Gravity and Thermodynamics:
What exactly do we want?

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*-- Thanks to the organizers: **Stefano, Daniele and Lorenzo** for their hospitality. (They shouldn't feel obliged to abide by the old rules. We want to hear you talk!)*

Let’s first try to agree on a few terminology:
Quantum and Emergent Gravity

Quantum Gravity: A theory for the microscopic structure of spacetime

• **Conventional approach:** Quantize the **metric g** or **connection** Γ forms

• **My view: [GR as Hydro** (1996) **Cosmology as Condensed Matter Physics** (1988)]

- GR could merely be a **hydrodynamic theory** valid only in the long wavelength, low energy limits of some unknown microscopic theories
- Spacetime is an **emergent entity** so are its symmetries
- **(g, Γ) are collective variables:** Quantizing them gives phonons, not atoms.

Quantizing macro variables does not (always) yield micro structure

(Cases which work: *Macro and micro variables are the same.* **EM → QED**, *He 4)*
But not as a rule

Need to Redefine the goals and tasks of: ***E/Q Gravity***

Emergent vs Quantum Gravity

Our task is two fold: ***E/Q Gravity***

***Emergent Gravity**:*

understand how the macroscopic structure of spacetime emerge/evolve from micro structures

***Quantum Gravity**:*

how to induce micro structures from Macro

Top-down or Bottom-up?

Q-C versus m-M

Quantum → decoherence, robustness, stability → **Classical**

← **Traditional effort:** quantizing the metric or connection forms

Quantum Gravity (Strings Loops Simplices, Causets – micro const.)

MICRO fluctuations

coarse-|-graining MESO kinetic theory

v Emergent hydrodynamics

MACRO spacetime *General Relativity*

Issues: Coherence, Correlations, Fluctuations, **Stochasticity**;

Collectivity, Variability, Nonlinearity, **Nonlocality**

Top Down: Emergence of Effective Theories

Collectivity and Emergence

Issues:

$\mu \to M$

- What constitutes a stable level (e.g. Ren Grp concepts)
- Effective Theory : How good is it?
- What are the most appropriate collective variables at each level of structure & Dynamics.

{ to different microscopic theories

"Hydrodynamics of M-Theory"
(C. Herzog)

$Q \to C$:

- Emergence of quasi-Classical domain : Conditions
- | Decoherence : Who choose how the projections?

Criteria in coarse-graining :
- stable structures / insensitive to CG
- robustness / variation

Dynamically generated?

• See my article in JJ Halliwell's book on "Time Asymmetry"

Guideposts :

- Coherence • correlation • fluctuations • variability • collectivity • nonlocality

nonlinearity FDR stochasticity (e.g. emergence of forms)

B. L. Hu, *in " The Physical Origin of Time Asymmetry" gr-qc/9302021.*
Proceedings of Conference in Huelva, Spain, Oct. 1991. Edited by J. J. Halliwell,
J. Perez-Mercader and W. H. Zurek (Cambridge University Press, Cambridge, 1994).

Micro-theorists should be working on **Emergent Gravity**! Micro =>micro

NOTE: Macro-structure is largely insensitive to the details of the underlying micro-structures.

Many micro-theories can share the same macro-structure. It is the collective properties of these micro structures which show up at the long wavelength, low energy limit.

We should look first at the commonalities of all competing micro-theories rather than their differences, namely, their hydrodynamic limits (at the lowest order approximation) rather than the detailed micro- (string, loop or set) behavior.

General Relativity as Hydrodynamics

Hu, 1996 Sakharov II

3). Our Approach: $\boxed{\text{Collectivity \& Emergence}}$ viewpoint:

Bottom-Up (Green Party)

GRas Hydro

▶ (Our view) Obtaining a Quantum theory of a classical theory seems not as important as finding the micro-structure of the macro-world & its dynamics

Which is a more relevant task
- (a) quantizing the vibrations of a lattice
- (b) or finding the atoms ?

misleading

$C/M \xrightarrow{(a)} Q$

$C/M \xrightarrow{(b)} \mu$

▷ Find the microstructure, its quantum feature will reveal itself

Need (Nonequilibrium) Statistical and Stochastic Mechanics

Quantum Gravity: macro =>Micro

Instead of trying to quantize macro- collective variables, we should look for micro constituents:

How does the familiar macro structure of spacetime arise?

