Intelligent Control Imitating Biology: Promises, Challenges, Lessons

Prelude to Plenary Panel Discussion Comments

to be presented by

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Outline

- What is Intelligent Control?
- Why are we Talking about Biology?
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- Whither Intelligent Control (where are we today)?
- Purpose of Intelligence
- Components of Intelligence
- Organization of Intelligence
- Organization of Intelligence Research Directions
  - New Paradigms for Modeling
  - New Paradigms for Architectures
  - Examples
- Places to Look for Ideas (but not answers!)

What is "Intelligent Control?" -1

First, what is "intelligence"

- ... the ability of a system to act appropriately in an uncertain environment.
- ... requires the ability to sense the environment, to make decisions, and to control action.
- ... may include the ability to recognize objects and events, to represent knowledge in a world model, and to reason about and plan for the future.
- ... provides the capacity to perceive and understand, to choose wisely, and to act successfully under a large variety of circumstances so as to survive, prosper, and reproduce in a complex and often hostile environment.
- ... is the integration of knowledge and feedback into a sensory-interactive, goal-directed control system that can make plans, and generate effective, purposeful action directed toward achieving them.
- ... is the integration of perception, reason, emotion, and behavior in a sensing, perceiving, knowing, caring, planning, acting system that can succeed in achieving its goals ...

What is “Intelligent Control?” -2

Some definitions of “intelligent control”

- Discipline which implements intelligent machines to perform anthropomorphic tasks with a minimum of supervision and interaction with a human operator;
- ... [is] to be used by systems operating autonomously or semi-autonomously in a structured, unstructured, or partially unstructured environment.
- ... is the use of a general purpose control system which learns over time how to achieve goals (or optimize) in complex, noisy, nonlinear [and possibly unknown or uncertain] environments.
- a system that ... has the ability to comprehend, reason, and learn about processes, disturbances, and operating conditions.

What is “Intelligent Control?”-3

- Intelligent control is ... internal function and mechanism of a system that
  - produces enhanced performance
  - generates and creates actions based on stimulus,
    - derived from a set of alternatives
      - based on accumulated knowledge (information)
        - » from a diverse set of sensors
          - ·interacting with the environment.
- Intelligent control should involve *intelligence* and *control theory*.

What is “Intelligent Control?”-4

Intelligent control is “officially” defined as follows in [1] (June 1994):

- An intelligent system has the ability to act appropriately in an uncertain environment, where an appropriate action is that which increases the probability of success and success is the achievement of behavioral subgoals that support the system’s ultimate goal
- Intelligent controllers are envisioned as emulating human mental faculties such as adaptation and learning, planning under large uncertainty, coping with large amounts of data, etc.
- Autonomous (intelligent) control aims to attain higher degrees of autonomy and even setting control goals rather than stressing the intelligent methodology that achieves those goals.

Intelligent Control has “been around” and is still perceived as “coming around”

Two notes [2] (April 2003):

- The **goal of cybernetic engineering**, already articulated in the 1940s and even before, has been to **implement systems** capable of exhibiting highly flexible or “**intelligent**” responses to changing circumstances.

- The role of logic and decision-making in control systems is becoming and increasingly large part of modern control systems … includes … higher levels of abstract reasoning using high-level languages … **effective frameworks** for analyzing and designing systems of this form **have not yet been fully developed**.

Why are we Talking about Biology?

1. Many of the **(intelligent) things** we want machines and man-made systems to do **are done well by nature** (particularly humans/animals).
   - Thus it is reasonable to hope that imitating nature might provide "intelligent controllers" to provide solutions to complex control problems.
   - Ex: Neural nets, FLC, GAs, expert systems are inspired by brain cells and the way humans solve problems.
2. **Feedback is widespread in biological systems**
   - Thus, reasonable to hope that the application of control and systems theory might lead to advances in biological sciences.
   - Ex: Dynamical system modeling of cell signaling; leads to general topic of *systems biology* [3].

Therefore, ask: what are connections between control and biology? What can one learn from the other? What are the challenges in this area?

<u>Note</u>: Nothing says intelligent control must imitate biology.

Perspective on the Evolution of Engineering Disciplines

(not completely original with me, also arguable)

Date	Quantitative Sciences	Engineering Disciplines
1850	Physics	Civil, Mechanical
1950	Chemistry	Electrical, Chemical, Petroleum, Nuclear, Aerospace
2050	Biology	Biological Eng. ??? Genetic Eng. ???

Today – we can make **proteins** from DNA/RNA
Next – we need to understand how to make **functions** from proteins [4]
Then – it will be time for **bio-engineering (biology “by-the-numbers”)**

Systems Imitating Biology

- More and more is being learned about what makes biological systems "click."

- Implications for engineered system include:

  - Hardware: distributed (wireless) and embedded.
  - Software: ??
  - Systems: distributed and embedded, issues include:
    - Information management.
    - Information processing.
    - Decision making.
    - Control (can become more intelligent?).

- Smaller, larger, more complex:

  "smaller becomes larger."

Whither Intelligent Control? -1
(where are we today?)

- If success = use, then we can conclude that some aspects of the **promise of intelligent control** have been achieved:
  - NN are ubiquitous (at least FFNNs).
  - Any/every undergrad with the Matlab Fuzzy toolbox can do/does FLC.
- And, there have been a large number of ideas on **architectures**:
  - Subsumption (Brooks).
    - Input-output relations to solve small problem; prioritization
  - Behavior-based hierarchical (Arkin)
    - Motor schemas
  - Behavior-based reinforcement learning (Barto/Sutton/Anderson)
    - Output of a difference engine measuring state-goal mismatch and taking action to minimize that mismatch (Minsky)
  - Deliberative/Reactive
    - AI-based planning approach
  - 4D/RCS (Albus).
  - Etc.

Whither Intelligent Control? -2

(where are we today?)

- But, are the current state-of-the-art intelligent controllers based on NN, FLC, or GA algorithms using existing architectures really intelligent?
- **In my opinion**: **No**.
- Most NN or FLC controllers are better described as **biologically-inspired computational elements**.
  - Primarily compute I/O maps (nonlinear) for use in feedback control systems.
  - Do some pattern recognition tasks.
  - Self-organize to achieve a functional property.
- Most architectures are "best guess" engineering approximations to current state of knowledge about **biological function and its organization**.

