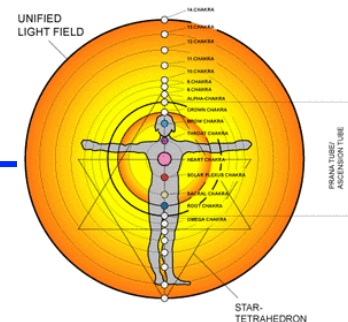
AS-74.4192 Elementary Cybernetics

Lecture 10:

Special Challenge: Cognitive Systems



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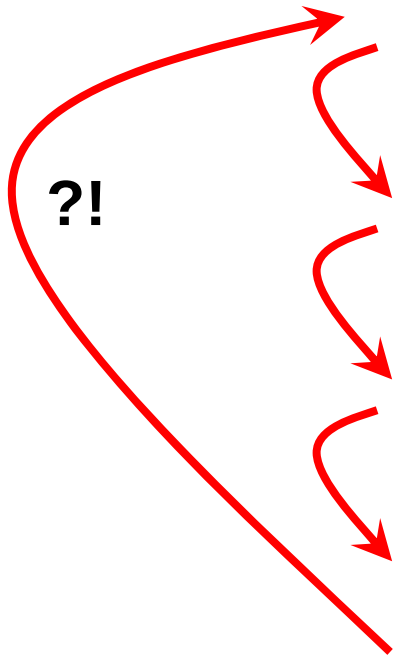
Cycles into spirals?

- The history of cognitive science is rather turbulent...



- **Behaviorism (early 1900's)**
  Emphasis on input-output reactions
- **Cognitivism (1960's)**
  Emphasis on mental structures
- **Constructivism**
  Emphasis on adaptation and learning
- **"Brooksianism" (1990's –)**
  Emphasis on interaction and survival

– Indeed, back to *Immanuel Kant*!

- Neocybernetics emphasizes *both* environment and structure

Neocybernetic view

- The analyses started from neurons – now let us return there!
- There are many levels of emergence in the brain:
  - First, there are the *symbols* / *concepts* / *categories* emerging from data
  - Then, there is *intelligence*
  - Finally, there is *consciousness...*
- Do we now have some tools to discuss these issues in the neocybernetic framework?
- First observation: The numeric nature of dynamic attractors as constituting the patterns helps in some age-old problems:
  - *Hermeneutic cycles* change to convergent series, as does
  - *Infinite regress of homuncula*

Contribution to artificial intelligence?

- One of the traditional AI challenges – the "frame problem", not understanding the context, absence of "common sense" – is solved because of high dimension of data!?
- Another traditional problem – the gap between symbolic and numeric representations – is solved by applying computation to make distinct structures (symbols) emerge from data!?
- Paradox of the "Brain Prosthesis": Yes, the "self" remains even if all neurons are substituted – the structure is relevant, and the "basins of attraction", not the momentary states
- Paradox of the "Chinese Room": Yes, the system can "understand" its observations in the narrow sense of *contextual semantics*

- Cognition, and especially intelligence, are sensitive areas – it is something that is human's *own*
- There are many arguments + counterarguments, enthusiasm and disappointments

- Claim 1 (extreme pessimism): "Human mind cannot study its own functioning"
- Claim 2 (extreme optimism): "After twenty years computers are so fast that they beat the human"

Why is it *always* 20 years in AI?!

- Here, take the middle course:
- Cognition can be explained if only correct model structures and powerful conceptual tools are available

- Again, apply neocybernetic intuition:

  Search for stationary and statistically motivated structures where high-dimensionality and interactions suffice to result in functionalities corresponding (?) to the cognitive ones

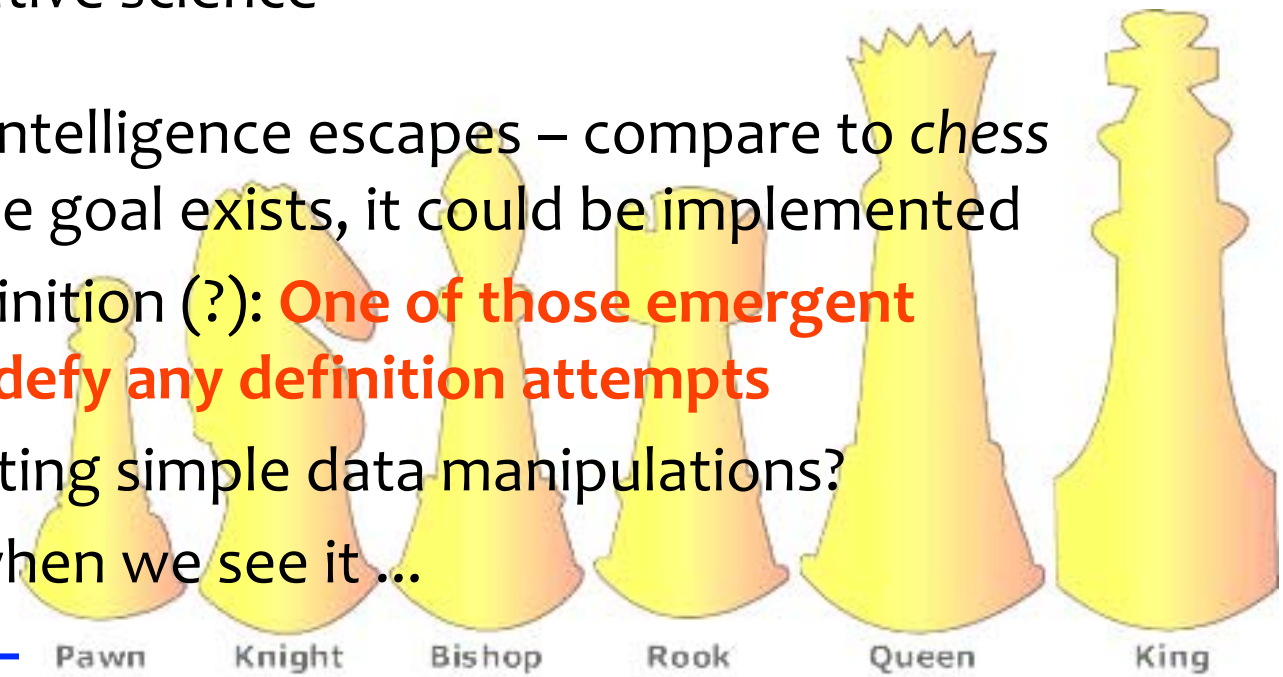
- Assume that there are (despite the low-level hard-wirings) no specialized faculties in the brain – taken to the extreme, one can employ the "tabula rasa" metaphor

But first...

What *is* intelligence?

- Is it enough that behavior *looks* intelligent (Turing test)?
  This is still today the main approach in robotics (Brooks)
- This "black box" approach has its roots in *behaviorism*; however, today *cognitivism* or *constructionism* are mainstream cognitive science

- The definition of intelligence escapes – compare to *chess game*: If a concrete goal exists, it could be implemented
- Best available definition (?): **One of those emergent phenomena that defy any definition attempts**
- Illusion of cumulating simple data manipulations?
- We recognize it when we see it …



Goal now: "Deep" rather than "shallow" intelligence

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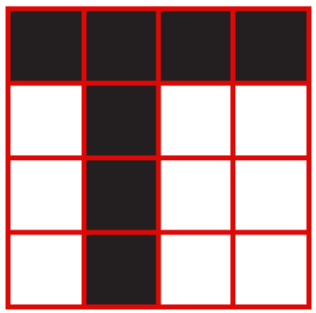
How experts see intelligence (?)

- "Intelligence = ability of recognizing *similarities* or *patterns*" – and the Mensa members should be experts in defining it!



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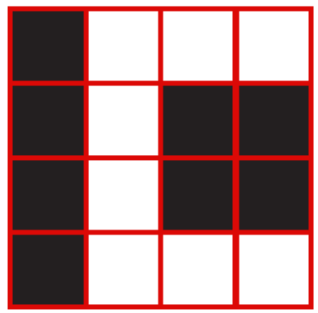

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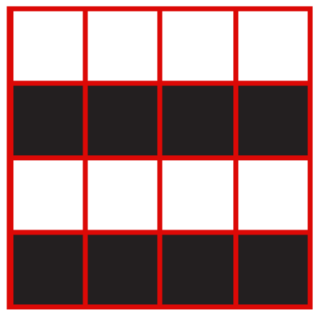

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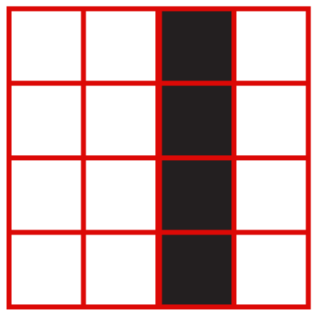

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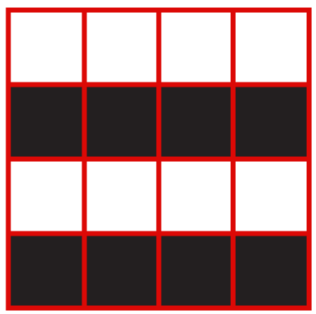

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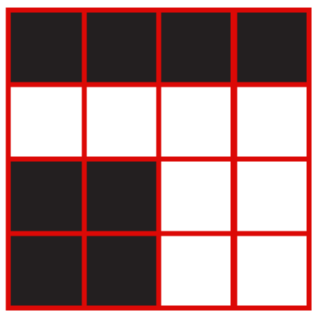

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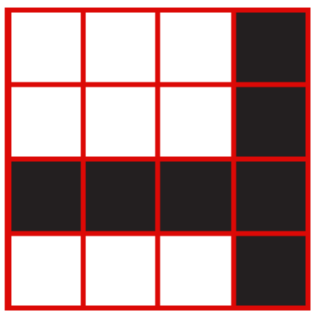

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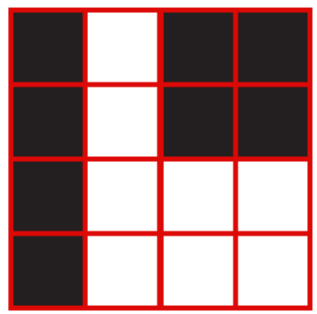


NO

Eastern vision

- For example, in Zen Buddhism the role of *awakening* as a moment of intuitive, associative understanding, lacking all interpretation, is emphasized
- A *koan* is a saying which challenges the habitual and rational thought processes of the mind

...If you meet the Buddha, kill him. – If you are *thinking* about Buddha, this is delusion, not awakening.

... "Exactly how do you help people?" a disciple inquired. "I get them where they *cannot* ask any more questions", the Master answered.

Before Zen, men are men and mountains are mountains, but during Zen, the two are confused. After Zen, men are men and mountains are mountains again.

"Understanding" is **not** declarative nor procedural

Hands on – bottom-up view

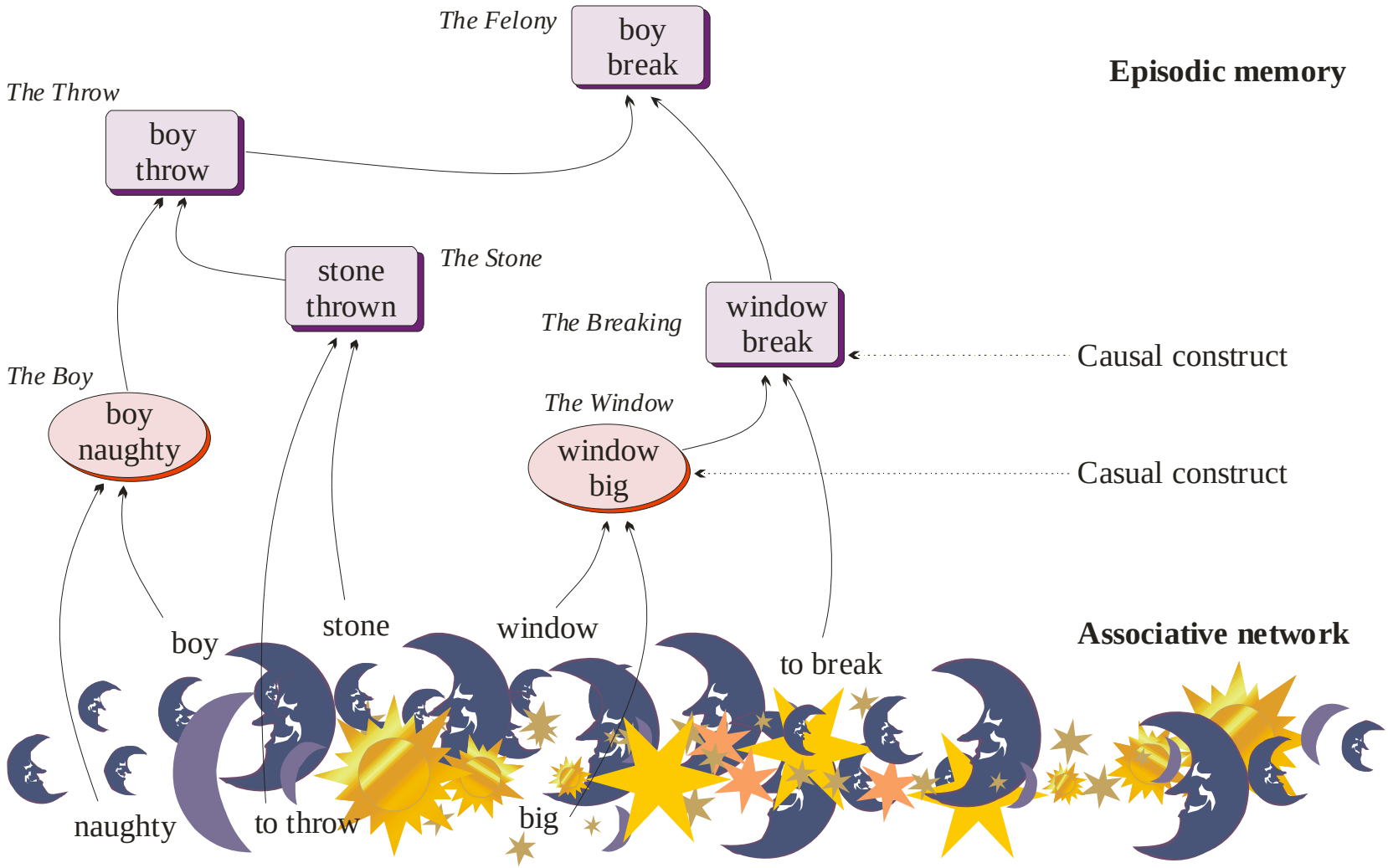
- Assumption: Cognition is based on identical neurons, neurons follow Hebbian learning principles

  What kind of structures are possible in such a system?

- Neurons are the *atoms of association* – localized centers of association
- The pool of neurons compete for activation
- No additional functionalities are needed: The neuron grid suffices to implement non-trivial cognitive functionalities assuming it has high enough dimension and there is enough iteration provided – without "operating system"

  ...But how can a *story*, for example, be stored?

Flow of thought with a network of neurons



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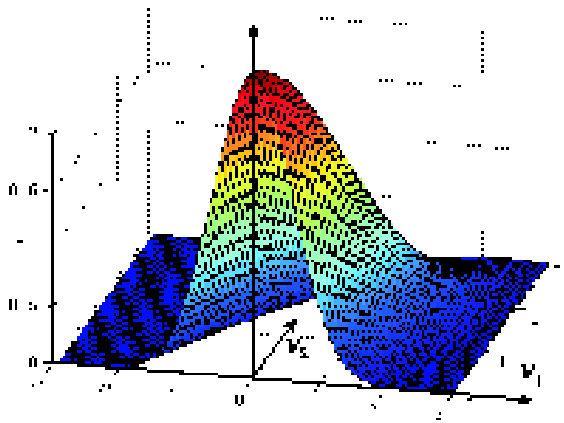
A neuron (set of neurons) connects the simultaneously active signal sources

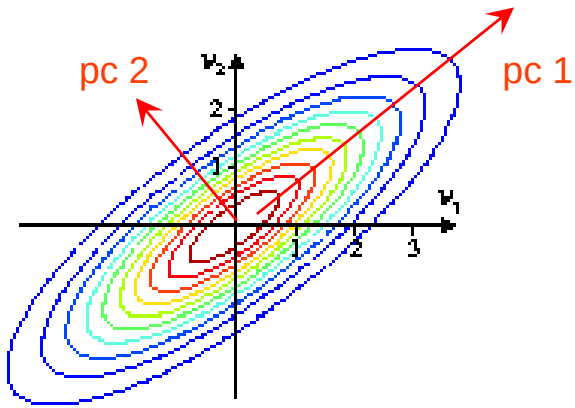
What's special about cybernetic neurons?

