



Science, Complexity, and the Natures of Existence

George Ellis

University of Cape Town

- G Ellis: *Nature* **435**: 743 (9 June 2005).
- G Ellis: *Physics Today* **58**: 49 (July 2005)

1: The nature of true complexity

Not catastrophe theory, sand piles,
or reaction diffusion equation

Truly Complex Systems :

A: Molecular Biology

B: Animal and Human Brains

C: Language and Symbolic Systems

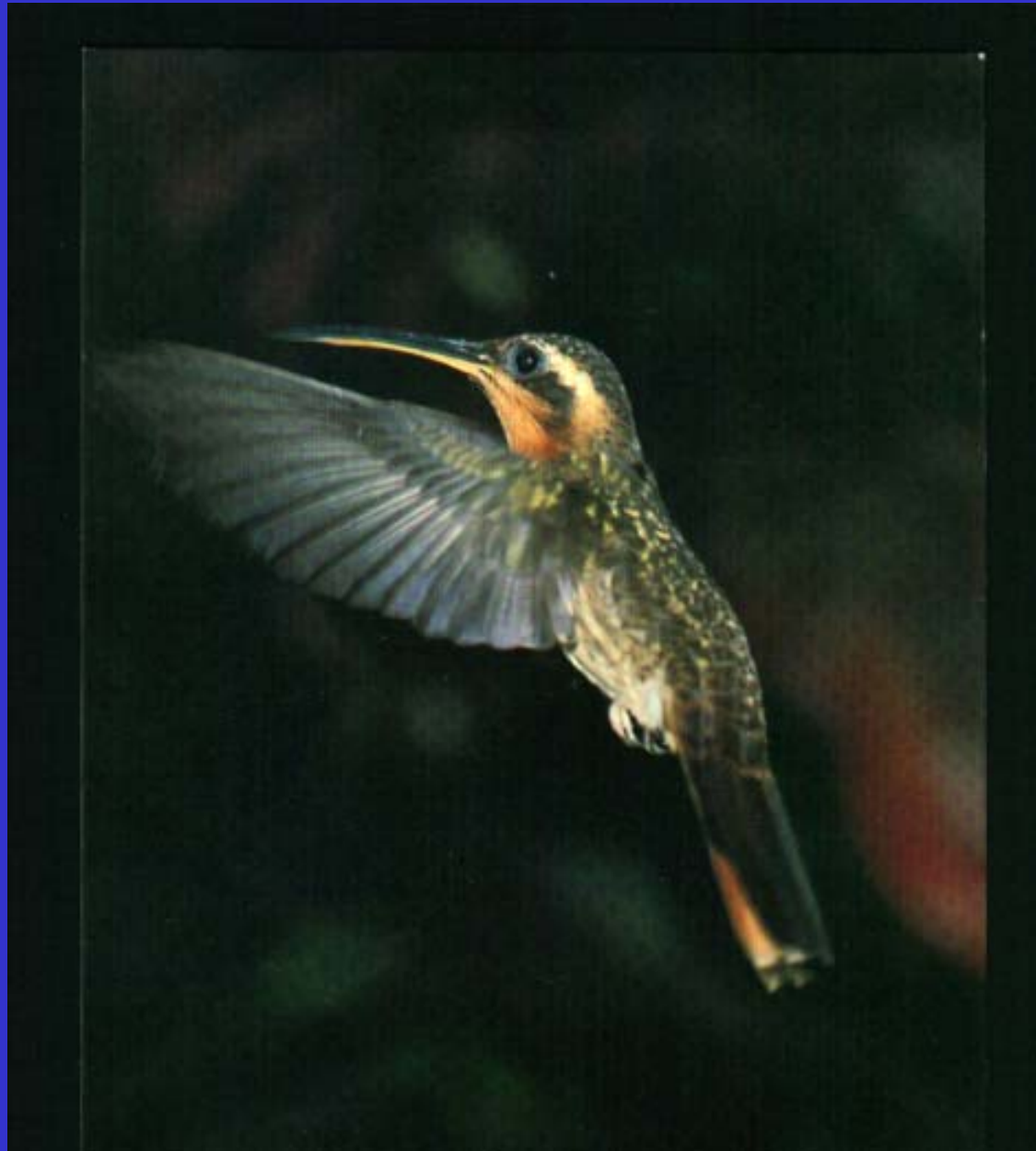
D: Individual Human Behaviour

E: Social and Economic Systems

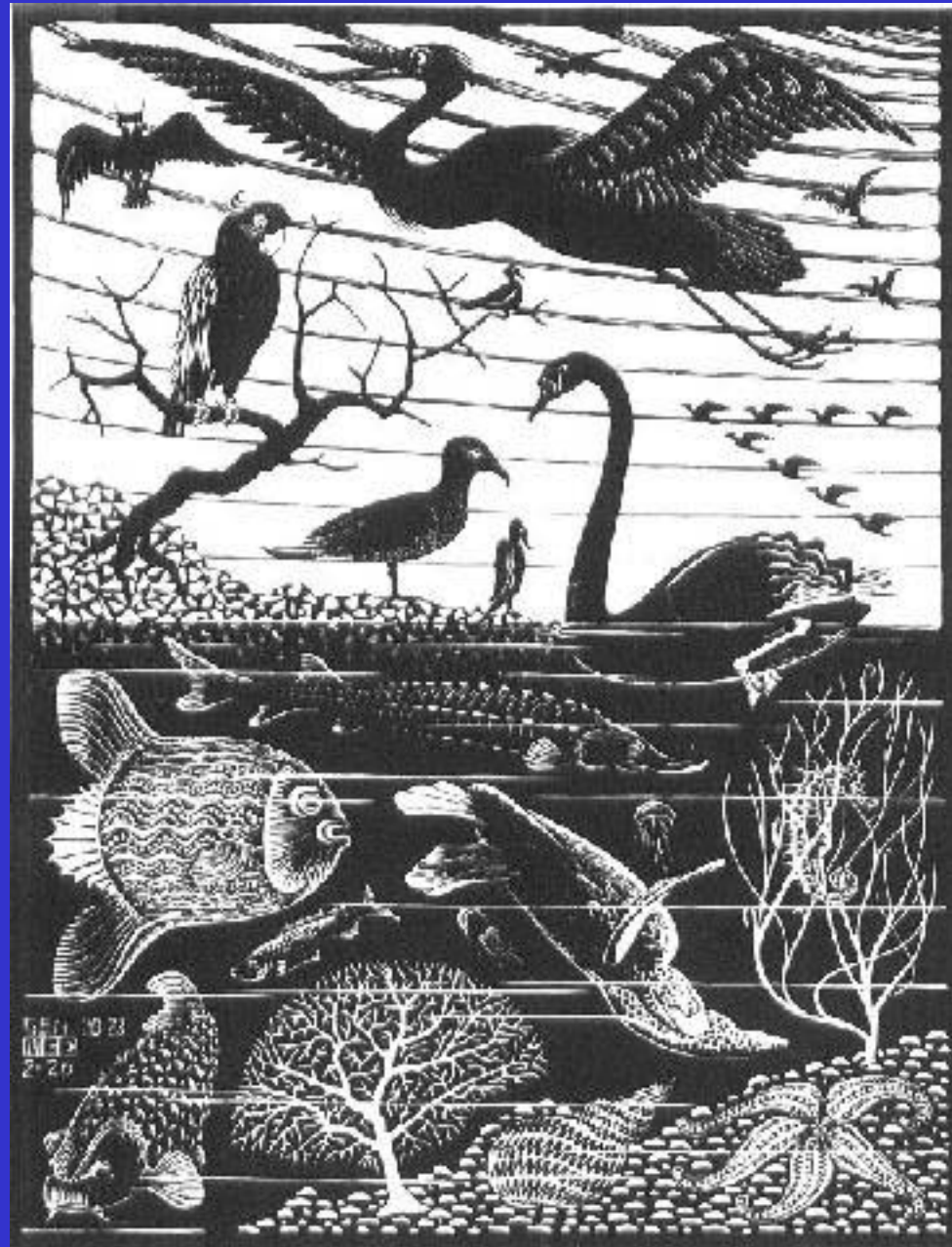
F: Complex Machines ($> 10^6$ active parts),
particularly Computer Systems.

G: The Biosphere, made up of interacting ecosystems





Fifth day of creation:
M C Escher



Complexity and Structure

Physics underlies all complexity, including life. How does it work?

True complexity, with the emergence of higher levels of order and meaning, occurs in *modular hierarchical structures* because this is the only viable ways of building up and utilising real complexity on the basis of the underlying physics

- *with many layers of structure built upon each other*
- *at each level made of components ('modules') that work coherently together*
- *thus underlying effective theories of behaviour at each level,*
- *giving higher-level understanding of behaviour independent of the lower level structures*
- *described in the language suitable to that level of the hierarchy*

The Hierarchy of Structure: 1

Sociology/Economics/Politics

Psychology

Botany/Zoology/Physiology

Cell biology

Biochemistry

Chemistry

Atomic Physics

Particle physics

Hierarchy

- The key to handling complexity is *hierarchical information structure and analysis*, and associated physical structuring
- A **hierarchy** represents a decomposition of the problem into constituent parts, and into processes to handle those constituent parts, each requiring less data and processing, and more restricted operations, than the problem as a whole.
- The levels of a hierarchy represent *different levels of abstraction*, each built upon the other, and each understandable by itself. This is the phenomenon of *emergent order*.
- The success of hierarchical structuring depends on:
 - (a) *implementing modules to handle lower-level processes,*
 - (b) *integration of these modules into a higher-level structure.*

Hierarchy examples

- *physical structure hierarchy* (quarks/protons/ atoms/ molecules/rocks/planets/solar system/galaxies)
- *biological organisms* (atoms/biochemical molecules/cells/organs/organisms/ecosystems).
- *brain* (atoms/molecules/neurons/neural nets/cortex).
- *information hierarchy* (encyclopaedias: animals/mammals/dogs/Corgis/Joe).
- *organisations/society* (head office/branch office/ accounts/billing section/billing clerk).
- *machines*, e.g. cars, aircraft, computers (wire/coil/generator/electrical system/car).