- rely on (NEq) Stat. Mech. Esp ***fluctuation*** *phenomena and* ***topology***

  e.g., quantum order (Wen).

- **String theory:** our view is acceptable to them. They would agree that “Spacetime is Emergent”. How so from string interaction is still unknown.
- **Loop QG:** They start from a macro variable, quantize and end up with a micro variable. How so? This point is not always made clear.
- **Spin-foams, Dynamical triangulation, Causets, Quantum Graphs**

Spacetime as a condensate:

-Today’s universe described by ultra-low temperature/energy physics.

-The cosmos is an ultimate macroscopic quantum phenomenon.

Gauge Particles are all Collective Variables (of string-nets?) --- Volovik

Models from fermions on lattices to examine **emergence of graviton and gauge** degrees of freedoms **as collective modes** (Wen and Levine).

Going **from macro looking for micro** structure is always difficult, if not impossible.
BUT not hopeless.. that is how physics has progressed through centuries!

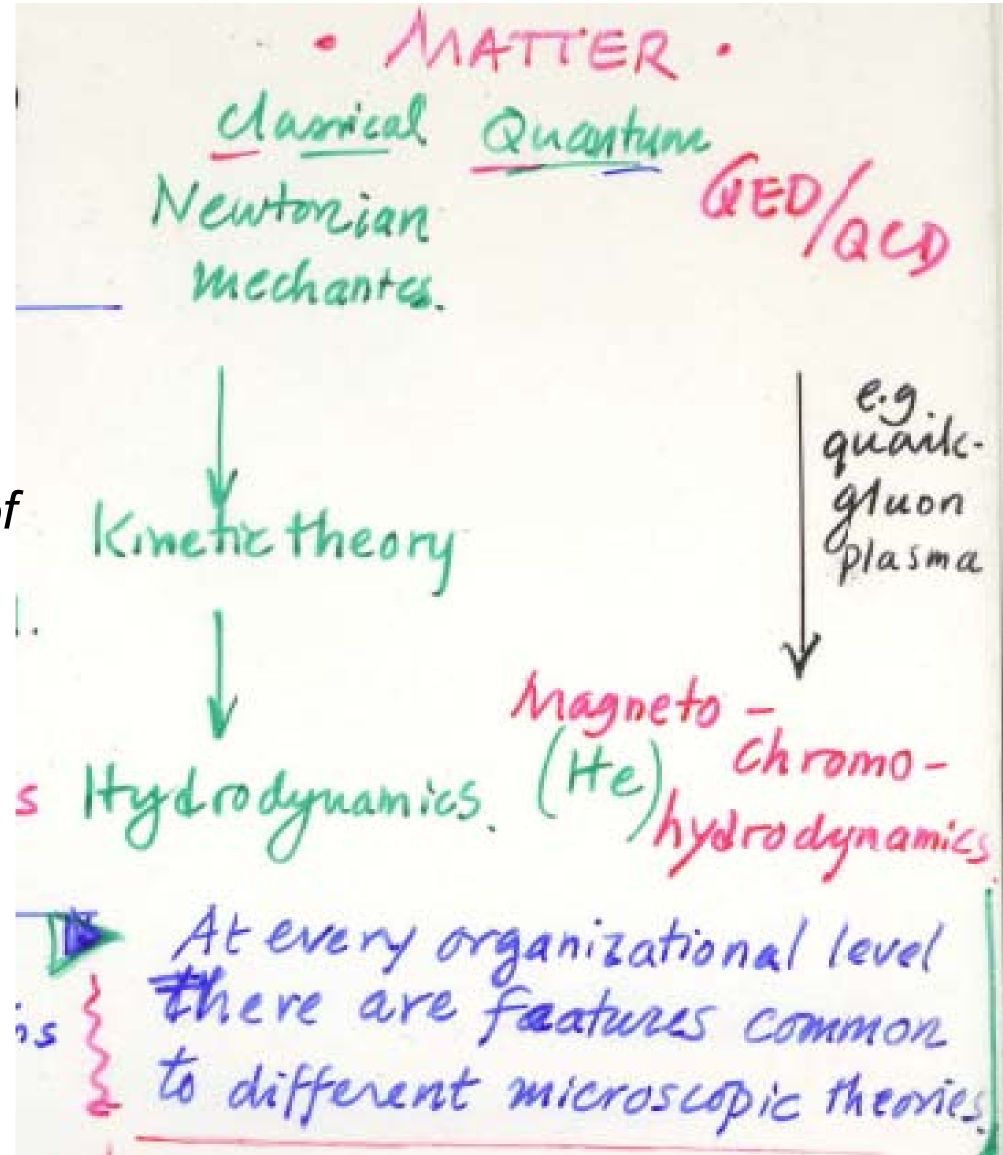
Common Features of Macroscopic Phenomena:

