What have the string theorists been doing?

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Joint IIHE and HEP@VUB colloquia

November 16th, 2021

I'll be trying to describe the kind of questions we're trying to answer and some cool things we have been doing.

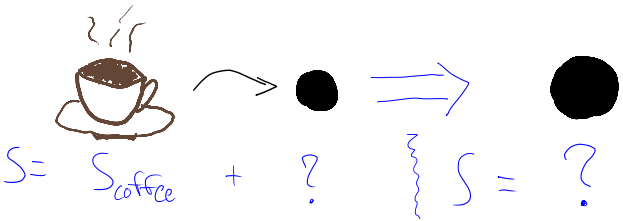
The 9^{th} floor ivory tower has two directions:

- **Black holes, holography, entanglement**
  Craps; Balasubramanian, De Clerck, Evnin, Hacker, Hernandez, Khramtsov, Knysh, Pavlov
- **Superstrings, duality, geometry**
  Sevrin; ASA, Blair, Eloy, Hulík, Thompson, Zhidkova

The major focus is on **string theory as quantum gravity**.

Black holes, holography, entanglement

Bekenstein's gedankenexperiment: pour coffee into a black hole. Where does its entropy go?



$\Longrightarrow$ black holes have entropy, else 2$^{\text{nd}}$ law of thermodynamics is broken

$\Longrightarrow$ black holes are made up of *microstates*.

In General Relativity the **Bekenstein-Hawking entropy** is the black hole's **surface area**, and its **temperature** is the **surface gravity**.

Black holes, holography, entanglement

String theory implies *gauge-gravity duality*: (quantum) **gravity** on $-$vely curved **bulk** spacetime is equivalent to **gauge theory** at **boundary** (which has 1 dimension fewer)

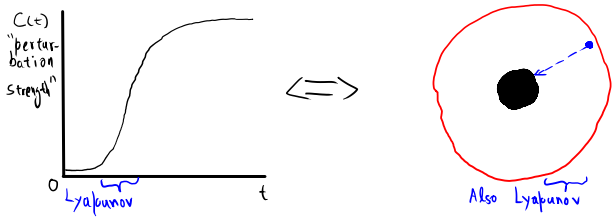
Holographic decription also for **thermal field theory**: just put a black hole in the **bulk**!

The **boundary** strong-coupling limit is the **bulk** semi-classical limit. So we do General Relativity on the **bulk** to calculate otherwise inaccessible physics on the **boundary**.

Black holes, holography, entanglement

In arXiv:2009.08518 [Craps, De Clerck, Hacker, Nguyen, Rabideau] they study quantum chaos in 2D gauge theory via holography.

Perturbations of the 2D theory away from equilibrium are dual to insertions of particles on the 3D black hole spacetime. In the approximation of 2009.08518 these are point masses that interact with each other via gravitational shockwaves.



The Lyapunov behaviour characteristic of chaos is dual to the blueshift in the energy of particles accelerating towards the black hole.

Black holes, holography, entanglement

In quantum gravity the singularity inside any black hole needs to be resolved.

One proposal is that the black hole is a superposition of *microstate geometries*: horizonless spacetimes that approximate the BH well from "far away". Some microstate geometries can be constructed in string theory (depending on the BH in question).

The novelty in arXiv:2009.08518 is the study of 3D black holes at *zero* temperature, for which microstate geometries are known.

Quantum chaos in the dual field theory can distinguish the black hole from its constituent microstate geometries!

Superstrings, duality, geometry

(This is what I actually do)

A quantum particle on a circle has quantised momentum (m, n integers)

$$p = \frac{\mathrm{m}}{R} \qquad R = \text{circle radius}\,.$$

A quantum *string* on a circle has quantised momentum and *winding*

$$w = \mathrm{n}R$$

and both enter near symmetrically in the energy (for ℓ_{s} the string length scale)

$$E = (p\ell_{\mathrm{s}}^2)^2 + w^2\,.$$

(m, n) *string state on circle of radius R has same energy as an* (n, m) *string state on a circle*

$$R' = \frac{\ell_{\mathrm{s}}^2}{R}!$$

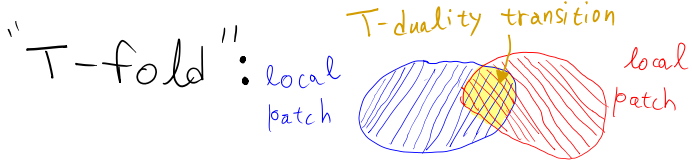
Superstrings, duality, geometry

T-duality

String physics on a spacetime with some circle of radius R is equivalent to string physics with radius $R' \propto 1/R$.

