Developing an Emergent Perspective: from Quantum Physics to Complex Adaptive Systems to Science Education

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- Emergence
- Gateways to Emergence in Quantum Matter
- An Emergent Perspective on Complex Adaptive Systems
- Emerging Societal Challenges
- Science Education and Engagement

Emergence is a bulk property. When we bring together the component parts of any system, be it people in a society or matter in bulk, the behavior of the whole is very different from that of its parts, and we call the resulting behavior *emergent*.

More turns out to be not only different, but unpredictable from a knowledge of its component parts and their interactions

It follows that we need to rethink reductionism* as the fundamental paradigm for understanding phenomena in science or in society

***according to Wikipedia, reductionism can either mean (a) an approach to understand the nature of complex things by reducing them to the interactions of their parts, or to simpler or more fundamental things or (b) a philosophical position that a complex system is nothing but the sum of its parts, and that an account of it can be reduced to accounts of individual constituents**

The dream of some twentieth century reductionists-discovering a "Theory of Everything" is hollow; we know the simple equations that govern our world, but find these are useless in telling us about the emergent behavior we see all around us, whether we are working on a problem at the frontiers of science, cooking a meal, or seeking to understand and change societal behavior.

- **From the discovery of novel ordered states in quantum matter to eggs cooking, birds flocking, collective behavior in ant colonies, the development of consciousness in infants, the latest measurements on the early universe, global climate change, or our current global economic meltdown — emergence is all around us.**

An Emergent Perspective

What replaces the reductionist dream? The short answer is an *emergent perspective*—*a focus on using experiment and observation to identify the collective organizing concepts that characterize or bring about emergent behavior.*

These organizing principles, not the individual constituents, are the *gateways to emergence* one needs to build a model that explains emergent behavior.

The chef cooking eggs has found through experiment the organizing principles at work that change their state from liquid to semi-solid-(over- easy, shirred, scrambled, omelet, soufflé, fritatta…)-and has learned that the pan, the butter, the temperature of the stove top or oven, the added ingredients, the altitude, and especially the chef—all play a role in determining the outcomes.

- **The physical scientist studying bulk matter identifies from theory and experiment the collective building blocks (effective fields, quasiparticles, collective modes, symmetry, broken symmetry, coherent and competing states, criticality, feedback, energy landscapes, frustration, protected (scaling) behavior, etc.) that are candidate gateways to emergence in the system under investigation, and to understand their range of applicability.**

Some Quantum Matter Collective Concepts

Effective fields and effective interactions provide a gateway to emergent behavior in the form of collective behavior and quasiparticles

More is Different: In any many body system, a given particle, a, feels not only the influence of particle b, but the effective field it induces in all the other particles.

That field modifies the interaction between a and b, can give rise to collective behavior of the system as a whole (plasmons, zero sound,magnons…) and leads naturally to the idea of quasiparticles—particle a, plus the fields it induces that move with it

Electron density and spin density fluctuations often replace quasiparticles as the lingua franca

An emergent strategy for quantum matter

•focus on the experimental results--search for regularities (patterns, possible scaling behavior, etc…) in the experimental or observational data obtained by many different probes

***consult one's catalogue of organizing concepts and decide, at a qualitative level, on candidate organizing concepts that might be responsible for the most important experimental regularities**

***develop a phenomenological description that incorporates these organizing principles and links the results obtained using different experimental probes**

•only then put on a "reductionist" hat-- developing a candidate microscopic "theory" by proposing and solving a simplified "toy" model that embodies the candidate organizing principles.

Superconductivity- the ability of some metals at very low temperatures to carry current without any appreciable resistance was discovered in 1911 by Kamerlingh-Onnes. Their ability to screen out external magnetic fields was discovered in 1933 by Meissner. But despite the best efforts of Einstein, Bohr, Heisenberg, Landau, Feynman, Bardeen, et al, a microscopic theory was not developed until 1957 for this poster child for quantum emergence.