Micro

There are commonalities in the MACroscopic collective behavior of different MICroscopic constituents

Macro

Separate the common features
So as to pinpoint the particulars



Bottom-up: Macro to Micro

We choose to rely on:

A. Topological structures:

More resilient to evolutionary or environmental changes.

See approaches of Volovik (He3 analog, Fermi surface)

Wen (string-nets, emergent light and fermions)

B. Noise-fluctuations: Fluctuations can reveal some sub-structural contents and behavior (**critical phenomena**).

Information contained in remnants or leftovers. Yet, by reconstructing from corrupted and degraded information one hopes to get a glimpse of the nature of micro-structure.

What do we want? 5 levels of inquiry

1. **Black hole thermodynamics**:

   Bekenstein 73, Hawking 74, Wald 75, Sorkin 76, Ted J. (read his lectures notes) …

   well established, beloved results

Holography: ‘tHooft, Susskind, Buosso, ..

2. Gravity **as** Thermodynamics (TJ 95) GR **as** Geometro-Hydrodynamics (96)

- Gravity/GR is a classical theory which makes sense only at the macro scale. Like phonons physics, not atoms,

- Metric and connection forms are collective not “fundamental” variables. Geometry known in the classical context.

  (Don’t know what quantum geometry means)

- GR is an effective theory, only the low energy, long wave-length limit of some as yet unknown (unconfirmed) theory (many to one) for the micro structure of spacetime and matter.

- Manifold and metric structure, together with the symmetry of physical laws defined thereby (e.g., Lorentz and gauge invariance), are emergent.

3. Gravity **from** Thermodynamics?

Reversing the arguments of Bekenstein (73)

- Ted J (95) considered a Rindler observer and derived the Einstein Eq from TD.
- Padmanabhan (2000s) equipartition law at the horizon
- Verlinde (2010) gravity as entropic force ..

… I’ll show my line of inquiry in Part II of talk

4^{th} level: Emergence: processes and mechanisms

- Part III of my talk

5^{th} level of inquiry: Microstructure of spacetime

- I don’t know. Many of you have good answers.
- I expressed my view on this point earlier: It is the **commonality of these micro-theories**, not their finer differences which matters, likely some mesoscopic properties (like kinetic theory) that dictate the low energy (hydro-thermo) theory. Plse **work together to find them**.

Part I: General Issues: SM-TD, Q-C

Look more carefully at the relation between:

- **Thermodynamics (TD) –Stat. Mech (SM),**
- **Q**uantum –**C**lassical,
- micro (m) Macro (M)

Q-C, μ-M

- Quantum-classical correspondence
  Many criteria: $h \to 0$, $n \to \infty$, Hi T,

  Coherent state: the most classical quantum state
  Wigner function: closest to classical distribution

  Quantum Decoherence: Environment induced

- Micro-macro: Statistical Mechanics
  Thermodynamic / hydrodynamic limits

- Macro - Quantum? Usually Macro $\Leftrightarrow$ Classical

Q-C, μ–M

Classical =/= Macro:

Macroscopic Quantum Phenomena (MQP): BEC, superconductivity

Micro-Meso-Macro

Molecular dynamics (Gaspard et al) : N= 1,2,3 micro, N>100 macro, macro features begin to show even ~10

E.g., “quantum” universe: even at scale of 100 Planck length it begins to show classical features