Whither Intelligent Control? -3

(where are we today?)

- Using the earlier bio-engineering discussion:
  - Know computation (i.e., DNA/RNA to protein).
  - Don't know many function (i.e., protein to function).
  - Don't have a solid idea of how functions are organized.

- What is needed are better understandings of
  - Purpose of intelligence (goals).
  - Components of intelligence (memory, learning).
  - Organization of intelligence (models, language, architecture).

- Central Postulate: Biologically-inspired intelligent control will only be as good as our understanding of biological intelligence.

Whither Intelligent Control? -4

(where are we today?)

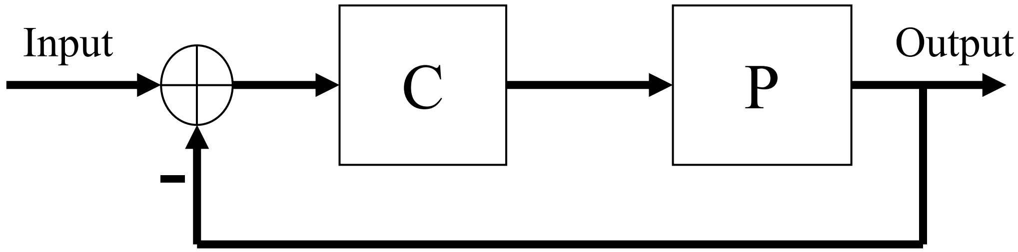
- "Designing a conventional or intelligent control system is essentially an optimization problem. The designer imposes certain **criteria**, e.g., optimality, stability, and performance robustness, and uses a mathematical, empirical, or heuristic **procedure** to obtain a controller that best satisfies these criteria. [5]

- I don't exactly agree with this (from a biologically-inspired viewpoint, I am not convinced biological systems optimize in a control-theoretic sense of the word), but it does point to two key points:

  – A criteria should exist (i.e., a purpose for the system).
  – Implies the need for a model (i.e., language for intelligence).

Purpose of Intelligence -1

- Consider this block diagram:



- Let
  - "C" denote the controller.
  - "P" denote the plant or process or system to be controlled
- Question: Given P, how to pick C so the system performs as desired
- Answer: It depends on three things:
  1. What do you want the system to do
  2. The "world" in which P lives
  3. The features of P

Purpose of Intelligence -2

- Performance Issues (what you want it to do?)
  - Do you simply want stability or also optimization?
  - Do you want to track time-varying inputs and/or reject disturbances?
  - Can you quantify a cost or performance index?
  - Does the cost index lead to a solvable problem?
  - Can you express the objective in terms of signal norms?
  - Is robustness an issue?
- Context Issues
  - Is this a local problem or a global problem?
  - Does the system operate around a set point?
  - Is the system subject to load disturbances?
  - Can you measure the aspects of the process you want to control?
  - Is there noise in the measurements? What kind?

Purpose of Intelligence -3

- To summarize: intelligent control needs a suitable criteria.
- Note: as a philosophical aside (due to Y.Q. Chen),
  - One might ask: is there any reason to expect that a controller motivated by, or imitating, a biological system will be intelligent?
  - I.e., are biological systems intelligent?
  - Could reply: Yes, because biological systems have an “ultimate purpose”: survival and they seek to optimize this purpose.
  - But, a purpose is not enough to make something intelligent.
  - We also need self-awareness and motivation, an ability to set goals, etc.
  - But, I believe we can agree that biological systems are intelligent or have aspects of intelligence.
  - However, this does raise the question: can we make an intelligent system without recourse to imitating biology. **My opinion is yes.**

Purpose of Intelligence -4

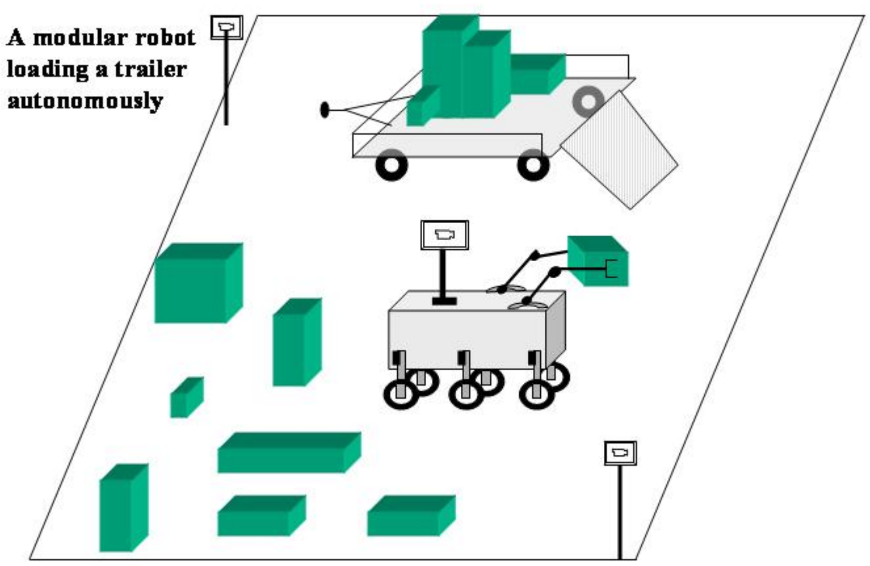
- But the question remains:
  - For what purpose is an “intelligent controller” intelligent?
- We might refine the question by asking:
  - At what level is an “intelligent controller” intelligent?
- Could consider degrees or levels or dimensions of intelligence:
  - Parameter adaptation (for lumped systems).
  - Structural adaptation.
- Must also consider the “environment” of the intelligent controller in defining its purpose:
  - Structured, semi-structured, un-structured?
  - Autonomy desired (does autonomy = intelligence?)
  - Relationship between users and the intelligent system.
  - Complexity is another issue, as is resolution.
- Purpose of intelligence is context dependent; thus intelligent controllers are context dependent.

