EmQM15 - Symposium Introduction
Jan Walleczek and Gerhard Grössing

Is the World Local or Nonlocal?
Towards an Emergent Quantum Mechanics
80 Years After EPR
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We start with a general orientation. Why ‘Emergence’?
What are the objectives of the symposium?
What to look out for during the next three days?
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Towards Unification?

Quantum Theory  ↔  Gravity – GRT

Emergence Theory?
Towards Unification?

Quantum Theory
- Indeterminism (non-causal)
- Non-Reality (micro-level)

Gravity – GRT
- Determinism (loc. causal)
- Reality (macro-level)

“There is no quantum world.”
Niels Bohr
Towards Unification?

**Quantum Theory**
- **Indeterminism** (non-causal)
- **Non-Reality** (micro-level)

**Gravity – GRT**
- **Determinism** (loc. causal)
- **Reality** (macro-level)

“Total Contradiction of Metaphysical Assumptions”
“The Measurement Problem!”
Towards Unification?

Quantum Theory

- **Indeterminism** (non-causal)
- **Non-Reality** (micro-level)

Gravity – GRT

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- **Reality** (macro-level)

“Total Contradiction of **Metaphysical Assumptions**”

“The Measurement Problem!”
Why ‘Metaphysics’ in ‘Quantum Physics’?

What are metaphysical assumptions?

- Metaphysical is neither “mystical” nor “irrational”.
- A metaphysical analysis refers to the first principles, the foundational physical assumptions, which inevitably underpin any scientific analysis of nature.
- Metaphysical assumptions essentially constrain the application of any mathematical theory to quantum phenomena!

“World View of the Scientist”
Towards Unification?

Quantum Theory

Indeterminism (non-causal)
Non-Reality (micro-level)

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“Total Contradiction of Metaphysical Assumptions”

“The Measurement Problem!”
Towards Unification?

- Quantum Theory
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“Emergent Gravity”
Emergent Space-Time

“Total Contradiction of Metaphysical Assumptions”
“The Measurement Problem!”
Towards Unification?

David Gross (2012):
“Many of us are convinced that space is an emergent, not fundamental concept. We have many examples of interesting quantum mechanical states, for which we can think of some (or all) of the spatial dimensions as emergent. Together with emergent space, we have the emergent dynamics of space and thus emergent gravity.”

“But it is hard to imagine how time could be emergent? How would we formulate quantum mechanics without time as a primary concept? Were time to be emergent, our understanding of quantum mechanics would have to change.”

Towards Unification?

Emergent Quantum Mechanics (EmQM)

Quantum Theory

Indeterminism (non-causal)
Non-Reality (micro-level)

Gravity – GRT

“Emergent Gravity” Emergent Space-Time

Determinism (loc. causal)
Reality (macro-level)
Towards Unification?

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Quantum Theory
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“Emergent Gravity” Emergent Space-Time
Towards Unification?

Emergent Quantum Mechanics (EmQM)  
Quantum Theory

“Determinism” (“causal”)  
Reality (micro-level)

Gravity – GRT

“Emergent Gravity”  
Emergent Space-Time

Determinism (loc. causal)  
Reality (macro-level)

“Total Contradiction of Metaphysical Assumptions”
Towards Unification?

Emergent Quantum Mechanics (EmQM) → “Emergent Gravity”

Quantum Theory

“Determinism” ("causal")
Reality (micro-level)

Gravity – GRT

Determinism (loc. causal)
Reality (macro-level)

“Less Contradiction among Metaphysical Assumptions?”
“Resolving the Measurement Problem?”
Towards Unification?

Emergent Quantum Mechanics (EmQM)

Quantum Theory

Emergent Space-Time

“Emergent Gravity”

Gravity – GRT
Towards Unification?

Emergent Quantum Mechanics (EmQM)  
Quantum Theory

“Emergent Gravity” Emergent Space-Time  
Gravity – GRT

?
Towards Unification?

Emergent Quantum Mechanics (EmQM)  "Emergent Quantum Gravity?"

Quantum Theory  "Emergent Gravity" Emergent Space-Time

Gravity – GRT

What is “Emergence”? 
What is “Emergence”? 

Complexity Theory
Chaos Theory
Self-organization Theory
Nonlinear Dynamics
Fractal Set Theory
Cellular Automata
Synergetics

“Emergent Events” are characterized by:

“Sensitive Dependence on Initial Conditions”

“Global Order from Local Randomness”

“Indefinite to Definite State Transition”
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“Sensitive Dependence on Initial Conditions”

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What is “Emergence”? “Emergent Events” are characterized by:

“Non-Equilibrium Thermodynamics”

“Self-Referential, Recursive processes”

“Computationally non-reducible processes”
What is “Emergence”?  