Modules and linkages

“We find separate parts that act as *independent agents*, each of which exhibit some fairly complex behaviour, and each of which contributes to many higher level functions. Only through the mutual co-operation of meaningful collections of these agents do we see the higher-level functionality of an organism. This is *emergent behaviour* – the behaviour of the whole is greater than the sum of its parts” (and cannot even be described in terms of the language that applies to the parts)

“Intra-component linkages are generally stronger than inter-component linkages. This fact has the effect of separating the *high-frequency dynamics* of the components – involving their internal structure – from the low-frequency dynamics –involving interactions amongst components” (this is why we can sensibly identify the components)

Modularity: Inheritance

- Complex structures are made of **modular units** with **abstraction**, **encapsulation**, and **inheritance**; this structuring enables the modification of modules and re-use for other purposes.
- Efficiency and usability introduce the aim of reducing the number of variables and names that are visible at the interface, as is implied by **encapsulation**
- **Inheritance** is the most important feature of a hierarchy: it allows an object class to inherit all the properties of its superclass, and to add further properties to them (it is a 'is a' hierarchy).
- Thus subclasses refine the properties of their superclasses and can be understood as modifications of them with more precise properties.

Modularity: Abstraction

Abstraction and Labelling: Unable to master the entirety of a complex object, we choose to ignore its inessential details, dealing instead with a generalised idealised model of the object. *An abstraction* denotes the essential characteristics of an object that distinguishes it from all other kinds of objects.

It focuses on the outside view of the object, and so serves to separate its essential behaviour from its implementation; it emphasises some of the system's details or properties, while suppressing others. "Information has to be thrown away by the billion bits all the time, because all the alternatives cannot be examined".

Key feature: *Compound objects can be named and treated as units by appropriate labelling.* This leads to the power of abstract symbolism and symbolic computation.

Modularity: Encapsulation

Encapsulation and Information Hiding: consumers of services only specify what is to be done, leaving it to the object to decide how to do it; this is an aspect of decentralisation of control.

Encapsulation is when the internal workings are hidden from the outside, so its procedures can be treated as black-box abstractions. “No part of any complex system should depend on the internal details of any other part”.

It involves *information hiding* – hiding all the internal aspects of an object that do not contribute to its essential characteristics [corresponding to coarse-graining in physics; the accompanying loss of detailed information is the essential source of entropy].

2: Bottom-up and Top-down action

Bottom-up action is when the **lower levels** of the hierarchy causally effect what happens at the **higher levels** in a **causal way**.

Top-down action is when the **higher levels** of the hierarchy causally effect what happens at the **lower levels**, in a **coordinated way**.

- *multiple top-down action as well as bottom up action, enables self-organisation of complex systems*

- *enables higher levels to co-ordinate action at lower levels, and so gives them their causal effectiveness*

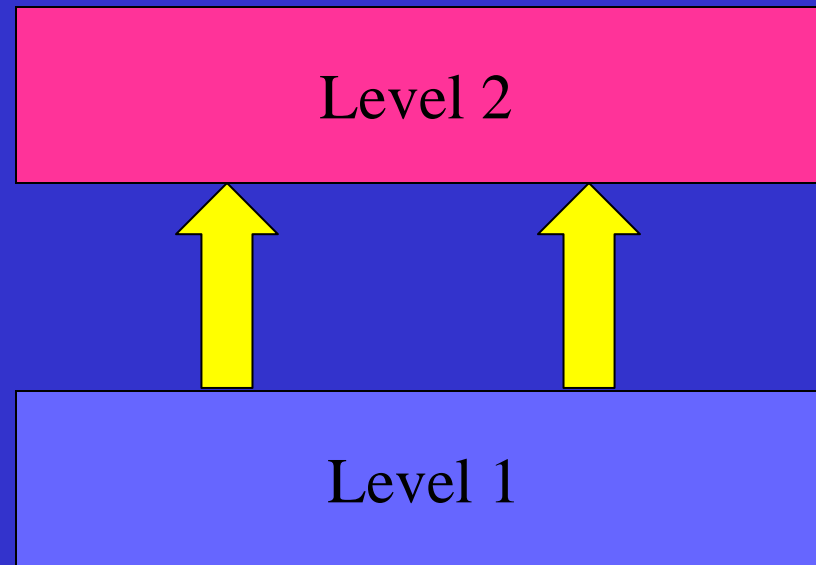
- is prevalent in the real physical world and in biology, because no real physical or biological system is isolated.

- boundary effects (linking the system to the environment) as well as structural relations in the system itself effect top-down action.

Bottom-up action

Bottom-up action is when what happens at the higher levels is controlled by what happens at the lower levels

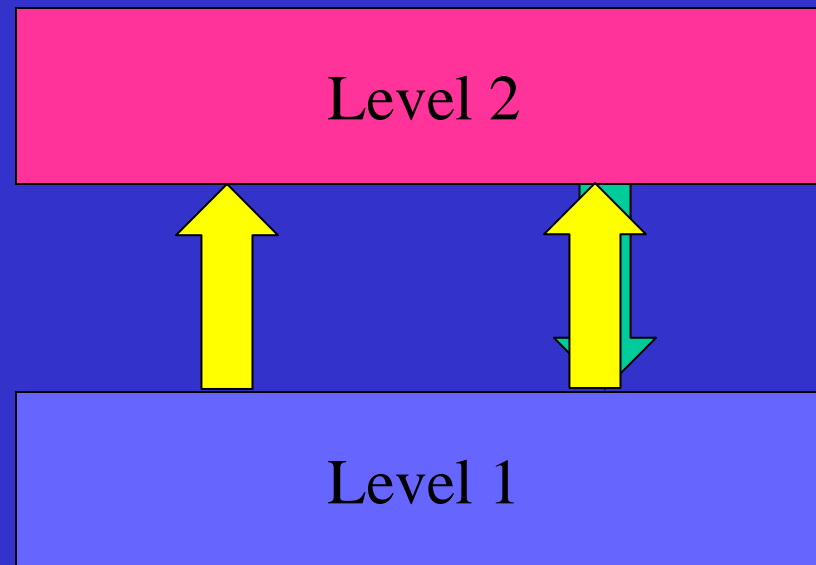
- *micro-physics underlies macro physics, e.g. kinetic theory of gases, theory of solids (conduction, thermal capacity)*
- *physics underlies chemistry, e.g. nature of chemical bond*
- *protein folding and recognition based on chemical bonding*
- *cell biology underlies all life, energy flow in citric acid cycle*
- *physics and chemistry underlie the functioning of the brain*
- *individual human behaviour underlies the functioning of society*



Bottom-up causation alone:

Micro forces determine what happens at the higher levels

They are the foundation of higher level activity



Bottom-up and top-down causation:

*Additionally the higher levels control
causal effects at the lower levels*

Four examples from physics, two from biology

Top-down action: temperature of gases

Top-down action occurs in compression of a piston in a cylinder. The cylinder itself is a macro object – it causes many microscopic particles to move faster as it is pressed down. Thus it changes their detailed movement.

Top-down action occurs in the synthesis of light elements in the early universe. The amount of helium produced depends on the rate of change of temperature in the expanding universe, which is controlled by the gravitational equations and the average amount of matter in the universe.

Thus quantities defined at the cosmological level control the products of detailed nuclear reactions at the micro level.

Top-down action: quantum measurement

Top-down action occurs in the **quantum measurement process** - collapse of the wave function to an eigenstate of a chosen measurement system [as well as in state preparation].

The experimenter chooses the details of the **measurement apparatus** - e.g. aligning the axes of polarisation measurement equipment - and that decides **what set of microstates** can result from a measurement process, and so crucially influences the possible micro-state outcomes of the interactions that happen.

The choice of **Hilbert space** and the associated **operators** and functions is made to reflect the experimenter's choice of measurement process and apparatus, thus reflecting this top-down action.

Top-down action: the arrow of time

Top-down action occurs in the **determination of the arrow of time**.

One cannot tell how a macrosystem will behave in the future on the basis only of the laws of physics and the properties of the particles that make up the system, because **time-reversible micro-physical laws** allow two solutions - one the time reverse of the other - but **only entropy-increasing solutions in one direction of time occur at the macrolevel**; this does not follow from the microphysical laws (but quantum measurement introduces an arrow of time).

Physically, the only known solution to this arrow of time problem seems to be that there is **top-down action by the universe** as a whole, perhaps expressed as **boundary conditions at beginning of space-time**, that allows the one solution and disallows the other.

