D instantons. Getting the two sides to match exactly required perfect understanding of the string perturbation theory, including the precise choice of contours, etc, in all integrals.

Study of String Compactifications

- The study of compactifications of 10 or 11 dimensonal string theory down, especially to 4 dimensions, continues to be active area of investigation in string theory.
- Already in the 80s compactifications of the $E_8 \times E_8$ Heterotic String were intensively explored, with the goal of obtaining MSSM type physics at low energies. More recently, compactifications of M on 7 dimensional manifolds with G_2 holonomy have been studied. Compactifications of Type II theory in the presence of D branes, fluxes and geometrical singuarities have also been studied. Finally, nonperturbative Type II compactifications involving (sometimes coincident) 7 branes have been investigated by analysing singular compactifications of F theory. Finally supersymmetric flux compactifications (especially in Type II) as well as some scenarios for susy breaking, including the KKLT scenario, have also been intensively investigated.

- One clear conclusion that emerges from the studies of string vaccua is the following: the number of topologically inequivalent consistent $N = 1$ compactifications of string theory - though likely finite - is mindbogglingly large.
- What can this observation be used for? One application is to scan the vast set of available vacuua for those that will give rise to MSSM type physics at low energies. This activity has been moderately successful: several 100s of vacuua that contain the MSSM gauge groups and matter content (but possible also additional groups and non chiral multiplets) have already been identified, both in the context of Heterotic, Type II and F theory compactifications.

String Phenomenology

- In the Heterotic and F theory context getting the right gauge group and chiral spectrum turns into a well posed mathematical problem in algebraic geometry. Yukawa couplings are easily computed in Heterotic models (they are related to intersection numbers of homology cycles).
- Yukawa couplings are harder to compute in Type II models (related to instanton computations of superpotentials). Also computation of Yukawa couplings in F theory models is harder (progress is being made in reducing these computations to well posed questions in algebraic or ennumerative geometry).
- One lesson from these studies is that many models come with several non QCD axions, an observation that has spurred some experimental interest.
- Finally, the biggest challenge is retaining any semblence of technical control after SUSY breaking.
- Sandip is the only DTP expert on string phenomenology.

Landscape and Swampland

- In recent years there has been another application of the extensive data obtained from the extensive data generated by the detailed study of $N = 1$ compactifications.
- This philosophy has generated several so called 'swampland' conjectures. One of the most solid of these is the 'Weak gravity conjecture' : a consistent theory involving gravity and a $U(1)$ gauge field necessarily includes a charged particle with charge by mass ratio greater than that of an extremal black hole in its spectrum. Fair amount of evidence for this conjecture, but no proof.
- No one in DTP is really part of the swampland gang. However Abhijit and I are responsible for a conjecture on the uniqueness classical scattering amplitudes in perturbative string theory. This is a sort of swampland conjecture, and would benefit from a 'swampland type' confrontation with data.

Topics not touched upon

- The many topics I have not touched upon in my little review include
- First, the strong, powerful and continuing impact of recent developments of string theory on mathematics, especially on algebraic and ennumerative geometry.
- The amazing recent progress in the understanding of the structure of S matrices e.g. (Cachazo's scattering equations) and onshell methods for the computation of the same.
- The potential progress in generalizing the mathematical structures of QFTs to theories with subsystem symmetries (e.g. fractons)
- Attempts to generalize holography in *AdS* to holography in flat space and *dS*.
- .....