SM-TD,   Q-C

- **Stat mech =/= Quantum.**

- At the mundane level: counting of “micro”-states. Ping Pong balls in two partitions: Purely statistics. h added on → micro
- More sophisticated: Stat mech = Euclean QFT formally
- Many quantum geometry calculations are actually summing over classical geometric configurations (simplices) – distinguish

- **TD=/= classical**. Quantum fluid hydrodynamics
- key ingredients in Q: in SM textbook, Q refers to **spin-statistics** but no **q coherence** by virtue of the two basic postulates of SM: 1) random phase 2) equal a priori probability (equilibrium)
- **quantum levels, discrete structure, etc.**

- **TD limit**: large N, V, finite n: **may not exist for small quantum systems.**
- How `large’ a spacetime or how big a composite configuration can one begin to use TD description and talk about **gravity from TD?**

II. Gravity and (as) Thermodynamics

Gravity as Thermodynamics,

Jacobson, Padmanabhan, Verlinde (JPV)

GR as Hydrodynamics (long wavelength, low energy limit of theories of the microscopic structure of spacetime) -- Wen, Volovik, Hu

Both veins => Gravity is Emergent (as thermodynamics and hydro are from molecular dynamics)

I see the need for two stages of inquiry: First classical then quantum. Why?

Both gravity and TD are macroscopic and classical.

Can we deduce a relation between

Gravity and Thermodynamics

without invoking any quantum consideration:

q fluctuations, q information.

This question can be posed in the 19c:

Gravity existed before black hole physics,

Thermodynamics before quantum theory

NEq thermodynamics / stat-mech. No Quantum, yet

Temperature, and thermodynamics, are associated with an event horizon, black hole or uniform accelerated observer.

1. Can we go beyond equilibrium conditions?

   Many gravitational systems do not have event horizons.

   Gravity (Newton-Einstein) is intrinsically nonequilibrium. Dynamics (Newton's 2^{nd} law) is not amenable to a thermodynamic equilibrium formulation (uniform accel is)
   But we don't accelerate, let alone uniformly, all the time.

This is a more generic perhaps also more demanding way of posing the problem than what was tackled by JPV.

Minimalist Approach

A. No quantum, no Bekenstein-Hawking-Unruh, no holography, no quantum information.

- We want to find out what in the familiar black hole thermodynamics cannot be obtained from the more basic and generic features of systems with negative heat capacity (NHC) or systems with long range interactions (LRI) which place gravity under the same roof with many other physical systems.

- For a summary of this line of reasoning, see, e.g.,

  B.L.Hu, [arXiv:1010.5837]

Gravity and Nonequilibrium Thermodynamics of Classical Matter

B.L.Hu, [arXiv:1010.5837]

Gravity is intrinsically non-equilibrium:

Jeans instability, negative heat capacity, no stable configuration by itself. Need box or AdS space to contain it (cf bosonic string: Hagedorn spectrum.)

Try to understand the familiar physics from this perspective: NEq condition prevails, not Equilibrium.

With the recognition that many hitherto labeled `fundamental' forces are emergent, NEq physics should play a pivotal role in main stream physics.

B. Add quantum fluctuations of the vacuum subjected to geometric constraints: Entanglement Entropy, Quantum Information.

use NEqQFT to understand Q/G/TD

3 takehome problems to try to understand Grav-TD with Q on the side

1. Try a humble start: SR+EP only

(A poor man's way of understanding -- getting by with the bare essentials – Wheeler's Austerity Principle.)

- **Special relativity** only: like how Taylor and Wheeler introduced black hole physics. "Scouting the Black Hole" Obtain the geodesic motions from g_{00} alone.

- **Equivalence Principle**. Allowing the knowledge of thermal radiance in a uniformly accelerated observer, but no more quantum physics.

See how far we can go, in understanding gravity from a TD viewpoint

2. Black Hole Atom

Yes, start out Quantum: Work out macro-features from a simple model of BH atom. Try to Understand

1) **Thermodynamic properties** of single to many atom systems from atom-field interaction (spectroscopy)
2) **Gravitational properties**. I think it is again just the event horizon, BH microscope / zoom lens – bringing out the micro features to the macro world.