- Novice information processing is declarative, whereas expert information processing is associative
- The key dilemma in cognitive science are those of *shift from novice to expert* and *automatisation*: *Now one can study it*
- When the neurons start adapting according to the reformulated Hebbian laws, such a shift can be explained:
  - If some neurons are often activated at the same time, connections are constructed between them
  - Later, the sequential chain of neurons becomes a parallel group of simultaneously active neurons, competing for the same input resources
  - Finally, when the connections are complete, the neuron is "swallowed" in the *associative medium* of pre-existing (conscious or subsymbolic) concepts – being available for "next-level" associations

“Associative medium”?

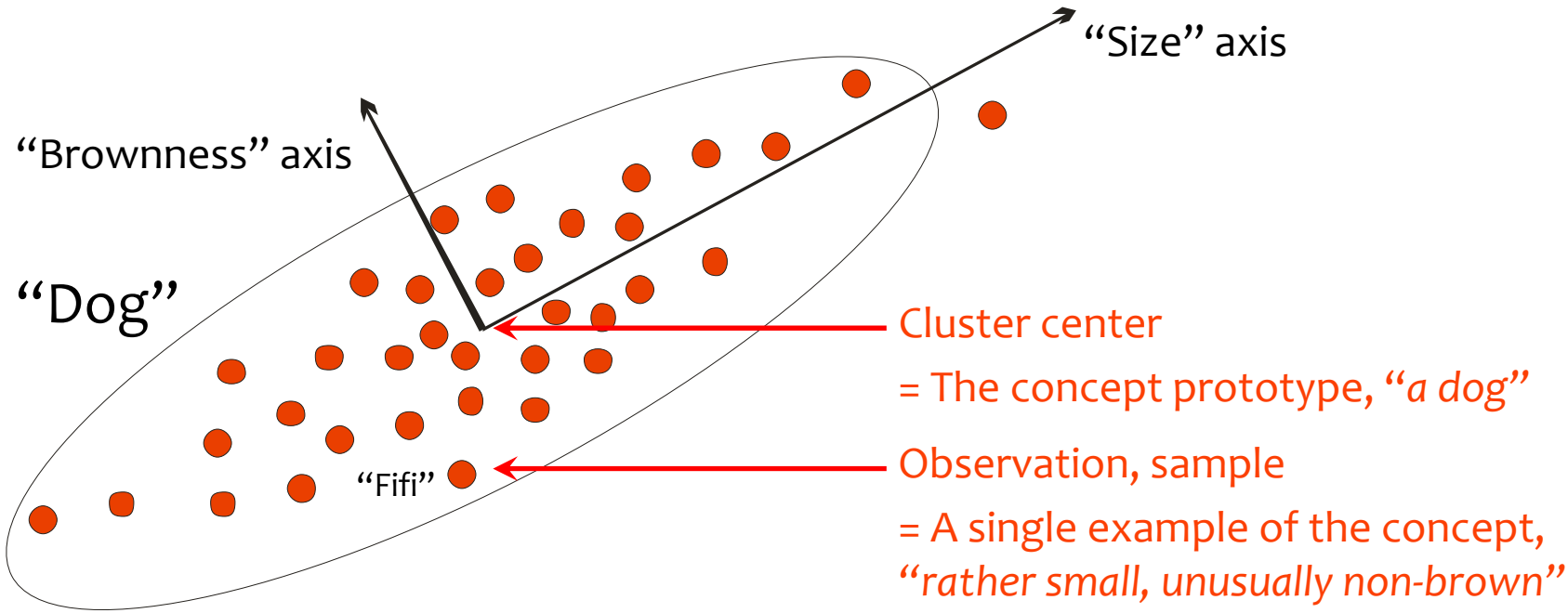
- What do the above conceptual structures tell about the structures in the (hypothetical) observation data?
- So, assume the mental machinery is cybernetic:
  - The neocybernetic model structure is based on principal components
  - This structure is *forced onto the observation data*
- So, assume the data can be characterized by the pc’s:
  - Principal components can be interpreted in terms of *Gaussian distributions*
  - *Ellipsoids* in data space (“conceptual space” of Gärdenfors)





“Numeric chunks”

- Data clusters, relevant conglomerates of observations:
  Category centers, patterns, “concepts”, chunks
- Degrees of freedom in data, fine tuning within the cluster:
  Features, nuances, “attributes”



Connections

- "Prototype theory" by Eleanor Rosch and others:

  Semantic categories (concepts) are determined in terms of examples, where some examples are more central than the others
- AI implementation: Case-Based Reasoning (CBR)

  Problem: Difficult to quantify "distances" between examples
- Now, in the neocybernetic framework, the distances are easily calculated

- Embodied Embedded Cognition (EEC):

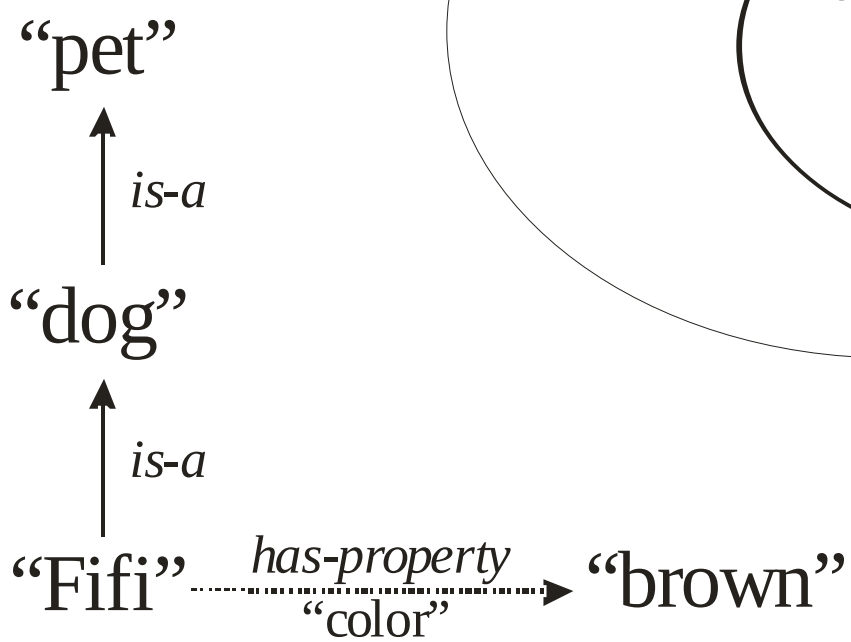
  Real intelligence emerges out of the interplay between brain, body, and world

- The behavior of an associative network structure can be characterized in different conceptual frameworks:

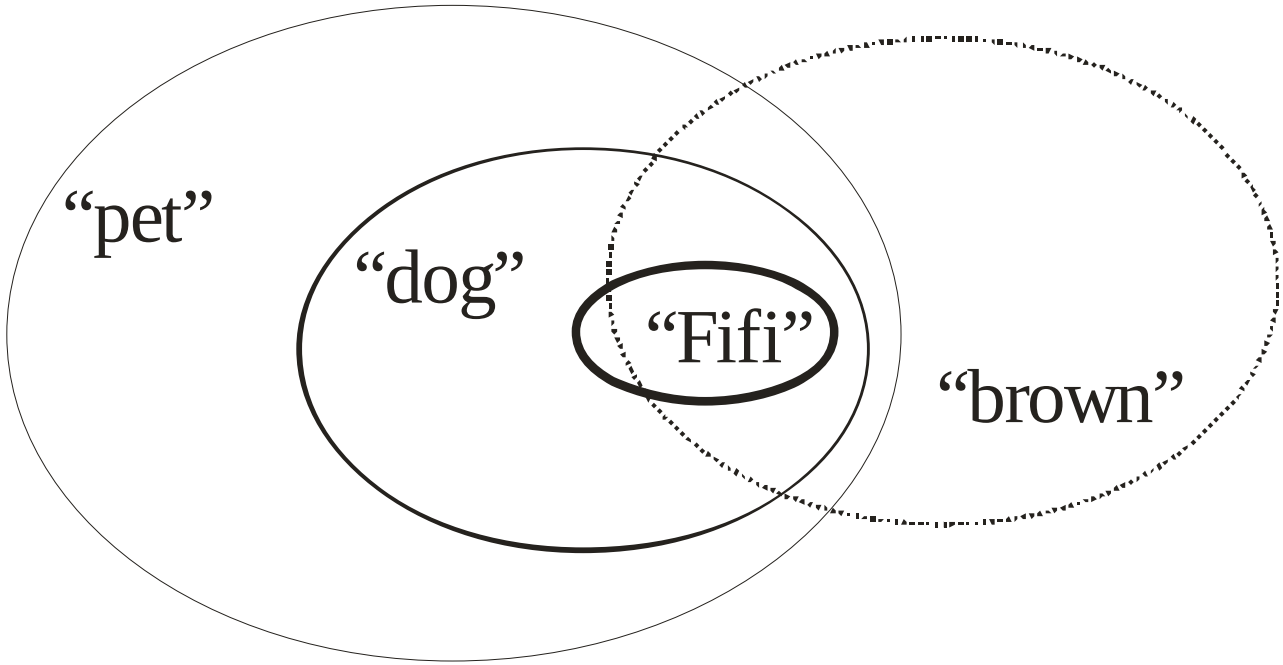
- Fuzzy subsets: The internal classes are defined contextually. What is more, there is no strict distinction between super- or subclasses: Subclasses also partly determine superclasses
- As compared to object-oriented modeling, it needs to be noted that there is no distinction between “classes” or “objects”, or even “methods” (or “properties”)
- Semantic net: Similarly, the relationships between concepts and their properties can be described using a network formulation (see next page)

"Fifi is a brownish pet dog"

- "Fifi" has "dog" properties and others, too

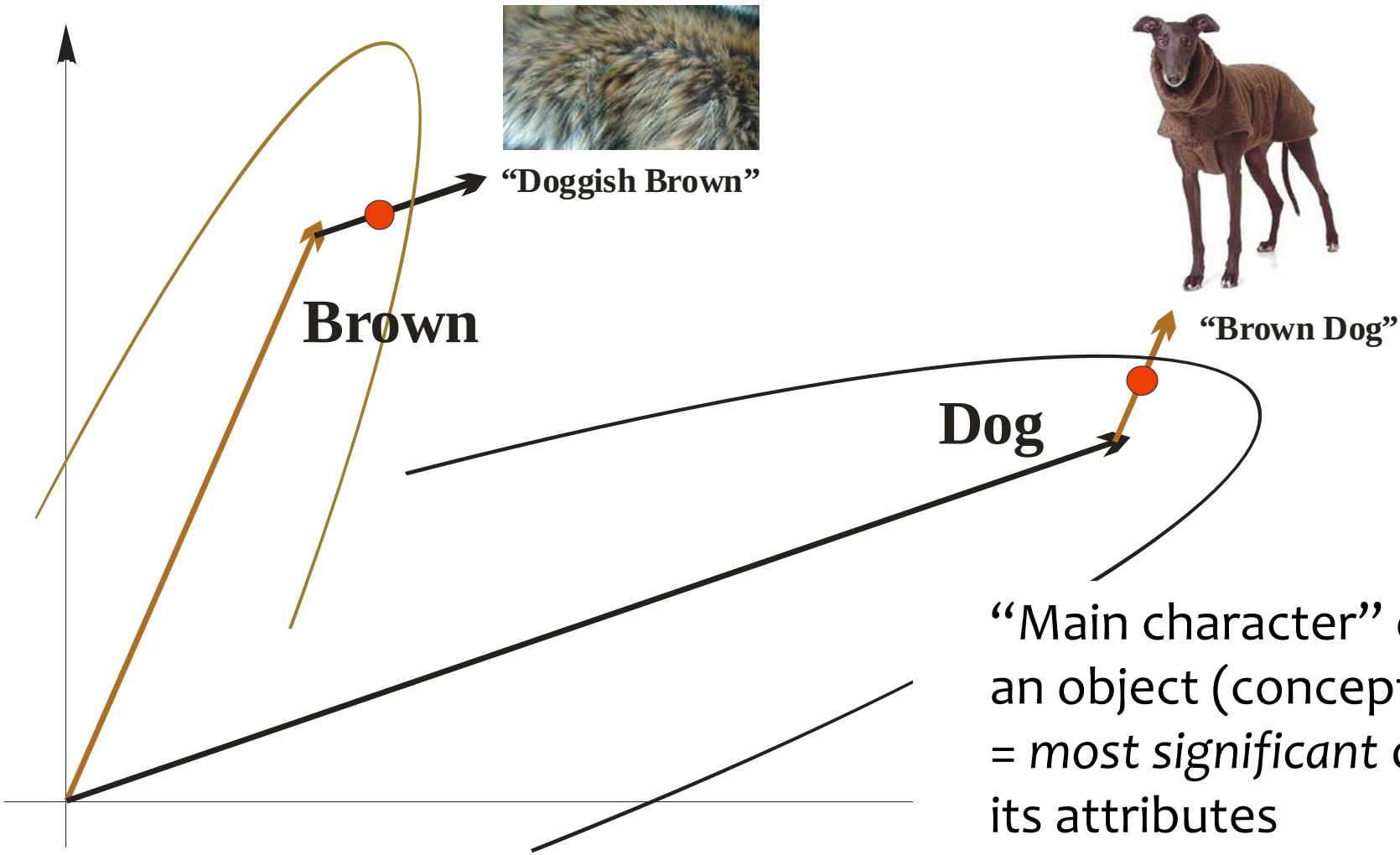


All "concepts" have the same internal representation



- "Fifi" partly *defines* what is a "dog" and how "brown" looks!

