The Biology of Memory

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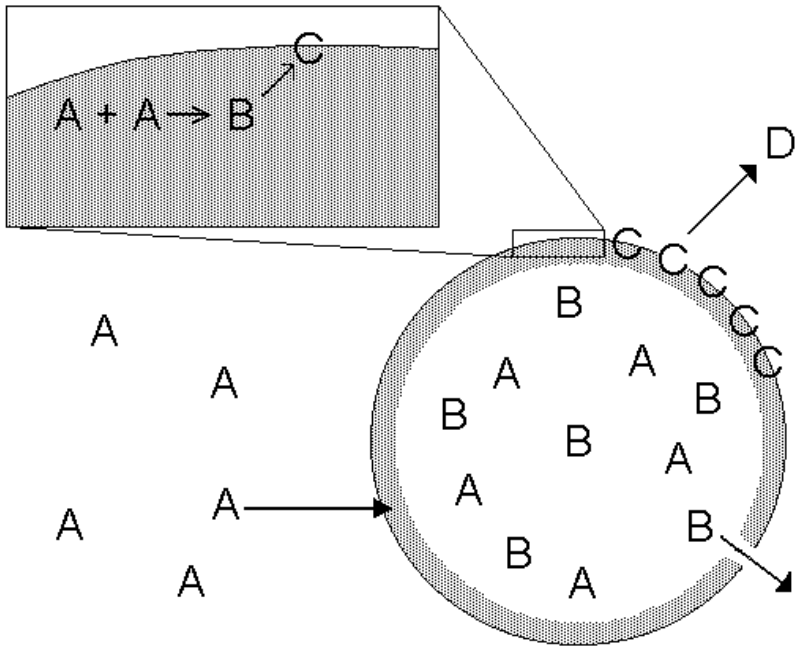
Plan

- Two fundamental questions
  - Both involve memory
  - Both inadequately addressed by contemporary biology
- Unicellular organisms :
  - The origin of genetic systems
- Multi-cellular organisms :
  - The organization of ontogeny

I. The origin of genetic systems

- Enaction is rooted in autopoïesis



No memory, no learning…..

- Autopoïesis does help us to get away from (overly) gene-centred Molecular Biology
  - Few biological molecules are as inert as DNA
  - Genes do *not* « produce themselves », nor « reproduce themselves »

BUT

- Don't throw the baby out with the bathwater
  - Maturana and Varela talk about « natural drift »
  - But natural selection *is* important, indeed essential to understand the "creative evolution" (Bergson) from prokaryotic to eukaryotic to multi-cellular organisms to vertebrates with Central Nervous Systems…
  - In fact, NS is essential to understand the origin of even the simplest current living organisms (bacteria)
  - And for Natural Selection, a "genetic system" is essential

A « genetic system » is a structure with the following abstract properties :

- It contains information (!)
- It can be copied
- It can vary, with a suitable rate of mutation, and the variants can be copied so that there is inheritance.

Cairns-Smith :

- *IF* there are such a structures, and
- *IF* the variations cause differential reproduction of the organisms that carry them (Darwinian fitness), and
- *IF* there is potential overproduction
- *THEN* these entities will get better at reproducing their kind.

« There can be no accumulation of appropriate accidents, no kind of progress, without the means to remember ».

MEMORY !!!

« Information » is neither more (nor less!) than « a difference which makes a difference »

(Bateson)

- « Information » does *NOT* specify :
  - How it is to be copied;
  - How it is to be interpreted.
- An informational genetic structure is *strictly differential* :
  - *All other things being sufficiently equal (ceteris paribus),*

    A *difference* in a genetic structure causes

    A *difference* in the phenotype of the organism
  - Thus, genetic information is blind to everything that is *invariant* in the organism (notably its autopoïesis)

A « middle way » ?

- Genetic information is *NOT* a “set of instructions about how the rest of the organism, its phenotype, is to be made and maintained”.

BUT

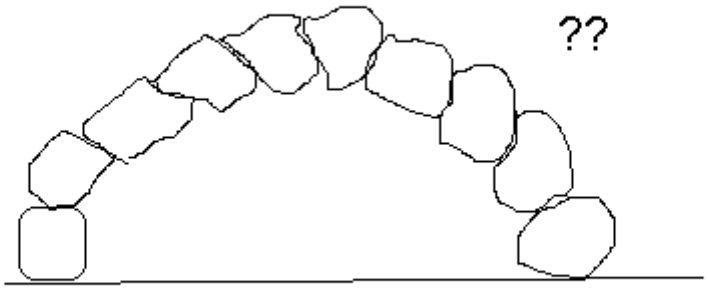
- If the “ceteris paribus” clause is satisfied - and it can be - then genetic differences can encode phenotypic differences; and
- This can give rise to memory - and “creative evolution”

How could a « genetic system » come into existence?