We now know that the gateways to the emergence of a superconducting state are: a macroscopically occupied single quantum pair state characterized by an order parameter and an effective quasiparticle interaction that is attractive, and that any toy model that contains these ingredients will yield quantitative results in agreement with experiment.

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The gateways to the microscopic theory

1950 A phenomenological theory of coherent superfluid motion and condensate order parameter fluctuations

1950 The sc transition temperature depends in a simple way on the isotopic mass

1954 A basic repulsion between electrons can turn to attraction in presence of the additional fields coming from quantized lattice vibrations (phonons)-the electronic waterbed

1956 A quasiparticle energy gap phenomenology ties together many existing experiments

1956 An attractive interaction between quasiparticles can lead to bound states or instabilities

Superconductivity is solved in 1957 by Bardeen. Cooper, and Schrieffer (BCS)

Schrieffer proposed a superfluid wavefunction that was based on the idea that in the presence of attraction pairs of quasiparticles of opposite spin and momentum would condense into a single quantum state

BCS then used this to describe excited quasiparticles with an energy gap and worked out the details of a toy model with results that explained existing experiments and predicted successfully the results of new ones

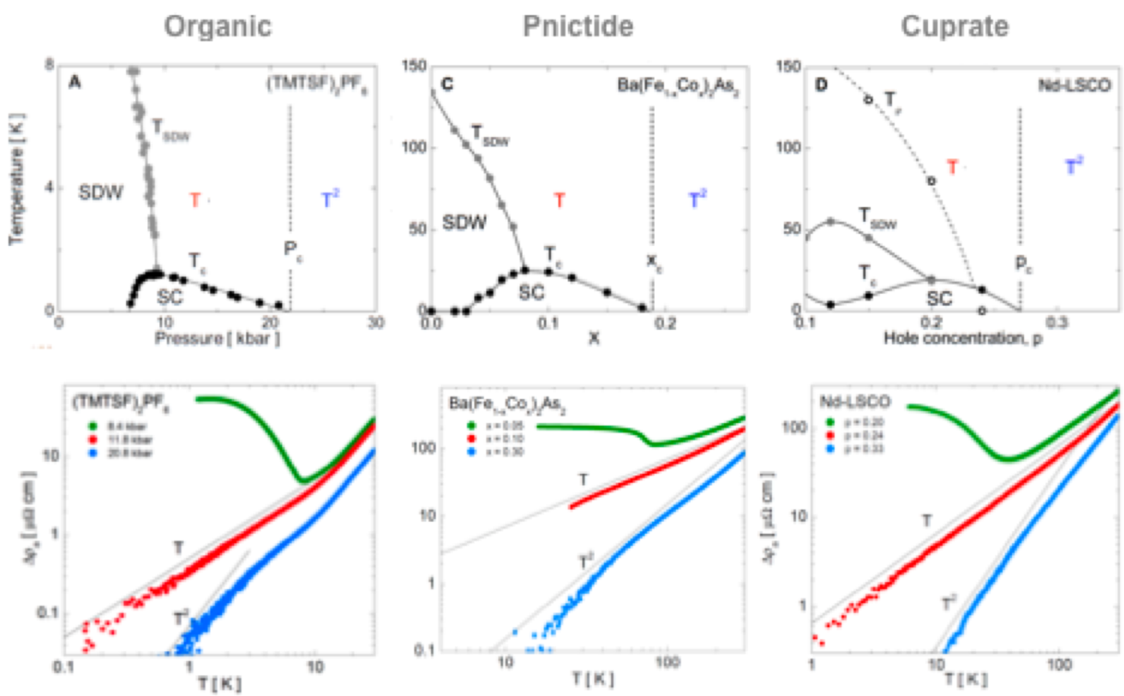
Lesson learned: Because the superconducting state is protected (its emergent behavior is independent of the details) this toy model with right ingredients led to a remarkably accurate description of emergent behavior using only three parameters

Fast forward to 2010: Novel Superconductors

Four families of unconventional superconductors have now been discovered, with remarkably similar "strange" normal state and sc state properties and sc transition temperatures that can far exceed those measured for conventional sc materials (T_C less than 25 degrees K)

