The gravitational arrow of Time

(joint work with J. Barbour and F. Mercati: PRL 113 (2014) 18, 181101)

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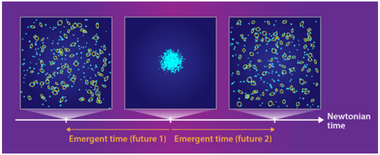

Problem of the arrow of time

CPT theorem:

laws of physics are *invariant* under simultaneous operation of time-reversal, charge conjugation and spatial inversion

Problem of arrow of time

The notions of

particle	vs.	antiparticle,
left handed	vs.	right handed

are conventional choices. We make these choices by fixing local relational conventions within the universe.

E.g. we call the lepton in local chemistry ”electron”.

⇒ Why do we experience time as moving forward?

Two proposals for arrow of time

Thermodynamic arrow of time

Second law: ”entropy never decreases” (in a large enough system)

Second law of thermodynamics appears to be *universally* valid.

⇒ arrow of time as the direction of increasing entropy

Records of the past (will become gravitational arrow of time)

Idea: We remember the past because there are local records

E.g. fossils, history books, recorded measurements on hard drive, state of our brain, ...

⇒ arrow of time as direction of generation of complexity

complexity = approx. measure for amount of local records

(I will argue that this is the fundamental arrow of time.)

Opposing uses of Information

Thermodynamic arrow of time

$$S = \ln(\text{number of microstates compatible with macrostate})$$

i.e. evolution from max. info about microstate to decreasing info

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requires past hypothesis: ”very special initial state of the universe”

⇒problems:1. arrow of time not explained, only postulated

2. initial cond. for universe is extremely fine-tuned

Records of the past approach

evolution from no (few) local info about past to increasing info

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does **not** require past hypothesis

⇒ has potential to solve fine-tuning problem

Objective of this talk

1. provide a physical framework for records approach
2. give concrete example (gravitational arrow of time)
3. show spontaneous emergence of thermodynamic arrow of time

and thereby solve the fine-tuning problem (in the toy model)

Framework: Physics is evolution of relational d.o.f.

Common objection:

"relational yes,
but GR teaches physics is events in spacetime not evolution..."

Shape dynamics description of Einstein gravity

- implements relational principles for frame and scale
- describes gravity as evolution of spatial conformal geometry
- local scale and duration are "experienced quantities"

  (i.e. weak matter fluctuations provide clocks and rods that experience scale and duration)

⇒ spacetime is an effective description of weak fluctuations

importantly: SD disentangles physical from gauge d.o.f.

Toy model: Newtonian N-body problem (as Newtonian limit of SD)

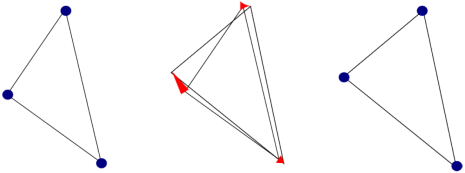
Relational prerequisite: No background structure

No coordinate origin, no frame, no scale and no duration:

$\Rightarrow$ $\vec{P} = 0$, $\vec{J} = 0$ and $E = 0$.

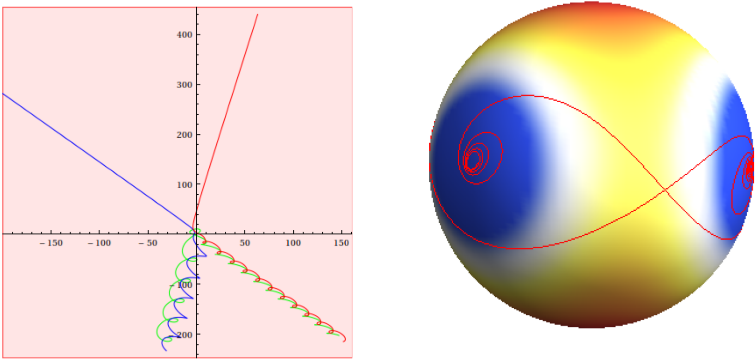
(this system is completely describable by internal relations)

Example: Newtonian 3-body problem



change generated by: $H = \ln\left(\frac{T_{sh}(p_\theta,p_\phi)+\lambda^2}{V_{sh}(\theta,\phi)}\right)$.

Relation of descriptions



left: Newtonian description of 3-particle trajectories
right: Shape space with the same solution

Description of general N-body solution (assuming $E = 0, \vec{J} = 0, \vec{P} = 0$)

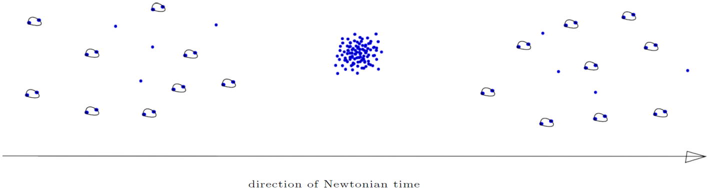
Generic late time behavior

- system fragments into subsystems

  centers of masses separate asymptotically linearly

  subsystem expansion is bounded by $O(t^{2/3})$
- subsystems will consist of clusters

  clusters remain bounded by (for all t)
- the time-reverse is true for very early times
- generic state at moment of minimal expansion (midpoint)



Subsystems provide phys. clocks, rods and records

Generic subsystem for $t \to \infty$

- develops asymptotically conserved quantities (records):

$E(t) = E^\infty + O(t^{-5/3})$, $\vec{J}(t) = \vec{J}^\infty + O(t^{-2/3})$ and $\vec{X}(t)/t = \vec{C}^\infty + O(t^{-1/3})$.