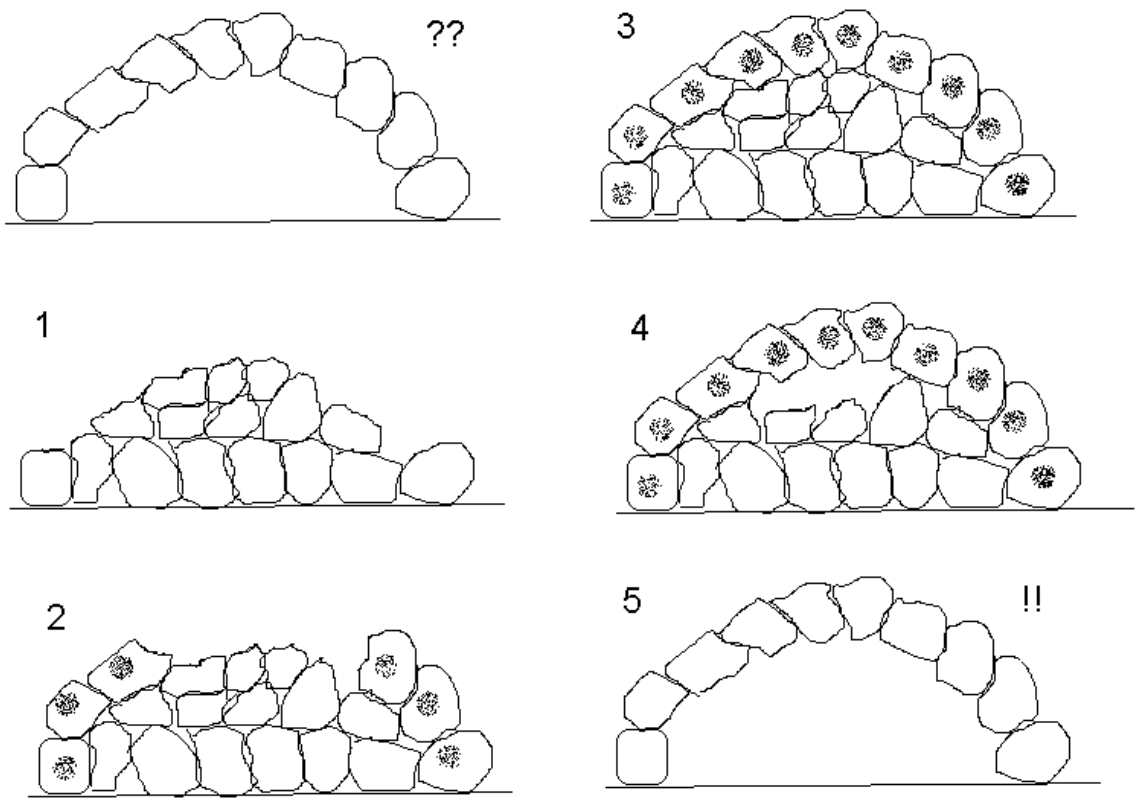
- Working backwards: a circular impasse (??.. -> genes -> proteins -> genes ..??)
- The problem of the arch :

Given that if any one stone is taken away (or is not yet there) the whole arch collapses, how on earth can it be built stone by stone?

The problem of the arch



The solution : *scaffolding*



Scaffolding for a genetic system

- A « genetic takeover » :
  - A primitive genetic system allows progressive complexification of biochemical metabolism
  - In particular, elaboration of the nucleic acid-protein system
  - At this point, the present system (DNA-RNA) could « take over » from the primitive system, which could then disappear without trace…
- If so, what was the « primordial genetic system » like ??

Scenarios for a primordial genetic system

- Cairns-Smith : clay crystals
- JS : a *dual* system :

  a) A purely dynamic dissipative structure, a sort of “chemical whirlpool” – but which is already autopoïetic, without having a genetic system.

  b) A very primitive genetic system - which does not have to be autonomous! Neither does it have to « direct the production » of the organism as a whole. This makes it very much easier to envisage - but still not trivial…

End of Part I

Over to you !!

Part II :
The Organization of Ontogeny

- II.1. The nature of the problem
- II.2. Form and Matter
- II.3. Snowflakes
- II.4. Early embryogenesis
- II.5. Beyond outside versus inside