“In-Principle Unpredictability of Individual Events” 

**Infinite** amount of computational resources would be required! 

“Determinism without Pre-Determinism” 

“Emergent Events” are characterized by: 

“Non-Equilibrium Thermodynamics” 

“Self-Referential, Recursive processes” 

“Computationally non-reducible processes”
What is “Emergence”?  

Quantum Mechanics is incompatible with the proposition that measurement outcomes have pre-determined values independent of actual measurement.

Emergent Quantum Mechanics (EmQM) agrees with Orthodox Quantum Mechanics!

“Determinism without Pre-Determinism”

EmQM: Measurement in emergent processes describes the transition of an indefinite ontic structure (IOS) into a definite ontic structure (DOS).
What are “Emergent Events/Structures”?  
[Self-Organizing Relational Dynamics]
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“Weak or Epistemic Emergence” → “Theory Emergence” → BOTTOM-UP CAUSALITY

Emergent Macroscopic Structure

Global → Macroscopic

Local → Microscopic

“SUPERVENIENCE”: Global, emergent structures SUPERVENGE on local processes described by reductionism.
What are “Emergent Events/Structures”?
What are “Emergent Events/Structures”?

NOT Emergence! (e.g. Aristotelian formal causation) → “Scientifically Untenable”

Emergent Macroscopic Structure

Global

Local

Macroscopic

Microscopic

TOP-DOWN CAUSALITY
What are “Emergent Events/Structures”?

“Strong or Ontic Emergence” → “Physical Emergence”

Emergent Macroscopic Structure

Global

Local

Macroscopic

Microscopic

TOP-DOWN CAUSALITY + BOTTOM-UP CAUSALITY

RELATIONAL CAUSALITY
What are “Emergent Events/Structures”? 

“Strong or Ontic Emergence” → “Physical Emergence”

RELATIONAL CAUSALITY

Information

Causality

Global

Macroscopic

Local

Microscopic

BOTTOM-UP CAUSALITY + TOP-DOWN CAUSALITY

What are “Emergent Events/Structures”??
What are “Emergent Events/Structures”? 

“Nested Hierarchies” of emergent states connecting different organizational levels 

“Fractal Universe” 

Scale-free 
“Relational Continuum”
An Emergent Quantum Structure?

An Emergent **Quantum Structure**?

"Strong or Ontic Emergence" → "Quantum Emergence" → RELATIONAL CAUSALITY

**Quantum State** → Emergent Quantum Structure

Sub-Quantum MEDIUM? → "Microscopic" → "Sub-Microscopic Interactions"

Computationally Irreducible ("probabilistic") yet Deterministic Processes
An Emergent **Quantum Structure**?

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“Strong or Ontic Emergence” → “Quantum Emergence”

Quantum State → Information

Causality

Sub-Quantum MEDIUM?

“Microscopic”

“Sub-Microscopic Interactions”

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Computationally Irreducible (“probabilistic”) yet Deterministic Processes

RELATIONAL CAUSALITY
An Emergent *Quantum Structure*?

"Quantum Emergence"

Information

???

Causality
An Emergent Quantum Structure?

Towards a “New Causality”?  

Nonlocal Causality  
e.g., Bohm/Hiley, Bell, Maudlin.

Quantum Causality and  
Indefinite Causal Order:  
“We have only begun to scratch the surface of quantum causality. The deeper we dig the more questions arise.”  
Časlav Brukner  

Time-symmetric “Causality”  
e.g., Aharonov/Tollaksen

Relational Causality  
e.g., Walleczech/Grössing

What if causality is not fundamental?
We start with a general orientation. Why ‘Emergence’?

What are the objectives of the symposium?

What to look out for during the next three days?
EmQM15 Symposium Objectives

1. Is the world **local** or **nonlocal**? What is nonlocality?

2. If nonlocal, i.e., superluminal, influences exist, then why can’t they be used for **superluminal signalling** and communication?

3. How is the role of the **scientific observer/agent** to be accounted for in realistic approaches to quantum theory?

4. How could recent developments in the field of **space-time as an emergent phenomenon** advance new insight at this research frontier?

5. What **new experiments** might contribute to new understanding?
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5. What **new experiments** might contribute to new understanding?
What is “Nonlocality”?

Can quantum-mechanical description of physical reality be considered complete?

A Suggested Interpretation of the Quantum Theory in terms of “Hidden” Variables.

Bell (1964) Physics 1, 195-200.
On the Einstein Podolsky Rosen Paradox.
What is “Nonlocality”?