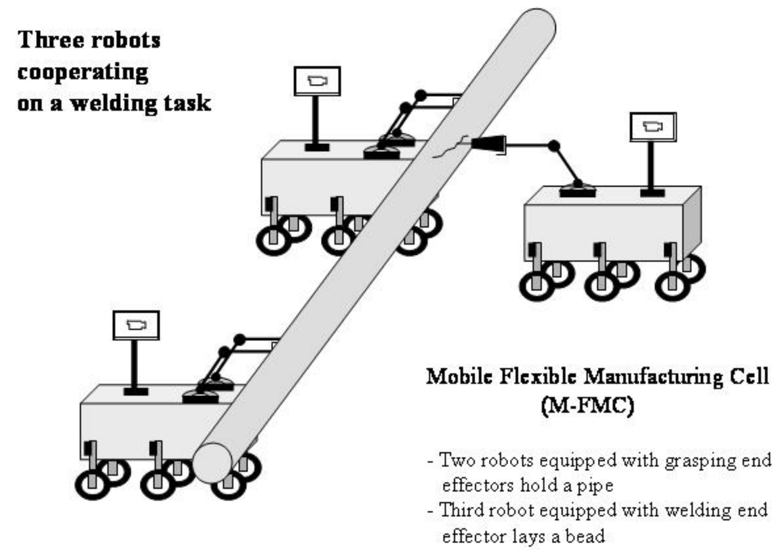
Purpose of Intelligence -5

- **In my opinion**:
  - Researchers understand that the previous questions exist.
  - Answers to these questions have been provided in situational ways.
  - Solutions to date are heuristic and limited by our current understanding of how biology answers the same questions.
  - There does not exist a general theory:
    - Could argue there should not exist a general theory.
    - Perhaps ultimately we must say intelligence is context dependent and leave it at that.
  - We do not know enough about how the purpose of intelligence is defined in the context of biology.

Purpose of Intelligence -6

- **Alternate view**: Don’t bother trying to define these things. Simply ask: what do you want it to do. Ex. – a single machine to do either of the following task via semantic (verbal) instruction from a (human) supervisor.





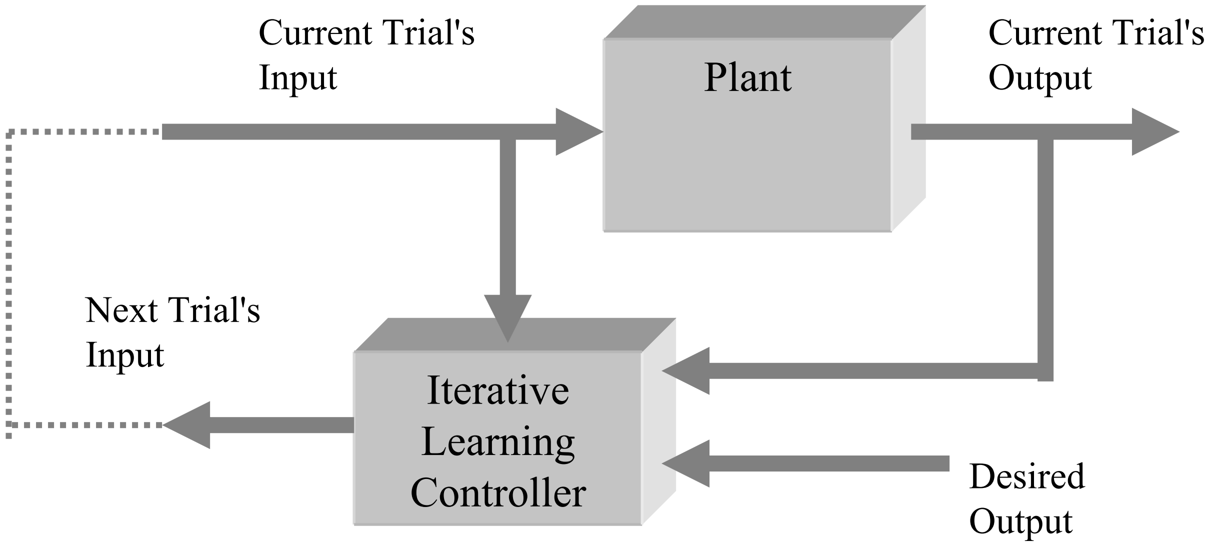
Components of Intelligence – Learning -1

- What is learning? From Webster's:

  … modification of a behavioral tendency by experience…
- The idea: copy human tendency to learn from experience.
- Generally, learning from repeated trials.
- Typical Examples:

  – Iterative Learning Control (ILC)/Reinforcement learning: update the input to the system, based on previous system operation results.
  – Neural nets: Update weights (SEE OTHER SLIDES ON NN).
  – Learning with fuzzy logic: Update the membership functions and possibly including the number of membership functions (SEE OTHER SLIDES ON FLC).

Iterative Learning Control



$$\text{Plant}: \; Y_k(t) = HU_k(t) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \; t \in [0,T]$$

$$\text{ILC}: \quad U_{k+1}(t) = Q_k U_k(t) + L_k(Y_d - Y_K) \; \ldots t \in [0,T]$$

Fundamentally: ILC updates parameters in a fixed structure,
as do NN and FLC, adaptive controllers, etc.

Components of Intelligence – Learning -2

Adaptation and learning are fundamentally different.

Adaptation	Learning
Reactive: maintain desired behavior (local optimization)	*Constructional*: synthesize desired behavior (global optimization
Temporal emphasis	Spatial emphasis
No memory → no anticipation	Memory → anticipation
Fast dynamics	Slow dynamics
Known structure and slowly time-varying behavior	Structural uncertainty and nonlinear dependencies

(Due to ??)

Components of Intelligence – Learning -3

Precision loses intelligence/Intelligence loses precision

Fixed designs		Flexible designs	
Static Feedback	Dynamic Compensation	Adaptive Control	(Possible) Learning Control
$u(s) = Ke(s)$	$u(s) = K(s)e(s)$	$u(s) = K(s, p)e(s)$ Change parameter *p*	$u(s) = K(s)e(s)$ Change controller *K*

→Increasing use of performance feedback→

→ Increasing use of past information →

→ Increasing uncertainty →

(Due to ??)

Components of Intelligence – Learning -4

- **In my opinion**:
  - For most "learning controllers" to date in the intelligent control field:
    - "Learning" is no more than parameter adaptation.
  - The view of NN or FLC controllers as **biologically-inspired computational elements** reinforces this view.
    - We still only understand "learning" at the DNA/RNA to protein level, but not at the functional organizational level.
  - Iterative updating is not learning.
  - Parameter adaptation is not learning.
  - Learning requires adaptation at the meta-level.
  - We do not know enough about learning in the context of biology (deeper understand will include another component: memory).