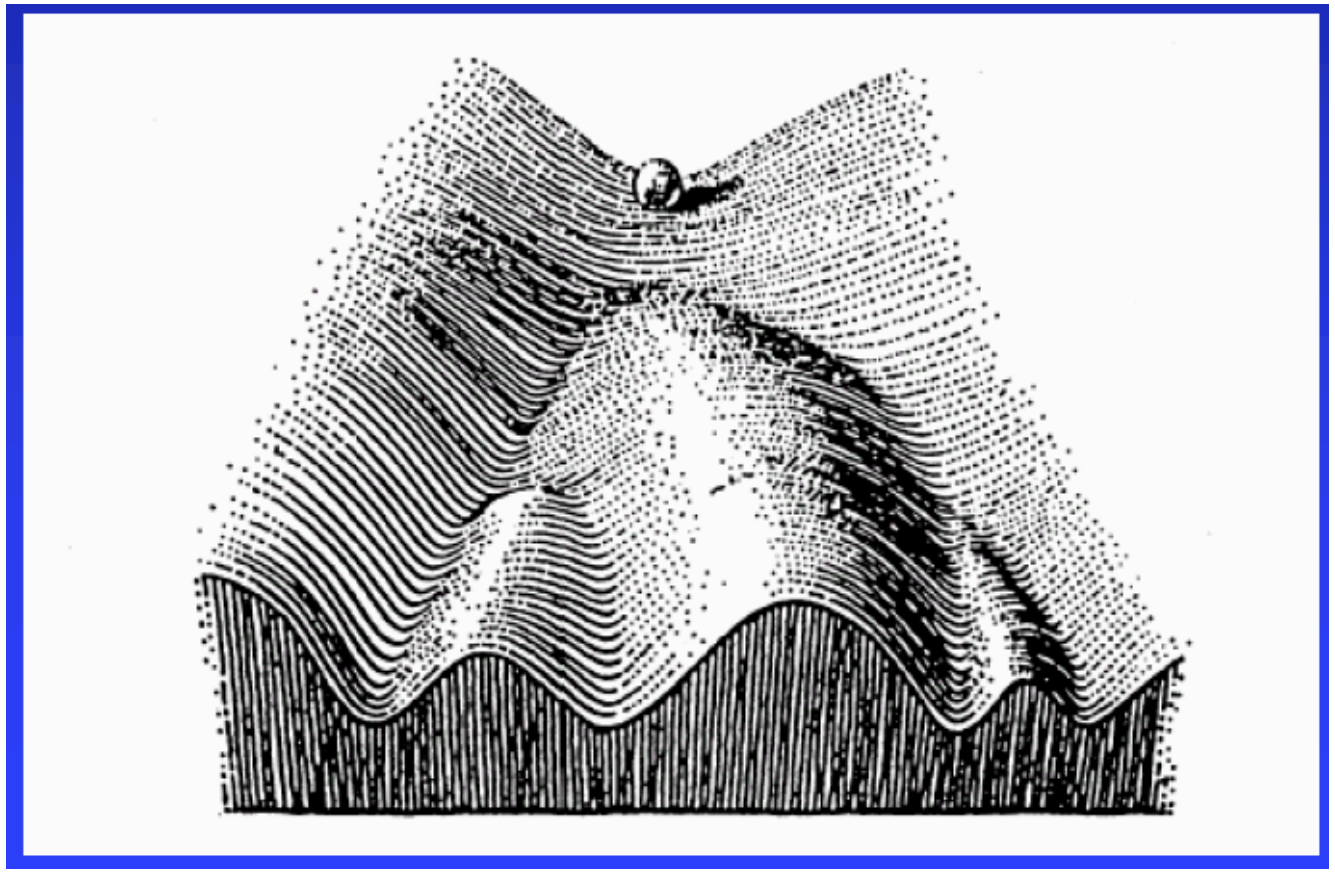
II.1. The problem of ontogeny

- The Cambrian explosion (600 MY): the emergence of multi-cellular animals
- Ontogeny: the process leading from a fertilized egg-cell, through embryogenesis, to birth, maturation,… aging and death.
- The fantastic *regularity* of ontogeny calls for an explanation: « memory of the species » ?

Ontogeny (cont)

- Fragility, delicacy
- Reliability (rate of malformations astonishingly low)
- Dynamic self-organization (e.g. identical twins: separation -> ***2*** perfect embryos)
- Waddington: canalization and chreodes, the « epigenetic landscape »

The « epigenetic landscape »



Ontogeny (cont)

- …. Spemann, Waddington, Medawar (aging) … *characterize* ontogeny as a dynamic, self-organized process
- However, none of this work (valuable though it is in setting the problem) constitutes a proper scientific *explanation* of the regularity of ontogeny.
- What are the *mechanisms?* How does it come about that the process is so regular? **We do not know**.
- It is this absence of a proper scientific explanation that lends its superficial appeal to the disastrous notion of a "genetic programme": *descriptively,* ontogeny does indeed unfold ***as though*** it were "programmed"… the result of some form of **MEMORY??**