Leibniz: Object is identified by its attributes

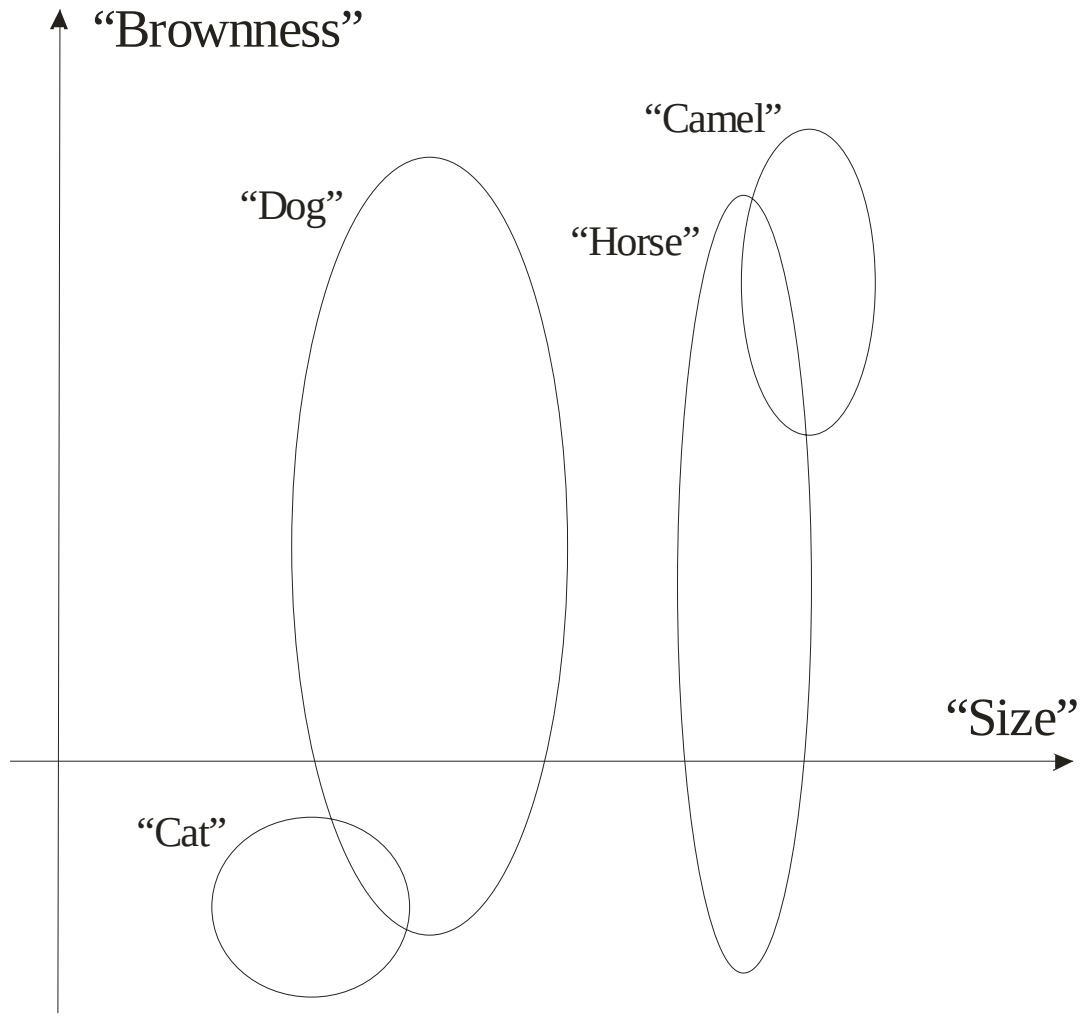


"Main character" of an object (concept) = *most significant* of its attributes

Concepts = *Attractors in the Space of Ideas*

- In the neocybernetic spirit, concepts are statistically relevant constructs abstracted over individual observations
- Bias in data, or average vector = category prototype ("center of mass")
- Typical examples are located near this center in data space
- The features determine the "orientation" and extent of the cluster, most significant components revealing the directions of most variation
- Remember that the data dimension is assumed to be huge:
  - An observation data sample can simultaneously belong to various clusters
  - Seen from another perspective, an attribute can be interpreted as the category, and vice versa (appropriate interpretation depends on mutual "activities")...

Extensions needed…



- Unimodal data = only one cluster (assume normally distributed) – direct connection to linear models
- This expressive power is not enough for real domains
- Multimodal data = many clusters – *nonlinearity* needed (*sparse coding*)

Role of sparse coding

- Linear model = A single Gaussian distribution = a single data cluster = a single "category" can be implemented

  How to implement multiple categories in the same structure?

- One needs to have a mechanism to implement *alternative structures* on demand

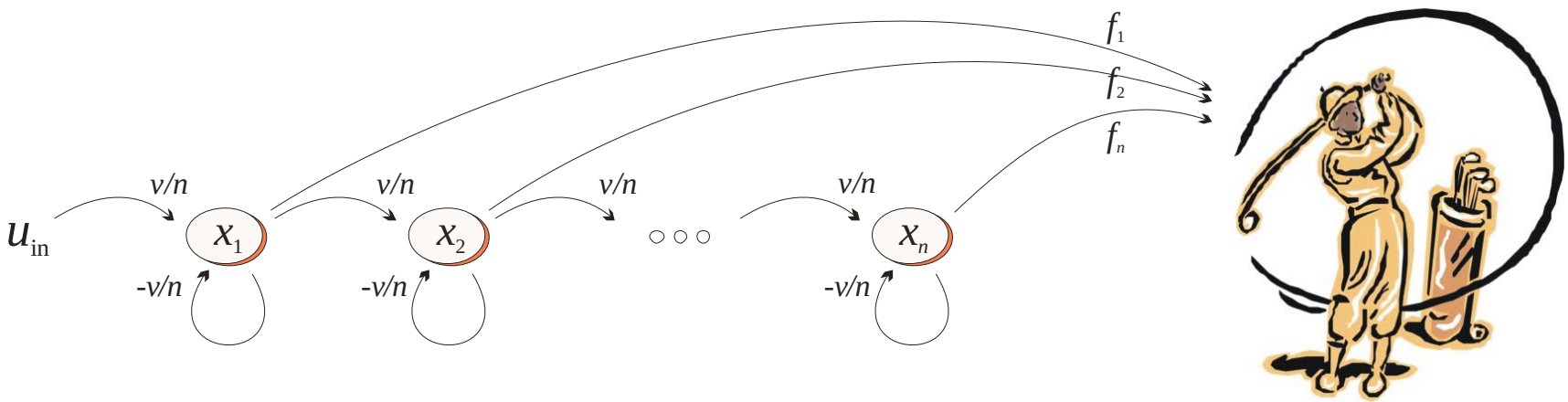
  A simple way to implement multiplicity is *sparse components*

- Sparse coding: The goal is not extreme compression, or the minimum number of model components (as it normally is) – The goal is *minimum number of simultaneously active model components* – only a *subset of latent variables is non-zero*

Learning – first one has many connections, later *less* connections!

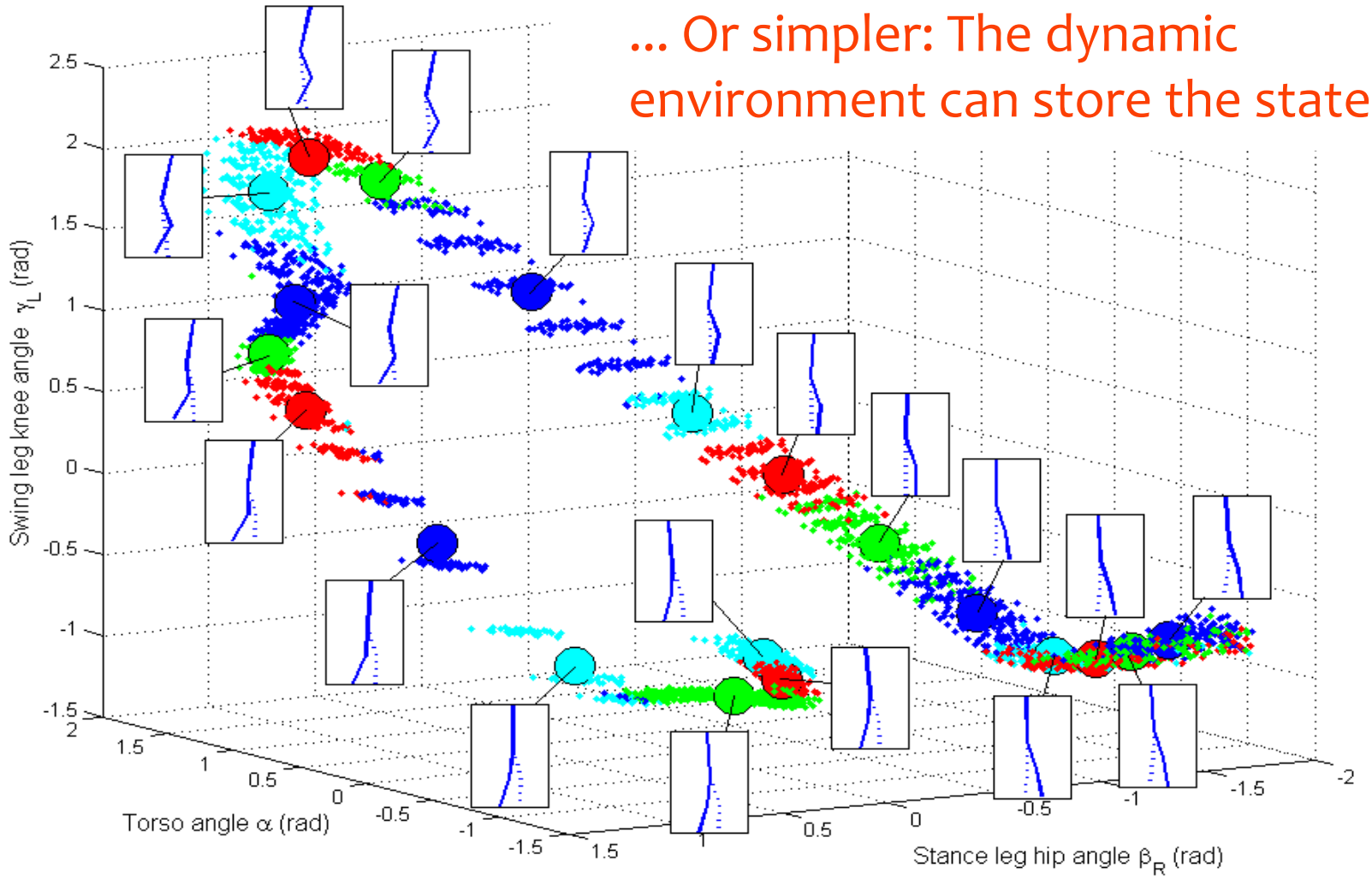
Deep structures beneath “eigenbehaviors”?

- State progression can be implemented as linked sequences of neurons (?)
- The same seems to apply to all declarative knowledge representations (“feedforward reasoning”)
- Also motoric activation trajectories can be implemented applying the same neuron structure:



Walking gait: Locally linear submodels again

... Or simpler: The dynamic environment can store the state!



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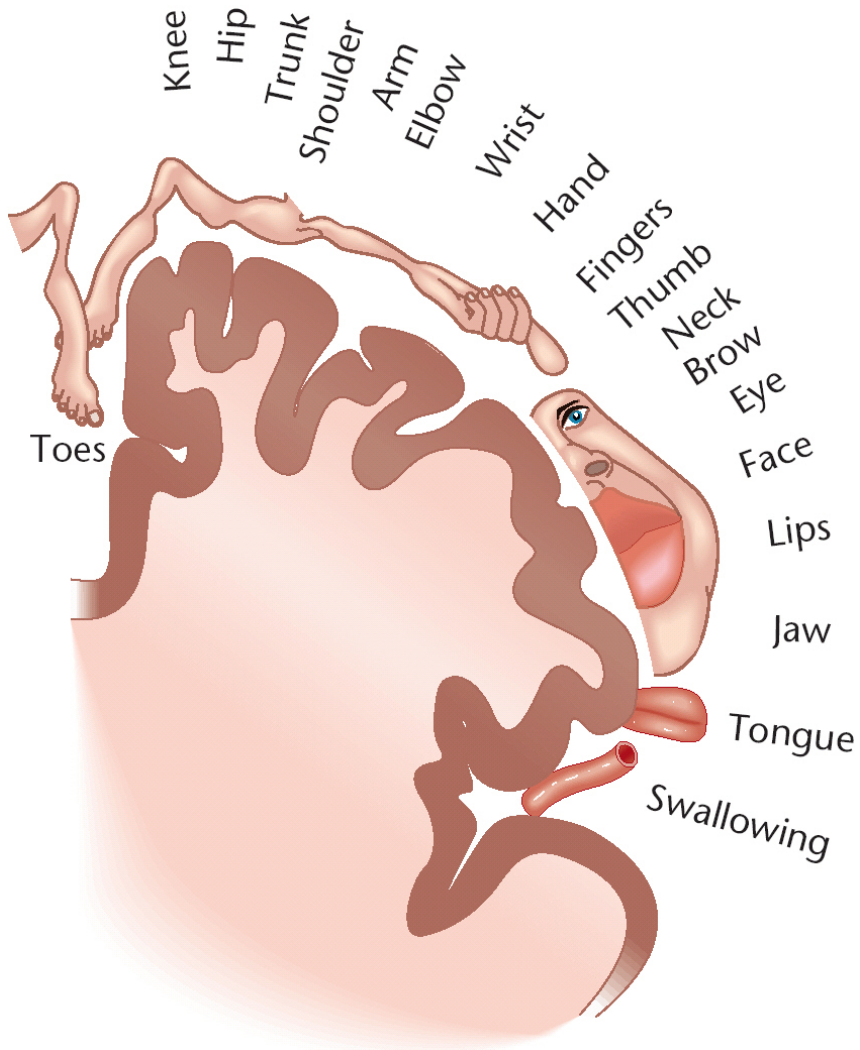
- The neocybernetic approach extends the Kohonen SOM: One just selects the matrix Q so that it represents topology or "neighborhoods" among the neurons
  - Now there is no central control
  - There are "various winners"
  - The codings are less abrupt
  - There is inner structure in nodes
  - There exists a concrete cost criterion, and the adaptation algorithm is rather efficient.



Relation to cognitive science concepts

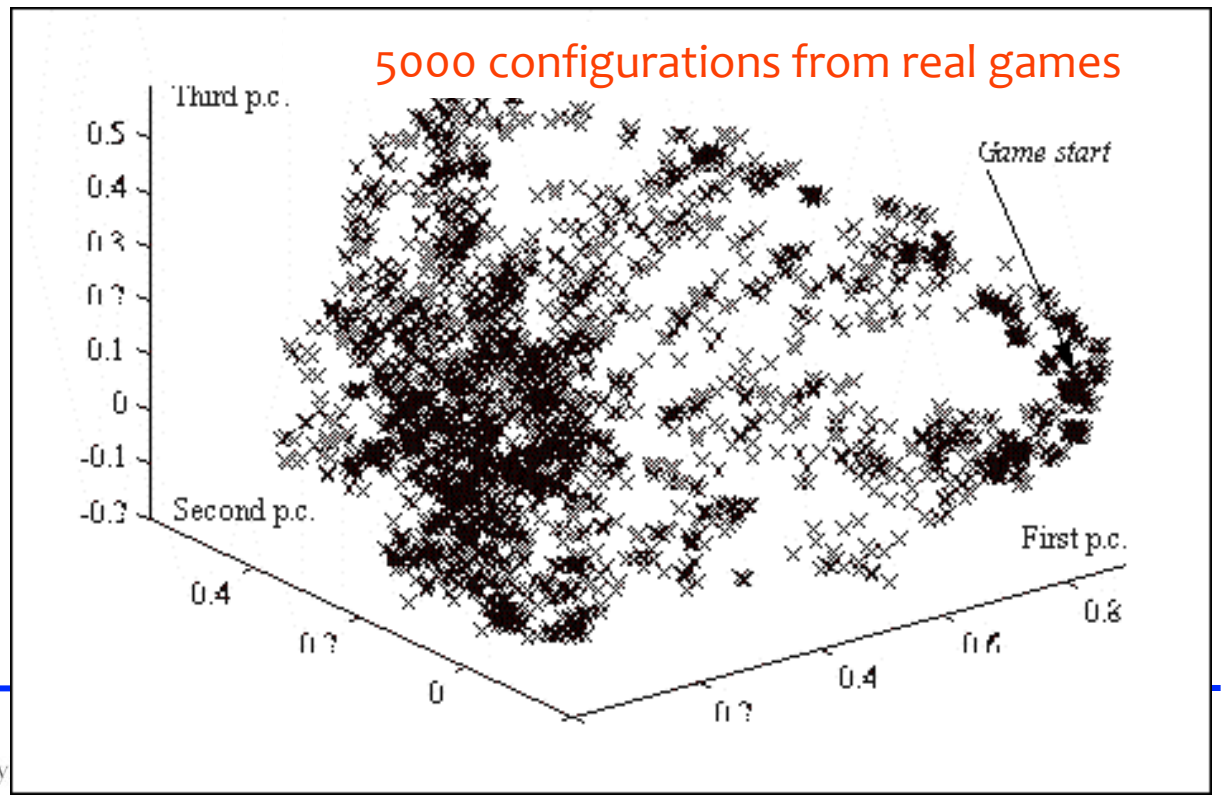
- Traditional theory: Cognitivistic observations
  - Only some 4–7 different items can be kept in *short-term memory* (STM) simultaneously; these items are addressed in the "all-or-nothing" manner
  - The physical limit for STM cannot be essentially extended, whereas there are no such acute limitations for the size of *long-term memory* (LTM)
  - The STM capacity can only be extended through employing more appropriate "items" to be stored ("expert chunks")
- Cybernetic model: Interpretation of cognitivistic observations
  - Now n = LTM and the number active ones of the sparse components = STM
  - The vectors ϕ_i are the long-term memory elements, constituting a structure connecting the m incoming signals together appropriately
  - There are no separate localized physical STM memory registers; rather, short-term memory is implemented in terms of on-line associations of LTM elements through individual neurons
  - References to LTM units are not binary but "non-negative"