Heavy electrons (T_C less than 18 K) $CeMIn_5$
Organics (T_C less than 12 Kelvin)
Cuprates (T_C less than 160 Kelvin) $YBa_2Cu_3O_4$
Pnictides (T_C less than 60 Kelvin)

The "SDW paradigm"



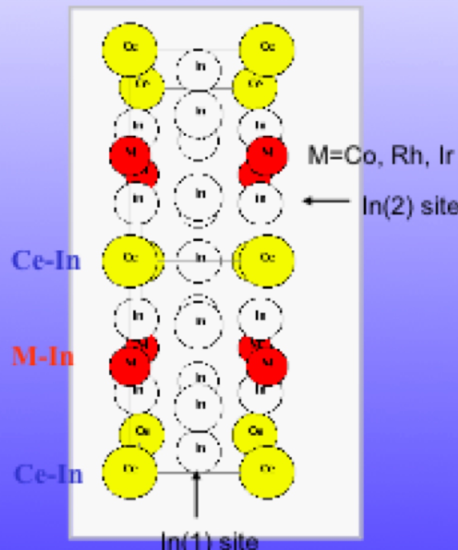
Doiron-Leyraud et al., arXiv:0905.0964

Fang et al., arXiv:0903.2418

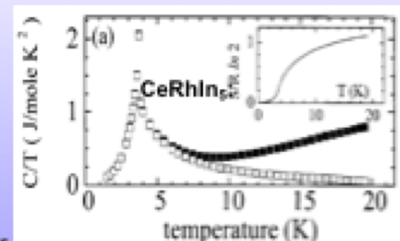
Daou et al., Nature Physics (2009)

115 Heavy electron materials

CeMIn$_5$

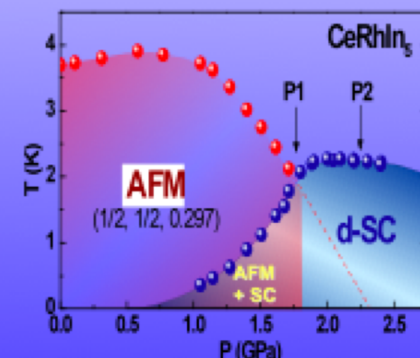


Petrovic et al. JPCM 13, (2001)



Hegger *et al.*, PRL 2000

LaRhIn$_5$:
γ=5.7 mJ/mol K^2
CeRhIn$_5$
γ (10K) ~ 200 mJ/mol K^2



Park *et al.*, Nature 2006

How to view these novel superconductors from an emergent perspective?

***Keep BCS theory as framework, but consider Superconductivity Without Phonons--new (non-phonon) glues as source of attraction and more complex condensates (order parameters) as consequence**

***Focus first on clues experiment (many new probes of emergent behavior) can provide and develop phenomenological description**

***Use effective fields to carry out toy model calculations of relative effectiveness of candidate glues**

Searching for new novel superconductors:
An emergent strategy

Follow the magnetism

Toy model calculations show nearly 2d behavior is better than 3d, and that antiferromagnetic fluctuations provide a better glue than ferromagnetic fluctuations

In existing novel superconductors there are two competing states-local (magnetic) and sc (itinerant) and sc appears optimum in vicinity of doping, pressure range at which locality emerges. Is this a guiding principle?

Complex Adaptive Systems (CAS)

***The first 8 years of SFI were devoted to CAS--complexity in all its various guises--with the hope of some that there might emerge a general theory of complexity, and the hope of many that metaphors or models developed for one kind of CAS might be applicable to another.**

***The 1993 SFI Conference, chronicled in Vol. 19 of the SFI series as Complexity: Metaphors, Models, and Reality", cast doubt on general theories and suggested that a path forward within a reductionist framework was not especially promising**

Since all CAS exhibit emergent behavior, is an emergent framework more promising?

First, let us agree that yesterday's "metaphor" is today's collective organizing principle or concept

Second, let us ask whether the emergent strategy developed for the study of quantum matter can translate to CAS

Third, if it does, is this now an appealing path forward for SFI?