II.2. The Heart of the Problem :
Form and Matter

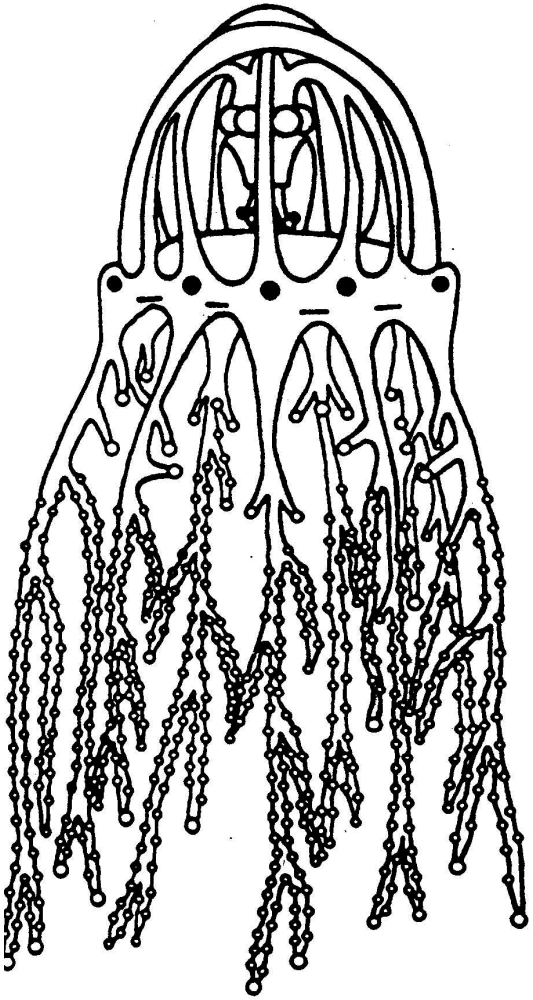
The whole of Western thought, ever since Plato and Aristotle, has been coloured by a deep prejudice :

- « Matter », left to itself, is essentially inert or at best chaotic.
- Therefore, any material process which is "organized" must have been literally "in-formed" from a source essentially *exterior* to the process itself.
- In the case of a living organism, and in particular a developing embryo, there are two potential reservoirs of external information:
  - the environment (manifestly external to the organism);
  - the other is genetic information (epistemologically external).
- Hence the hoary "nature versus nurture", "innate versus acquired" debate… which is profoundly mistaken (Oyama).

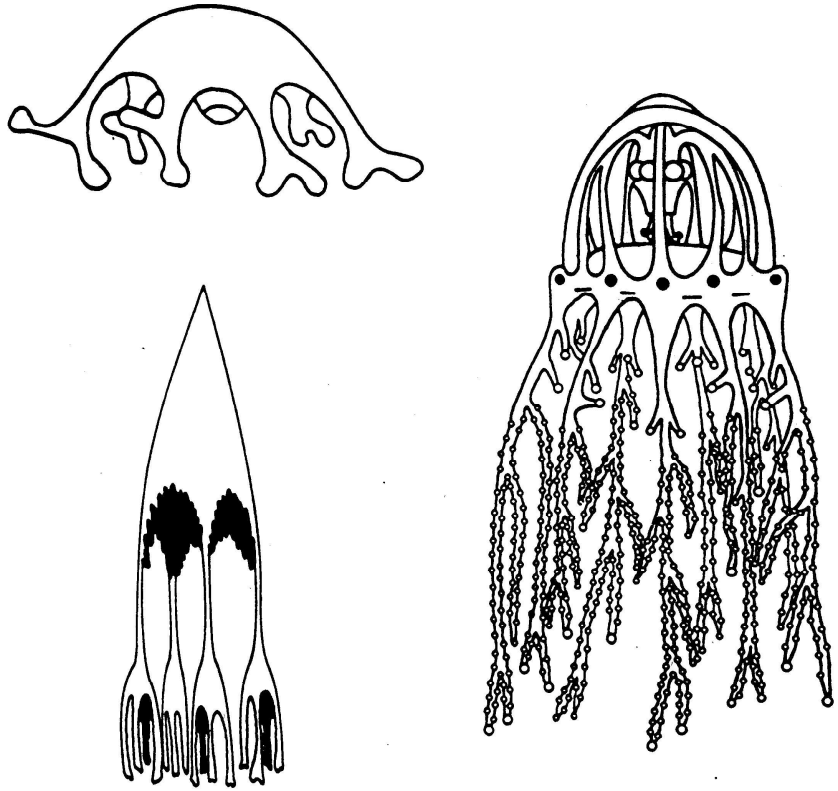
D'Arcy Thompson (1917) *On Growth and Form*

- material processes are not necessarily inert or chaotic; on the contrary, under certain conditions, they can display remarkable properties of *self-organization.*
- morphogenesis in living organisms is *necessarily* based on the same physical principles as morphogenesis in natural non-living systems.
- D'Arcy Thompson was particularly impressed by landscapes and coastlines; he gave another suggestive example, even closer to biology - the shape of a small jellyfish

