Making a Splash; Breaking a Neck: The Development of Complexity in Physical Systems

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Edgarton picture

summary of talk:

The fundamental laws of physics are very simple. They can be written on the top half of an ordinary piece of paper. The world about us is very complex. Whole libraries hardly serve to describe it. Indeed, any living organism exhibits a degree of complexity quite beyond the capacity of our libraries. This complexity has led some thinkers to suggest that living things are not the outcome of physical law but instead the creation of a (super)-intelligent designer.

In this talk, we examine the development of complexity in fluid flow. Examples include splashing water, necking of fluids, swirls in heated gases, and jets thrown up from beds of sand. We watch complexity develop in front of our eyes. Mostly, we are able to understand and explain what we are seeing. We do our work by following a succession of very specific situations. In following these specific problems, we soon get to broader issues: predictability and chaos, mechanisms for the generation of complexity and of simple laws, and finally the question of whether there is a natural tendency toward the formation of complex 'machines'.

who am I ?

A physicist and a mathematician.

I have worked on many different things in the almost 50 years that I have been a mathematical scientist but in recent years, I have worked mostly on problems related to our familiar world of fluids. That would includes clouds and waves, splashes and storms, sonic booms and the quiet ripples on ponds. My own work involves mostly working out the mathematical descriptions of things in fluids using pencil and paper and perhaps a computer. I do work closely with experimentalists who measure and photograph what happens in fluids.

There are three purposes for such work:

a. To demonstrate that these familiar phenomena can be understood and predicted and hence are not at all mysterious.

b. To train students to use their own minds to understand and predict within the areas in which they work and observe.

c. To develop tools and concepts which can be used in practical work with fluids.

References

This lecture is based in part upon: *Simple Lessons from Complexity*, N. Goldenfeld and LPK, Science 284 (1999).

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A Question

To start and organize any scientific work, it is often useful to think about the great questions that nature poses for us, and how they might be answered.

Why is the world so complicated?

One of the great concepts of my physics profession is the simplicity of the laws of physics. The equations for electricity and magnetism, or the ones for classical or quantum mechanics can be each be expressed in a few lines. Most often, physical laws are expressed in partial differential equations (PDE) which give precise predictions of time rates-of-change, in terms of rates-of-change in space.

The ideas which form the foundation of our world-view are also very simple indeed:

the world is lawful and the same basic laws hold everywhere and always. New domains of nature may require new laws, but all the different laws are consistent with one another.

Everything is simple, neat, and expressible in terms of everyday mathematics, either partial differential equations , or ordinary differential equations.

Everything is simple and neat--except, of course, the world.

Before understanding comes observation.....

Look at examples:

Different Types of Complexity

Simplicity. The same thing repeated again and again.. Esher’s framework picture

Some complexity, the same thing repeated with variations. The variations give Type I complexity

flow behind cylinder, estuary, cake of soap.

complexity in motion

Edgerton turbulence and splash

Type II complexity. A machine with many different parts each with a function to perform, each one set up to do that function.

mosquito

Words:

Complexity means that we have structure with variations.

Chaos means that there are many different variations and that it is hard to predict which one will come out in a given place and time

A Complex world is interesting

In a Chaotic world we do not know what is coming next

Let's Look at Dynamics

Our world is both Complex and Chaotic

Before understanding comes observation.....

Example: A drop falling into a glass of milk: Harold Edgerton--Inventor of Strobe Photography.

Picture 1. A splash. Edgerton had great trouble getting the picture. Every time it seemed to be different. Every time each point was different from the others.

Picture 2. Dynamics of Splash formation. Unexpectedly complex and structured. Basic Instability of pattern magnifies effect of small breezes at beginning and produces drops that come off at many different times. The technical word for this behavior is *chaos*. However, every drop looks the same as it separates. The technical word for this behavior is *universality*.