Top-down action: evolution

Top-down action is central to two main themes of molecular biology:

Development of DNA codings (the particular sequence of bases in the DNA) through an evolutionary process which results in adaptation of an organism to its ecological niche. This is a classical case of **top down action from the environment to detailed biological microstructure** - through the process of adaptation, the environment (along with other causal factors) fixes the specific DNA coding. There is no way you could ever predict this coding on the basis of biochemistry or microphysics alone. *You can't even ask the appropriate questions in their languages.*



Environment

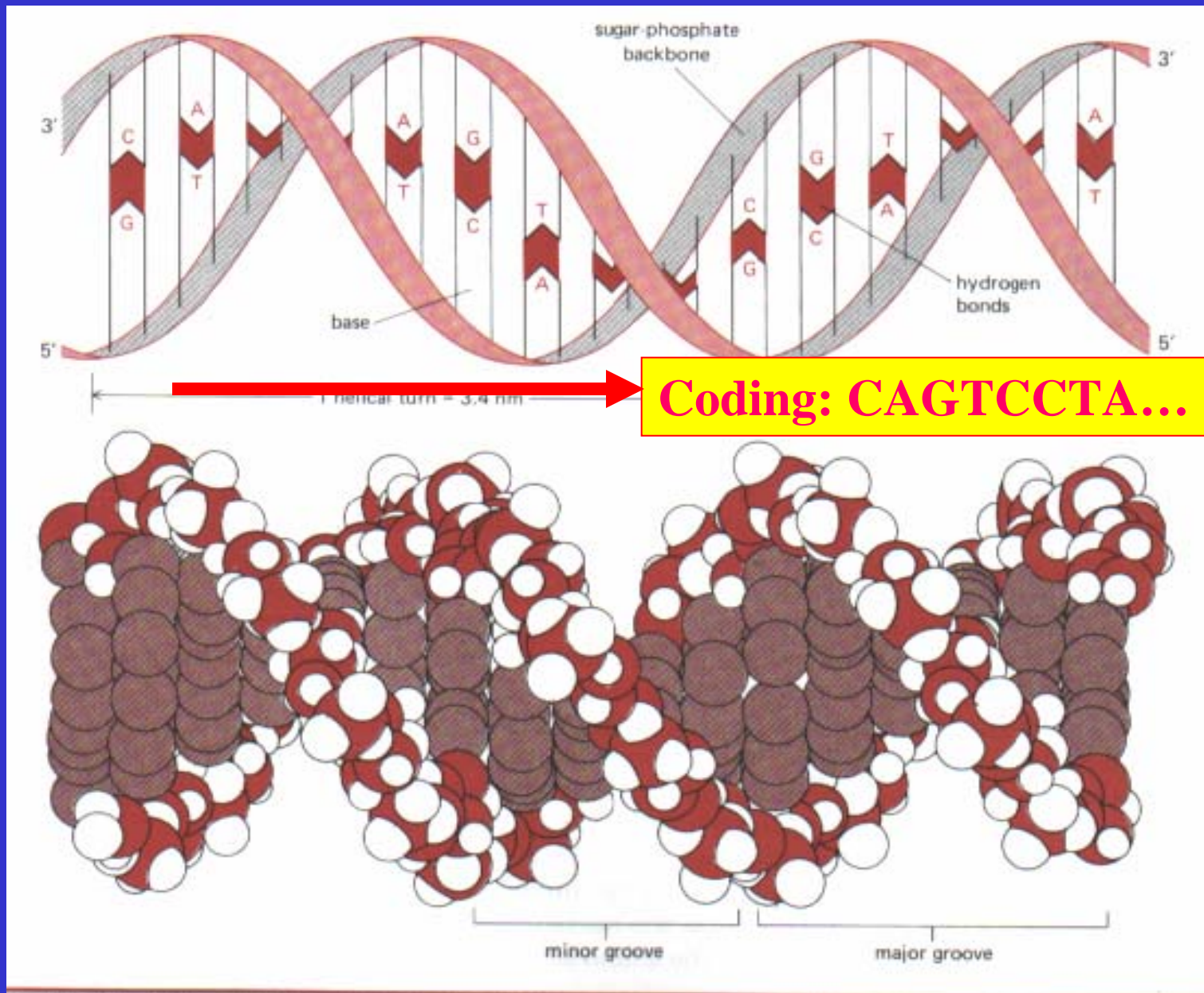


Animal



DNA sequence

Top-down action from the environment codes information about the environment into the base sequence in the animal's DNA

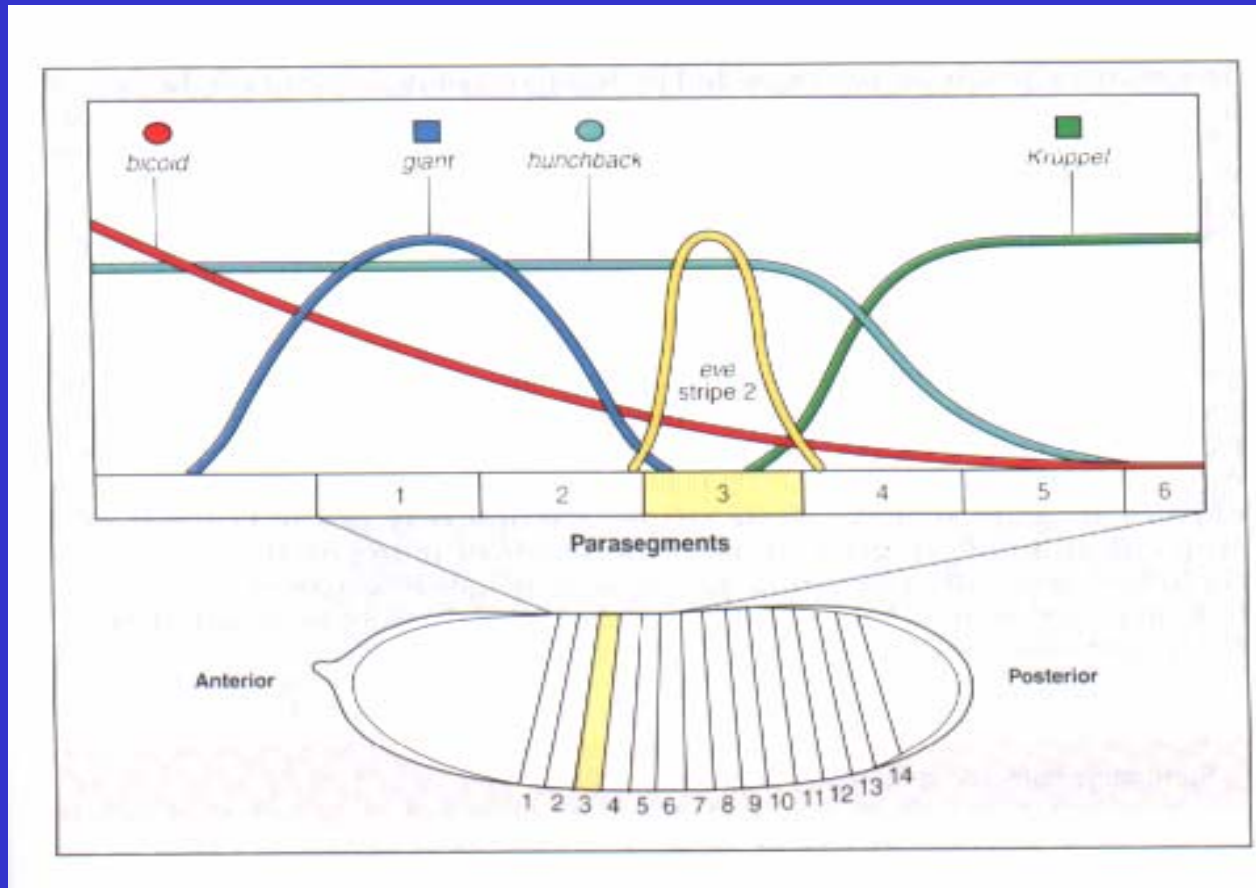


The DNA double helix with complementary base pairs

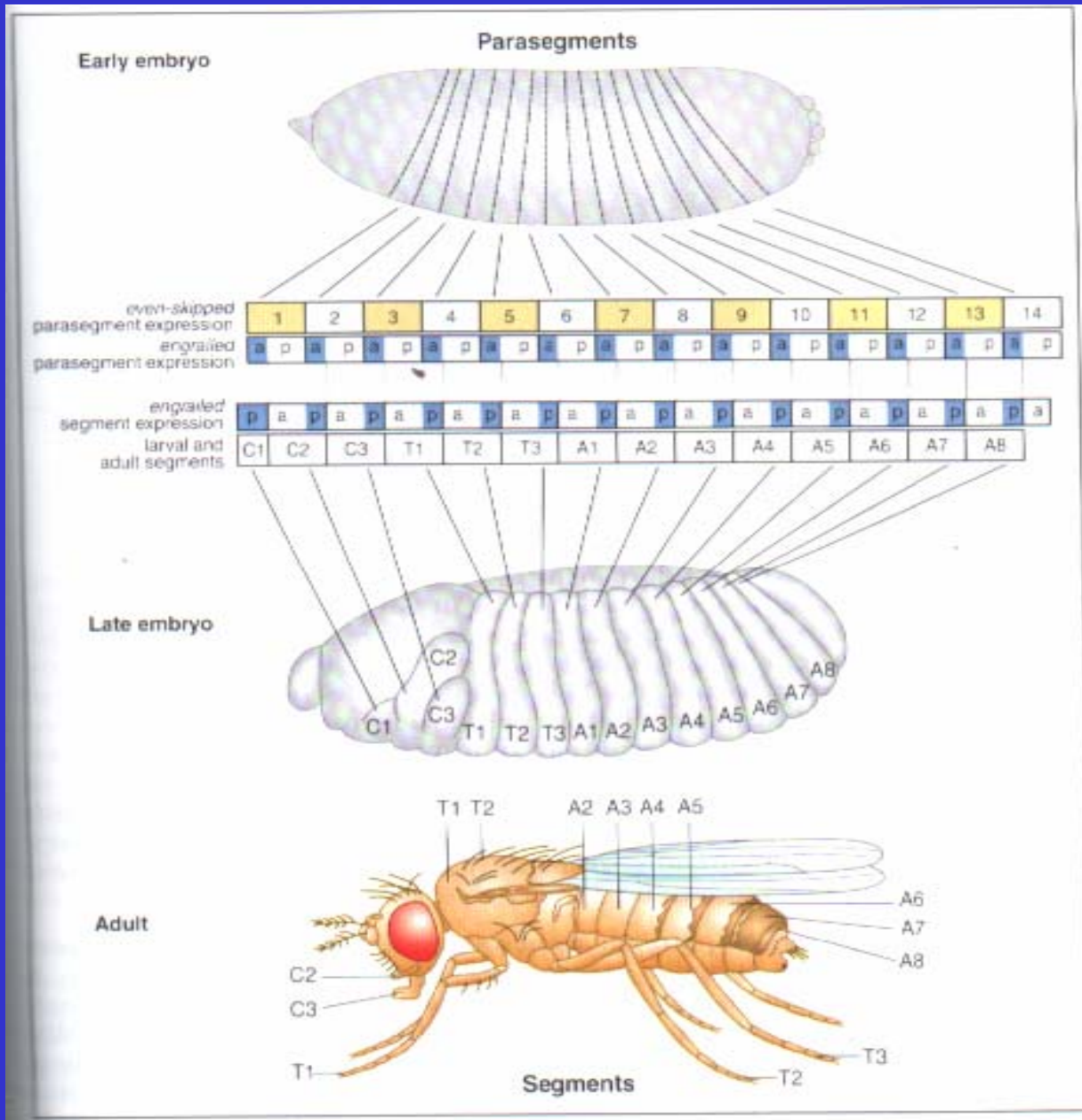
Top-down action: biological development

Reading of DNA codings: The central process of developmental biology, whereby positional information determines which genes get switched on and which do not in each cell [Lewis Wolpert], so determining their developmental fate, is a top-down process from the developing organism to the cell, largely based on the existence of gradients of positional indicators (morphogens) in the body.