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What is “Nonlocality”?

Bell (1964) Physics 1, 195-200.
On the Einstein Podolsky Rosen Paradox.

**Nonlocality**: “… means that what you do here has immediate consequences in remote places.”

John S. Bell, Interview at CERN in 1990

What the exact nature is of this “immediate consequence” of nonlocality is what is under dispute ever since EPR (1935)!
What is “Nonlocality”?  

Can quantum-mechanical description of physical reality be considered complete?

EPR (1935) had concluded that ‘orthodox quantum theory’ must be incomplete, because otherwise the world would actually have to be “nonlocal”! [“Violation of local realism!”]

Einstein rejected what he called “spooky action at-a-distance”, or, as Bell said later, the idea that actions here can have “immediate consequences” on remote places!
What is “Nonlocality”? Bohr and Einstein Agree!

“There cannot exist “real nonlocal influences”, i.e., ‘intrinsic, or objective, nonlocality’!”
What is “Nonlocality”?  

A Suggested Interpretation of the Quantum Theory in terms of “Hidden” Variables.

In 1952, along comes David Bohm, and publishes an alternative approach towards accounting for quantum correlations based upon the “forbidden idea” of “intrinsic, or objective, nonlocality”.

In 2015, 80 years after EPR, we call such nonlocal quantum theories ontological or ψ-ontic quantum theories.
What is “Nonlocality”?

A Suggested Interpretation of the Quantum Theory in terms of “Hidden” Variables.

Is the world local or nonlocal?

According to ψ-ontic, realist, quantum mechanics, the world is nonlocal.

According to Bohm’s theory, the world is not “intrinsically random” but “fundamentally interconnected”.
What is “Nonlocality”?

According to the textbook, operationalist (Copenhagen, epistemic, etc.) interpretation of quantum mechanics, what is represented by “nonlocality”?  
Quantum Theory

Orthodox Quantum Mechanics

“Operationalist Quantum Mechanics”

Indeterminism (non-causal)
Non-Reality (micro-level)

e.g., Copenhagen Interpretation (Bohr)

“There is no quantum world. There is only abstract quantum physical description.”

“It is wrong to think that the task of physics is to find out how nature is. Physics concerns what we can say about nature.”
What is “Nonlocality”? 

According to the textbook, operationalist (Copenhagen, epistemic, etc.) interpretation of quantum mechanics, what is represented by “nonlocality”? 

**“Operationalist Quantum Theory”:** Negative Definition

“Nonlocal correlations are correlations that cannot be explained by a local realist theory”.

**“Realist Quantum Theory”:** Positive Definition

“Nonlocal correlations are correlations that can be explained by a nonlocal realist theory”.

Two Ways of Interpreting Bell’s Theorem (with “free choice”) [vis-a-vis ‘Nonlocal Correlations’]

**Operationalist Quantum Theory**  
⇒ LOCALITY + REALITY  
⇒ LOCALITY + UN-REALITY  
   Intrinsic Randomness  
   Non-Causal Subjectivity

**Realistic Quantum Theory**  
⇒ LOCALITY + REALITY  
⇒ NON-LOCALITY  
Einstein’s “spooky action at-a-distance”

Two World Views

The world is **local** and irreducibly **random**!  
“Locality without Causality”

The world is **nonlocal** and deeply **interconnected**!  
“Causality without Locality”
**Two Ways of Interpreting Bell’s Theorem** (with “free choice”)

[vis-a-vis ‘Nonlocal Correlations’]

<table>
<thead>
<tr>
<th>Operationalist Quantum Theory</th>
<th>How could “free will” prevail in a world that is “intrinsically random”?</th>
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<tbody>
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**Two World Views**

The world is **local** and irreducibly **random**!

“Locality without Causality”

The world is **nonlocal** and deeply **interconnected**!

“Causality without Locality”
An Open Question….

**Operationalist** Quantum Mechanics

and/or

**Realist** Quantum Mechanics

Objective
The EmQM15 Symposium “invites the open exploration of the quantum state as a reality.”
FAREWELL TO REALITY:
How Modern Physics Has Betrayed the Search For Scientific Truth
Jim Baggott (2013)
An Emergent *Quantum Structure*?

Towards a “New Causality”? Towards a “New Reality”?  

Nonlocal Causality  
e.g., Bohm/Hiley, Bell, Maudlin.

Time-symmetric “Causality”  
e.g., Aharonov/Tollaksen

Relational Causality  
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Causality

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John Fetzer and David Bohm at the Fetzer Institute (ca. 1990)

[Photo by courtesy of Jeff Tollaksen]
END