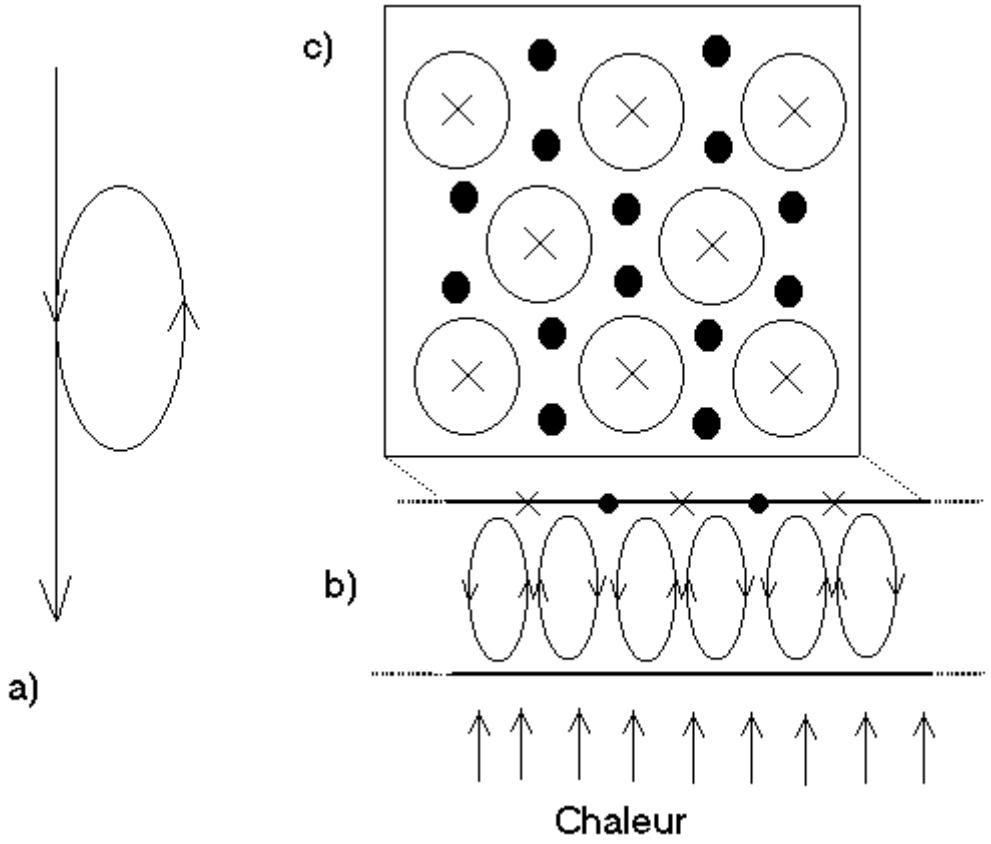
The shape of a jellyfish….



… compared to a drop of paraffin oil



A more modern example: Bénard cells and dissipative structures



Snowflakes (cont)

- In every snowflake, each of the six arms is (almost) exactly like the 5 others; *BUT*
- No two snowflakes are (even remotely) alike.
- So: how does each growing arm « know » what form to adopt, to conform to the pattern?
- It seems almost as if there must be a « genetic programme » somewhere, « in-forming » the process
- But in this case, we know that there *is* no « programme »…

Snowflakes: the explanation

- The formation of snowflake crystals, directly from gaseous phase to solid phase and close to the tri-critical point, is hyper-sensitive to the exact combination of 3 physical variables: temperature, pressure and humidity.
- Individual snowflakes are so small that the time-course of these 3 variables is (practically) identical for each of the 6 arms; but quite different from one snowflake to another.
- To this is added a fourth factor: the shape of the crystal up to that time. This is also identical, from moment to moment, for each of the six arms; but progressively different from one snowflake to another (cf deterministic chaos).
- To sum up: the astonishing similarity of the six arms is nothing other than a strict application of a basic scientific principle: the same causes produce the same effects.