A candidate emergent strategy for complex adaptive systems

•focus on the experimental results--search for regularities (patterns, possible scaling behavior, etc…) in the experimental or observational data obtained by many different probes

*consult one's catalogue of organizing concepts (can one borrow any from studies of matter?) and decide, at a qualitative level, on candidate organizing concepts that might be responsible for the most important experimental regularities

*develop a phenomenological description that incorporates these organizing principles and links the results obtained using different experimental probes

•only then put on a "reductionist" hat-- developing a candidate microscopic "theory" by proposing and solving a simplified "toy" model that embodies the candidate organizing principles

An emergent strategy for the ICAM and SFI communities to consider

Develop a "Gateways" Registry-a list of candidate organizing principles with examples of emergent behaviors to which these have been applied

Add to this registry by asking each workshop participant or seminar/colloquium speaker to do two things at the outset of her/his talk;

***Specify emergent behavior to be discussed, with references to experiments/observations that probe that emergent behavior**

***List her/his candidate gateways to that behavior**

Emerging Societal Challenges

For the citizen and world leader alike, an emergent perspective is essential as we confront emerging global challenges—climate change, our failed educational system, terrorism, our current global economic meltdown, etc. These are all caused by humans, and in searching for an appropriate emergent response, we properly begin by seeking to identify their origins in societal behavior.

But now there is a difference: their origins are many, not unique. Moreover, because feedback leading to non-linear behavior plays a significant role, these origins are both difficult to identify and nearly impossible to separate.

Armed with this emergent perspective, what is the right strategy ?

First, keep clearly in mind that *because emerging global challenges have no unique cause, it follows that there is no unique or even "best" solution to these.*

An emergent strategy for making progress means trying simultaneously many different partial solutions, inventing new institutions, and above all experiment, experiment, experiment, as we address candidate causes, hoping (and expecting) that in the process some of these experiments will work.

Next, an *emergent strategy* **typically includes recognizing that:**

***** *synergies between candidate solutions* **can accelerate progress, and priority should be given to those that offer promise of solving more than one problem at a time**

***** *behavior is a significant component of societal problems and their candidate solutions*

***** *behavioral change comes about through education,* **so** *education should play a significant role in every proposed solution*

******experimenting with new approaches and connecting the results* **can be accelerated by the using the vastly improved communication tools available through the internet.**

sharing "best practices" on the internet* **also enables local groups seeking change to become aware of the "best practices" developed elsewhere, and help them avoid "reinventing the wheel."

***pursuing candidate solutions will frequently require** *developing new institutions that are transdisciplinary and transprofessional*

Science Education and Engagement

Changing the landscape of education, including improving dramatically formal and informal science education at every level, may be the most difficult task we face

Teachers are key, but perhaps almost as important is the engagement of scientists in both formal and informal science education

What should be our goal?

Helping learners of all ages develop an informed perspective on science

For the non-scientist, developing an informed perspective does not mean receiving a scientific education, but rather an education about science— one that can lead to an understanding of the role played by scientific research in solving the global challenges we face today.

Some key ingredients for all of us in this room to consider are:

**enhancing and supporting the public engagement by scientists at every level from individual efforts to involvement in teacher, web, museum, and institution-based science educational programs*

**developing and enhancing teacher/scientist partnerships in the schools* *encouraging every major research institution to post on a web site links to its best SEE (science education and engagement) practices and to encourage active participation by its students, staff, and faculty in these SEE efforts*

making optimal use of the internet for both formal and informal science education

Because science education is global*, encouraging international SEE partnerships* such as GSEE (of which SFI and ICAM are founding partners) that develop and provide access to linked global libraries of teacher, web, and museum-based educational materials

An emergent SEE strategy can also include pursuing and finding synergies between some or all of the following initiatives:

***introducing middle school students to science by providing manuals about climate change and sustainable energy for middle-school teachers**

***providing new web-based training and toolkits for teachers and establishing a virtual laboratory that will allow students to do experiments remotely**