Picture 3. Edgerton

Picture 4. splash movie

First Interlude: Intelligent Design

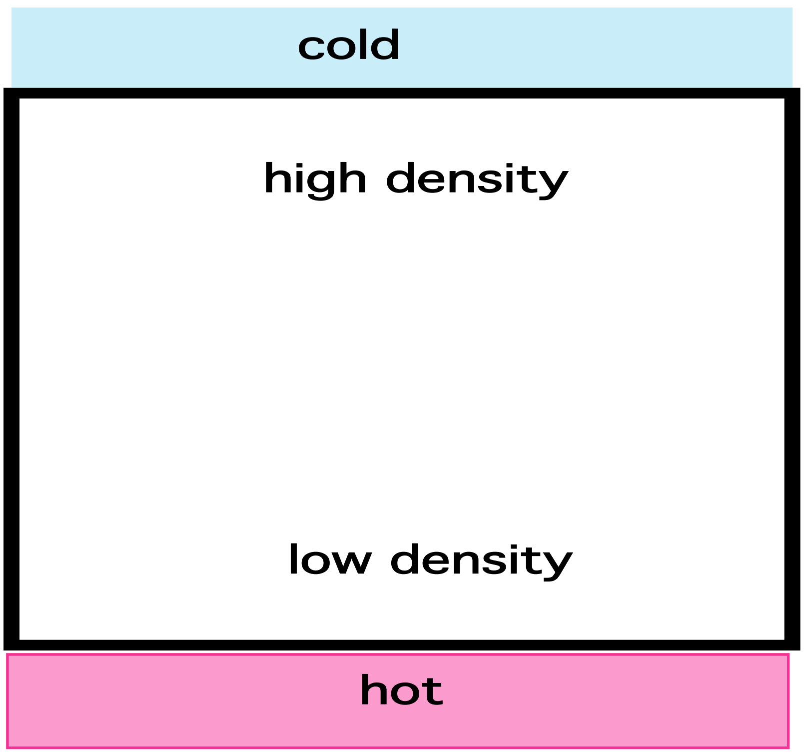
In the U.S., a political and intellectual discussion is going on concerning a point of view called Intelligent Design (ID). Its proponents argue that biological systems are too complex to have been the product of a natural evolution, Darwinian or otherwise, but instead are the result of a fashioning by some (super-) intelligent creator (or Creator).

The idea came from William Paley (1743-1805) who argued that the world contained things (like you and me) too complex to have arisen in any natural fashion. It has two main intellectual proponents today, M. Behe, a biochemist who cites the amazing complexity of biological things down to the level of a single cell and Bill Dembski, a philosopher and mathematician*, who argues that there are theorems which show that you cannot construct anything REALLY complex starting from only simple things. I sympathize with Behe's wonder in the observed world. More about Dembski anon. For now let's see how complex things happen.

* I was his thesis adviser for his math Ph.D..

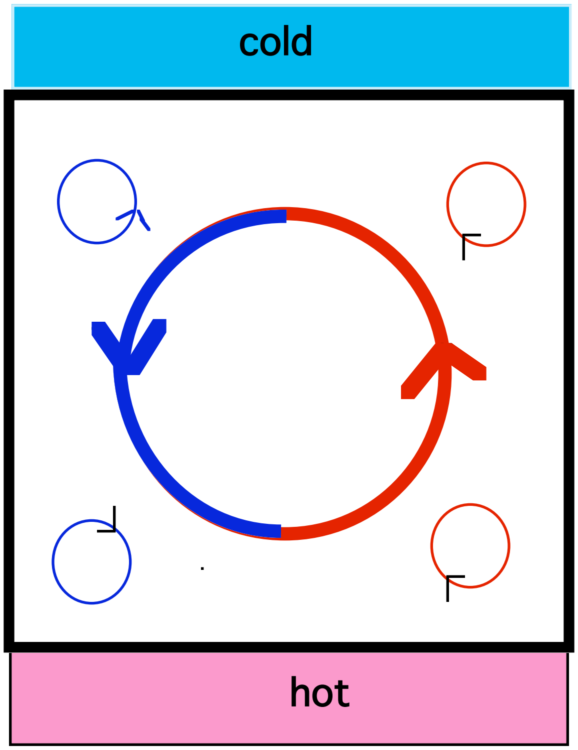
Observe Fluids Heated from Below

start from a box filled with fluid. A little heating of system from below causes no motion of fluid.