Organization of Intelligence -1

(models, language, architecture)

- Given a physical system that we want to control, along with a desired behavior or performance for the controlled system.
- We determine a controller that will cause the closed-loop system to exhibit the desired behavior by (the method of the “MAD” control theorist):
  - Modelling the system to be controlled;
  - Analyzing the model to determine the properties of the system;
  - Designing a control algorithm which, when coupled with the model of the system, produces the desired closed-loop behavior;
  - Implementing the controller through software and hardware realizations of the control law.
- Modeling is the key.
- A framework for describing the system in a precise way makes it possible to develop rigorous techniques for analyzing and designing systems.

Organization of Intelligence -2

(models, language, architecture)

- Modelling Issues:
  - Is the model dynamic or static?
  - Is the model linear or nonlinear?
  - Is the model finite dimensional?
  - Does the model change or degrade with time?
  - What kind of uncertainty do you have in the model: structured or unstructured?
  - Is the model stochastic?
  - Is the model qualitative or linguistic?
  - Do human operators perform well controlling the system manually?
- A variety of methods have been developed to deal with the factors that influence controller design.
- Each is distinguished by the assumptions made about the performance requirements, the system to be controlled, and available measurements.

Organization of Intelligence -3

(models, language, architecture)

- To summarize: intelligent control needs a suitable modeling framework.
- "… Essentially every thing done in the last [50] years of control theory rests on a common presumption of centrality [that all the information available about the system, and the calculations based on this information, take place at a single location]…" [6].
- **In my opinion**:
  - The classical, lumped parameter ODE paradigm of control (which has primarily been used in "intelligent control" methodologies) is inadequate for future progress.
  - Issues of centrality will impact our:
    - Understanding of functional-level intelligent control (e.g., motion control for advanced robotics needs spatial-temporal models).
    - Understanding of organization of functions (e.g., distributed intelligence such as swarms).
  - Advances are needed in understanding modeling, reasoning in the context of models (languages), and organization in biology.

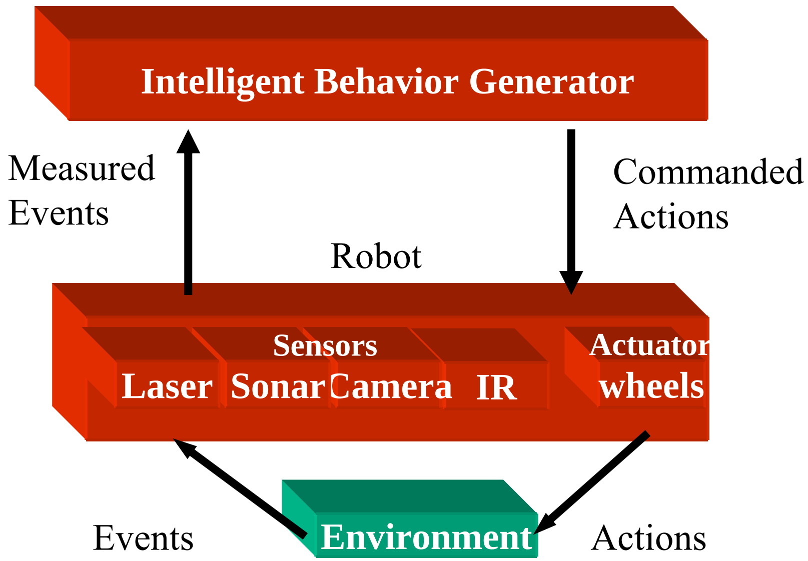
Organization of Intelligence Research Directions -1

- New Paradigms for Modeling
  - **In my opinion**, a language-based perspective is essential.
  - From the perspective of a linguist:
  - Dogs have no language (they are fundamentally driven by stimulus-response, which alone isn't intelligence) [7]
    - If we believe this, the implication for "intelligent control" is severe, as a key building block in intelligent control is "If/then/else," which is fundamentally a stimulus-response.
    - Thus, again we might conclude that much of "Intelligent Control" is not intelligent!
  - While these are arguable points, and perhaps only a matter of definition, the point remains that language is important.
  - So, perhaps hybrid control is the way?

(Note: I am unhappy with this slide, but can't see my way through it.)

Hybrid Approach

- A behavior generator can be interpreted as a discrete-event dynamic system (DEDS) driving a continuous system; the resulting system is called hybrid.



- In this interpretation commands and events are symbols in an alphabet associated with a (regular) language.
- This formalism can be used for synthesis of scripts.
- Other suggested approaches for synthesis include Pertri nets and recent results on controller design for finite state machine model matching [8].

Organization of Intelligence Research Directions -2

- New Paradigms for Modeling (cont.)
  - Some comments/conjectures about language as a model. Consider (submitted to me by Y.Q Chen):
    - "Aoccdrnig to a rscheearch at an Elingsh uinervtisy, it deosn't mttaer in waht oredr the ltteers in a wrod are, the olny iprmoetnt tihng is taht frist and lsat ltteer is at the rghit pclae. The rset can be a toatl mses and you can sitll raed it wouthit porbelm. Tihs is bcuseae we do not raed ervey lteter by it slef but the wrod as a wlohe. "
    - It has been suggested that
      1. Language is robust against the error in the "Atomic" word.
      2. Local association gives an added "robustness" - so the "spatial" plays an important role in intelligent control.

Organization of Intelligence Research Directions -3

- New Paradigms for Modeling (cont.)
  - Symbolic AI
    - Automated theorem-proving using high-level predicate logic (e.g., software system called *Theorema)*.
    - Gröbner bases provide an algorithmic, computational "…proving method for … Boolean combinations of equalities over an algebraically closed field …" [9].
    - Recently it has been shown that Gröbner bases can be used in theorem-proving software. Directions in this work could lead to algorithms that can do "inductive" thinking [9].
  - Spatial-temporal methodologies.
    - To achieve a human-like android (assuming suitable materials), hybrid system based motion control algorithms will not be "smart" enough (too "jerky").
    - Need intelligent distributed control (PDE-based?).
    - Need an analog perspective.