***developing mentoring programs at every level and using these to establish global scientist/teacher/community collaborations that bring to students in and out of the classroom the challenge and excitement of frontier research in science and society—topics that range from climate change to developing sustainable energy and the latest discoveries in living, soft, and quantum matter**

***encouraging the development of new interactive exhibits for existing on-line science museums, such as www.emergentuniverse.org**

*** developing and/or expanding on-line interactive exhibits based on existing physical exhibits at science museums and other institutions**

***establishing a global editorial board that will, in selected fields, review web-based public engagement materials as a first step toward establishing a linked global library of the best of teacher, web, and museum-based educational materials**

Eu.org went LIVE on Oct. 1, 2009!!

with 22 activities

- Home Page & Intro to emergence

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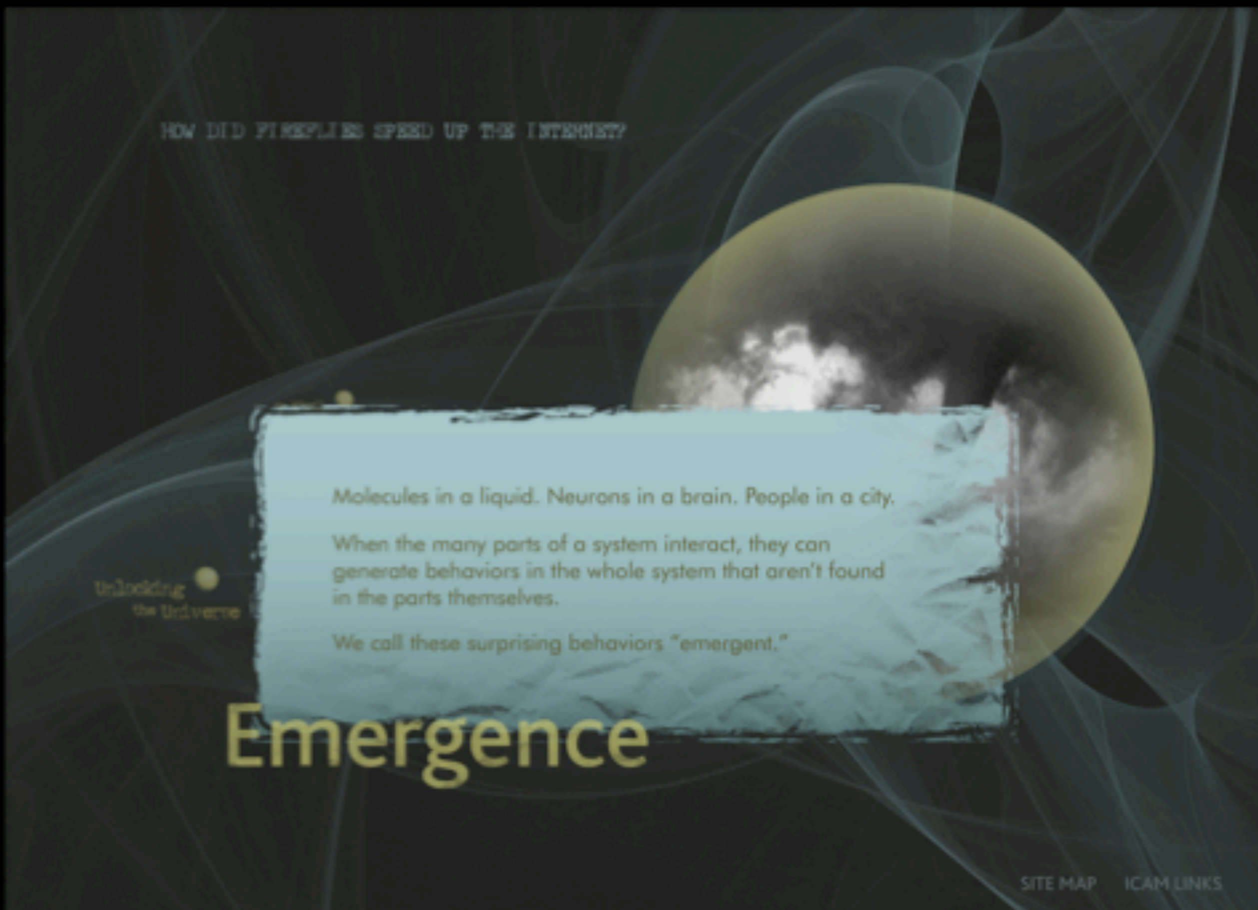