For small temperature differences nothing happens, but as this difference is increased we see an instability and the fluid starts moving

Ordered Motion



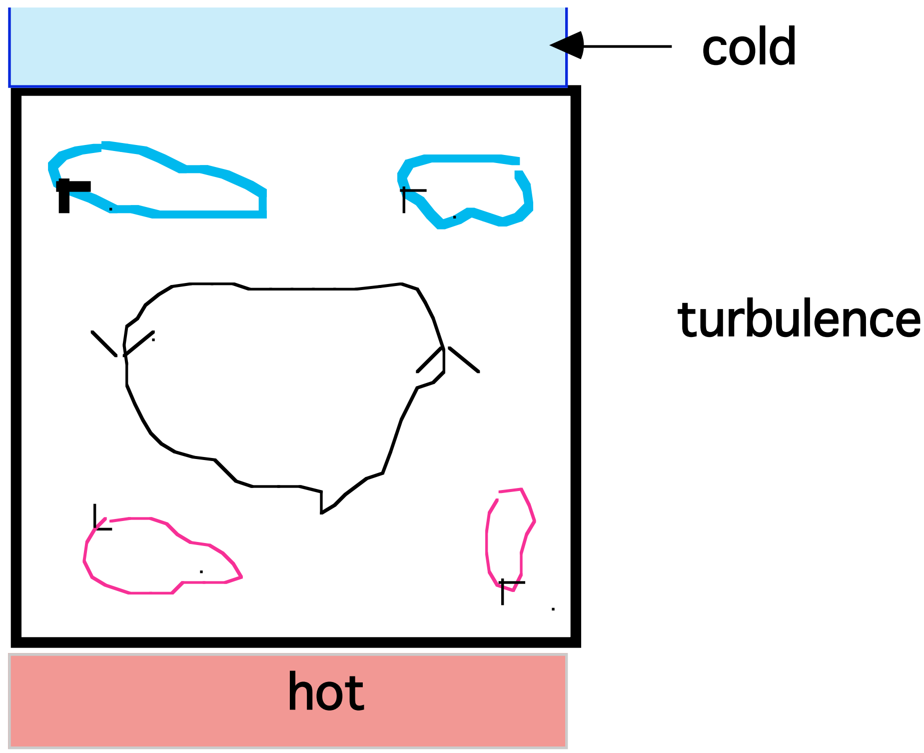
convection

More heating

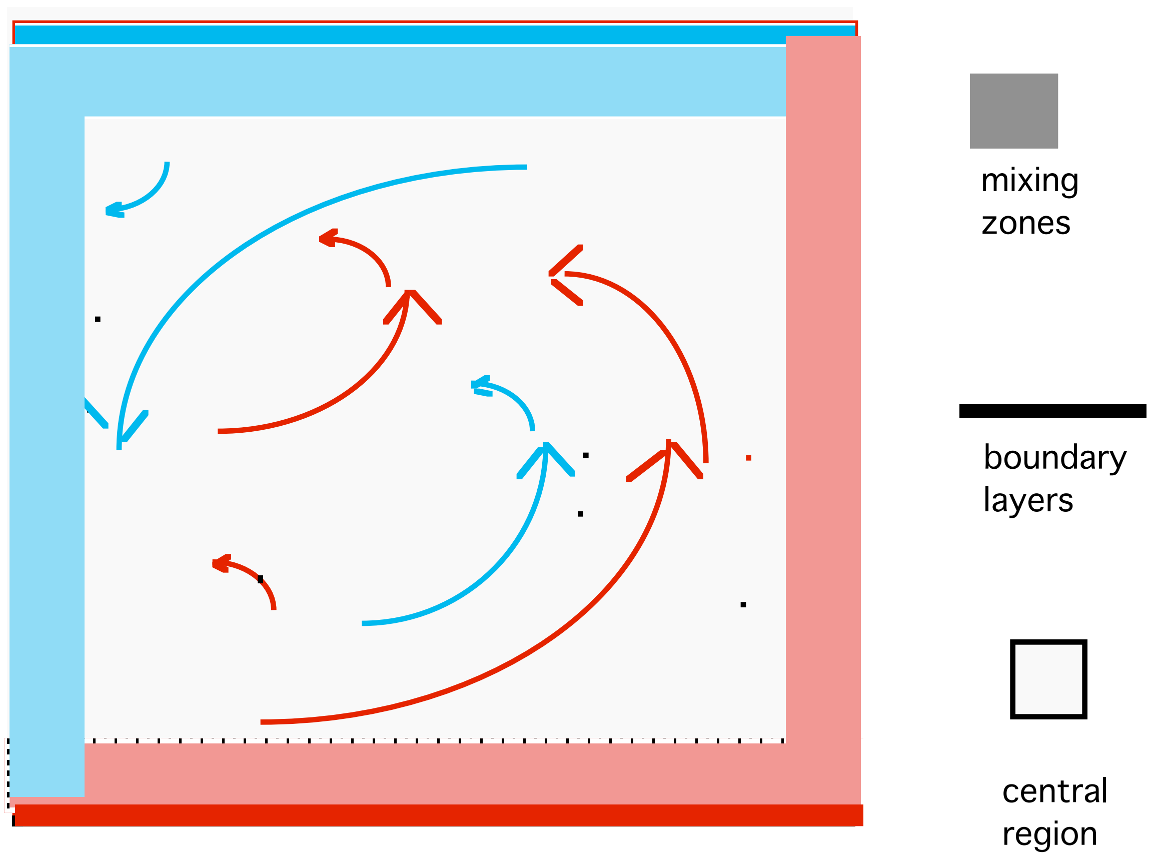
Then as the difference is increased the swirls start to move around in an oscillatory pattern.

