99 ideas from "Learning Outside the Brain: Integrating Cognitive Science and Systems Biology | IEEE Journals & Magazine By: Jeremy Gunawardena"

1. How did cognition evolve and how is it embodied?
2. biological learning can now be seen as a form of information processing, in which…
3. … the representation within the organism of the information that has been acquired forms a model of the environment…
4. … from which predictions are made about future events.
5. The question of systems biology: how do we get from dead molecules to living organisms?
6. How do the molecules collectively give rise to the phenomena of life?
7. Learning equips a machine with agency in the form of goals and purposes, and thereby captures an essential feature of life.
9. We perpetuate the myth to the non-scientific public that science is a unified approach to understanding the world.
10. Even within biology, different disciplines occupy different conceptual landscapes, …
11. … use different experimental paradigms, …
12. … talk different languages often with the same words, …
13. … and impose stringent border controls on foreigners.
14. "The spectacle of rival historians each established in their own fortresses of specialized knowledge, waiting to destroy the unwary trespasser." - Phillip Ziegler
15. Learning occurs when the organism is surprised by the failure of its own predictions.
16. Organisms appear to be extracting information from time series about the flow of events,
17. … assessing which series are predictive of others, and when these predicted events will occur.
19. They are undertaking computations to form an internal model, or temporal map, …
20. … of the experienced stimuli, which is being continually updated as new events are encountered.
21. a physiologically implemented internal representation of the external world
22. The agent seeks an optimal reward by iteratively learning how to control, …
23. … through its own actions, the environment that stimulates it.
24. The key problem lies in balancing short-term exploitation of reward, or immediate control,...
25. … with long-term exploration, or system identification.
26. The idea that agents use two types of models appears repeatedly in cognitive science from different perspectives, …
27. … with different terminologies and interpretations:
28. retrospective vs prospective, reflexive vs reflective, …
29. … habitual vs goal-oriented, model-free vs model-based.
30. Animals appear to use a balance of models rather than a dichotomy.
31. In computational terms, both types of models can be formulated from a RL perspective.
32. Gallistel and colleagues consider stimuli as stochastic processes impinging on an agent…
33. … and ascribe the predictive strength, or degree of contingency, of the two processes, …
34. … to the mutual information between them, suitably normalized.
35. If the agent is to estimate such quantities, the problem of temporal discretization still has to be confronted and …
36. … is addressed empirically using Weber's principle that…

37. … the minimal discernable difference in a measure, including a measure of a time interval, is proportional to its value.
38. The resulting theory is readily seen to be timescale invariant, …
39. … but so far lacks the neurophysiological basis of temporal difference error prediction.
40. The organism sensed departures from constancy and actively compensated for them.
41. To control a system, one must know something about it, and that knowledge must be represented within the controller.
42. Integral control is an instance of the internal models principle: …
43. … the controller contains a model of the perturbations to which the system is exposed.
44. Control theory tells us that internal models must exist as a consequence of homeostasis.
45. Bruce McEwan discovered receptors in the hippocampus for stress-related, …
46. … steroid hormones from the HPA axis, …
47. … showing that the endocrine system was signaling not only to the visceral tissues but also to the brain.
48. Brain regions involved in learning and memory were, thereby, seen to be implicated in homeostasis.
49. “Allostasis” proposes that efficient regulation requires anticipating needs and preparing to satisfy them before they arise
50. The focus on anticipation is suggestive of reflective, rather than reflexive, internal models.
51. Active inference brings the idea of “mind as model” to a Bayesian culmination.
52. Active inference has its roots in the concept of predictive coding in the brain, but approaches it from a variational Bayesian perspective.
53. Predictive coding stipulates a feedback loop between higher (more abstract) areas and lower (more concrete) brain areas, …
54. … in which the higher area sends down feedforward predictions about lower area activities based on an encoded internal model of the lower area activities …
55. … while the lower area sends up feedback errors between the predictions and its actual activities.
56. The internal model encodes assumptions about the hidden causes underlying lower area activities.
57. Inference of activities from models flows downward, …
58. … while learning of models from activities flows upward.
59. The feedback loops are arranged in a hierarchy between exteroceptive and interoceptive sensorimotor processes …
60. … in the periphery and cognitive abstractions in higher cortical areas.
61. Cognitive scientists locate internal models entirely in the brain, …
62. … but the physiological evidence suggests the involvement of other tissues and the endocrine system, …
63. … whose collective role in the internal models has not been clarified.
64. How can memories be biochemically encoded over a lifetime?
65. Single cells in multicellular organisms have relinquished their autonomy as independent agents for the benefit of the collective.
66. The dendritic arbors of pyramidal neurons are capable of computations, such as XOR, …
67. … which were previously thought to require neuronal networks.

68. Protein post-translational modification occurs much more broadly than in epigenetics, and operates on a faster timescale.
69. Eukaryotic cells have profound capabilities for multi-site post-translational modifications:
70. … The hub protein p53 has over 100 sites of modification, …
71. … giving each molecule of p53 the capacity to exhibit …
72. … some 10^30 “modforms,” or global patterns of modification.
73. Cells have an internal state, given by their pattern of gene expression, …
74. … nutrient and energy levels, time on their circadian clock, cell cycle period, and so on.
75. Cells have capabilities for action, such as secretion, phagocytosis, and movement.
76. Active inference suggests that cells have internal models of the world,
77. … which are continually updated by the discrepancy between the cell’s expectations …
78. … based on the model and the information received from its internal and external states.
79. From this perspective, the goal-directed behavior of cells is an emergent property of minimizing prediction errors.
80. How do organisms disentangle the effects of their actions on their own selves …
81. … from the effects of the environment?
82. … each cell autonomously attempting to minimize its own prediction errors in the collective context of all the other cells that are doing the same.
83. Methods that offer enough signals to detect an increase in mutual information between the system states and the environmental states.
84. Development may come to be seen not as the programmed construction of the organism,
85. … but as the process of collectively learning which organism to construct.
86. Two interconnected features: (1) increase of mutual information between environmental states and system states …
87. (2) in which the internal representation of external information can influence subsequent behavior.
88. The mutual information whose increase is detected by an observer may not itself be represented within the system, …
89. … whose intrinsic representation may encode only what is computationally relevant.
90. It may be necessary to understand how information is represented by individual neurons
91. … in order to understand how cognitive memories are represented by brains.
92. The question of how learned information is represented, encoded, and used …
93. … is the central challenge to be confronted in adopting a learning-centric perspective.
94. The amount by which mutual information is increased during learning may offer hints about the underlying representation
95. The problem of how learned information is represented and encoded remains one of the major problems of contemporary science.
96. Although biologists study life, they are often reluctant to grapple with its meaning.
97. It can have an ineffable, if not downright mystical, quality that repels scientific analysis.
98. Learning offers an alternative perspective, which is perfectly scientific, …
99. … but gives back to living systems some of the autonomy and agency that they have lacked as mere, unlearning machines.