Organization of Intelligence Research Directions -4

- New Paradigms for Architectures
  - Role of memory in intelligence needs to be understood.
  - Architectures must allow “growth” of knowledge (e.g., evolution of language)
- Other biologically-inspired modeling and architecture ideas:
  - Swarms (e.g., bacterial foraging [10], ants/bees, etc.).
  - Multi-agent systems (e.g., welding experiment [11]).
  - Self-organization, complex adaptive system (e.g., membrane formation [12,13]).
  - Architecture of cell functionality (e.g., genomics, proteomics [4]).
  - Cybernetic views (e.g., Miller’s Living System Theory [14]).

Organization of Intelligence Research Directions -5

- Example 1: Cooperative Agents for Gas Metal Arc Welding

- Each agent has a generic function and message protocol that can be understood by all others [11].

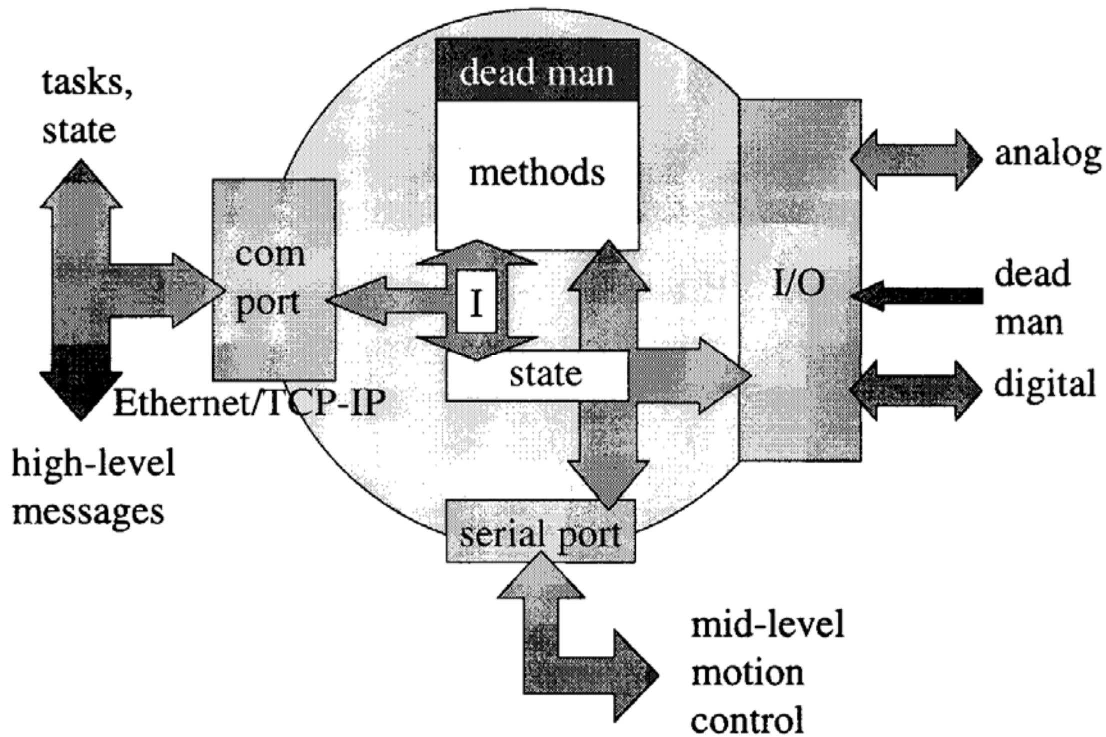


Figure from [11]

Organization of Intelligence Research Directions -6

- Example 1: Cooperative Agents for Gas Metal Arc Welding (cont.)

- A global "weld quality" measure is decomposed into individual agent quality measures and propagated to each agent [11].

- System was able to "learn" how to weld.

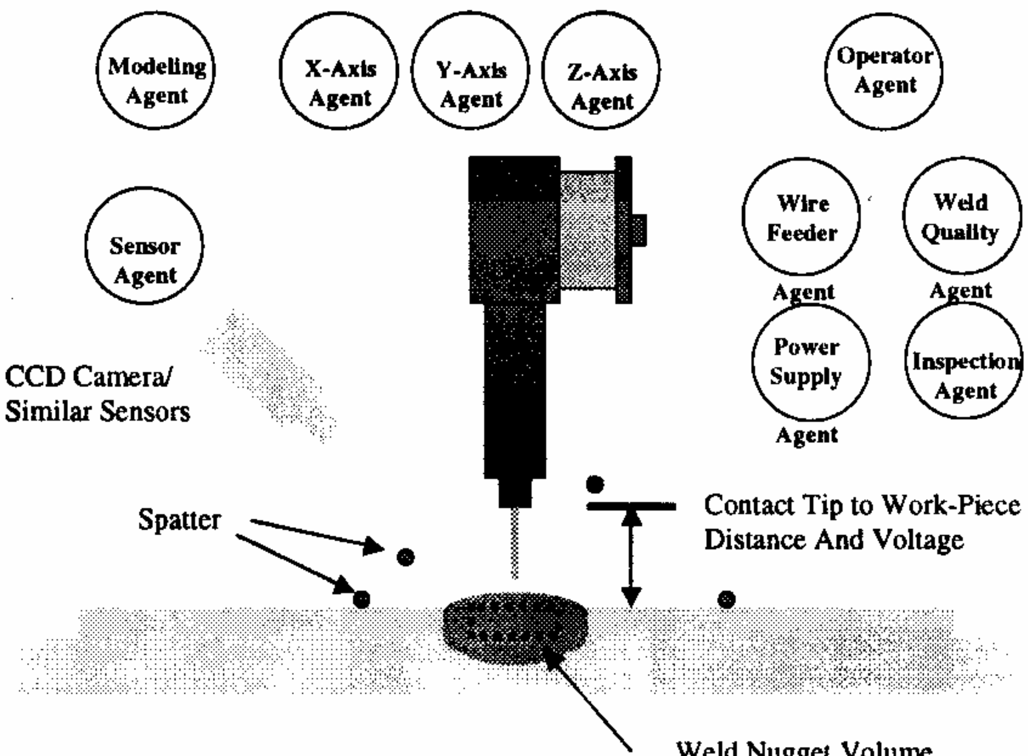


Figure from [11]

Organization of Intelligence Research Directions -7

- Example 2: Molecular membrane formation via self-organization.
  - Why do some lipids organize to form membrane walls.
  - Of course, it is "just chemistry," but in fact,
  - "…sorting appears to be based on the inclusion or exclusion of certain types of lipids in vesicles or tubules as they bud from membrane organalles …" [13].
  - I.e., there is a type of "winner-take-all" competition reminiscent of self-organizing ANNs.