Without this feature organism development in a structured way would not be possible, for each cell has the same genetic material. Thus the functioning of the crucial cellular mechanism determining the type of each cell is controlled in an explicitly top-down way .



Positional expression of genes leading to segments ...



Body position



Positional Information



Gene Expression



Amino acid sequence

Top-down action: mind on world and body

Top-down action occurs from **the mind to the body** and thence **into the physical world**:

When a human being **has a plan in mind** (say a proposal for a bridge being built) and this is implemented, then enormous numbers of micro-particles are moved around as a consequence of this plan and in conformity with it.

Thus in the real world, the detailed micro-configurations of many objects (which electrons and protons go where) is in fact to a major degree determined by the macro-plans that humans have for what will happen, and the way they implement them.

Hierarchical structure: 2

Cosmology

Astronomy

Geology

Materials

Sociology

Psychology

Physiology

Biochemistry

Chemistry

Physics

Particle Physics

Hierarchy of causal relations

* *The right hand side involves goals & conscious choices*

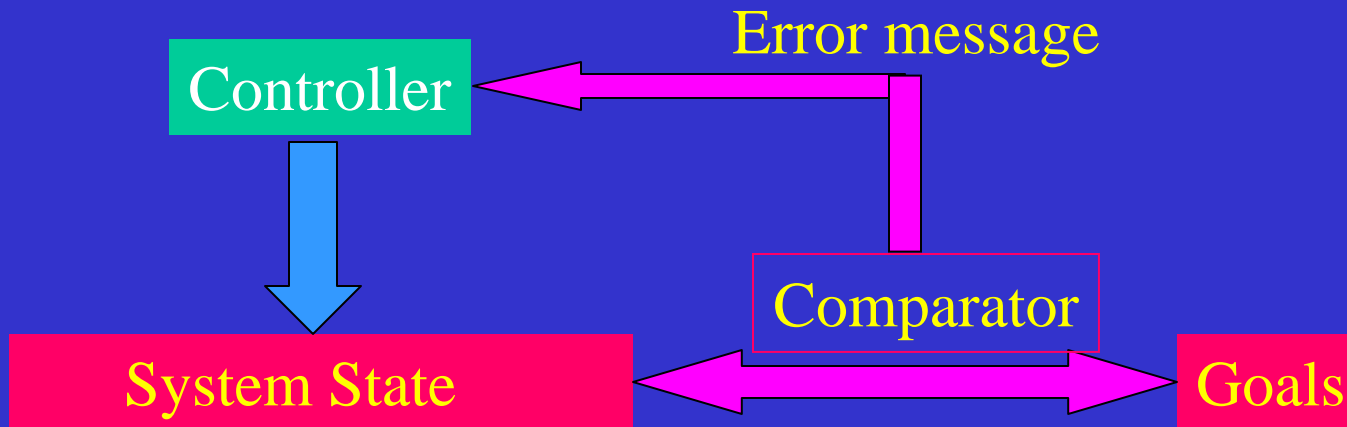
Top-down action: effect on components

A key feature of top down action is that it is not just an aggregation of invariant components. Rather it changes the nature of the components at each level.

- Atoms in chemical bonding (electron sharing, reactivity)
- Neutrons in nuclei (instability of free neutron)
- Electrons in atoms (Thomson scattering)
- Plants adapted to the environment in which they live
- Individuals in society (mind is shaped by other minds and by society: *see Merlyn Donald, Berger and Luckmann*)

3: Feedback control systems and information

Feedback control (*cybernetic systems*):



- Examples*
- the temperature of a shower
 - the speed of a steam engine
 - the direction of an automobile

This is the way information is causally effective

The role of goals and information

The series of goals in a feedback control system are causally effective

They embody information about the system's desired behaviour or responses – living systems are goal seeking (*'teleonomic'*)

These goals are not the same as material states, for they are desired rather than actual states, although they will be represented by material states and systems that will make them causally effective through such representations

A complete causal description must necessarily take them into account. They exist as emergent properties of the system – they are not embodied in any component on its own.

The role of goals in dynamics

The nature of causality is different when feedback control systems are guided by goals

Standard Physics

(physics, equations of state, initial conditions) → (outcomes)

(initial conditions) → (outcomes)

Feedback control systems

(physics, physical structure, goals) → (outcomes)

(goals) → (outcomes)

- *The outcome of a feedback control system is determined by the goals rather than the initial data*

The nature of goals 1

Homeostasis in the human body:

- Body temperature
- Blood Pressure
- Normal heart rate
- Transport across cell membranes

- each is governed by implicit goals, embodied in the physical structure of the body:

'the human body has literally thousands of control systems in it'
[Guyton]

- They occur at all higher scales in the hierarchy

- They have been built in through the adaptive process of evolution and so embody images of environment

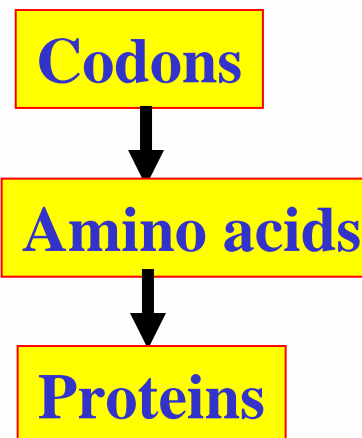
Supramolecular chemistry

The key step in the hierarchy: the chemistry of the intermolecular bond (Jean Marie Lehn): where physics underlies information use

- *self-organisation directed via molecular information*
- *enables programmed chemical systems and functional molecular devices*
- *information storage and read-out via structural features and states of connectivity of a chemical entity*
- *basis for adaptive systems where error correction takes place and design meets selection*
- *this in turn enables evolutive chemistry where the features acquired by adaptation are conserved and transmitted*
- *Chemistry of molecular information, particularly DNA*

1st position (5' end) ↓	2nd position				3rd position (3' end) ↓
	U	C	A	G	
U	Phe Phe Leu Leu	Ser Ser Ser Ser	Tyr Tyr STOP STOP	Cys Cys STOP Trp	U C A G
C	Leu Leu Leu Leu	Pro Pro Pro Pro	His His Gln Gln	Arg Arg Arg Arg	U C A G
A	Ile Ile Ile Met	Thr Thr Thr Thr	Asn Asn Lys Lys	Ser Ser Arg Arg	U C A G
G	Val Val Val Val	Ala Ala Ala Ala	Asp Asp Glu Glu	Gly Gly Gly Gly	U C A G

Figure 3-15 The genetic code. Sets of three nucleotides (codons) in an mRNA molecule are translated into amino acids in the course of protein synthesis according to the rules shown. For example, the codons GUG and GAG are translated into valine and glutamic acid, respectively. Note that those codons with U or C as the second nucleotide tend to specify the more hydrophobic amino acids (compare with Panel 2-5, pp. 54-55).



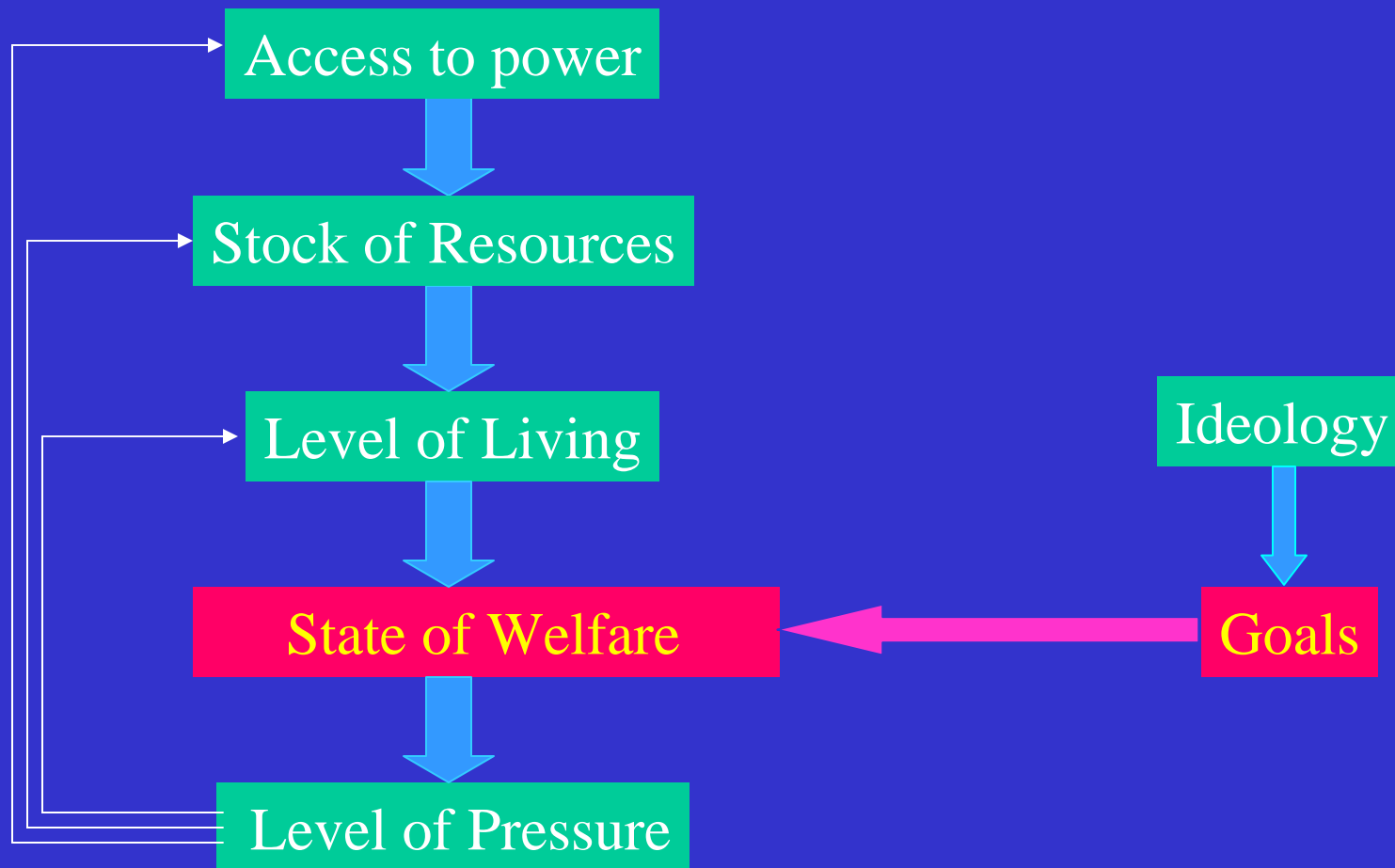
The genetic code: triplets of bases code for amino acids that form proteins