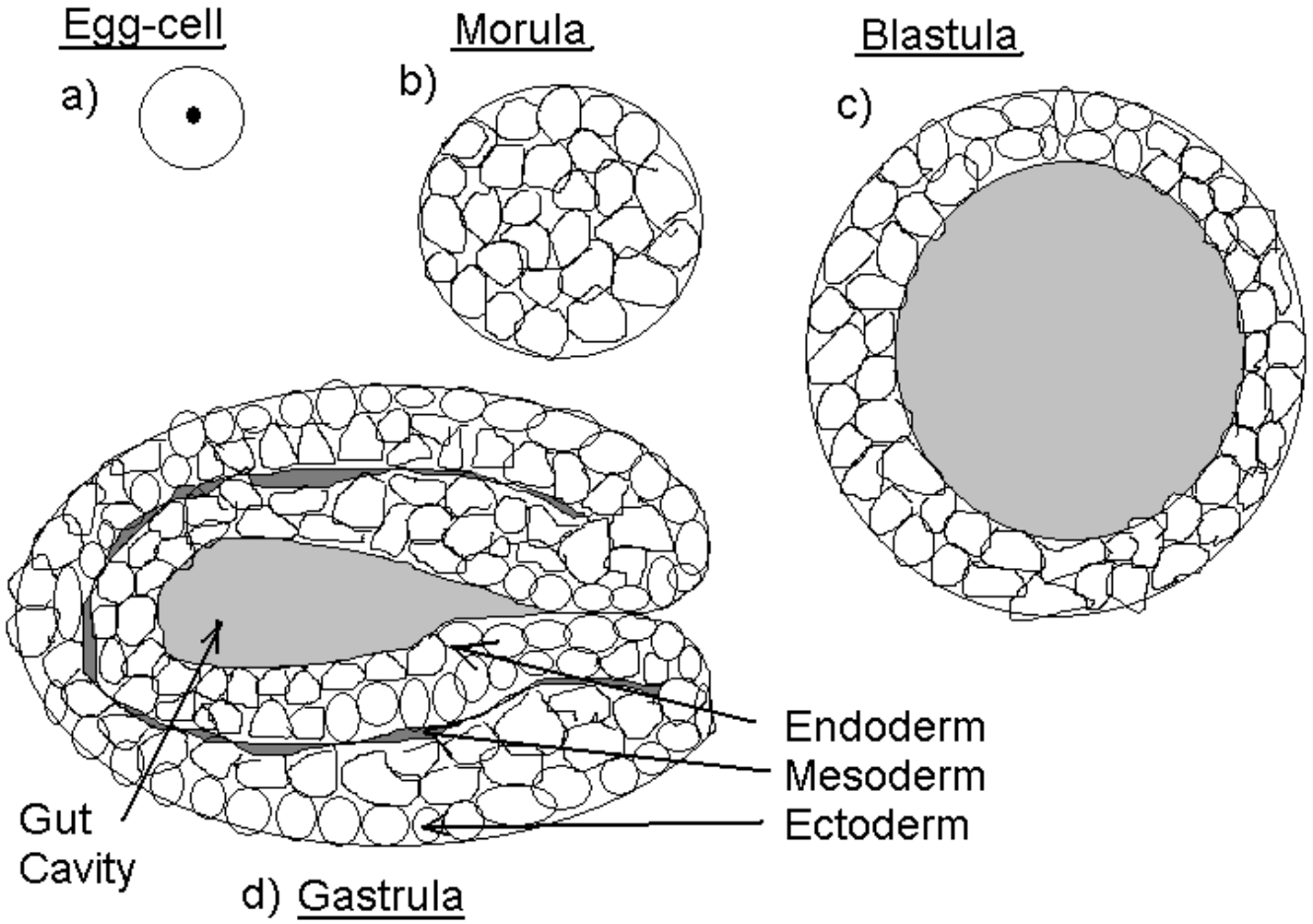
Snowflakes : conclusions

1) If there is anything like a “programme”, it is not localized anywhere; rather, it is *distributed* over all the elements that enter into interaction in the course of the process.

2) The putative “programme” does not even pre-exist; the “in-formation”, if one insists on keeping this concept, is created step by step, in real time, by the very process which “expresses” it.

- To sum up: a proper explanation in terms of physical processes renders the notion of “programme” superfluous: a “programme” that is not localized anywhere, and which does not even pre-exist with respect to the processes it is supposed to be directing, is hardly worth calling a “programme” at all.
- Might it be the same in the case of biological ontogeny? If the processes are so regular, is it (in part) because its organization is based on regularities which are reliably produced by the developmental process itself?