Two figures below from [12]

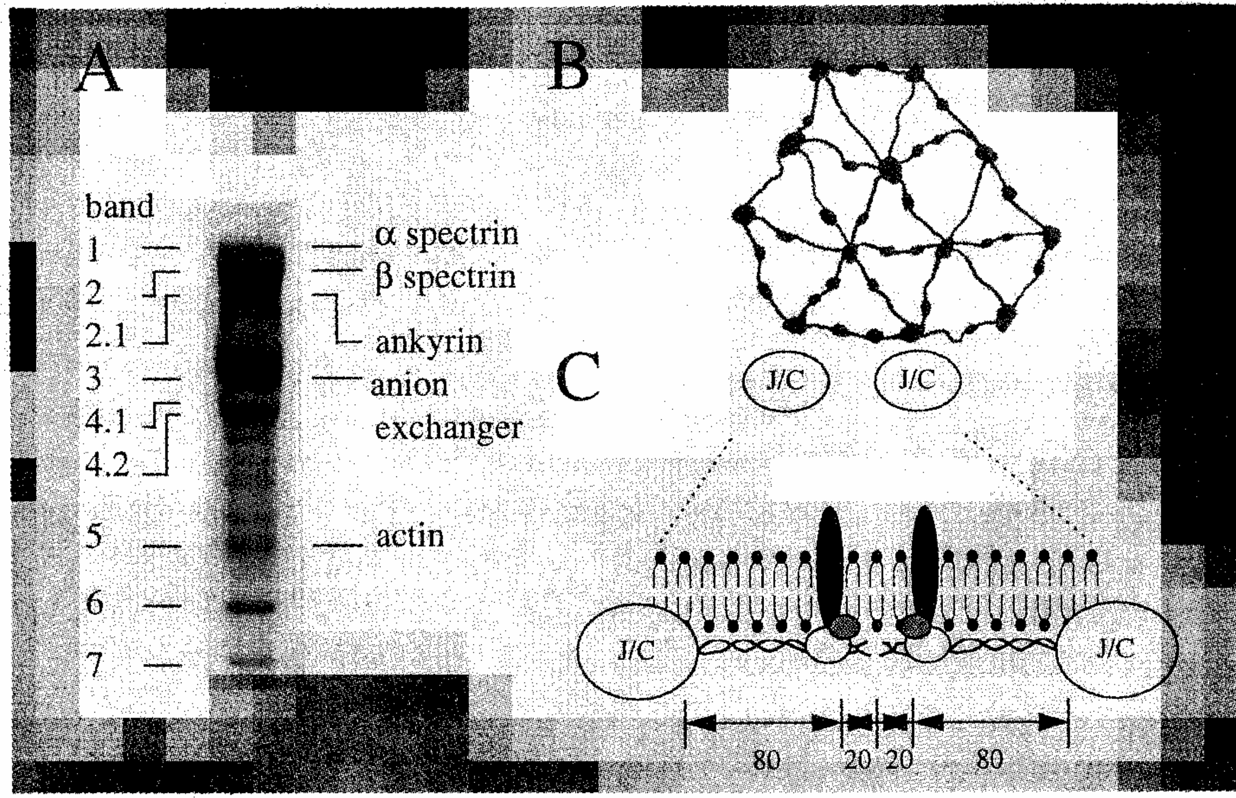


Fig. 1. The molecular organization of erythrocyte membrane skeletal network. (A) The protein profile of human erythrocyte membranes after being separated on the SDS-polyacrylamide gel. The specific names of the major proteins are on the right. The names of these proteins, based on their positions on the gel, are on the left. (B) The sketch showing the top view of the hypotonically expanded membrane skeletal network. J/C stands for junctional complex. The pair of smaller complexes between the two junctional complexes in mid regions of the spectrin tetramers, are protein 4.2/band 3/ankyrin complexes. (C) The sketch showing the side view of the erythrocyte membrane in between two junctional complexes. A spectrin tetramer is 200-nm long, consisting of two $\alpha\beta$ spectrin dimers, which are associated with a head-to-head fashion. The two tail ends of the spectrin tetramer joint the junctional complexes and the two head ends meet in the middle. A spectrin tetramer is associated with a pair of protein 4.2/band 3/ankyrin complexes, each is 20 nm away from the midpoint of the spectrin tetramer. The complex consisting of transmembrane proteins band 3 (in black), protein 4.2 (in gray), and ankyrin (in white), links the erythrocyte membrane skeletal network to the endoface of the lipid bilayer. Theses complexes are the major bridges that hang the spectrin-actin based membrane skeletal network to the lipid bilayer.