The nature of goals 2

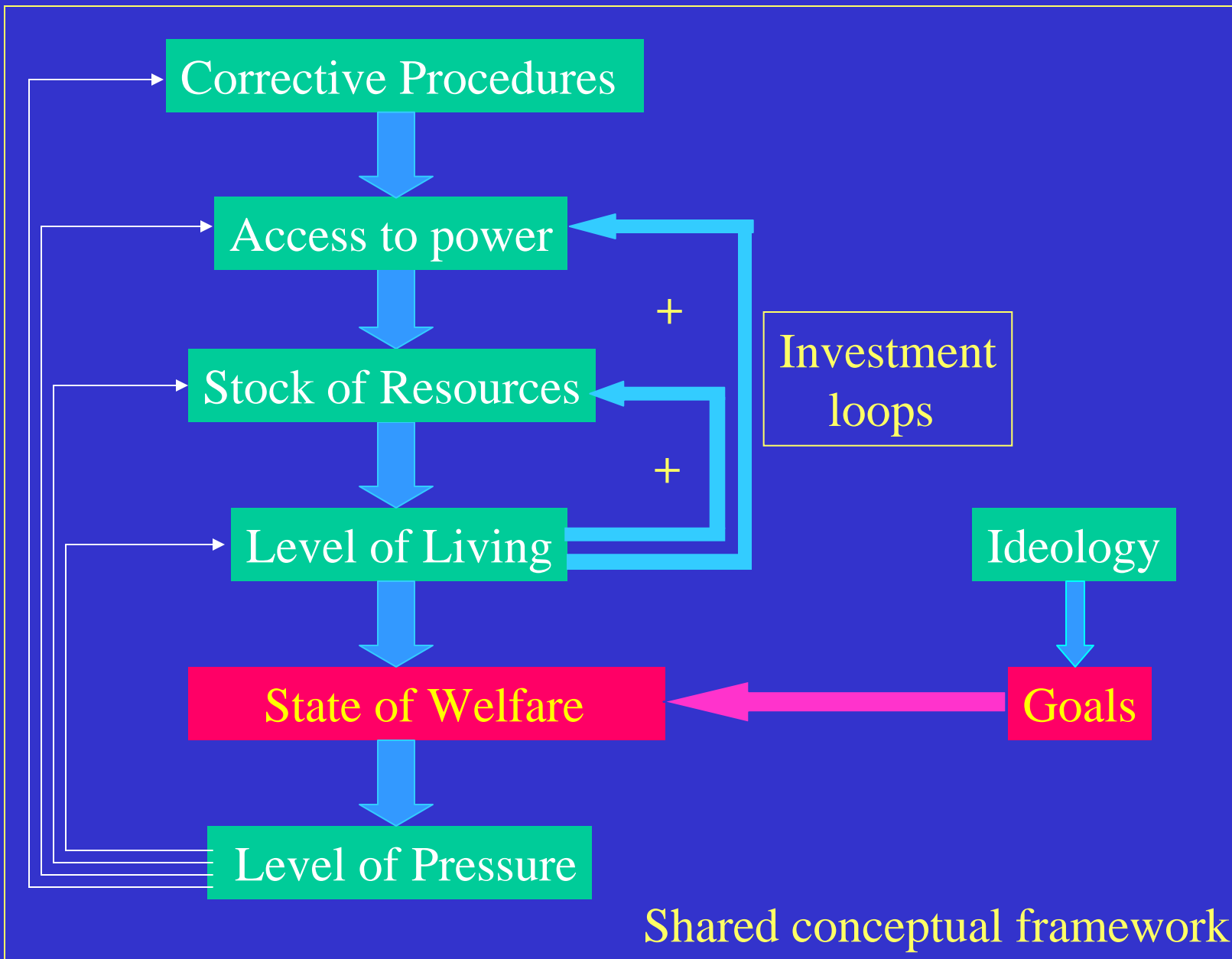
Conscious Goals in human activity:

- *our actions are governed by hierarchically structured goals at all structural levels in society*
- *these may be explicit or implicit, qualitative or quantitative*
- *they are not physical quantities*
- *they can be represented in many ways, so are effectively an equivalence class of representations*
- *they are adaptively formed in response to experience: learning takes place in particular contexts*
- *the mind responds to the meaning of symbols in the relevant social context*

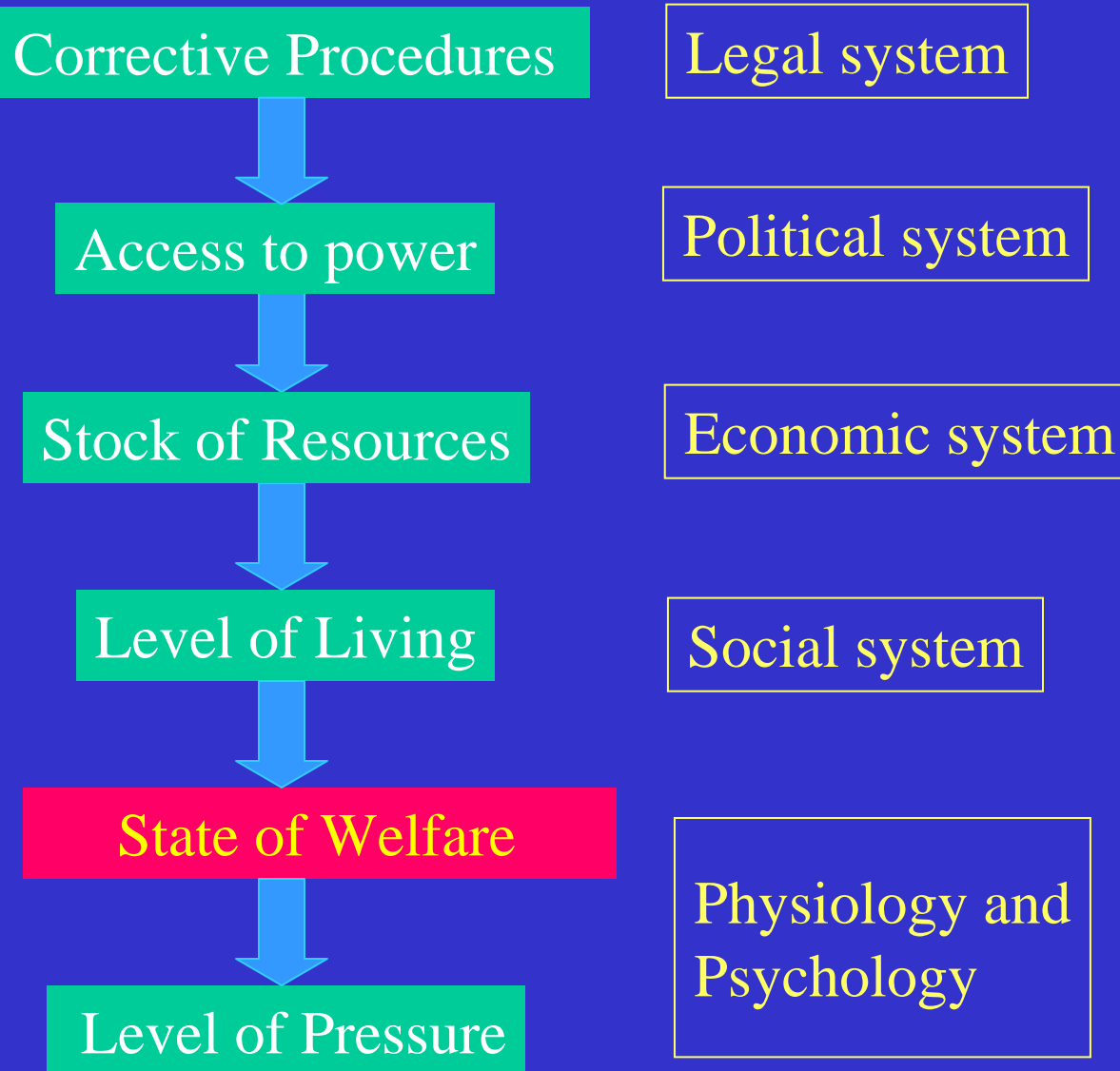
Society: The Quality of Life System



Society viewed as a multi-level feedback control system for the flows of 'resources' of all kinds enhancing well-being