Dynamically stored information $I(t)$

$I(t)$:=number of bits $(E_1, \vec{J}_1, \vec{C}_1, ...)$ that remain unchanged

- $I(t)$ grows monotonically
- is a measure of locally stored information

$\Rightarrow$ deduce arrow of time from growth of $I(t)$

Problem: $I(t)$ is teleological (not useful)

Example: Kepler pair

2-body clusters = Kepler pairs

- are abundantly generated by generic initial condition
- Kepler's third law becomes increasingly accurate
  - $\Rightarrow$ orbital period T becomes stable
  - $\Rightarrow$ emergent local units of time
- aphelion distance $|\vec{A}|$ becomes increasingly stable
  - $\Rightarrow$ emergent local unit of length
- asymptotic $\vec{J}$ and $\vec{A}$ define increasingly stable local frame

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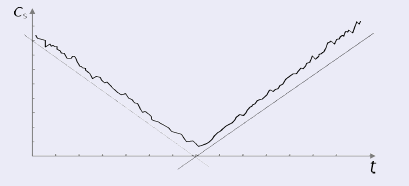
local units become increasingly compatible
(i.e. their ratios become asymptotically fixed)

$\Rightarrow$ spontaneous emergence of Newtonian spacetime
(i.e. local units can describe global Newtonian spacetime)

Complexity as an estimate for stored information

We want a simple estimate for abundance of local information

Complexity on N-body shape space $C_{sh} = -V_{sh} = l_{rms}/l_h$



- $l_{rms} = 1/M \sqrt{\sum_{a<b} m_a m_b \, r_{ab}^2}$ (dominated by large distances)
- $l_h = M^2 \left(\sum_{a<b} m_a m_b / r_{ab}\right)^{-1}$ (dominated by short distances)

Properties of C_{sh}

- measures number subsystems/clusters and their isolation
- is defined on shape space (relational quantity)

$\Rightarrow$ Gravitational arrow of time = dir. of growing complexity

Midpoint rather than initial condition

One past - two futures scenario

• gravitational arrow of time point away from the moment of minimal extension (midpoint)
• future points towards attractors on shape space with high complexity (a lot of locally stored information)

Generic solution on shape space

• attractors on shape space distort discussion of genericity
⇒ generic state on shape space only at midpoint
⇒ midpoint data is initial data for the two futures

Steps towards second law (I)

1. Midpoint state

slow particles in overdense regions contract, fast particles escape
⇒ the system fragments into "large" structures

2. Negative energy structures form

large structures with negative energy ⇒ system expands
⇒ the ratio $\frac{\text{typical structure size}}{\text{typical separation}}$ decreases

3. Small bound systems ("solar systems") form

small subsystems (e.g. Kepler pairs) provide local units
⇒ Units allow definition of structure pdf $f(\vec{q}, \vec{p})$
⇒ Boltzmann entropy $\int d^3p\, d^3q f \ln(f)$ becomes applicable

Steps towards second law (II)

4. Consider clusters as branch system

clusters evolve almost autonomously
rest of universe provides only units and reference frame
⇒ low entropy branch systems are formed

5. Antithermodynamic behavior of cluster

there is no equilibrium state for self-gravitating system
fast partilces evaporate while cluster contracts
⇒ cluster with low specific entropy is generated

6. Equilibration

non-gravitational forces become important for dense cluster
⇒ equilibrium state exists for dense cluster
⇒ low entropy initial condition will equillibrate

Effective second law

1. gravity generates branch systems with low initial entropy
2. rest of the universe provides units and reference frame for branch system
   ⇒ can define entropy for branch systems
3. branch systems with low entropy initial condition are generated by gravity
4. Second law starts:
   1. in branch system when non-gravitational forces become important
   2. when branch systems interact
5. interacting branch systems (e.g. collision of two clusters) starts with low initial entropy state
   (two separated clusters with definite energy and momenta) equilibrates to higher entropy state (one bigger cluster)

Secondary therodynamic arrow of time

1. generic mid-point condition leads to formation of branch systems
   ⇒ no fine-tuning (no past hypothesis!)
2. gravitational arrow of time prerequisite for generation of branch systems
3. thermodynamic arrow of time in generic branch system follows gravitational arrow of time

Summary

1. *Starting point:* The universe can be described as the evolution of relational degrees of freedom
2. *Problem:* The thermodynamic arrow of time proposal requires a fine-tuned initial state of the universe
3. There are attractors of dynamics of relational degrees of freedom
4. These attractors have high complexity (abundant local information)
5. Time-reversal symmetry spontaneously is broken to qualitative symmetry around midpoint
6. Generic midpoint conditions lead to gravitatinal arrow of time (away from midpoint), *without fine-tuning!*
7. Primary gravitational arrow of time induces secondary thermodynamic arrows of time