Bekenstein-Mukanov equal spacing spectrum -- a harmonic oscillator model, but with the principal quantum number being the area operator. (Bekenstein-Gour, PRD 2002)

Use Einstein coefficients of black holes (Bekenstein Meisel 77) to understand the **atom-field interaction**: like in laser physics

Use the Pauli master equation (Schiffer) to study the nonequilibrium, stochastic properties, easy to obtain **stat mech / thermo properties, classical limit**

Semi-classical Limit: quasi-normal modes-- (not revealing quantum micro-features, showing classical features)

Metric fluctuations (more sensational word: “spacetime foam”): Black hole event horizon fluctuations (Roura,Hu, Sorkin, Ford, Frolov et al) reveals the stochastic features beyond the semiclassical.

Not quite **spacetime atoms**, but may share some commonality in the projected macro behavior from microconstituents.

3) Quantum information Issues (information transfer / sharing between atom-field)

Other leads

- **Kinetic theory** approach to quantum gravity
  Stochastic gravity as mesoscopic theory

- **Spacetime Condensate:**
  Einstein equation on the same footing as Gross-Pitaevesky equation, Einstein-Langevin equation on the same footing as the stochastic GP eqn where the effect of atoms (non-condensate) on the condensate is captured as the noise.

- **Macroscopic Quantum Phenomena**
  vacuum energy density, cosmological constant issues

3. Classical Fluctuation Theorems

Consider a classical system, whose dynamics is governed by the Hamiltonian $H(\lambda_t)$. λ is a deterministic parameter with a prescribed time dependence. At some initial time t_0 which without loss of generality can be taken to be zero, the system is prepared in a thermal state $\exp(-\beta H(\lambda_0))/Z_0$. Then the parameter λ is changed according to a protocol up to a final time τ. Work done during this process is defined as[41]

$$W = \int_0^\tau \mathrm{d}t \frac{\partial H}{\partial \lambda} \dot{\lambda}(t) \tag{1}$$

where an overdot denotes derivative with respect to time. Although the Hamiltonian dynamics of the system is entirely deterministic, due to the probabilistic nature of the initial conditions that are sampled from the thermal phase space density work is described by a probability distribution $\mathcal{P}(W)$. Note that thermal equilibrium is only assumed at $t = 0$ as part of the preparation. In general the evolved system is not in thermal equilibrium.

Jarzynski equality is the statement:

$$< e^{-\beta W} >\equiv \int \mathrm{d}W\mathcal{P}(W)e^{-\beta W} = e^{-\beta\Delta F} \tag{2}$$

Here $\Delta F \equiv F_\tau - F_0$, where F_0 and F_τ are the initial and final free energies of the system at thermal equilibrium at inverse temperature β with the parameter λ assuming values λ_0 and λ_τ respectively. Eq.(2) is remarkable in that it relates an average of thermodynamical quantities over non-equilibrium processes to equilibrium properties at their end states.

For the statement of Crooks's fluctuation theorem one defines the reverse process in which the system is prepared initially at $t = 0$ in the thermal state $\exp(-\beta H(\lambda_\tau))/Z_\tau$ and the parameter λ is changed in a time-reversed manner to assume the value λ_0 at τ. The probability distribution of work associated with this process is denoted by $\mathcal{P}_R(W)$. Crooks's fluctuation theorem states:

$$\frac{\mathcal{P}_F(W)}{\mathcal{P}_R(-W)} = e^{\beta(W-\Delta F)} \tag{3}$$

where the subscript F stands for forward process and ΔF is defined as before. The Jarzynski equality follows from Eq.(3) by multiplying both sides by $\mathcal{P}_R(-W)e^{-\beta W}$ and integrating over W.

What motivated me to look in this direction:

1. **Gravity intrinsically Nonequilibrium**. That is where I've been digging. But I want to connect with my friends – they are basking under the nice warm mediterrainean sun: BH thermodynamics / Rindler horizon, with the blessing of the equilibrium conditions

2. **Gravity as entropic force**? Whatever.   I am looking for a relation which generalizes the Clausius relation to NEq conditions. **Mechanical work** in a NEq protocol (mechanics, including Newton's) related to **free energy difference** between the initial and final equilibrium states (entropy is a state function)

What I found fitting this profile is the Fluctuation theorems:
Jarzynski equality, Crooks's fluctuation theorem.