Completing the system: error correction, investment, understanding

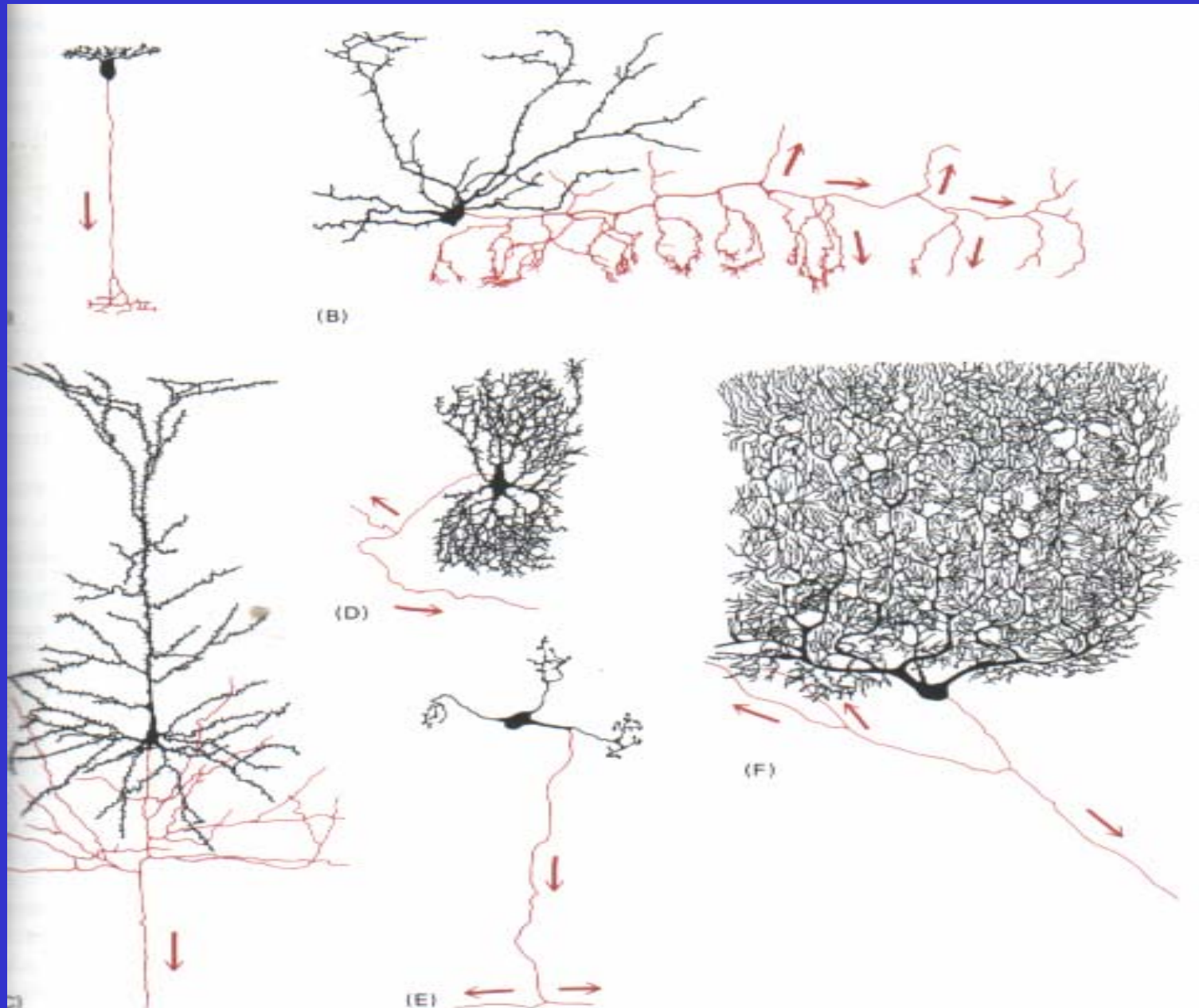


The different social systems/processes related to the resource flow

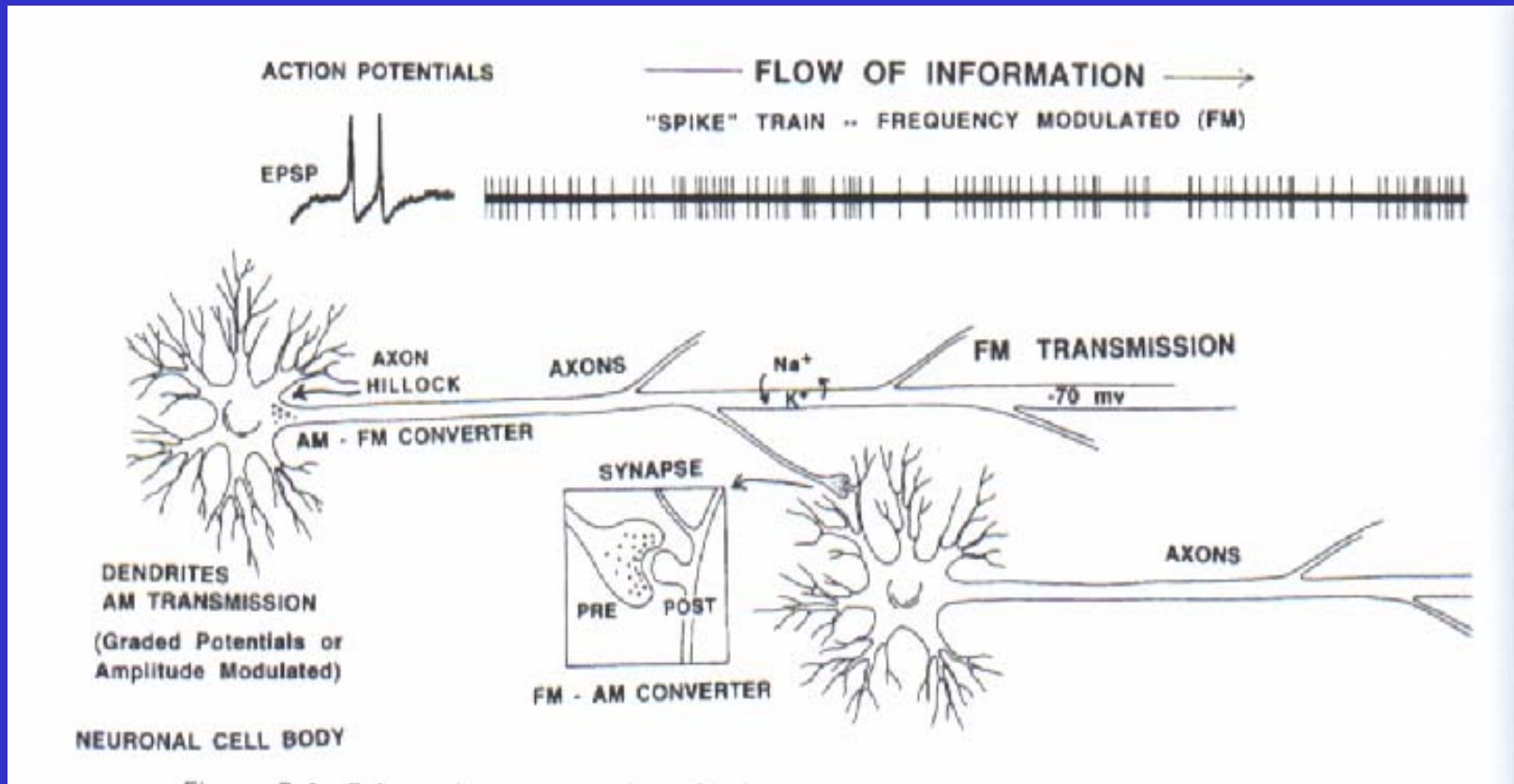
The Effectiveness of Consciousness

Dimensions of consciousness:

- rationality and understanding
 - feelings and intentions
 - social systems/constructions, e.g. laws/money
-
- *Concepts are not the same as brain states*
 - *They can be represented in many different ways*
 - *These are all causally efficient: they effect the nature of physical objects in the world*
 - *Function is based in neuronal structure*