Example: Modeling of a *chess board*

- Configurations are presented as real-valued vectors:
  - One segment for each location on the board (64)
  - One entry in each segment for each of the piece alternatives (12)
- Altogether 768 dimensional data space

- Visualization:

  No structures can be seen if projections are carried out in an incorrect way (mathematical, not physical)

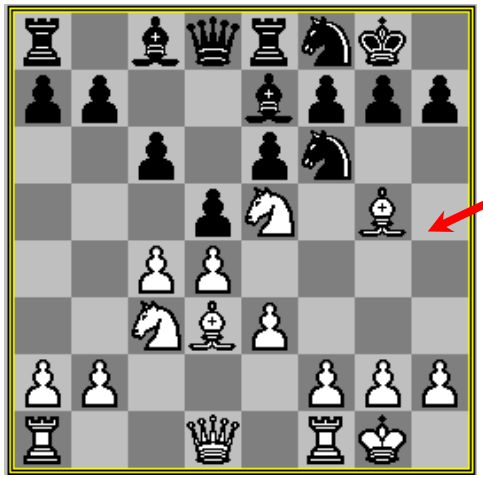


Chunks in chess

- For example, a *castling pattern* is a familiar chunk: Parts of the board are coded as one
- Traditionally, a chunk stands for a symbolic construct – there are problems if the patterns do not exactly match
- It has been assumed that some 50 000 chunks are needed to appropriately reconstruct the board

- Now chunks, being numeric correlation entities, are additive
- Typical cluster centers now: *Openings* ("Spanish", "Nimzo-Indian", ...), extending over the whole board
- Degrees of freedom around centers: Extra/missing pieces
- Only 100 chunks were extracted...

Reconstruction of the view

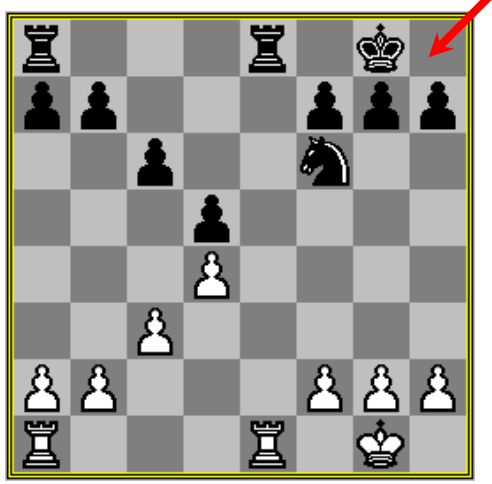


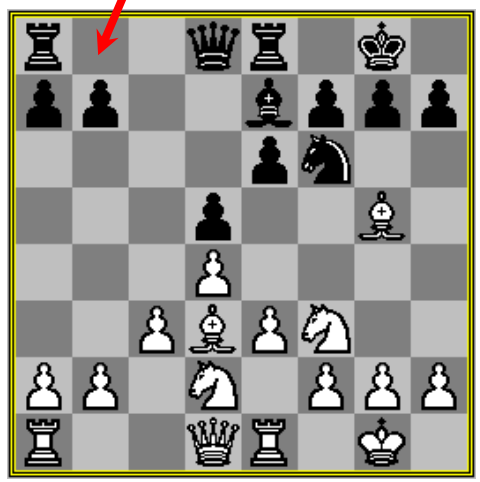
Original (observed) pattern

Reconstruction 1: One chunk

Reconstruction 2: Three chunks

Reconstruction 3: Five chunks



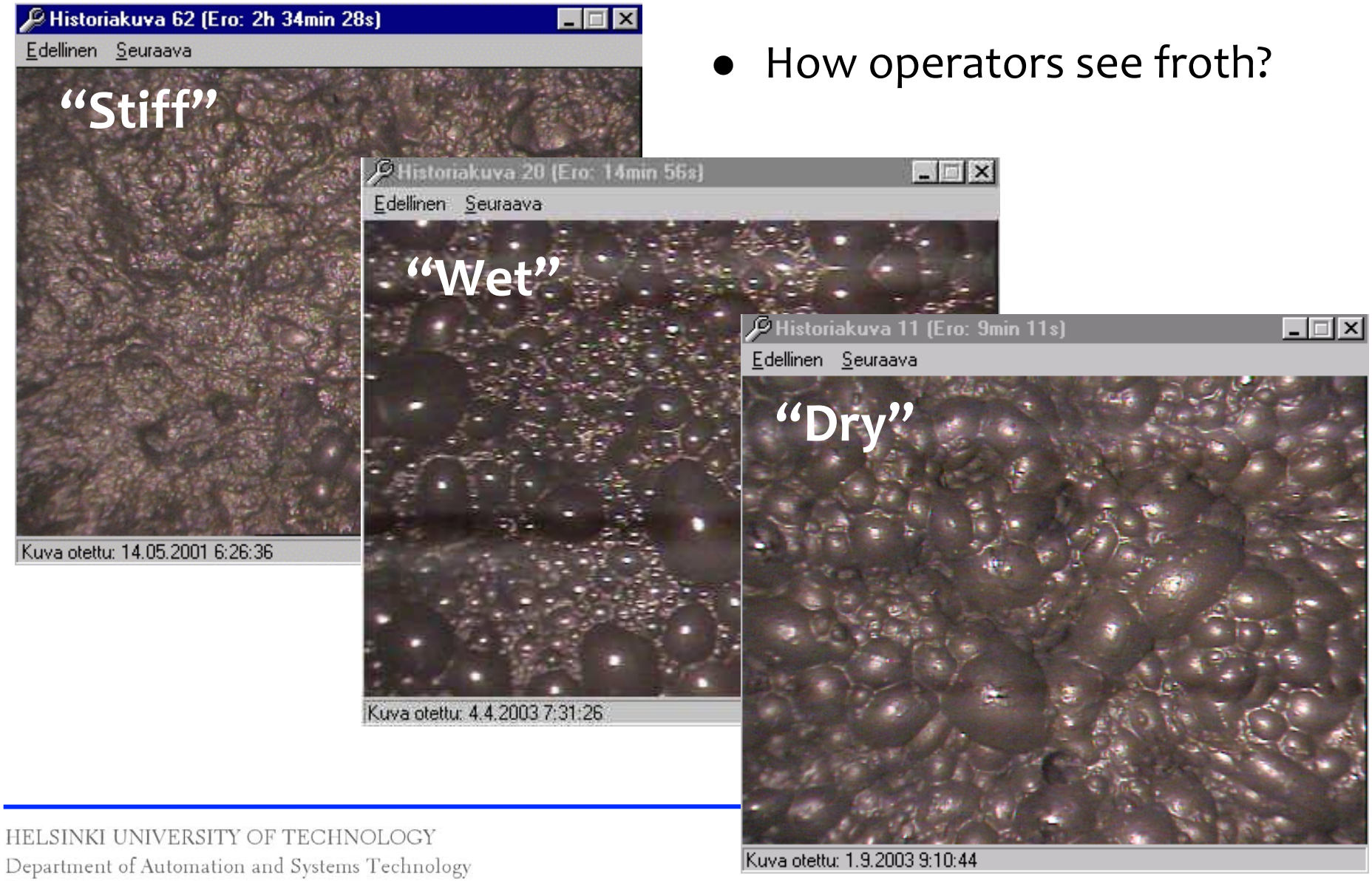


- Chess is a “banana fly” of cognitive science: Many of the interesting phenomena are visible in not too complex form
  - Experiments with human subjects have shown that, when a chess board is shown to them for a short period of time, the experts can recall all the pieces, whereas beginners can only remember a few pieces. What is interesting is that this is so *only if the shown chess configurations are characteristic to chess*; for random boards the recall rate did not differ significantly. The experts must have an internal model of what the board may look like.
- The experiments revealed that the qualitatively same behaviors were obtained with the cybernetic model
- What is interesting is that the *errors* that the model made were cognitively credible.

Further experiments

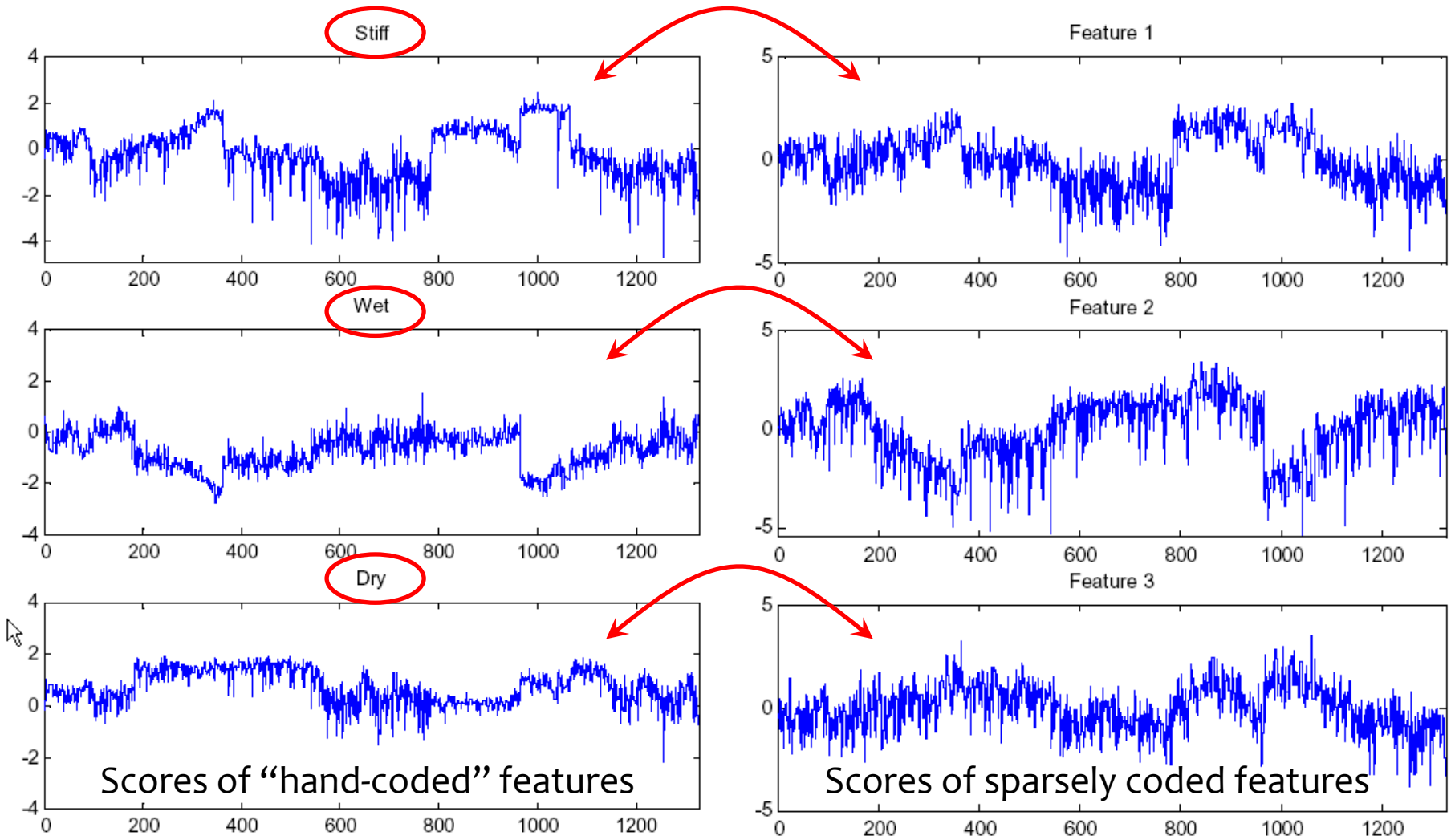
- Remember the Pyhäsalmi concentrator: Image analysis is applied to extract information of a frother cell
  - Extracted variables: Bubble size and "load", color, intensity, speed, ...
- Operator queries were carried out at the flotation plant:
  - "What are the main types of flotation froth?"
  - "How would you characterize those froth types?"
- The characterizations were hand-coded in a classifier
- Independently, the available data was modeled applying sparse coding, automatically extracting sparse structure
- The sparse components were also applied in a classifier...

“Conceptual froth types”



- How operators see froth?

Sparse coding captures cognitive essence?