Quantum and classical fluctuation theorems from a decoherent-history open-system analysis

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We rederived these theorems from a bona-fide quantum mechanical approach where we can see the transition from quantum to classical and can quantify the validity of trajectories by **the nature and magnitude of noise** in the environment. From this we can derive the range **where the classical FT's fail.** (low temperature)

Because we use a method (influence functional) which includes the back-action from its environment self-consistentlywe can define and quantify **heat flow** in terms of the dissipative dynamics of the open system

Application to Classical Gravitating systems, or with a quantum field

A. Laws of motion

1) near-uniformaly accelerated observer (Raval Hu and Koks PRD 97):
Need a confining potential to keep the particle in a near equilibrium conditon.

2) Gravity as entropic force: a bona-fide NEq treatment

B. Law of universal attraction – Poisson's equation. Gravitational potential. Then onto Einstein equation, NEq derivation.

C. BHs in finite temperature quantum field

- Hawking and Page (1982) AdS-Schwarzschild Phase Transition: Nucleation of black hole from hot AdS space
- Whiting and York (1987) Hot Schwarzschild BHs

This is actually the easier problem! ☺ Hopefully Yigit and I will get some meaningful results in the coming months.

Part IV: 4^{th} level: Emergence: processes and mechanisms

Emergence vs Reduction

- Not a strange new concept. Prevalent in condensed matter physics, biology
  It is observed to be more commonly instrumental in nature than the simpler (simplistic) **induction- reductionist view:**

E.g., **TOE!** If we knew all the elementary particles and their interactions, we could deduce everything in the physical world. QCD→nuclear physics,

QED → atomic, String → QG; physics → chemistry → biology, etc.

- In reality, there are new EMERGENT rules/laws (of organization, forms) and new modes of interactions and dynamics at every level of structure.

  “More is different!” (Anderson 1971)

  Progress in particle physics needs ideas from CMP (e.g., symmetry breaking)

- In truth these two aspects are always present in our quest to understand nature: **Elementary at low energy (resolution) is composite at higher energy (resolution).** For few body systems it is easy to construct models but the real world is governed by many body interactions. (Make nucleons from quark-gluon)

  Equally challenging both ways. (Molecular dynamics from hydrodynamics) More difficult to unravel, but that is what we’ve been doing in physics for centuries.

Emergence: Deductive versus Non-Deductive

Emergent behavior of macroscopic structure which **can or cannot** be deduced from microscopic structure and dynamics.

Deductive – Predictive

Hydrodynamics from kinetic theory from molecular dynamics.
-- But not always easy e.g., Turbulence.
-- Reverse is always more difficult.

Non-Deductive – **Un** (or not easily) **predictable from substructure / subdynamics**: e.g., Quantum Hall effect. Only after its discovery can one construct theories to `deduce'.

Of course, it depends on whether one can find the rules of emergence to deduce or predict. But how are those rules related to those of their substructure and dynamics, given there are possibly infinite of them?

--- gauge hierarchy problem, effective field theory, constituent vs collective.

Emergent Spacetime

- Spacetime emergent from `matter' – geometric structure deductible from interactions of sub-structural constituents.
  -- *Sakharov's* ***`metric elasticity'***,
  *spurred `induced gravity' (*Adler, Zee *et al, not successful).*

E.g., Build up lattice or condensate from atoms. Large scale features like crystals or elasticity can have nice geometric depictions,
but that fails for the substructures.

Derive hydrodynamics – thermodynamics from molecular dynamics. Hydrodynamic equations of motion, thermodynamic laws.

- Spacetime is a derived construct, manifold is a representation of the resultant large scale structure of many (likely strongly interacting) constituent particles – *strings, loops, spin-nets.*

- *HOW are they organized? How do they manifest collectively?*

EG: Top-down: Micro to Macro

Difficulties in top-down:

[tasks of string theory/ loops /spin-nets]

The micro constituents are believed to be known, need to get the macro limits -– Here we are dealing with deductive-predictive theories.

Still, not an easy treat.