Beginning of Chaos

Then as the heating is increased still further the motion of the swirls becomes non-repeating and the motion is chaotic. In Chaos the whole cell wiggles coherently



Then for the highest heating rates one gets turbulent behavior in which the different portions of the system each wiggle chaotically and independently of one another



Rayleigh Benard Cartoon

Description: via Equations

$[\partial_t + u\cdot\nabla]\, u(r,t) = -\nabla p + \nu\nabla^2 u \qquad +\mathbf{g}\alpha T$ (flow of momentum)

$\nabla\cdot u = 0$ (fluid is incompressible)

$[\partial_t + u\cdot\nabla]\, T(r,t) = \kappa\nabla^2 T$ (flow of heat)

The part containing the velocity u(r,t) is called the Navier Stokes equations. All together they are called the Boussinesq equations. Hardly anyone can tell by looking at the equations what they might imply for fluid in motion. Either computer studies or experiments are required to get one started. However, it is certainly true that the equations contain all the information one needs to describe the flow of fluids.

Get started. Look at pictures

picture of tank

In looking at these experiments, one sees some very characteristic structures.

One such structures is the plume. It is a mushroom shaped object always produced when hot fluid rises. The hot material comes up the stalk. When it reaches the top of the plume, it pushes aside fluid above it and is in turn deflected by this pushing

Candle

Nuclear explosion

Plume in tank

pair of plumes

motion of plumes

The Cell Becomes a Machine

But the plume is only a part of a more complex 'Machines': How does the machine work? drawing by Albert Libchaber and by LPK

Many structures work together to produce a machine which pumps heat.

The story: A cell is filled with a fluid. The fluid is strongly heated from below. Buoyancy raises the heated material and a flow starts.

The result: Flowing fluids can organize themselves to produce the most amazing complexity with many different working parts each serving a different function.

Second Interlude: No Free Lunch

My ex-student, W. Dembski, followed an old and good tradition by looking at biological evolution as a process by which an organism or a species searched to improve itself by looking at itself and its near relatives and picking the most viable biological features from among this group.

Dembski then noted that there was a mathematical theorem (the "no free lunch" theorem of D. Wolpert and W. Macready). This theorem imagined a search like this being conducted through a very long and unstructured list of possibilities, perhaps like a scrambled telephone book, without clues supplied from outside. In that case, no good strategy for conducting the search could possibly be constructed. To get the best result you would have to examine each and every possibility on the list. With a list of deominated by dud possibilities, nothing very complex and viable could possibly come out. Ergo, Dembski said, mathematics has proved that evolution cannot produce anything as complex as is actually observed.

Return to our main argument: what is the source of the complexities of fluid flow?

Can Complexity Arise from Simplicity?