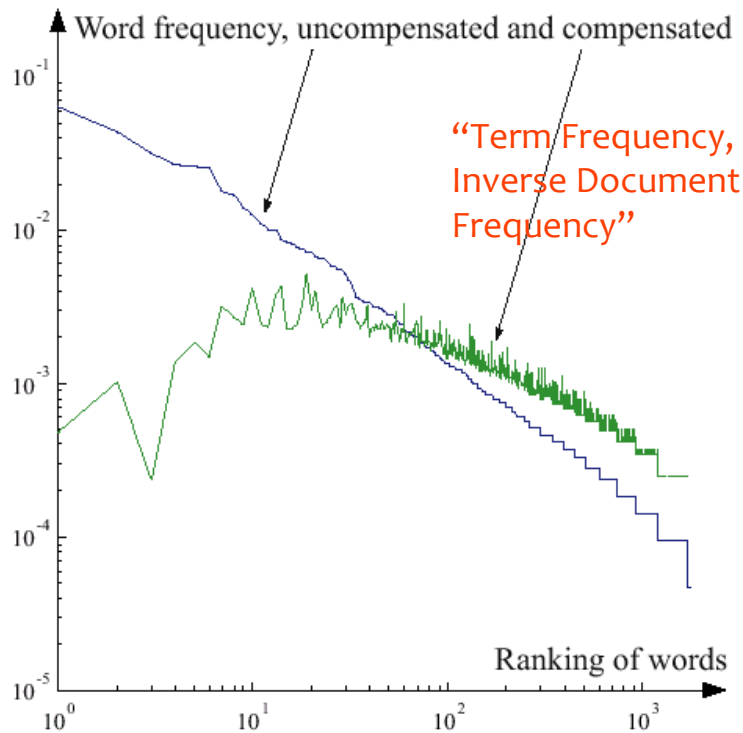
Large-scale applications

- Real test for cognitive model plausibility – truly big systems

  Data mining & exploratory analyses of textual documents

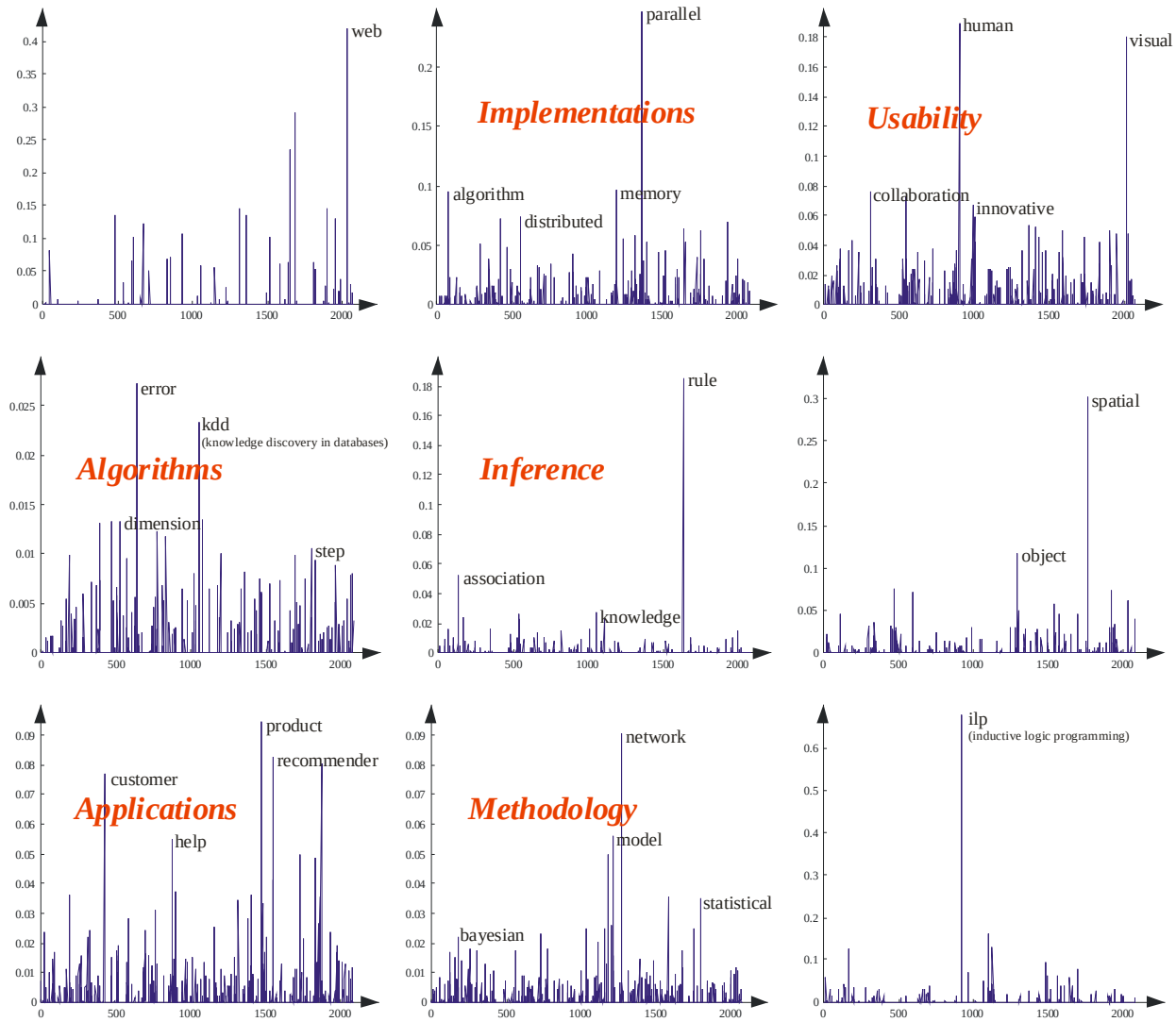
- There is a continuum from dense to sparse models:
  - WEBSOM (textual SOM) is *extremely sparse*, all documents being represented by only one of the prototypes
  - LSI (latent semantic indexing) is *extremely dense*, all documents being represented by all of the prototypes
  - Natural representations are between the extremes, being *relatively sparse*?
- Potential of sparse document models:
  - Sparse components are "generalized keywords" characterizing documents
  - Automatic "table of contents" into the text material is constructed
  - Applications: Structuring, search, collaborative filtering, ...

- Data material from INSPEC search: "knowledge mining"
  A few hundred documents, a few thousand words...
- Words in the document abstracts used as individual inputs
  Very little preprocessing of data, only TFIDF weighting
- Modeling *document fingerprints*
  = Histograms of term contents
- Common words determine similarity between texts (no deeper semantic analysis)
- Data is "static": No succession between texts observed, etc.

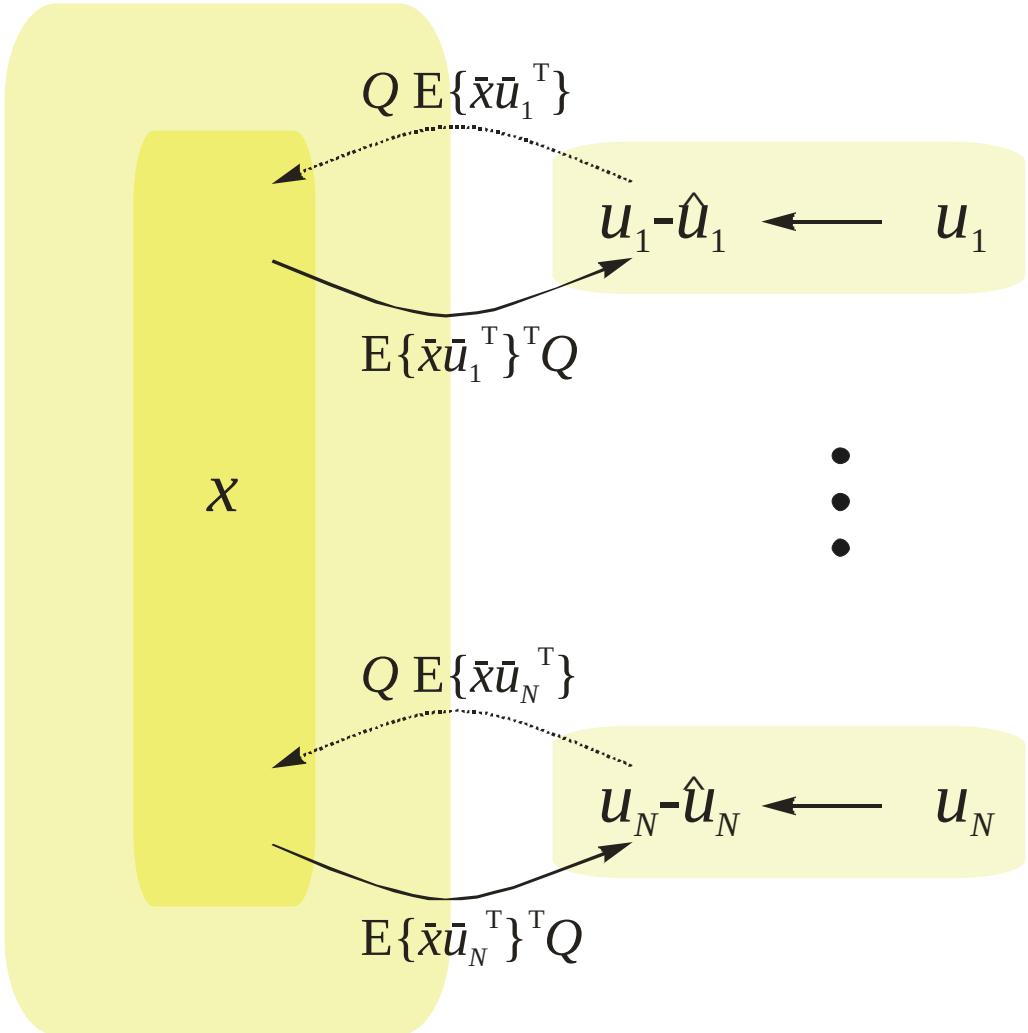


“Generalized keywords”

- $N = 3$, $n = 9$
- Visualization of the keywords shows which words are the most relevant
- Each document reconstructed approximately as a weighted sum of three such keywords



- How about categories when there there no unique clusters visible in data space?
- When applying the cybernetic learning, there can be various input channels – then there is the possibility of "learning by being told", or by *ostension*



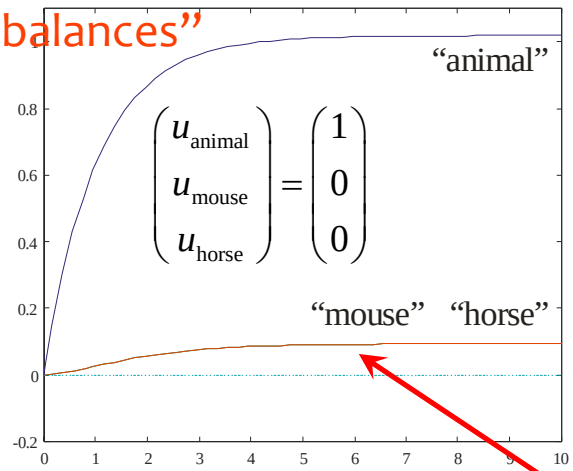
Associations based on correlations

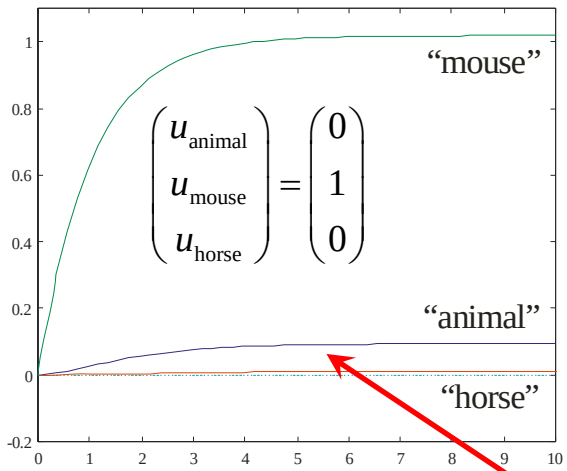
- Fully adapted system matrix is symmetric – this means that

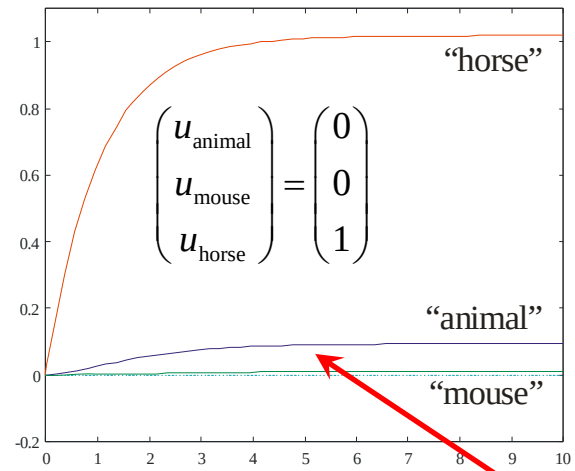
$$\frac{d}{dt}\begin{pmatrix} x_{\text{animal}} \\ x_{\text{mouse}} \\ x_{\text{horse}} \end{pmatrix} = -\begin{pmatrix} 1 & -\frac{1}{10} & -\frac{1}{10} \\ -\frac{1}{10} & 1 & 0 \\ -\frac{1}{10} & 0 & 1 \end{pmatrix}\begin{pmatrix} x_{\text{animal}} \\ x_{\text{mouse}} \\ x_{\text{horse}} \end{pmatrix} + \begin{pmatrix} u_{\text{animal}} \\ u_{\text{mouse}} \\ u_{\text{horse}} \end{pmatrix}$$

Internal "perception" External evidence/observation

"Idea balances"







"Associations"

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SPACE and TIME exist only in the mind?

- Kant: *Time* and *space* are "pure forms of sensible intuition", both are elements of a framework for structuring experience

- *Neocybernetic motivation*: concepts of time and space help to compress (model) the observation data…
- …This is because variables tend to change smoothly along the temporal and spatial axes – there is correlation
- This applies generally to all domains, so it is clever to always implement these dimensions in mental models *a priori*

- The higher-level model there is, the more relevant is the time axis – also in those models that are outside human mind!?

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Time is an ILLUSION caused by the model!

Towards modeling of causality (+ *intentionality*)

- Age-old observation (Hume): One can only see correlations in data, not causalities
- Another observation (Kant): Human still *for some reason* is capable of constructring causal models

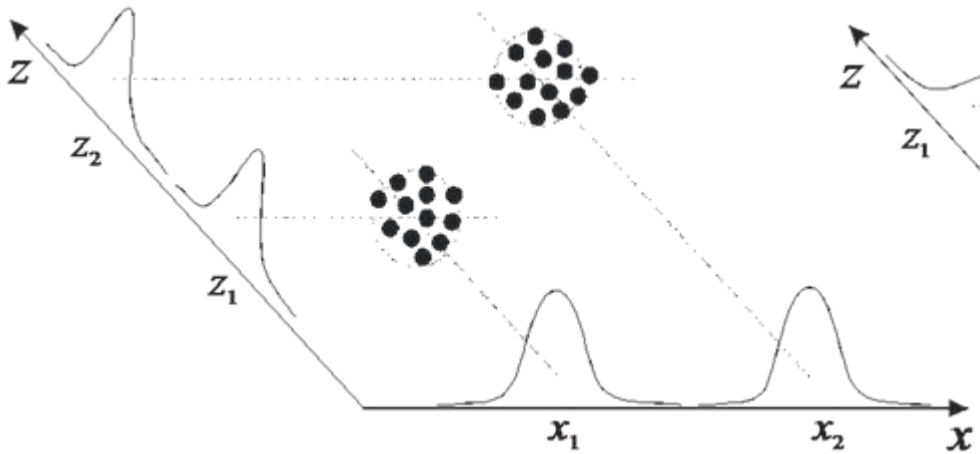
- Hebbian feedback learning:

  Modeling of *results of own actions* in the environment (actions being *reactions* to phenomena in the environment)
- Now one implicitly knows what is cause, what is effect

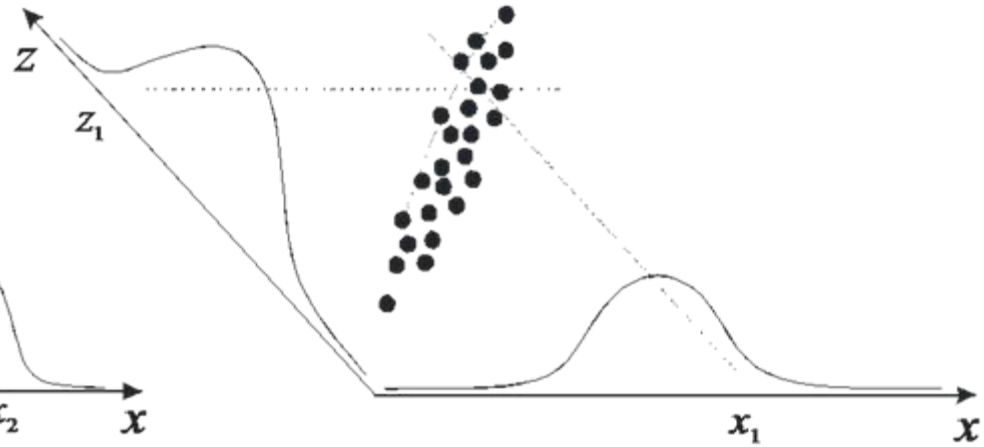
- Learning needs to be of "hands-on" type, otherwise learning (applying explicit anti-Hebbian law) becomes superficial?!

About *expertise*

- Reasoning = associative pattern matching of incomplete data
- Relation to *Case-Based Reasoning* (CBR): Now the patterns have continuous fine structure
- Relation to *expert systems*: Rules are projections of the high-dimensional data onto some distinct dimensions



Where rule systems work (IF $x = x1$ THEN $z = z1$, etc.)



...But here they do not

About *knowledge*

- Traditional definition of **knowledge:**
  1. Motivated,
  2. true
  3. belief

  Instead of *one* concept to be defined now there are *three!*

  Symbolic grounding is necessarily *hermeneutic*

- In neocybernetic framework the deepest concepts become matters of scientific study
- Instead of *truth* the essential thing now is relevance:
  Do there exist appropriate data structures in data
- Counterintuitively:

  Making "truth" *relativistic* it becomes *universal*!