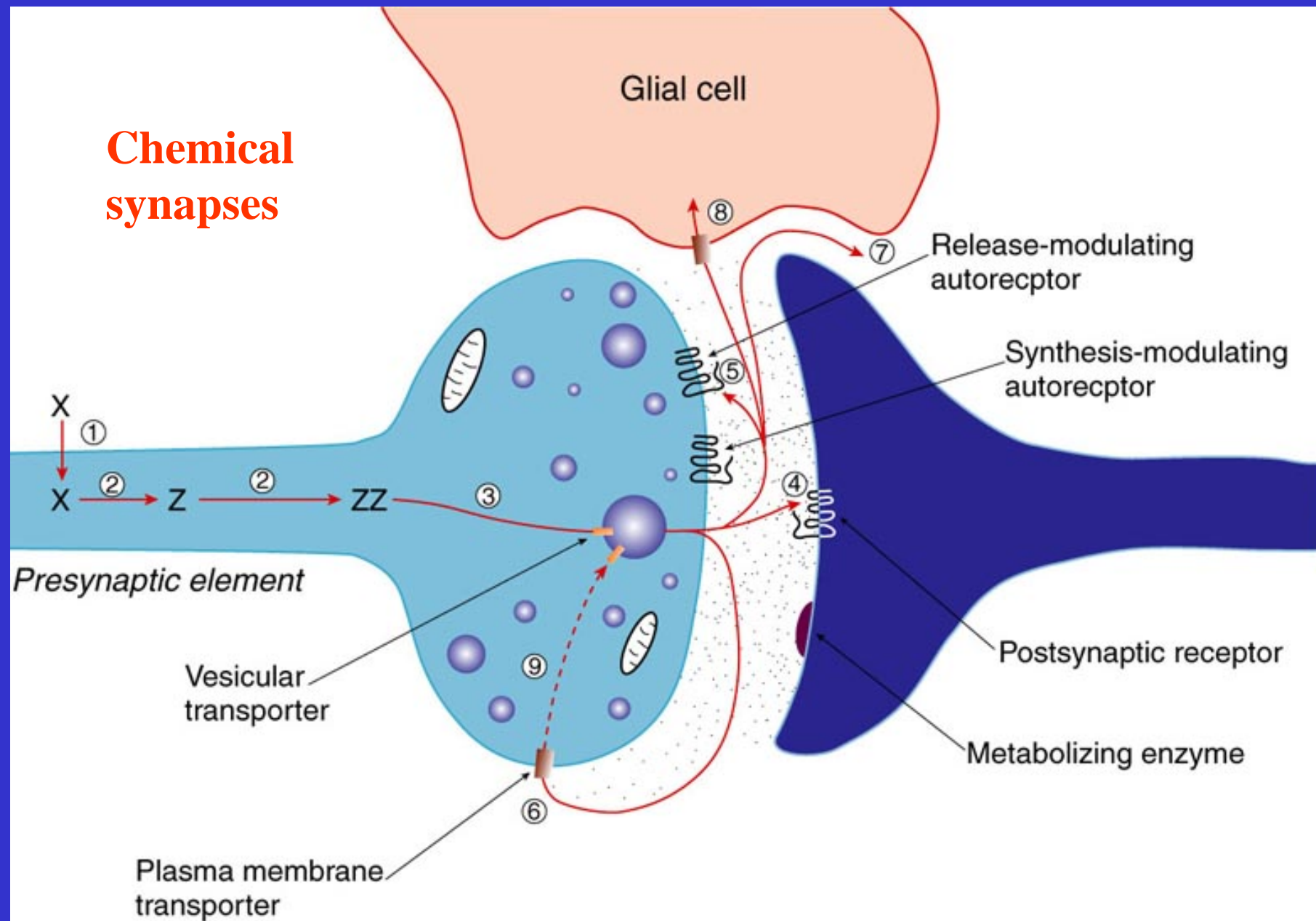


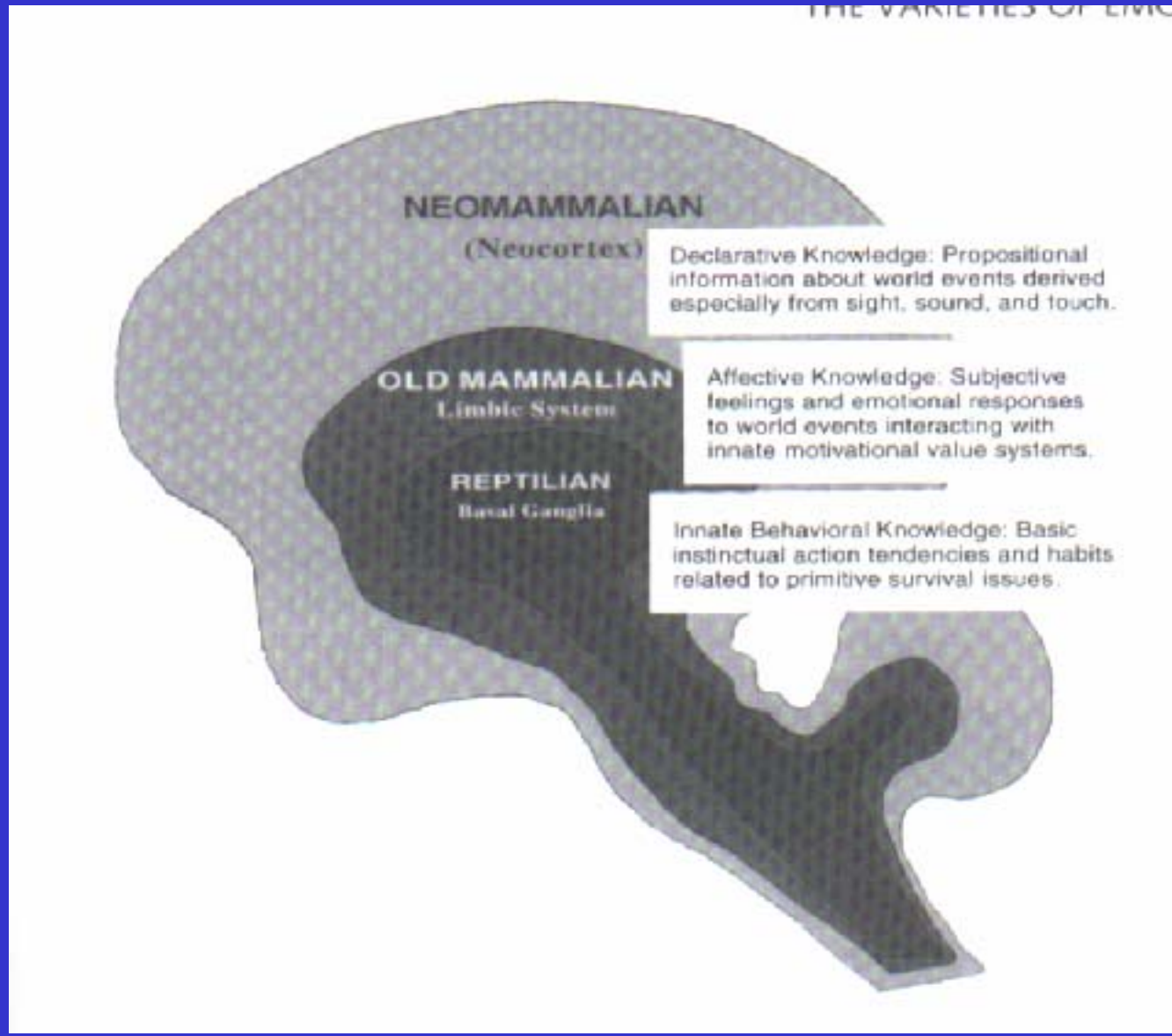
The complexity of real neurons



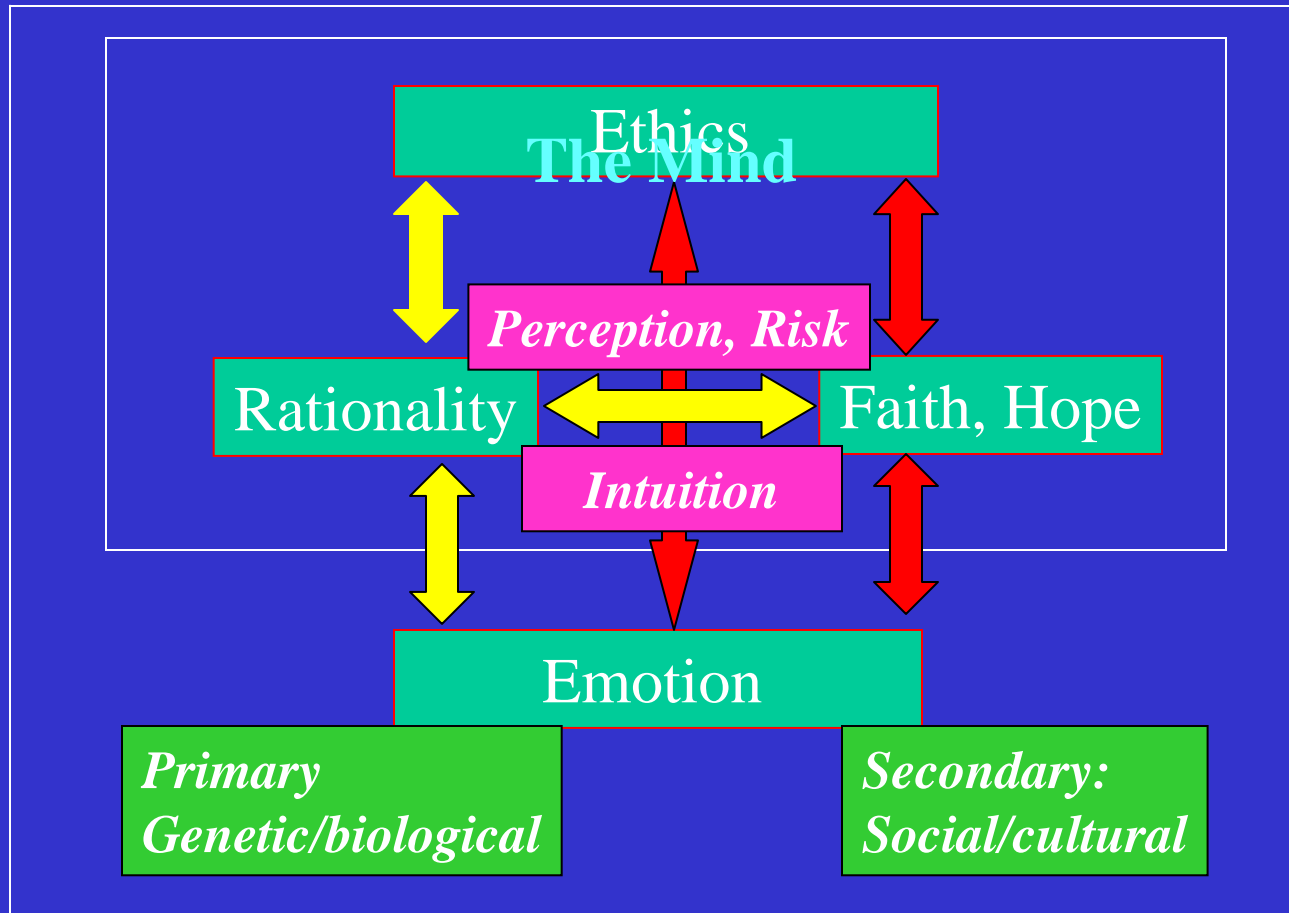
Information flows: dendrites to nucleus to axon to synapse

Chemical synapses





The value system originates in the limbic system



The individual mind: Each of Rationality, Emotions, Ethics, Faith and Hope are influenced by each of the other, with reason being the key player trying to bring the others into harmony.

