17. Quantum Gravity and Spacetime

Theory of Matter

Relativistic Quantum Field Theories (RQFTs)

Quantum Electrodynamics (1940's)
- RQFT of electromagnetic force.
- Matter fields: leptons, quarks.
- Force field: $\gamma$ (photon).
- $U(1)$ symmetry.

Electroweak theory (1960's)
- RQFT of EM and weak forces.
- Matter fields: leptons, quarks.
- Force fields: $\gamma$, $W^+$, $W^-$, $Z$.
- $U(1) \times SU(2)$ symmetry.

Quantum Chromodynamics (1970's)
- RQFT of strong force.
- Matter fields: quarks.
- Force fields: gluons (8 types).
- $SU(3)$ symmetry.

Standard Model (1970's-80's)
- RQFT of EM, strong, and weak forces.
- Matter fields: leptons, quarks.
- Force fields: $\gamma$, $W^+$, $W^-$, $Z$, gluons.
- $U(1) \times SU(2) \times SU(3)$ symmetry.
17. Quantum Gravity and Spacetime

**Theory of Matter**

*Relativistic Quantum Field Theories (RQFTs)*

- **Quantum Electrodynamics (1940’s)**
  - RQFT of *electromagnetic* force.
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- **Electroweak theory (1960’s)**
  - RQFT of *EM* and *weak* forces.
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**Theory of Spacetime**

*General Relativity (GR) (1916)*

- Classical (non-quantum) theory of *gravitational* force.
- $\text{Diff}(M)$ symmetry.

**Inconsistent!**

*Standard Model (1970's-80's)*

- RQFT of *EM, strong, and weak* forces.
- Matter fields: leptons, quarks.
- Force fields: $\gamma$, $W^+$, $W^-$, $Z$, gluons.
- $U(1) \times SU(2) \times SU(3)$ symmetry.
### Theory of Matter

**Relativistic Quantum Field Theories**
- Flat Minkowski spacetime, unaffected by matter.
- Matter/energy and forces are quantized.
- "Compact" symmetries.

### Theory of Spacetime

**General Relativity**
- Curved Lorentzian spacetimes, dynamically affected by matter.
- Matter/energy and forces are classical.
- "Non-compact" symmetries.

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**Two General Approaches to Reconciliation**

(A) **Background-Dependent Approach.**
- Start with a spacetime with a fixed metric (*e.g.*, Minkowski spacetime).
- Try to construct a quantized gravitational field on it.

*Problem:* Standard method of quantizing classical fields, when applied to the gravitational field, produces a "non-renormalizable" RQFT.

(B) **Background-Independent Approach.**
- Start with a spacetime with *no* fixed metric (as in GR).
- Try to construct a quantized gravitational field on it.

*Problem:* Standard method of quantizing classical fields requires a background metrical structure.
Background-Dependent. Ex 1: String Theory

- **General Idea:** Take QFT as a given and try to force GR into its mold.

**Procedure:**
- Replace 0-dim point particles with 1-dim strings.
  - **Consequence:** Many "non-renormalizable" divergences are tamed in the standard approach to quantization.

**Problems:**
1. Requires extra spatial dimensions.
   - Require that these extra dimensions are "compactified": severely "rolled-up" so that we can't normally experience them.
2. No testable predictions after ~30 years of work.
3. Takes no lesson from Einstein's insightful geometrization of gravity.
   - Gravitational force is treated on par with the other forces.
   - Spacetime is represented by flat Minkowski spacetime (background-dependence).
Background-Independent. Ex 1: Loop Quantum Gravity

- **General Idea**: Take GR as a given and try to force QFT into its mold.

**Procedure:**

- Try to identify the "observables" of GR: very hard to do!
  - Because of the strange Diff(M) symmetry of GR, its observables are strange; in particular, there are no local observables!
  - Identify non-local "loop" observables (quantities that depend on particular closed paths in spacetime).

- Spacetime structure is not fixed, but is determined by the quantum (loop) version of the Einstein equations.

**Problems:**

1. Constraint equations that result from quantization have yet to be solved.
2. No testable predictions after ~30 years of work.
3. Takes no lesson from the QFT approach's insightful suggestion that QFTs are low-energy approximations to a more fundamental theory.
**Question:** What do background-dependent and background-independent approaches to quantum gravity suggest about the nature of spacetime?

- **Background-dependent approach:**
  - No prior spacetime structure
  - Physical (and spatiotemporal?) fields

- **Background-independent approach:**
  - Physical fields

**Claim:** Both approaches may be interpreted in either *substantivalist* or *relationist* terms.

**Background-Dependence**
- A *substantivalist* may claim that the prior spatiotemporal structure is exhibited by real, substantival spacetime.
- A *relationist* may claim that the prior spatiotemporal structure is exhibited by a real physical field (the metric field, say).
**Question:** What do background-dependent and background-independent approaches to quantum gravity suggest about the nature of spacetime?

- **Background-dependent approach**
  - Prior spacetime structure
  - Physical fields

- **Background-independent approach**
  - No prior spacetime structure
  - Physical (and spatiotemporal?) fields

**Claim:** Both approaches may be interpreted in either *substantivalist* or *relationist* terms.

**Background-Independence**
- A *substantivalist* may claim that spatiotemporal structure depends (as in GR) on physical fields, but once it is so-determined, it exists in its own right.
- A *relationist* may claim that spatiotemporal structure is exhibited by the relations between physical objects, so only such objects exist.
Background-Dependent. Ex 2: Condensed Matter Approaches

- **General Idea**: Suppose GR and the Standard Model describe the low-energy fluctuations of a condensed matter system (like a superfluid, or a superconductor).

- **Then**: The condensate would explain the origin of *both* spacetime and gravity (as described by GR), *and* matter fields and the other forces (as described by the Standard Model).

- **In Fact**: Some non-relativistic condensed matter systems exhibit low-energy fluctuations that resemble aspects of GR and the Standard Model.

**Example**: Superfluid Helium 3-A. Low-energy fluctuations behave like relativistic massless fields coupled to an electromagnetic field.

- Tickle (non-relativistic) superfluid He\textsuperscript{3-}A with small amount of energy.
- Low-energy ripples behave like relativistic fermions coupled to EM field.
How can spacetime be thought of in the Condensed Matter approach?

• A background-dependent approach:
  - The fundamental condensate has prior non-relativistic (Galilean) spatiotemporal structure.

• A substantivalist may say:
  - "The prior Galilean spatiotemporal structure is given by properties of real spacetime points in a Galilean spacetime. Take the fundamental condensate out of the universe and real Galilean spacetime would be left."

• A relationist may say:
  - "The prior Galilean spatiotemporal structure is given by properties of the fundamental condensate. Take it out of the world and nothing would be left."

Problems:

1. No condensed matter system has yet been identified that reproduces GR and the Standard Model exactly in the low-energy regime.
2. Many disanalogies between real condensed matter systems and their idealized low-energy regimes.
Ex 3: AdS/CFT Correspondence

- **General Idea**: One can construct correspondences between certain types of simple general relativistic spacetimes ("anti-de Sitter", or AdS, spacetimes), and certain types of very simple quantum field theories in one less dimension (conformal QFTs, or CFTs).

- **Image**: The AdS spacetime lives in the "bulk", and the CFT lives on the "boundary".

- **Holographic Principle**: The essential properties of a physical system in a $d$-dim bounded space can be encoded in aspects of its $(d-1)$-dim boundary.

**Open questions**:
1. Which is fundamental: the flat boundary spacetime, or the curved bulk spacetime?
2. Is this a background dependent approach (CFT), or a background independent (AdS) approach?