About *wisdom*

Wisdom vs. intelligence:

"A clever person can manage in situations where the wise one never falls into"

Another way to put this:

The clever has the possibility of constructing such models of the environment that the wise one already *has*

About *emotions* and *qualia*

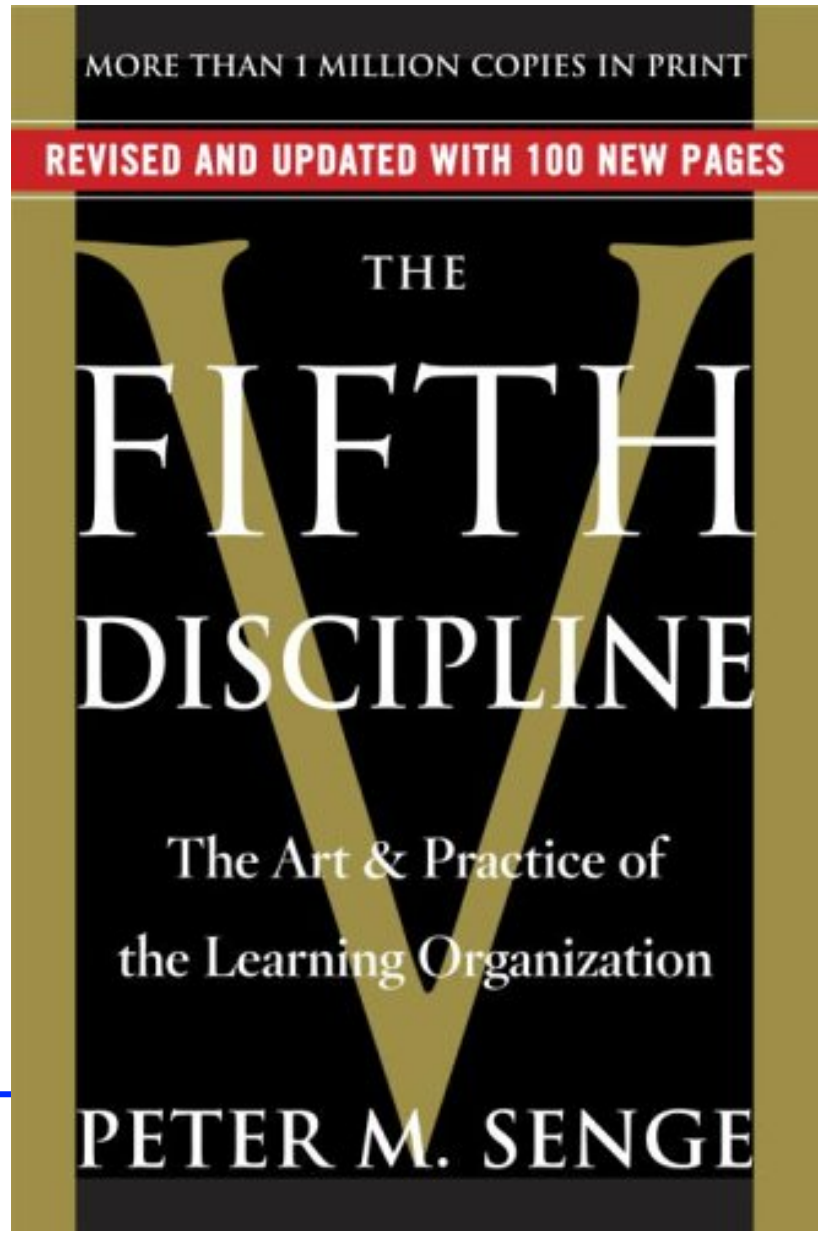
- Neurons are connected not only to other neurons
- In primitive levels, there are direct connections to physical variables, like chemical levels, not only to stored memories
- There is connection also to hormones (like adrenaline)
- Fear, etc., are thus "deeper-level thoughts", real "gut feelings"?

About *consciousness*

- The most challenging problem is that of *consciousness*
- There are different kinds of theories:
  - Consciousness is simply manifestation of the "soul" – only for humans!
  - Consciousness is manifestation of infinite recursion, ...
- There are also contradictory intuitions:
  - Essence of consciousnes = ability to feel pain
  - ...But then, rather than being topmost in cognitive hierarchy, it is the simplest!
- Cybernetic interpretation: It is about agent's modeling ability, consciousness = the capability of constructing sophisticated enough models where there is distinction between "self" and the environment
  - Consciousness is gradual; animals are conscious in varying degrees
  - *Small children are not conscious*?!

“Conversation Theory”

- Level *n* consciousness is modeled – consciousness of level *n* + 1 emerges?
- When in interaction with other people, when understanding their thinking, *higher-level consciousness* emerges?
- Intelligent organizations, “Systems Intelligence”?

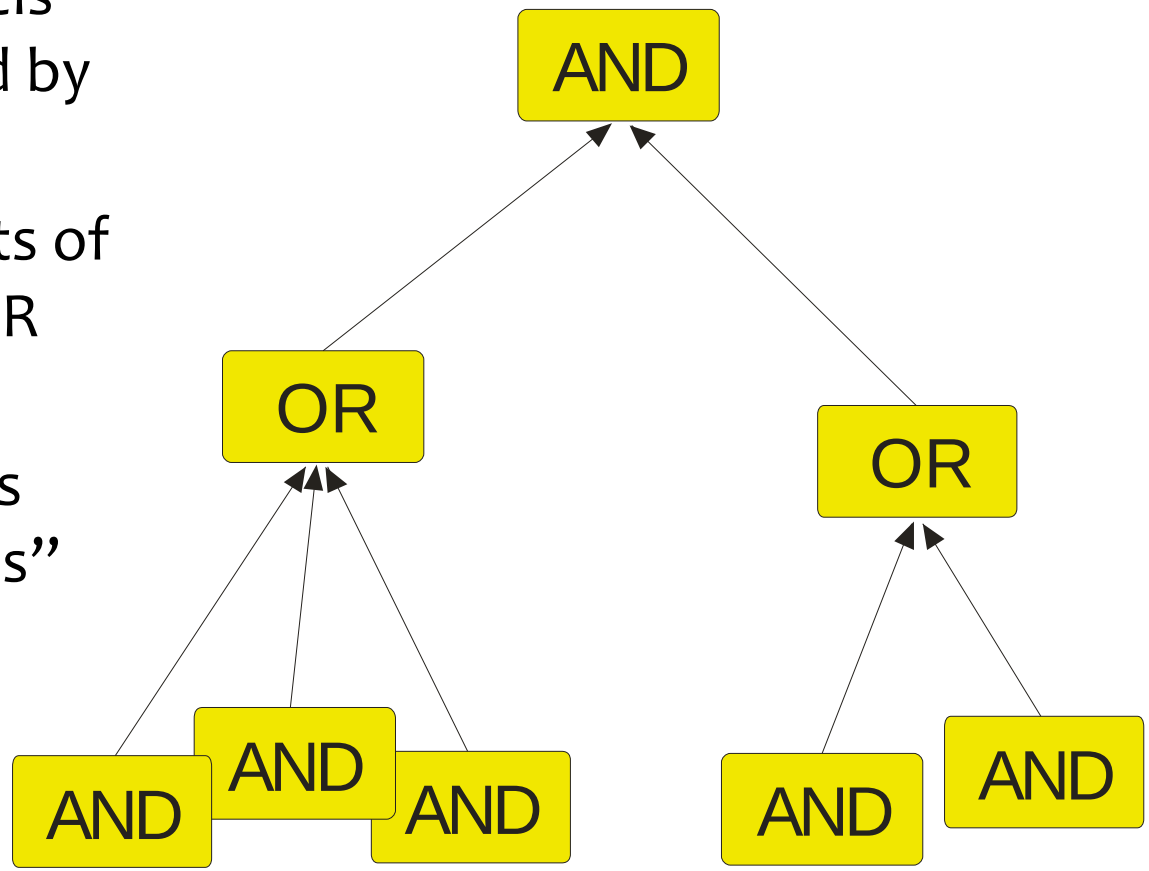


Deeper look at information and semantics

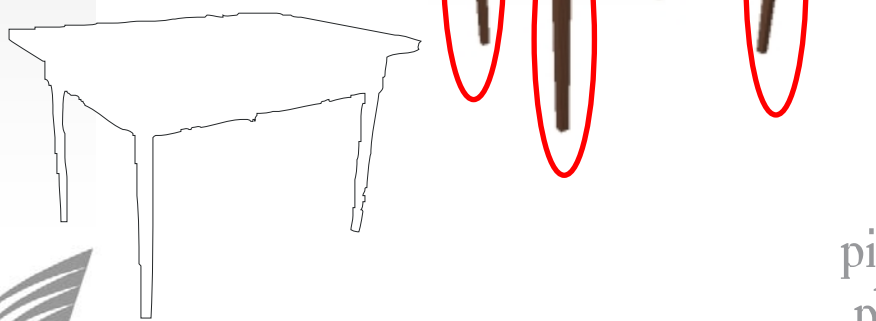
- How to interpret the layered structure of neuron grids?
- Assume that variables have the probability interpretation (actually, *relevance* interpretation as variables are unscaled)
- Remember that if variables are logarithmic, summations can be interpreted as multiplications of such probabilities
- This implements fuzzy AND operation among the variables
- Remember that if the model is sparse, different combinations of sparse components define alternative constructs
- This implements fuzzy (X)OR operation among the variables

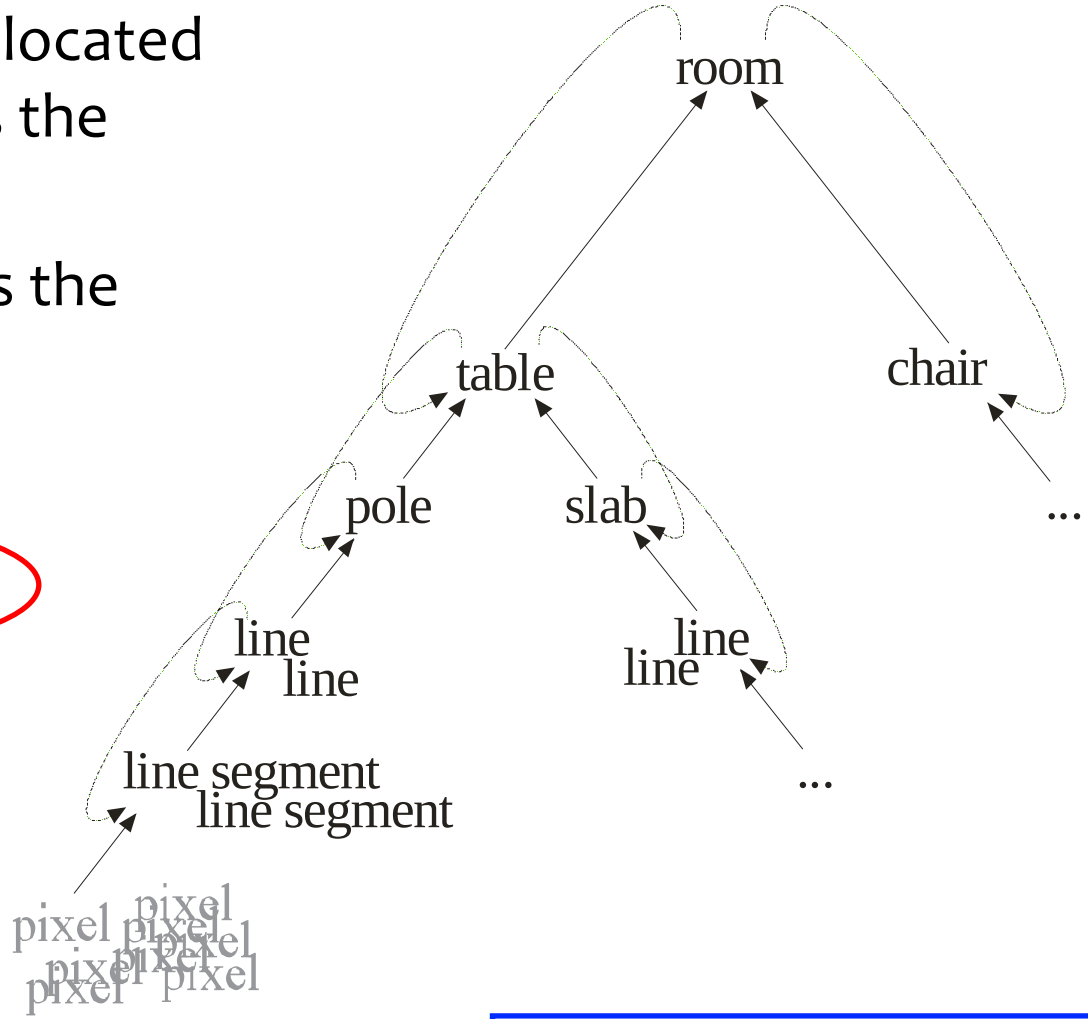
In general: *Fractal tree structures*

- Simple mixture models ("OR") are combined by constraints ("AND")
- Complex data consists of a hierarchy of AND/OR blocks
- Structure implements "mixtures of mixtures"



- Seeing *poles* and a *slab* located appropriately increases the probability of a *table*
- Inversely, a *table* makes the *poles* more probable!





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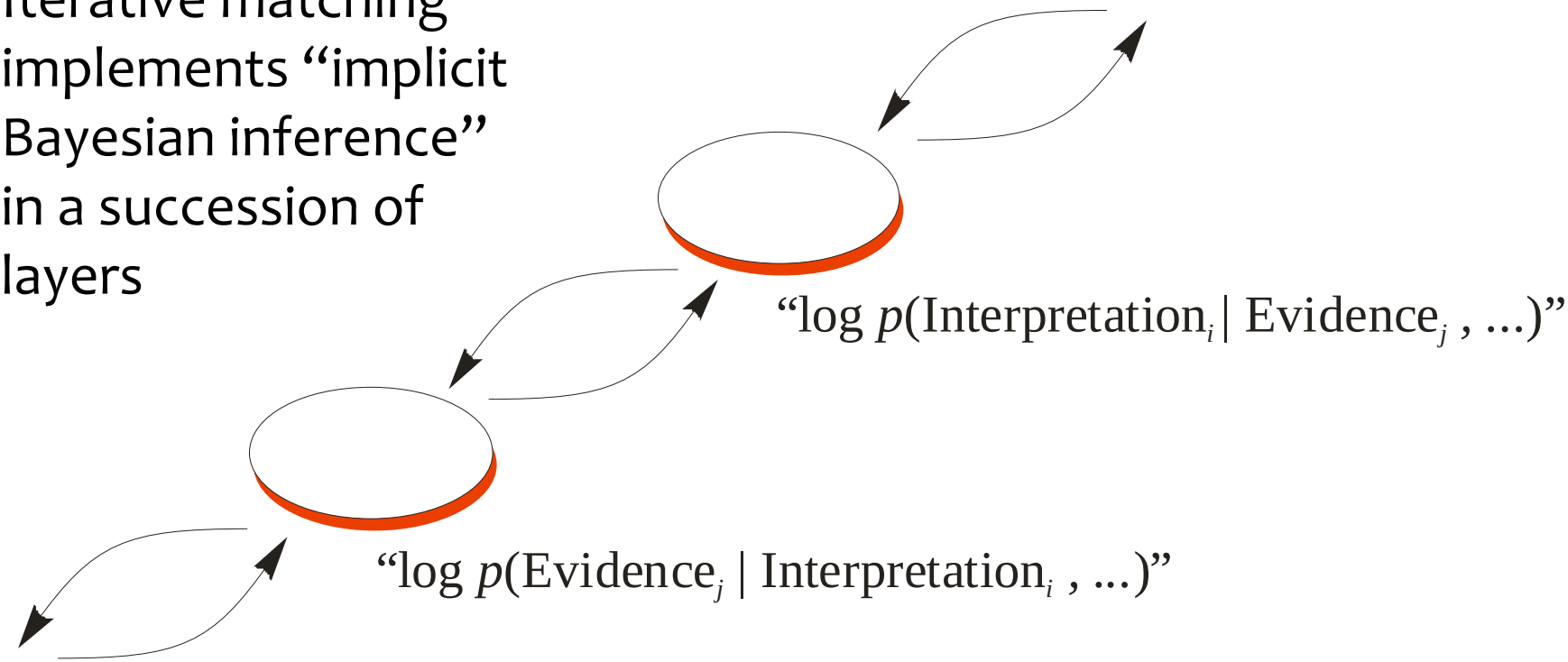
Is this a way to the "deep structure" of language?