Mathematically, the motion of a fluid is described by the Navier Stokes equations.

$$[\partial_t + u \cdot \nabla]\, u(r,t) = -\nabla p + \nu \nabla^2 u \qquad \text{(flow of momentum)}$$

$$\nabla \cdot u = 0 \qquad \text{(fluid is incompressible)}$$

I am going to give a example of a basically very simple situation which gives rise to these equations. We shall then be able to see something of the source of complexity in fluid flow.

I am going to give a description of fluids in several different ways: first I'll use the metaphor of a game board, then of a square dance, and finally describe how those metaphors can be converted into a computer program.

what do we wish to explain? As we have just seen fluids can show some beautiful and complex patterns of motion. What is the minimum amount of structure we can put in so that we get out these patterns/equations.

Fluids in motion: a square dance

theory: three basic ideas explain all this.

First:. A fluid contains many particles in motion

Second: ‘conservation laws’: some things (particles and momentum) are never lost only moved around

Third: Technical requirements (translational invariance, rotational invariance, locality)

The big idea: Do the above right (plus a little more.) and you will construct a model fluid with behavior just like a real one.

The Model System: A Game

A. The board and the pieces:

The Board: A regular pattern called a lattice.

The Pieces = Particles sit on the intersections of the lattice.

particles have a position and a direction. There are six possible directions. (The direction is a momentum.).

transparency

B. The rules of the game

trans,trans

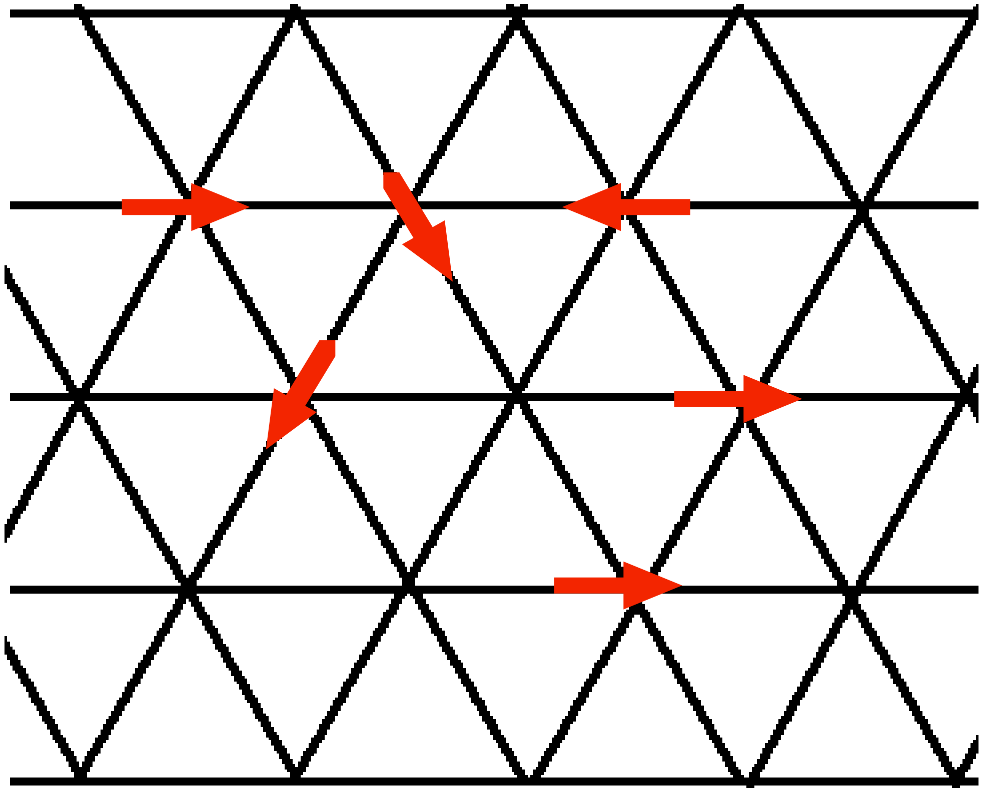
Its consequences-- The game makes a liquid