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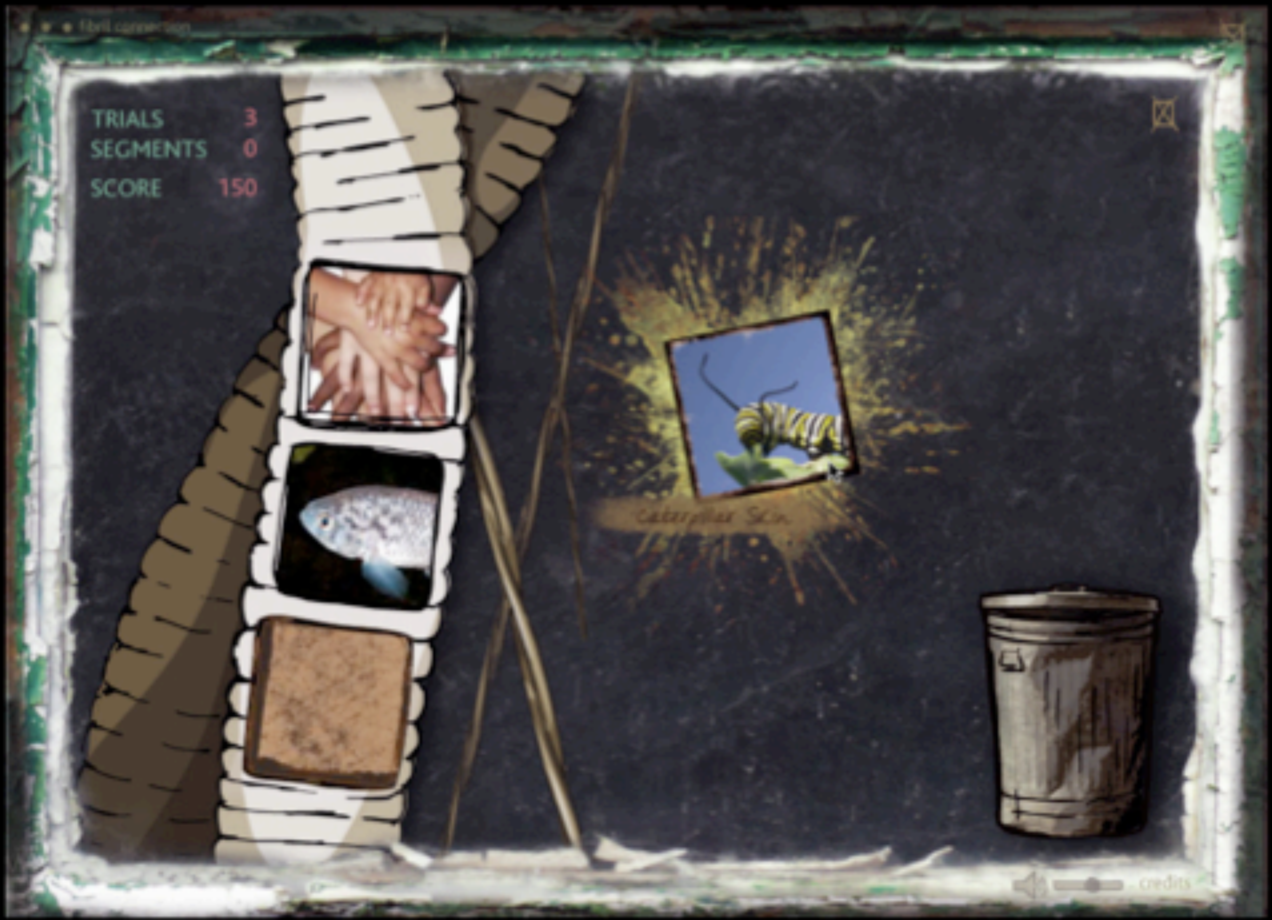