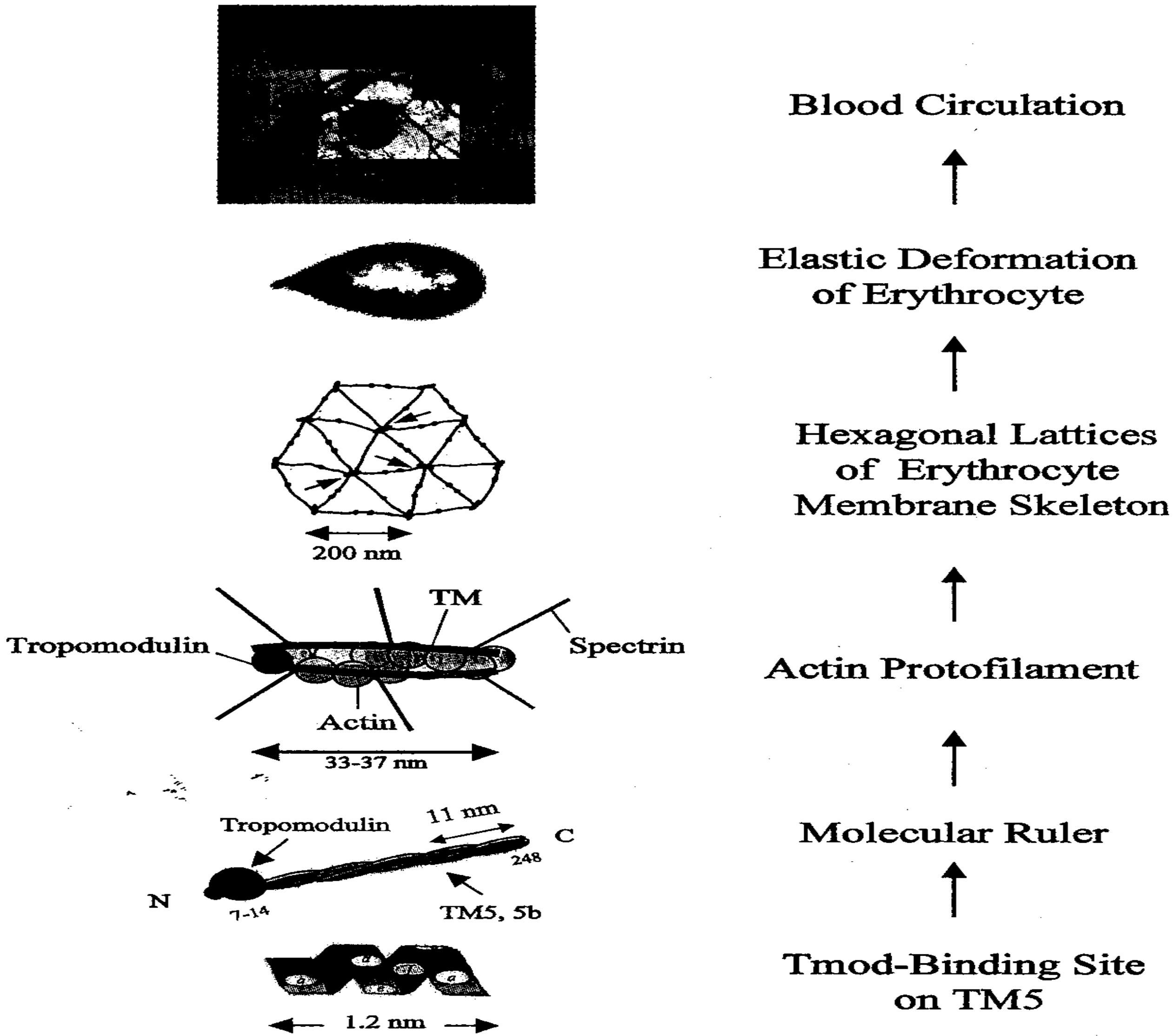
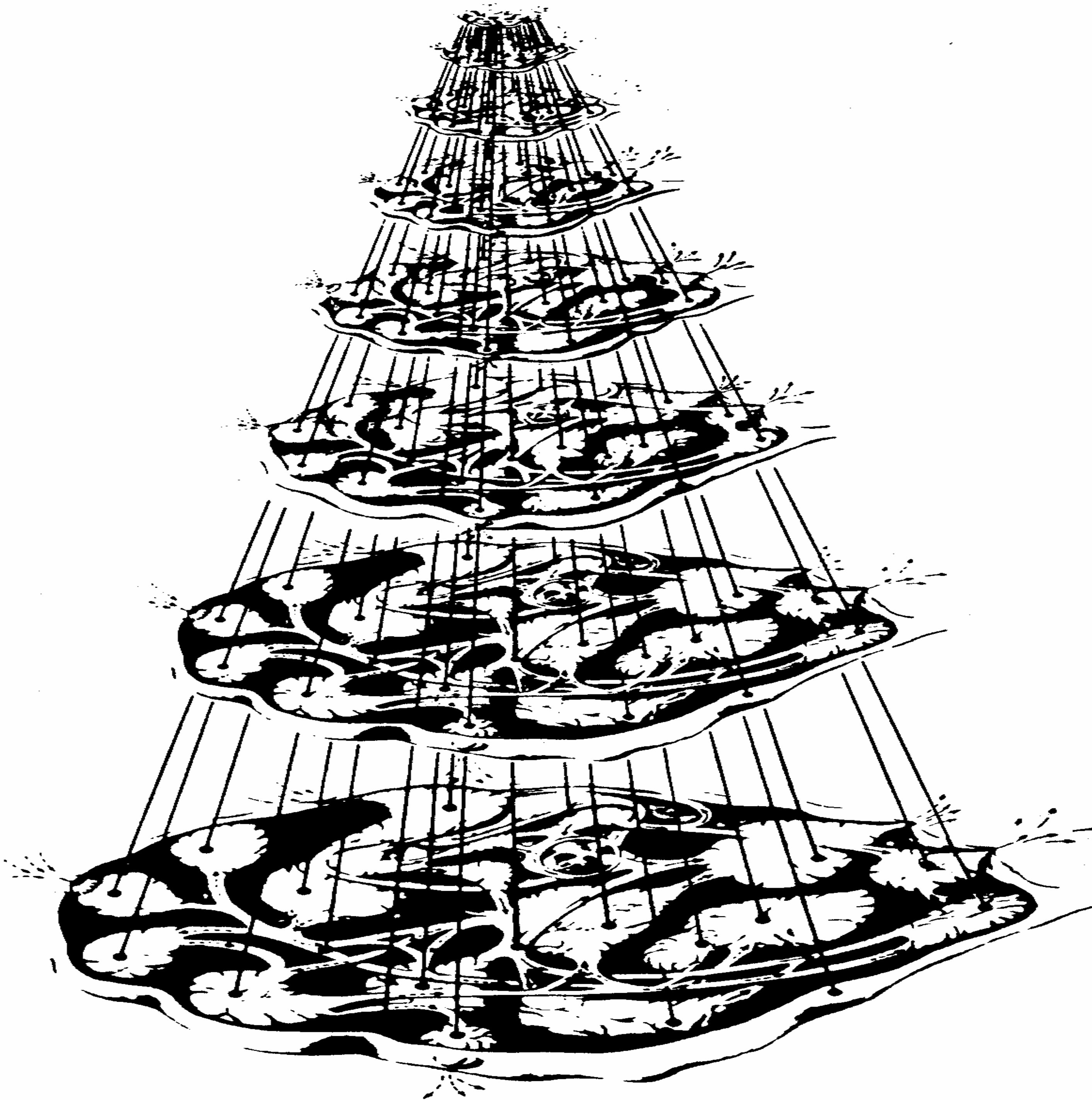