“Analysis through synthesis”

- Iterative matching implements “implicit Bayesian inference” in a succession of layers



- Positive feedbacks and competition among interpretations is balanced through the neocybernetic principles

When modeling temporal data, compare also to hidden Markov models (HMM)

Role of *a priori* information

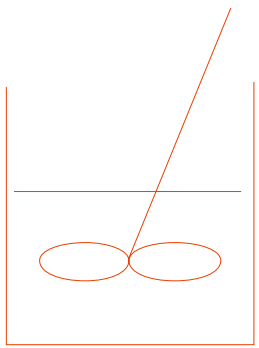
- When you know that it is Dalmatian, you cannot help seeing it there!

Connecting distributions

- Example: Closer look at the nonlinear titration process
  = “mixture of mixtures”

AND *Connection of mixtures*

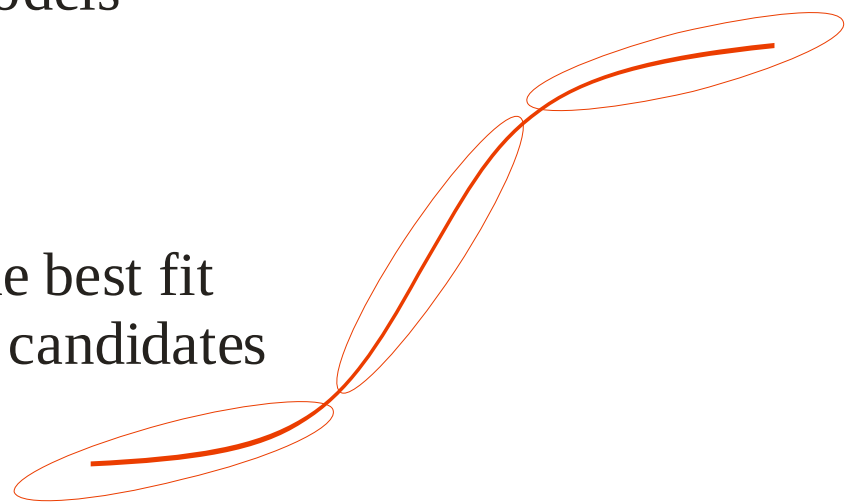
Make the variables
compatible in submodels



OR

Find the best fit
among candidates

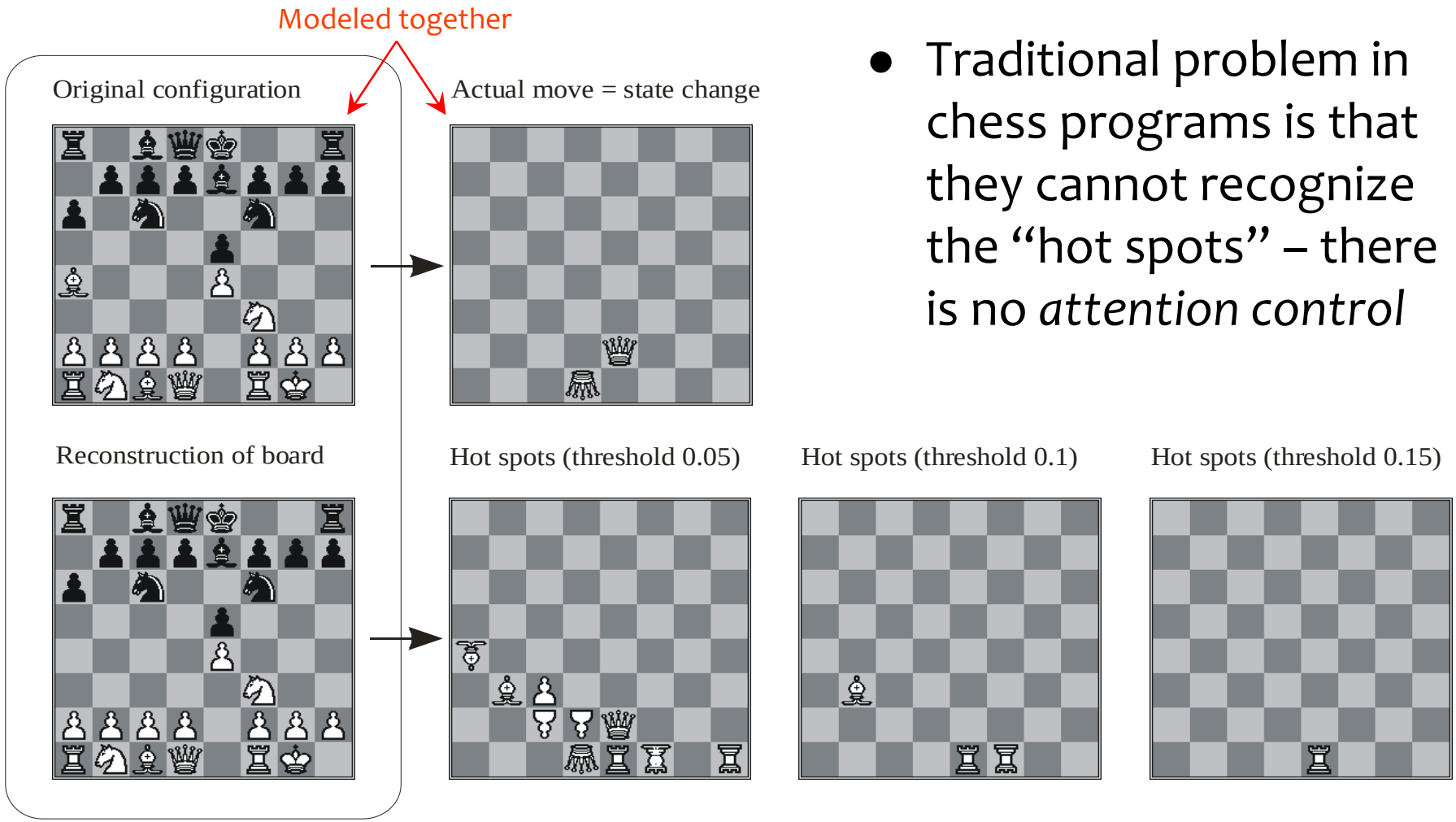
Mixture model



"Cybernetic semantics"

- How to assure that in a multi-layered system there are the necessary atoms of semantics present?
- Cybernetics is based on balances – the data has to reflect this – the balancing forces need to be included among data
- Or, as there is no standstill, it is the "flow" that is proportional to the imaginary forces that would balance the system
- It is not enough to capture the correlations among variables, or *contextual semantics*, but one has to couple the temporal structure, or the change tensions in the state
- These tensions are captured by gradients, or momentary changes in the state

Chess data augmented with the “flow of game”



- Traditional problem in chess programs is that they cannot recognize the “hot spots” – there is no *attention control*

- Tension can be modeled also without introducing new variables by using *complex numbers*: real parts of variables stand for the actual inputs, imaginary parts represent derivatives (differences between successive inputs)
- Physical motivation (?): Changes in inputs cause delays in signals, being manifested as phase shifts
- Phase shift view especially suited to frequency-domain signals
- In technical terms: All transposes are substituted with Hermitian conjugate transposes, otherwise formulations remain the same

- The resulting data structure can be called a *holographic associative memory*

Other interpretations of the "gradient features"

- The logical rule $u_i \wedge \cdots \wedge u_j \Rightarrow u_k$ is logically equivalent to $\neg u_i \vee \cdots \vee \neg u_j \vee u_k$, and when implementing reasoning, such rules can be "added together"
- Correspondingly, when logical variables have real values, rules can be written as $-u_i - \cdots - u_j + u_k$, and summing such expressions does not change the logic ... so that

Rules = Projections of the "fitness landscape"?

gradient features can be seen to represent *inference rules*, and when starting from some state of the world, *backward reasoning* is implemented when such rules are added together to reach zero state (assuming that rule weights are non-negative) – in the spirit of the *resolution principle*...

See "Studies on Emergence and Cognition", STeP'02

- The Hebbian learning can easily be extended to react only to such “activity changes”
- When many layers of models are there to exhaust gradients, time domain behavior of signals provides fresh information
- If the information (variance) in the system comes from the time-domain changes in the signals, elimination of variation means that the system tries to eliminate dynamics

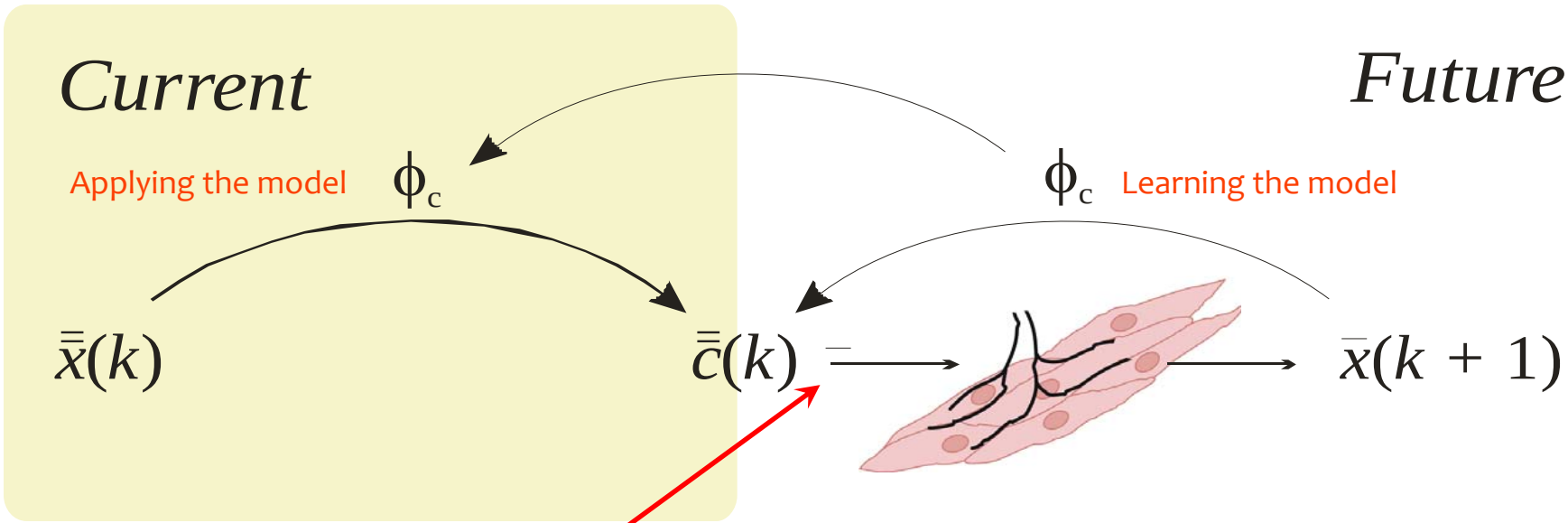
$$\frac{d^k u}{d\, t^k} \quad \rightarrow \quad 0, \quad \text{for all } k$$

- To reach this elimination of dynamics, the system has to *predict the future happenings* in its environment

From implicit to explicit model and control

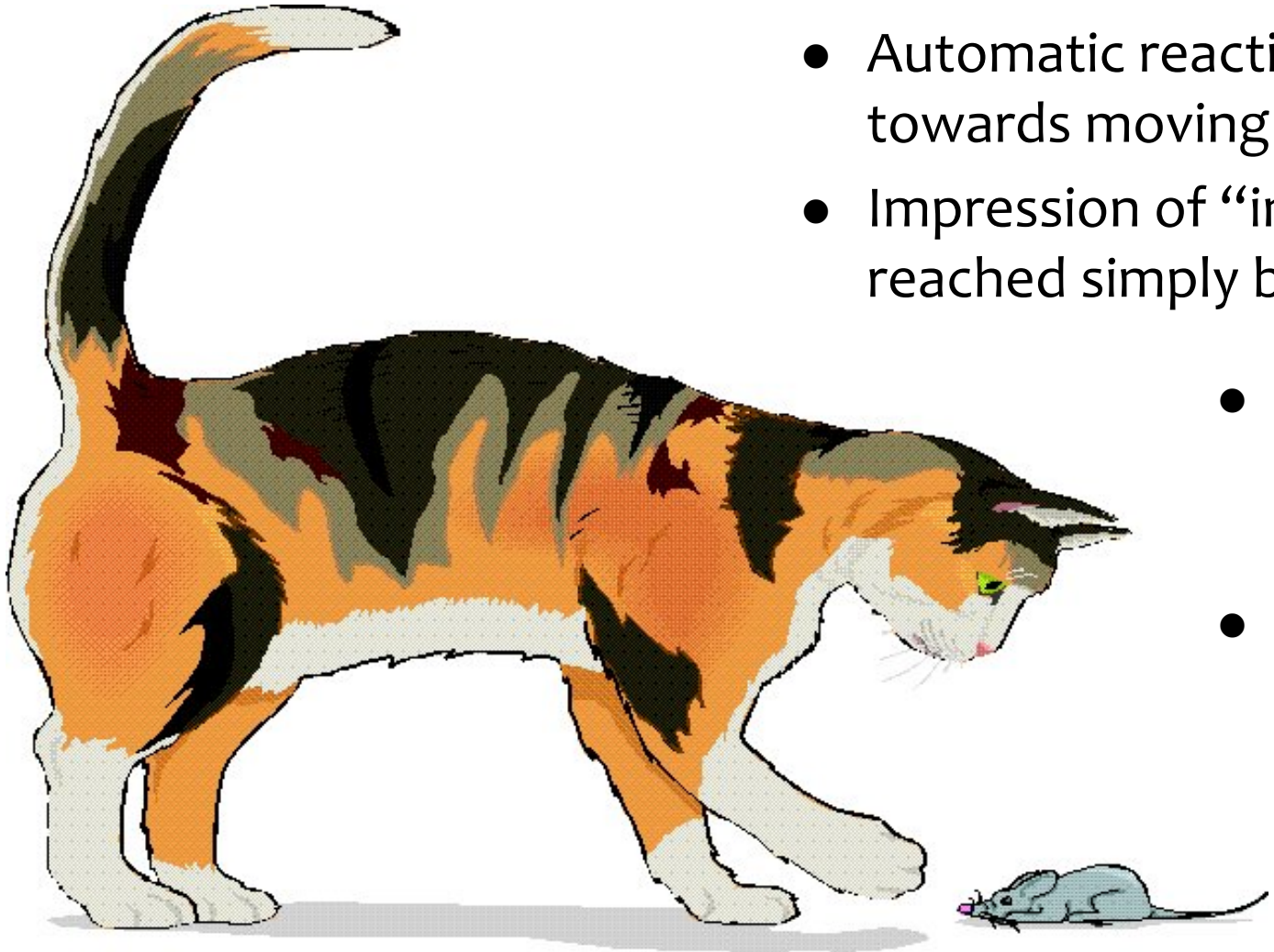
- In cognitive controls feedback comes from the dynamic world
- To implement cybernetic models, future has to be predicted
- Role of memory is not to remember past but to predict future!