A. For nondeductive emergent behavior, even micro → macro / sub → super structure is difficult, bordering on impossible

Need to Deal with Strongly Interacting and Correlated Systems

B. For deductive emergent behavior, path could be tortuous,

- Usually encounters **nonlinear interactions in strongly correlated systems.**

- Need to identify collective variables at successive levels of structure. Cumbersome to deduce m- from μ-dynamics (e.g., intermediate between μ (molecular) and M (hydro) are kinetic variables. Use maximal entropy laws at stages – but how are they related to each other, becomes maximal when?)

And, **nonlocal properties** can emerge. Very involved,

- requires not just hard work of deduction from one level, but new ideas at each level. Interesting challenge.

Micro locality =/= Macro locality

same for molecular-hydrodynamics and for quantum gravity

Example: in **loop quantum gravity**, a **weave state** is a kinematical state designed to match a given slowly varying classical spatial metric. [Ashtekar, Rovelli, Smolin 92]

The concept of **quantum threads** (spin-network) **weaved into a fabric** (manifold) of classical spacetime already **tacitly assumes a particularly simple kind of μ-M transition**, where there is a simple correspondence, or even equivalence, between **locality at the micro AND the macro levels**.

This is not the case for even simple examples of emergence like molecular to hydro- dynamics.

Very different **sense of locality** at the level of M theory for **string theory** or simplices for **dynamical triangulation** versus sense of locality in our macroscopic spacetime, presumably emergent.

<< nonlocal weave states >>

leave marks on the fabrics of spacetime

- **Bombelli** [gr-qc/0101080]; **Bombelli, Corichi and Winker**, gr-qc/ 0409006] use combinatorial methods to turn random weave (micro) states into (macro) states of spacetime manifold.
- **Markopoulou & Smolin** [gr-qc/0702044] recently pointed out:

  \- most weave states including Bombelli et al's assume that these weave states all satisfy an unstated condition of locality (edges connect two nodes of metric distance ~ Planck length)

  \- there are plenty of weave states which do not satisfy this condition: **existence of nonlocal weave states**.
- **Question**: How does one weave from these nonlocal micro states a fabric (manifold) with the familiar macroscopic locality?

  Fotini & Lee's answer : Disordered locality can be tolerated, even useful in the production of dark energy.

My attitude:

Take this **inequivalence of micro and macro locality** seriously. This is often a rule rather than an exception. We need to depart, even radically, from familiar concepts in our macro world. There is **new physics** to be uncovered**!**

[A good example: Recent discoveries that basic laws of non-equilibrium thermodynamics (like 2nd law) can be understood or derived from chaotic dynamics -- Gaspard, Dorfman et al]

Our conception and construct of the macro world may not bear any resemblance to the micro world.

- **(Non) locality at one level may have little to do with (Non) locality at other levels.**
- **The easy way of $\mu \rightarrow M$ (weaving) or $c \rightarrow Q$ (quantizing) may not be the true way.**

Three Senses of Emergence

1. Emergence in the sense of **manifestations**:

- Different manifestations at different layers of structures and interactions.
- Requires the identification of the range and precision of measurement, interface with an observer.
- Degrees and variety of coarse-graining, stability and robustness of stable structures. Hierarchical structures

2. Emergence in the sense of **conditioning** or control :

Adaptation and selection through interaction with the system's environments. E.g., Biological evolution

3. Emergence in the sense of "**dynamics"** (not time evolution, 'updates'): Self-organization. Growth and form from simple rules like cellula automata; driven diffusive systems; role of fluctuations in the genesis of new forms.

Sense of Time in Emergence

Relevance of time is in its ordering function.

Sequencing from interactions (steps in CA).

- Conjunction rules produce sequences
- Energetics of phase transition a la free energy density functional F (T): describes critical phenomena, not critical dynamics
- Fluctuation triggers instability of system, produces sense of evolution, but often a random process with bias.

No sense of direction yet. `Arrow of time' comes later with conditioning (environment or observer's range) or sequencing of biased random processes

Thank You
for your attention!

If you find

- My presentation unsophisticated to be worthy of the QG
- the way I render the issues too pedantic, or
- my questions trivially annoying.

My sincere apologies!

Hopefully this will stimulate some good debate (roaring protests) in the discussion sessions.