II.4. Early embryogenesis



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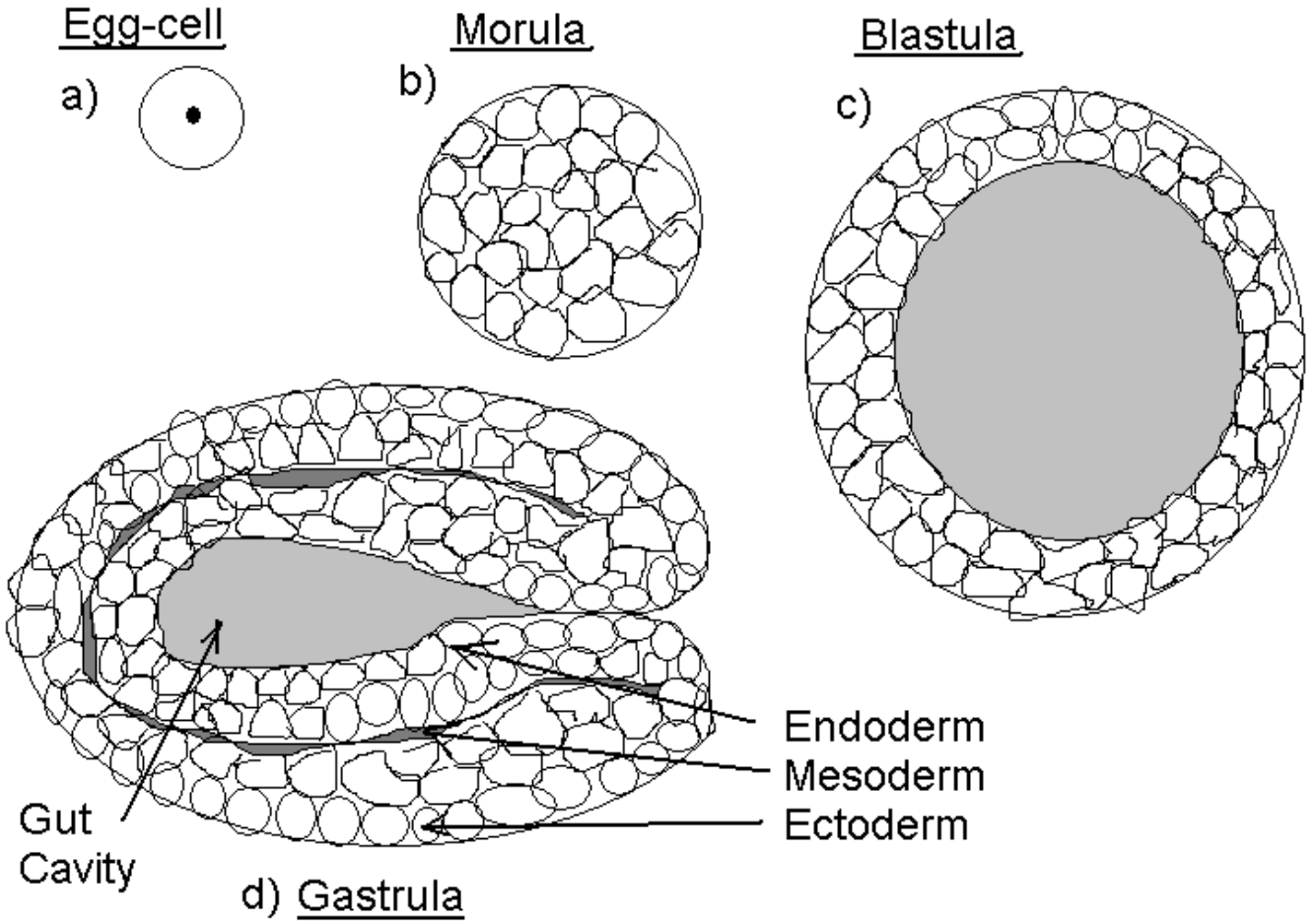
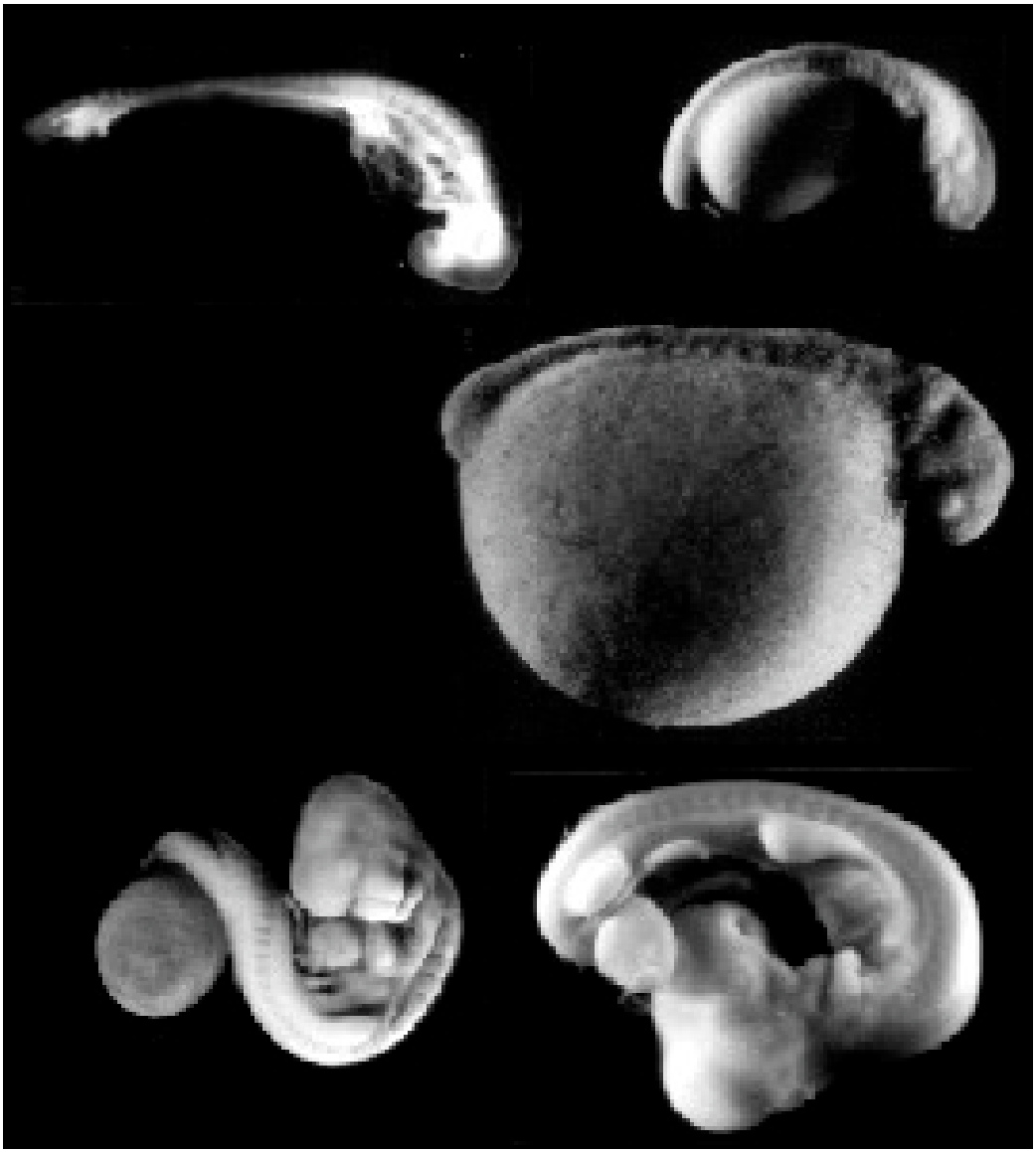
Early embryogenesis (cont)