Fig. 5. A view on how E-tropomodulin and specific TM isoforms contribute to the erythrocyte membrane mechanics. E-tropomodulin binding site is described in Section 3.1. Molecular ruler, protofilament, and hexagon are described in Section 3.2. Elastic deformation of erythrocytes is described in Section 1.2. The top panel shows "blue" *E-Tmod* +/− erythrocytes circulating in a 9.5 day old mouse embryo. The yolk sac is outside and the embryo proper with a "blue" heart is inside. Blood cells and candiomyocytes turned blue after the X-gal staining because the "knocked in" *lacZ* reporter gene, which replaced the *E-Tmod* gene, was highly expressed as described in Section 3.6. From Ref. 15, reproduced by permission of the American Society of Hematology.

Organization of Intelligence Research Directions -8

- Example 3: Miller's Living System Theory [14]
  - Postulated eight levels of living systems (idea of *fray out* whereby levels lead to levels like unraveling a rope).
  - Identified 20 critical subsystems of a living system
  - Each subsystem is found in each level

Two figures below from [14].


Cell
Organ
Organism
Group
Organization
Community
Society
Supranational System

The 20 Critical Subsystems of a Living System

SUBSYSTEMS WHICH PROCESS BOTH MATTER-ENERGY AND INFORMATION

1. *Reproducer*, the subsystem which carries out the instructions in the genetic information or charter of a system and mobilizes matter, energy, and information to produce one or more similar systems.

2. *Boundary*, the subsystem at the perimeter of a system that holds together the components which make up the system, protects them from environmental stresses, and excludes or permits entry to various sorts of matter-energy and information.

SUBSYSTEMS WHICH PROCESS MATTER-ENERGY

3. *Ingestor*, the subsystem which brings matter-energy across the system boundary from the environment.

4. *Distributor*, the subsystem which carries inputs from outside the system or outputs from its subsystems around the system to each component.

5. *Converter*, the subsystem which changes certain inputs to the system into forms more useful for the special processes of that particular system.

6. *Producer*, the subsystem which forms stable associations that endure for significant periods among matter-energy inputs to the system or outputs from its converter, the materials synthesized being for growth, damage repair, or replacement of components of the system, or for providing energy for moving or constituting the system's outputs of products or information markers to its suprasystem.

7. *Matter-energy storage*, the subsystem which places matter or energy at some location in the system, retains it over time, and retrieves it.

8. *Extruder*, the subsystem which transmits matter-energy out of the system in the forms of products or wastes.

9. *Motor*, the subsystem which moves the system or parts of it in relation to part or all of its environment or moves components of its environment in relation to each other.

10. *Supporter*, the subsystem which maintains the proper spatial relationships among components of the system, so that they can interact without weighting each other down or crowding each other.

SUBSYSTEMS WHICH PROCESS INFORMATION

11. *Input transducer*, the sensory subsystem which brings markers bearing information into the system, changing them to other matter-energy forms suitable for transmission within it.

12. *Internal transducer*, the sensory subsystem which receives, from subsystems or components within the system, markers bearing information about significant alterations in those subsystems or components, changing them to other matter-energy forms of a sort which can be transmitted within it.

13. *Channel and net*, the subsystem composed of a single route in physical space, or multiple interconnected routes, over which markers bearing information are transmitted to all parts of the system.

14. *Timer*, the subsystem which transmits to the decider information about time-related states of the environment or of components of the system. This information signals the decider of the system or deciders of subsystems to start, stop, alter the rate, or advance or delay the phase of one or more of the system's processes, thus coordinating them in time.

15. *Decoder*, the subsystem which alters the code of information input to it through the input transducer or internal transducer into a "private" code that can be used internally by the system.

16. *Associator*, the subsystem which carries out the first stage of the learning process, forming enduring associations among items of information in the system.

17. *Memory*, the subsystem which carries out the second stage of the learning process, storing information in the system for different periods of time, and then retrieving it.

18. *Decider*, the executive subsystem which receives information inputs from all other subsystems and transmits to them information outputs for guidance, coordination, and control of the system.

19. *Encoder*, the subsystem which alters the code of information input to it from other information processing subsystems, from a "private" code used internally by the system into a "public" code which can be interpreted by other systems in its environment.

20. *Output transducer*, the subsystem which puts out markers bearing information from the system, changing markers within the system into other matter-energy forms which can be transmitted over channels in the system's environment.

Places to Look for Ideas -1

(but not answers!)

From Biology:

- Neuro-anatomy has produced extensive maps of the interconnecting pathways making up the structure of the brain.
- Neuro-physiology is demonstrating how neurons compute functions and communicate information.
- Neuro-pharmacology is discovering transmitter substances that modify value judgments, computer reward and punishment, activate behavior and produce learning.
- Psycho-physics provides clues as to how individuals receive objects, events, time and space, and how they reason about relationships between themselves and the external world.
- Behavioral psychology provides information about mental developments, emotions, and behavior.

Places to Look for Ideas -2

(but not answers!)

From Math/CS:

- Learning automata, ANN, brain modelling - insight into learning and the similarities and differences between neuronal and electronics computing processes.
- Computer science and AI - probes the nature of language, image processing, rule-based reasoning, planning, and problem-solving.
- Game theory and operations research - methods for decision-making under uncertainty.

Places to Look for Ideas -3

(but not answers!)

From Engineering:

- Robotics and autonomous vehicles research - real-time sensory processing, world modelling, navigation, trajectory generation, obstacle avoidance.
- Automated manufacturing and process control - intelligent hierarchical methods, distributed databases, object geometry and materials representations, data-driven task sequencing, network communications, multi-processor operating systems.
- Control theory - understanding of stability, adaptability, controllability.
- Sonar, radar, and optical signal processing - methods for fusing sensory input from multiple sources, and assessing the believability of noisy data.

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