Each of these aspects is causally effective.

4: The nature of causality

The key point about *causality* in this context is that **simultaneous multiple causality** (inter-level, as well as within each level) is always in operation in complex systems.

Any attempt to characterise any **partial cause** as the whole (as characterised by the phrase `nothing but') is a fundamentally misleading position. Indeed this is the essence of *fundamentalism*: claiming a partial truth to be the whole truth.

This is important in regard to claims that any of physics, evolutionary biology, sociology, psychology, or whatever are able to give *total* explanations of any specific properties of the mind. *Rather they each provide partial and incomplete explanations.*

The nature of explanation

The key point about **explanation** is that we take for granted most of the causes in operation in any particular situation and then ignore them, focusing on the particular item of interest that is needed to understand what happens *when all the rest are taken for granted but without which it would not happen.*

She died

- because I sent her to get some cigarettes from the shop
- because the road was wet so the car could not stop in time
- because she was inattentive to the traffic
- because she saw her dog on the other side of the road
- because of Newton's laws of motion applied to the car
- because her heart stopped beating
- because the ambulance took too long to get here

All are true aspects of the causal nexus that lead to her death

Causality: Bottom-up and top-down explanation

- always multiple levels of explanation that all hold at the same time:
no single explanation

so one can have a top-down system explanation as well as a bottom-up explanation, *both being simultaneously applicable*

e.g. why aircraft fly [Russell Ackoff]

- the bottom up view: kinetic theory/Bernoulli's law
- the top down view: it was designed that way
- the same level view: the pilot is flying it to fulfill the timetable

In particular: the highest level of intention [values/ethics] is causally effective: *this is the choice of criteria for what are acceptable goals, and so controls all lower level goal choices.*



Ivy Mike mushroom cloud, Nuclear bomb test, Bikini Atoll.

Hierarchical structure: 3

Ethics

Cosmology

Sociology

Astronomy

Psychology

Geology

Physiology

Materials

Biochemistry

Chemistry

Physics

5: Emergence and the Laws of Nature

- Laws of nature underlie this
- Permit but do not completely causally control what happens
- Hence are of *fine-tuned nature*
- How they do it is not fully clear – what fine-tunings at the lower levels are needed for the entire higher level hierarchy to exist

Emergent Properties

While emergent properties can in principle be determined from lower level properties, in practice this is not possible

- *chemistry from physics*
- *neuronal behaviour from physics and chemistry*

In practice we have to introduce **new phenomenological laws at each level** in order to understand the higher level behaviours

“**Effective theories**” (not always directly deducible from the underlying theory) are the way we attain understanding of the hierarchy of structure).

- *e.g. the Fermi theory of weak interaction*

`Fundamental physics`

Human thought and physics :

- *Human thoughts can cause real physical effects*
- *This is a top-down action from the mind to the physical world*
- *This is not included in what physics deals with*

For example: Chess

Physics cannot predict the movement of chess pieces as that involves human volition – it cannot predict the choices that will be made

Physics cannot even characterize the origin of the possibility space for chess pieces – the set of allowed moves – as that derives from social agreements

There is no charge and force field for each kind of chess piece.

`Fundamental physics`



'Fundamental physics'

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`Fundamental physics`

Thus even if physics attains its goal of a “Theory of Everything” such as M-theory, it will be causally incomplete because it will not include in its ambit human intention . *This is not a statement of vitalism or dualism: it is a simple fact about the nature of physics, independent of your theory of the brain*

Yes of course elementary forces determine what happens in then brain in a bottom up way – but that is only part of the picture
- *top down action is also taking place implementing higher level meaning, which is why physics alone cannot give an answer*

- *Just stating `what happens at higher levels is determined by these bottom-up interactions` is a theory with zero predictive power. It does not begin to characterise what is actually going on or the nature of the outcomes, which have crucial higher level aspects.*

`Fundamental physics`

In particular this applies to the development of human beings themselves. For example, child development depends on

- *Parental responsiveness to the child's attachment needs*
- *Parental presence or separation from the child*
- *The mother's ability to intuit her child's subjective state, and respond to it appropriately*

[Stevens and Price, *Evolutionary Psychiatry*]

These effects are amongst those that determine the health of the infant, and hence the physical state of its body: thus the micro-states of numerous electrons and protons in the bodies of living beings. They are thus causally effective in the real world.

- *Physics cannot even characterize the relevant variables, let alone the interactions that are causally effective in this context.*

`Fundamental physics`

Human thought and physics :

* At present there is no way to express this kind of interaction in the language of physics, even though our causal schemes are manifestly incomplete if this is not taken into account

-physics accounts for bottom-up actions in the hierarchy, but not crucial aspects of top-down causation

•The minimum requirement to do so is to include the relevant variables in the variables considered [c.f. weather forecasting]:

- to somehow attempt to include consciousness in physics

• *That then makes these variables and their effects a part of physics - or perhaps of fundamental physics [Wheeler, Penrose]*

Physics Itself

In particular this applies to the physics itself

- *Is physics itself (the theory through which we understand the physical nature of the material world) `nothing but' a brain state?*

No: it is the accumulated wisdom of 300 years, realised in an abstract space of social agreement

- supported by numerous experiments realised through collaborative endeavours and use of sophisticated measuring apparatus

- based in sophisticated theories of how things work

- realised through a guild system of training and passed on from generation to generation by social communication

- *Physics cannot characterize its own nature and activity within its own paradigm [the self-referential problem]*

6: The challenge to physics and chemistry

- The challenge to physics and chemistry is that the higher levels of the hierarchy of complexity are demonstrably causally effective, in particular this is true of *consciousness* and *ethics*;
- But conscious plans and intentions and emotions are not describable in present day physical terms.

For example:

there is no physics experiment that can determine what will be the next experiment to be undertaken by the physicist!

- the intentionality of classical measurements is outside its scope

If physics were causally complete this would not be so

The challenge to physics and chemistry

- *Thus physics (and chemistry) has two choices:*

Either

- 1. *Extending their scope of description to encapsulate such higher level causal effects,*

for example *including new higher level variables $\Psi(x,t)$ representing thoughts and intentions* and so enabling them to start to model the effects of consciousness and its ability to be causally effective in the real physical world,

or

The challenge to physics and chemistry

- 2: *Deciding that these kinds of issues are outside the province of physics*, which properly deals only with inanimate objects and their interactions.

In that case physics and chemistry must give up the claim to give a causally complete description of interactions that affect the real physical world.

They cannot even account for a pair of spectacles.

- Hence physics and chemistry do not *by themselves* provide an adequate basis for metaphysical speculations about the nature of existence. They represent part but not all of the causal nexus in operation.

The challenge to physics and chemistry

- *The cosmic context: Physics cannot give a complete causal account of higher level meanings because if it did they would be uniquely determined by the random initial data for the universe at the time of decoupling of matter and radiation*
- The content of this talk would be implied by that data. That is not remotely plausible. Meaning comes into being that did not exist at earlier times. This is possible only because the higher levels develop their own autonomous independent of the lower levels of causality and structure.
- *The Challenge: Showing how physics and chemistry can underlie higher levels of existence with their own autonomous causal powers.*



Questioning the taken-for-granted

- The key to deep philosophical (and scientific) understanding is often the readiness and ability to question the taken for granted aspects of the situation that are normally not questioned
 - e.g. *Einstein and the nature of space and time*
- **Biology**: the existence of laws of physics that allow emergence of biological structure
- **Physics and chemistry**: the ability of theoreticians to create and develop sophisticated theories, and of experimenters to decide on and carry out the specified experiments
- *Because these are taken for granted they are not often questioned. But they are key issues.*

Hierarchy and Modularity

The principles of **hierarchy** and **modularity** have been investigated usefully in the context of computing, and particularly in the discussion of *object-oriented programming*, and it is helpful to see how these principles are embodied in physical and biological structures. They enable simultaneous **top-down** and **bottom-up** action, with responses based on **stored information** and **past history**.

This is the basis of the coming into being of and the effectiveness of higher levels of **emergent order** in terms of

- *enabling higher-level phenomenological understanding of behaviour,*
- *described in the language suitable to that level of the hierarchy*
- *thus underlying effective theories of behaviour at each level.*

Fundamental physics 1

- *What feature of physics is the key to existence of truly complex structures?*
- What for example allows **modular separation** of sub-nuclear, nuclear, atomic, and molecular properties from each other in such a way as to allow the development and functioning of DNA, RNA, proteins, and living cells?
- Whatever it is, this must claim to be the **'truly fundamental' feature of physics**
- *what physics underlies supramolecular chemistry?*
- it is the foundation of the complexity we see

The Hierarchy of Structure:

Psychology/ Behaviour

Botany/zooology/physiology

Cell biology

Biochemistry

Chemistry

Atomic Physics

Particle physics

Separation of structural levels, independence of levels

Fundamental physics 2

Is the key:

- the general nature of *quantum theory* (e.g. superposition, entanglement, decoherence) and its classical limit?
- the specific nature of *quantum field theory* and *quantum statistics*, [Yes: stability of matter] and/or Yang-Mills *gauge theory* ?
- the specific *potentials* and *interactions* of the standard particle physics model and its associated *symmetry groups* ?
 - *basic particle properties* (existence of three families of quarks, leptons, and neutrinos, for example)?
 - *basic properties of forces* (effective existence of four fundamental forces; their unification properties)?

Fundamental physics 3

Is the key:

- the specific *masses* and *force strengths* involved?
- the value of *specific constants* such as the fine structure constant?

Or is it

- *The combination of all of these?*

[Craig Hogan: *out of the twenty parameters of the standard model, complexity depends on just five of its parameters.*

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- But then why do they work together so cunningly?
- *they are the foundation of human life and of the brain*