Big motivating questions in this direction include

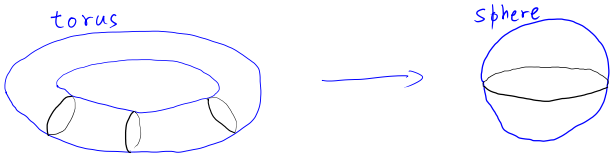
- What is the geometry that accommodates stringy dualities?
- Can we find stringy structures *beyond* string theory? What are their physical implications?



(Part of) of a string background that is not conventionally geometric. Distances are not defined in the overlap region, even though stringy physics is consistent!

Superstrings, duality, geometry

So duality alters geometry. *More radically*: T-duality-mediated **topology change**. A famous example is $S^1 \times S^2 \to S^3$ (which can't be drawn) which is analogous to $S^1 \times S^1 \to S^2$, which can:



In arXiv:2110.08179 [ASA, Blair, Thompson] (last month!) we exhibited a new type of topology change for a 'non-abelian' generalisation of T-duality — meaning, a generalisation where circles and tori are replaced by (non-abelian) group manifolds.

(We also showed that string probes "see" the same physics in either topology.)

Superstrings, duality, geometry

The geometry that accommodates T-duality is some kind of **doubled geometry**: one that has conjugate positions for both momenta p and string windings w. The doubled geometry is (should be!) good even if its 'singled' shadows are singular.

Is there an associated "doubled General Relativity"?

. . . How do we see string theory gives GR (+ matter + corrections) anyway?

Answer: (closed) strings have **gravitons** in their spectrum. Scatter them against each other, compare against GR scattering amplitudes.

This is fundamentally a calculation in the *field theory of strings* a.k.a. 2nd quantisation. (Although this is usually deemphasised.)

Superstrings, duality, geometry

In arXiv:2106.08343 [ASA, Hohm, Hull, Lekeu] we gave an algorithm to construct the lagrangian for this doubled GR ('double field theory') from the field theory of strings! This was an open problem for a while.

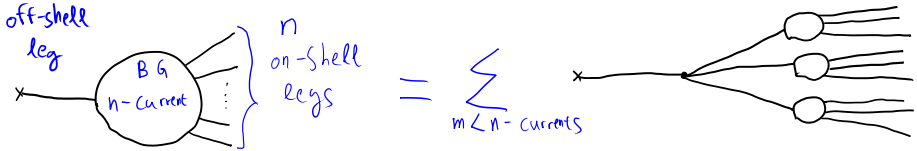
We exploited the presence of *higher symmetries* in string field theory, and the technology of the associated *higher algebras* ('higher Lie algebras' to be precise). These defy nontechnical explanation except by vague analogy:

symmetries	$\leftrightarrow$	particles
higher symmetries	$\leftrightarrow$	extended objects e.g. strings

Higher symmetries are a universal — if arcane — feature of QFT [ASA 2019]. They have, however, some down-to-earth implications. . . !

Superstrings, duality, geometry

Berends-Giele **off-shell recursion** techniques give a nice example. They provide efficient tree-level scattering amplitude calculations, relevant for — I hear — real-world experiments.



The collection of all BG currents for all numbers of legs $n \geq 1$ form a map of higher algebras $\implies$ **off-shell recursion for any field theory** [Macrelli Sämann Wolf 2019] and in principle to any loops as well (via [ASA 2019]).

- Now you know (an impression of) what the theorists have been up to!
- Feel free to ask me questions over drinks.

Thank you!