outcome: D. d'Humieres, P. Lallemand, T. Shimomura

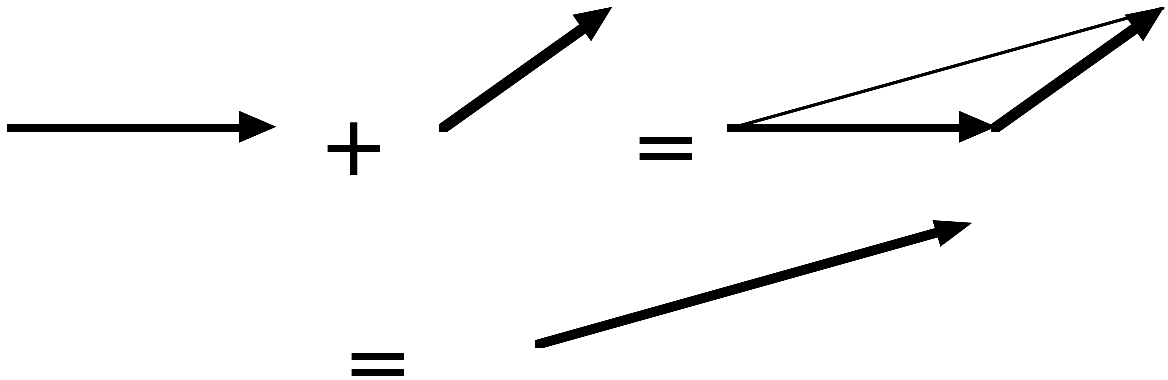
trans

Cf real fluid motion trans

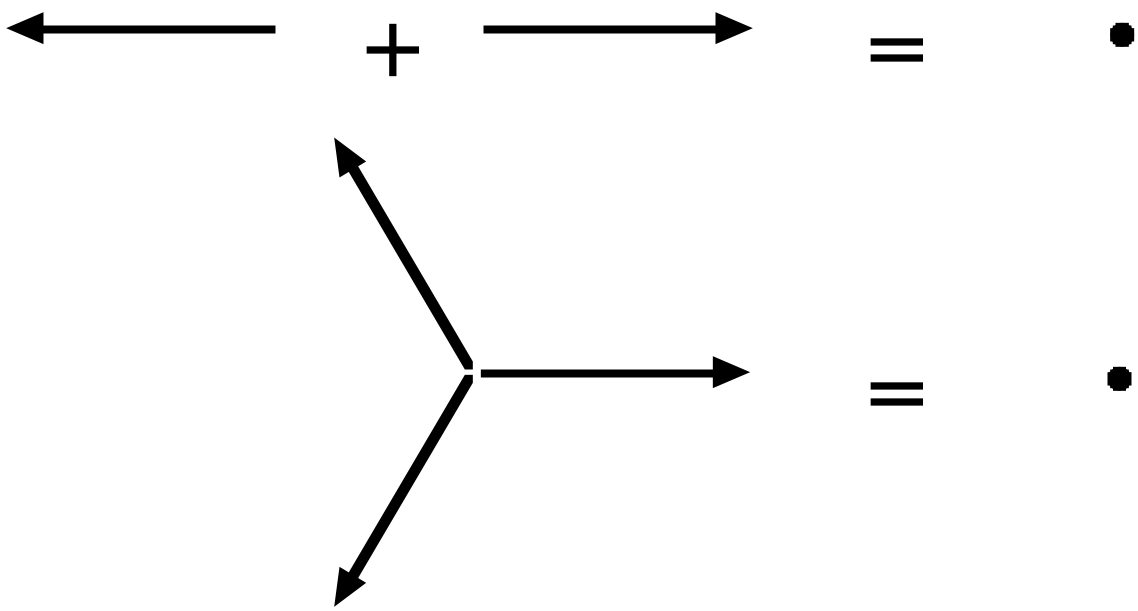
Or find flow down a pipe LPK., G. R. McNamara and G. Zanetti trans



Rule for Adding Momentum



Configurations which add up to zero.



What did we learn from the square dance?

Gradually, through examples like this, it has dawned upon us that very simple ingredients can produce very beautiful, rich, and patterned outputs. Thus, our square dancers through their simple "promenades" and "swing your partners" make the entire beautiful world of patterns produced by fluid motion. For simple elementary actions to produce patterned and complex output, we require many events. This will arise either when there are many simple actors or there is enough time to have only a few actors go through many events. The square dance example had both many actors and much time.