Simple example of how the learned past can help to control the unknown future



Model the next state + apply *negative* control, thus hopefully "zeroing" that state

Simple case, *but there is that something ...*



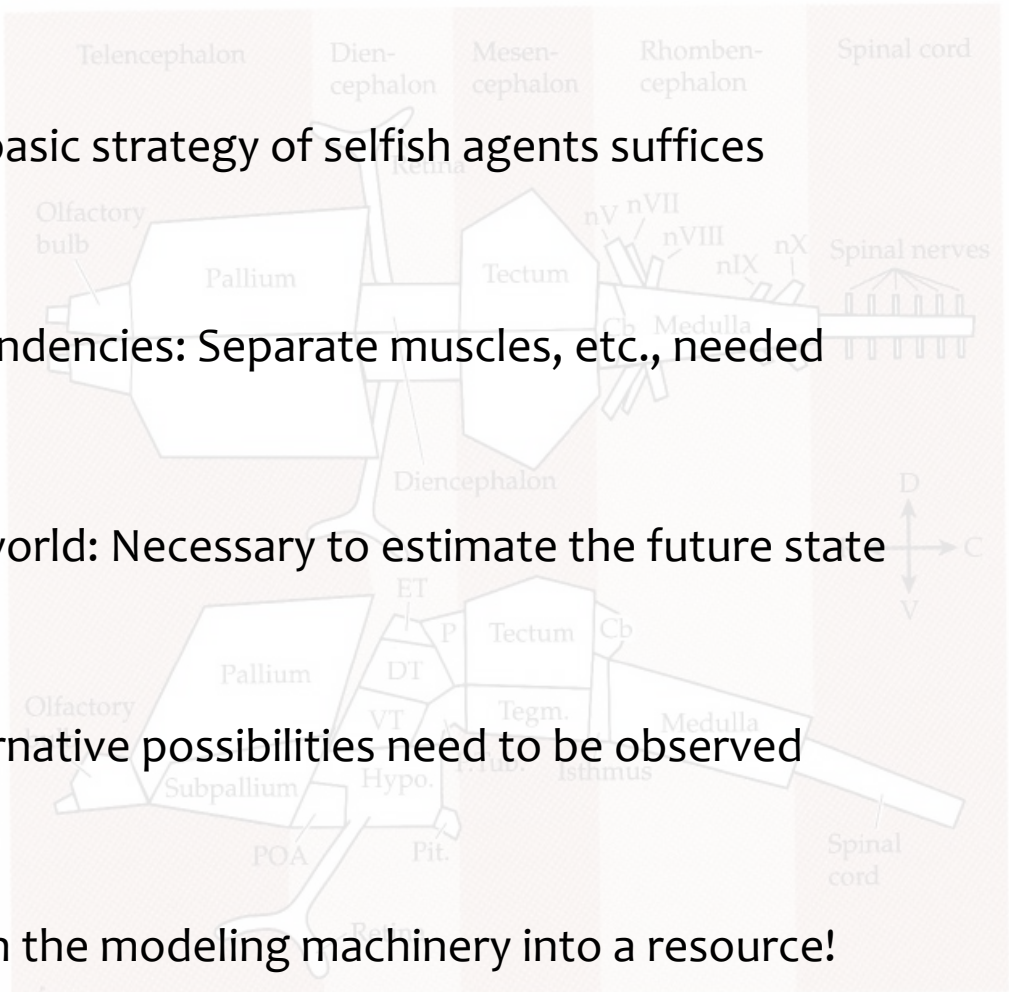
- Automatic reaction: Turn head towards moving object
- Impression of "intelligence" reached simply by *feedback*

- Reflexes = elements of cognition
- Key point: *Change the subjective world*

"Goals" emerging: *Affect the world!*

***intentionality* – and beyond**

1. Implicit control
   - Simple world: Neocybernetic basic strategy of selfish agents suffices
2. Explicit control
   - Complexity of real world dependencies: Separate muscles, etc., needed
3. Prediction
   - Dynamicity and delays in the world: Necessary to estimate the future state
4. Scenarios
   - Uncertainty of the world: Alternative possibilities need to be observed
5. Imagination
   - Exploit the "inner world": Turn the modeling machinery into a resource!



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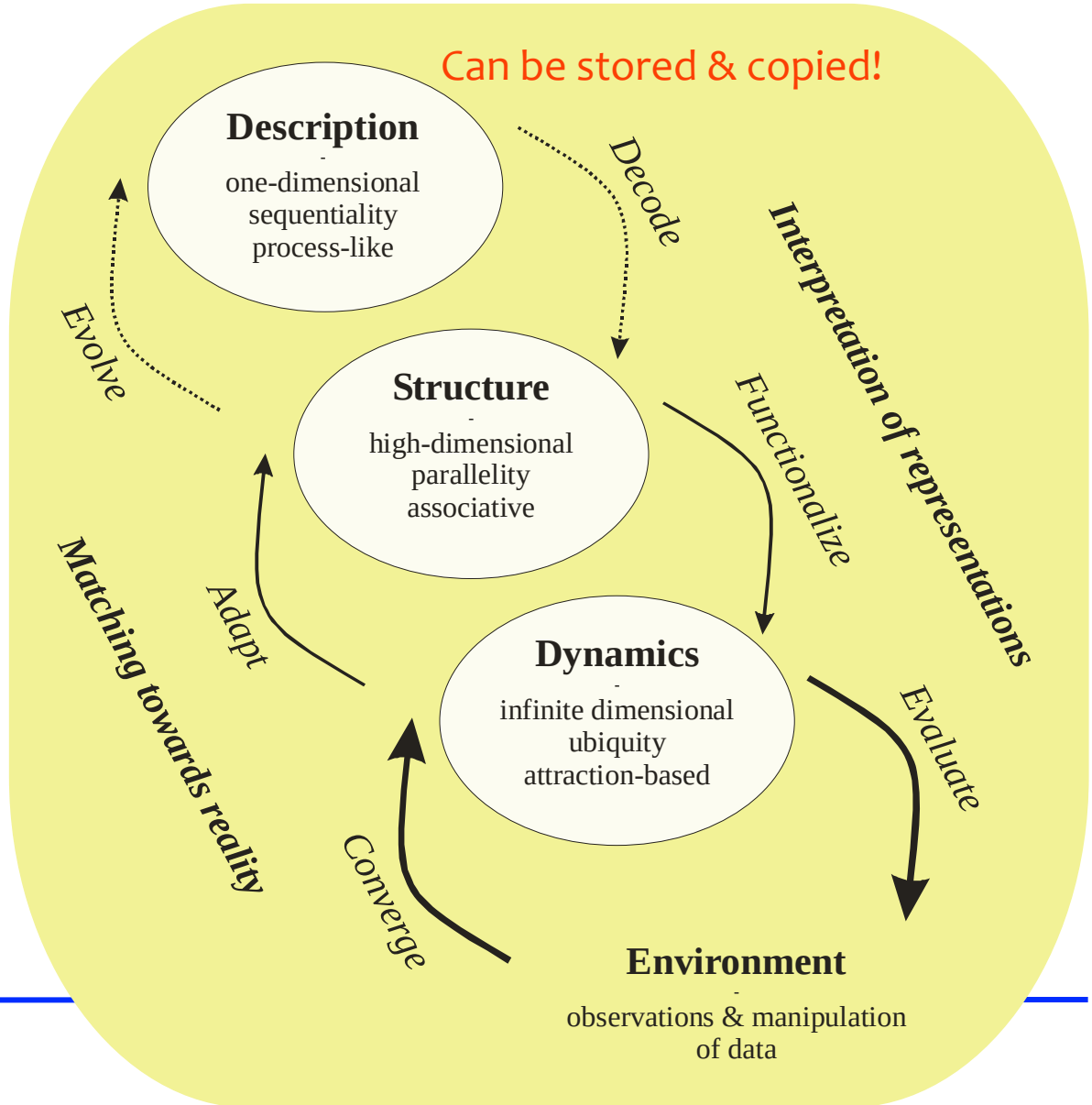
- But, intuitively – can cognition be merely data filtering?!
- For example, where do the wild associations come from? (This is studied next time)

How can the system implement "tree transforms"?

- ... Or, how are sequential representations decoded from the associative, parallel representations?

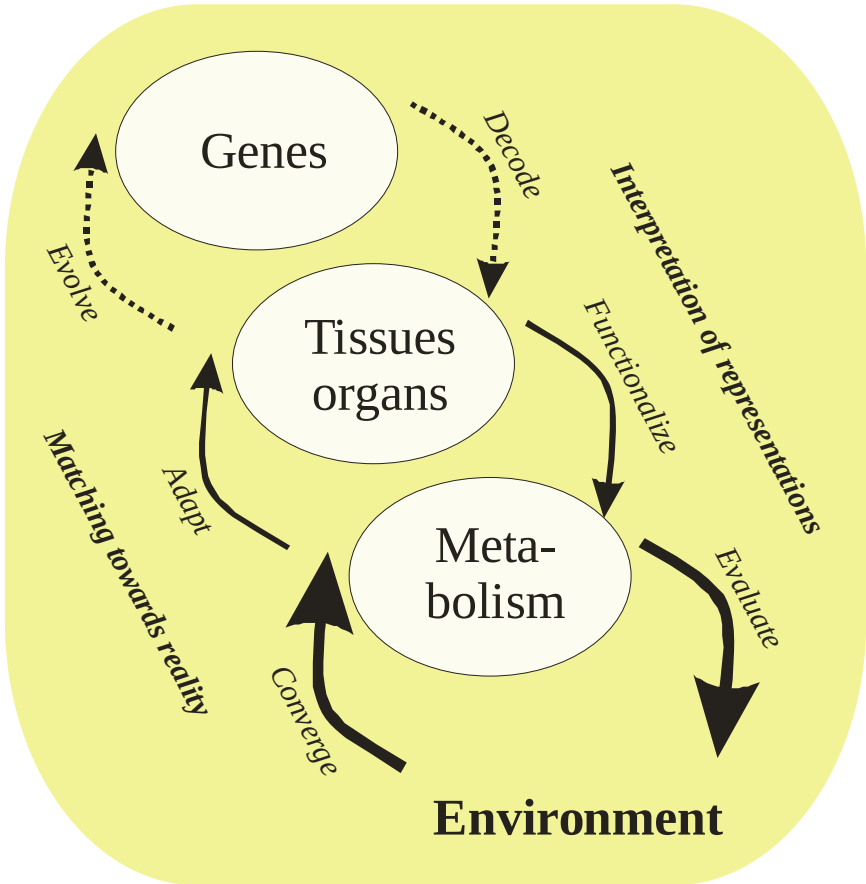
Mystery of static codes vs. dynamic processes

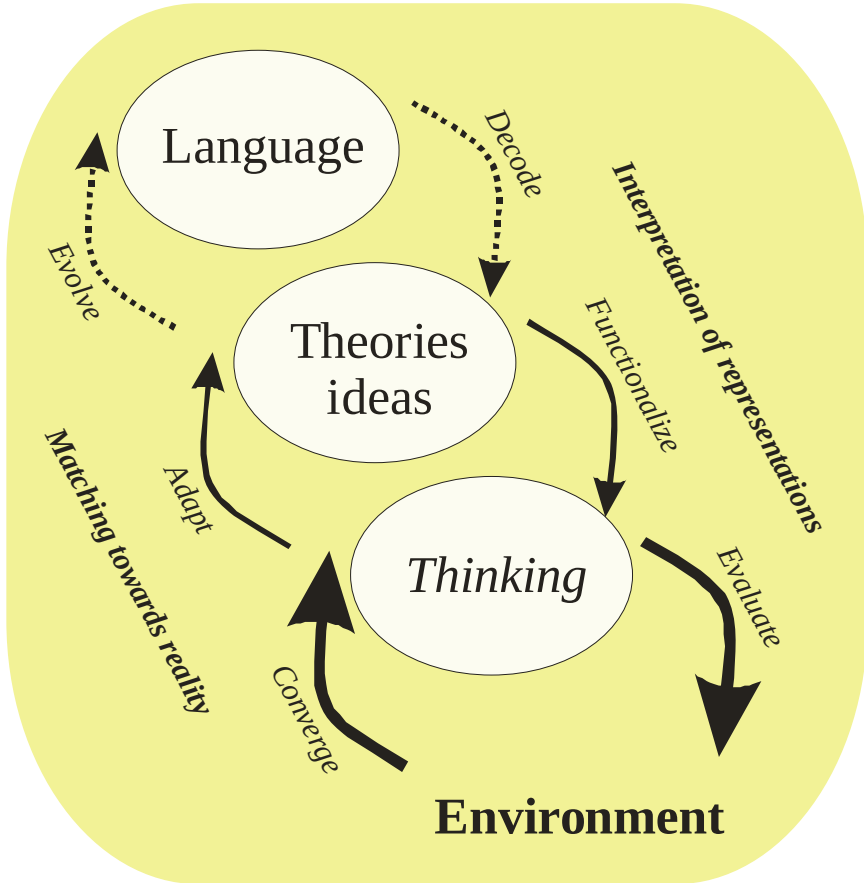
- Hierarchical search for balances within environments
- Everything takes place as through interpretation by the environment
- Systems have to be started step by step, subsystem at a time – always



Analogy

Biological domain





Cognitive domain

Deeper relations to biology?

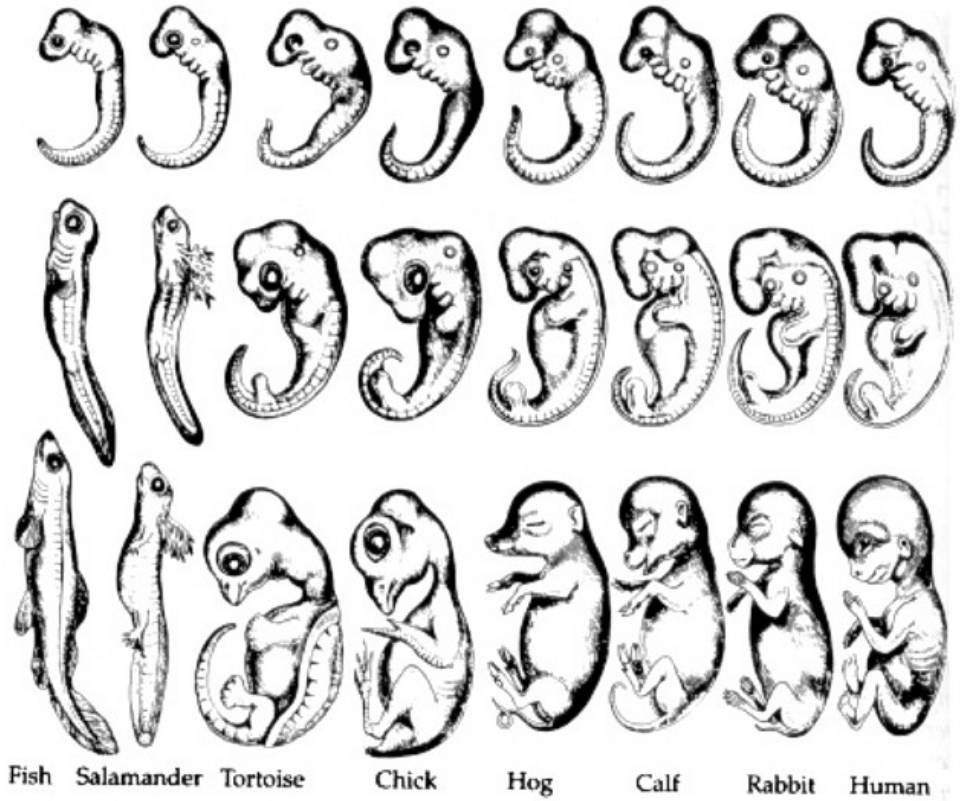
- Genetic system implements the reservoir of prototypical structures to choose among
- Genes are either inactive, or they are active in varying degrees, determining which structural alternatives are employed, and to what degree
- Active gene combinations determine the "basins of attraction", and continuous state optimization within these structural constraints takes place
- Genes seem to be highly redundant, making the inherently discontinuous coding look more continuous
- Gene activity/inactivity can be modeled in the same way as chunk activity/inactivity in the cognitive system?

Systems must be started from beginning

– Also cognitive systems start from zero!

- Ernst Haeckel: "Ontogeny recapitulates phylogeny"

  = "Embryo development repeats the evolutional species development"?
- Explanation: Essentially the same genes are there regardless of the species; in "higher" species the more primitive functions have become faster, and new ones have evolved



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More analogies next time!