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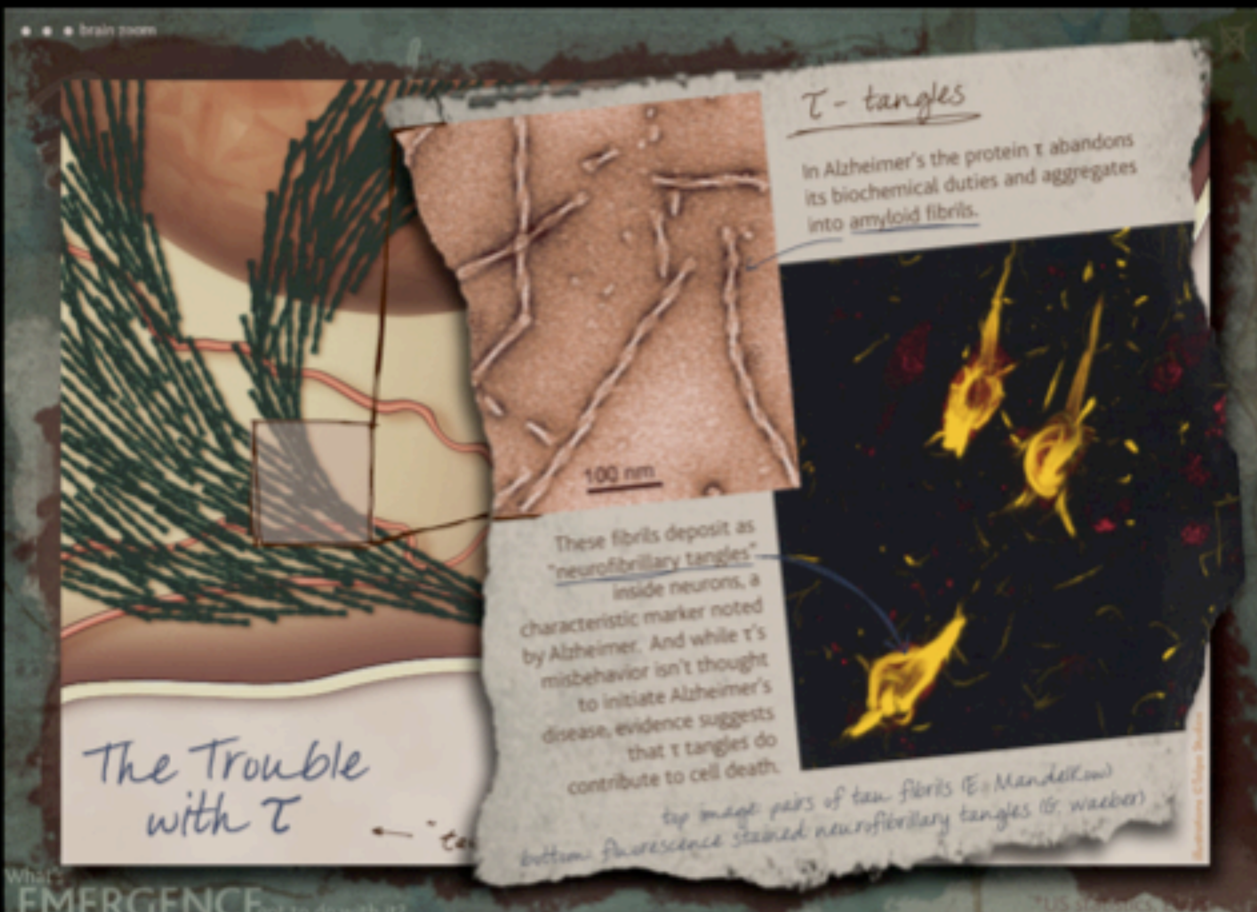

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Won *Best Male Choreography* at the *InShadow* Int'l Dance Film Festival, Lisbon