Indeed we have good technical arguments to show that on a large scale our square dancers are the same as fluids since they both obey the Navier Stokes equations. And we know from direct experience that fluids can produce many things that are quite complex. Simple events, linked together, and repeated sufficiently often can produce complex outcomes. This possibility for natural production of complexity is one thread of the argument about the plausibility of earth based origins of life.

Another Interlude: Dembski's world and ours

Recall that Dembski imagines evolution as a process of searching a long list, without a clue as to the list's contents or ordering, looking for a possible improvement in one's species. However, the bag of biochemical compounds that were our remote forebearers were exactly a part of the nature around them. And if nature had a tendency to make things more complex, as does our heat engine, these bags could work in concert with the nature around them--and themselves become more complex.

Our experience with natural things tends to show that they have a tendency to produce complexity. We have even seen how that happens. Physical situations, and the mathematics that describes them, naturally grow structures. Because the structure growing may be chaotic the structures may arrange themselves in complex patterns. Complexification seems to be a natural tendency of nature.

More on the Physics and Maths of Fluids

I will say more about Dembski & Co. But now I wished to show you some pictures which illustrate our most recent work on fluid flow

1. The Universal form of a slender neck trans

2. A splash (again) Nagel movie, movie

3. A jet from sand Jaeger movie, movie

We think we fully understand the shape of the neck formed in case 1.   We don't understand the effect of air in cases 2 and 3. Everyone who has seen these experiments consider these results a great surprise. But we all do expect that it will be possible to understand these things. Science just has not gotten there yet.

Conclusion

Our square dance example shows that wonderfully complex and rich ‘worlds’, like the world of flowing fluids can arise from absurdly simple basic rules. In the example, one applies the same rules again and again, to lots of dancers going through many different twirls. The outcome is a system capable of making structures (like the plume) and machines (like the heat engine).

Thus complexity can arise from simplicity. Comploex patterns arise naurally and ubiqitously. What if ... these patterns themselves rearranged themselves into superstructures, like the “machine” we saw in the heated box, and these were chaotic and these superpatterns arranged themselves into chaotic structures.....   Such piling of complexity upon complexity could work to produce the richness of biological systems.

We are not done yet.

the previous slide contains the words

What if ...

and earlier slide states my presupposition

the world is lawful and the same basic laws hold everywhere and always. New domains of nature may require new laws, but all the different laws are consistent with one another.

Behe and Dembski start from a different presupposition. They do, I think, believe in a Creator and then find this Creator in their studies. Their main conclusions are not, as I see it, compelling--- but they are possible. However, in my view, as we shall understand more about complexity, Behe's examples and Dembski's arguments will become less and less convincing.

I applaud their work: Good skeptics make good science. Behe and Dembski's work will drive further studies of complexity. However, many of their followers want their work to replace science in the school curriculum. I cannot applaud that.

What do I do?

I make little artificial world

I turn them over in my hands

Ask what is beautiful and general in them

And try to abstract rules for the real world

What did we learn from the square dance model?

Gradually, through examples like this, it has dawned upon us that very simple ingredients can produce very beautiful, rich, and patterned outputs. Thus, successive "promenades" and "swing your partners" can produce the entire beautiful world of patterns produced by fluid motion. For simple elementary events to produce patterned and complex output, we require many events. Thus in our previous example, to see the fluid behavior, we had to take many dancers and guide each one through the steps many, many times.

Lesson: In our study of physics, we start from a question about the world, in all its richness, and try to develop examples, 'models', which expose the basic ideas under consideration, and give us a better understanding.

Lesson: In our engineering work, we start from a question about how to design something, and try to develop examples, 'models', often computer models, which expose the basic ideas to be used in thinking about the behavior and design of the system. We may also use the models to predict the behavior of the system. But understanding come first.

This example shows that wonderfully complex and rich ‘worlds’, like the world of flowing fluids can arise from absurdly simple basic rules. In the example, one applies the same rules again and again, to lots of dancers going through many different twirls. The outcome is a system capable of making structures (like the plume) and machines (like the heat engine).