- Why is the morula a sphere? - for the same reason that an oil droplet in water is (approximately) a sphere
- *Because* the morula is spherical, certain cells will inevitably be placed at the surface, in contact with the aqueous environment; whereas other cells will be placed inside and surrounded by other cells.
- This can be used as a reliable signal to trigger a cell differentiation: the inner cells secrete a liquid.
- This *explains* how the embryo comes to have the form of a *blastula,* a hollow sphere filled with liquid.

Early embryogenesis (cont)





Ontogeny (cont)

Early embryogenesis (cont)

- The “hollow sphere” of the blastula in turn provides the pre-condition for the next stage, a special sort of movement called “gastrulation”.
- A group of cells initially situated on the surface of the blastula plunge into the centre of the hollow sphere to give rise to the characteristic form of the *gastrula.*
  - These inner cells form the *endoderm,* which will later give rise to the gut;
  - the cells which remain on the surface form the *ectoderm,* which will give rise to the skin and also to the nervous tissue;
  - the cells situated in between will form the *mesoderm*, which will be at the origin of the skeleton, the muscles and the blood.
- An essential task of embryology is to determine how the signals which give rise to this cellular differentiation into three types – endoderm, mesoderm and ectoderm – arise from their respective position in the developing embryo.

Early embryogenesis (conclusions)

- In one sense, the relational topology between endoderm, mesoderm and ectoderm is totally contingent;
- but in another sense, we can understand that it is actually inevitable (and therefore reliable and regular) precisely *because* it arises from the embryological process itself.
- Thus, the fact that the essential “information” for organizing the process does not pre-exist, but is constituted step by step during the unfolding of the process itself, is a key which may help us to understand scientifically the robust regularity of ontogeny.

II.5. Beyond outside versus inside : the story of a fruit-fly and the sun

- A critical moment in the ontogeny of insects: hatching from the chrysalis
- A tough climate: nights very cold, days very hot and dry
- If the young adult hatches:
  - During the night, it will die of cold
  - During the day, it will die fried by the sun before its body and wings can harden by contact with the air
- So hatching *must* be timed for early morning - warmer than the night, cooler than full day
- *What signal can be used to trigger hatching?*

The fruit-fly and the sun (cont)

- A first thought would be to use an intrinsic variable - temperature, which is what counts
- However, the hatching process takes a certain time to complete - and if the fly waits until it is already perceptibly warmer, by the time it gets out it will already be too hot and dry
- The (local, contingent) solution: it so happens that in this climate, it begins to get *light* some time before the temperature rises - and this gives just the lead-time necessary. So hatching is triggered by… *photo-receptors*
- The unfolding of ontogeny itself *creates* opportunities for tinkered biological organization

Conclusions (1)

- The relation between phylogeny and ontogeny (cf Part I and Part II of my talk).
- A genetic system can only encode for variation that can actually arise
- Ontogeny is such a rich and complex process that it can give rise to vast variation in phenotypes
- The « Cambrian explosion » marks a turning-point in the *rate* of evolution:
  - 3000 MY to get from bacteria to multi-cellular organisms
  - 600 MY from the first multi-cellular animals to now (e.g. in the vertebrate lineage: cartilaginous fishes, bony fishes, amphibia, reptiles, dinosaurs, birds & mammals…

Conclusions (2)

- So what, after all, *is* « memory » ?
- We have seen that when we even begin to understand the actual mechanisms, the notion of « programme » fades away into oblivion.
- Could it be the same for memory? Or at least, that memory is not what we thought? (cf Israel Rosenfield and « The invention of memory »)