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A Roadmap for Cognitive Development in Humanoid Robots
David Vernon
Claes von Hofsten
Luciano Fadiga
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A Roadmap for Cognitive Development in Humanoid Robots
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David Vernon, Claes von Hofsten,
and Luciano Fadiga

A Roadmap for Cognitive Development in Humanoid Robots

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Rüdiger Dillmann, University of Karlsruhe, Faculty of Informatics, Institute of Anthropomatics, Humanoids and Intelligence Systems Laboratories, Kaiserstr. 12, 76131 Karlsruhe, Germany

Yoshihiko Nakamura, Tokyo University Fac. Engineering, Dept. Mechano-Informatics, 7-3-1 Hongo, Bukyo-ku Tokyo, 113-8656, Japan

Stefan Schaal, University of Southern California, Department Computer Science, Computational Learning & Motor Control Lab., Los Angeles, CA 90089-2905, USA

David Vernon, Department of Robotics, Brain and Cognitive Sciences, Italian Institute of Technology, Genoa, Italy

Authors

David Vernon
Department of Robotics, Brain and Cognitive Sciences
Italian Institute of Technology
Genoa
Italy
E-mail: david@vernon.eu

Claes von Hofsten
Psykologisk institutt
Universitetet i Oslo
Oslo
Norway
E-mail: claes.von_hofsten@psyk.uu.se

Luciano Fadiga
Section of Human Physiology
University of Ferrara
Italy
E-mail: fdl@unife.it

and

Department of Robotics, Brain and Cognitive Sciences
Italian Institute of Technology
Genoa

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Preface

The work described in this book is founded on the premise that (a) cognition is the process by which an autonomous self-governing agent acts effectively in the world in which it is embedded, that (b) the dual purpose of cognition is to increase the agent's repertoire of effective actions and its power to anticipate the need for and outcome of future actions, and that (c) development plays an essential role in the realization of these cognitive capabilities.

Cognitive agents act in their world, typically with incomplete, uncertain, and time-varying sensory data. The chief purpose of cognition is to enable the selection of actions that are appropriate to the circumstances. However, the latencies inherent in the neural processing of sense data are often too great to allow effective action. Consequently, a cognitive agent must anticipate future events so that it can prepare the actions it may need to take. Furthermore, the world in which the agent is embedded is unconstrained so that it is not possible to predict all the circumstances it will experience and, hence, it is not possible to encapsulate *a priori* all the knowledge required to deal successfully with them. A cognitive agent then must not only be able to anticipate but it must also be able to learn and adapt, progressively increasing its space of possible actions as well as the time horizon of its prospective capabilities. In other words, a cognitive agent must develop.

There are many implications of this stance. First, there must be some starting point for development — some phylogeny — both in terms of the initial capabilities and in terms of the mechanisms which support the developmental process. Second, there must be a developmental path — an ontogeny — which the agent follows in its attempts to develop an increased degree of prospection and a larger space of action. This involves several stages, from coordination of eye-gaze, head attitude, and hand placement when reaching, through to more complex exploratory use of action. This is typically achieved by dexterous manipulation of the environment to learn the affordances of objects in the context of one's own developing capabilities. Third, since cognitive agents rarely operate in isolation and since the world with which they interact typically includes other cognitive agents, there is the question of how a cognitive agent can share with other agents the knowledge it has learned. Since what an agent knows is based on its history of experiences in the world, the meaning of any shared knowledge depends on a common mode of experiencing the world. In turn, this implies that the shared knowledge is predicated upon the agents having a common morphology and, in the case of human-robot interaction, a common humanoid form.

The roadmap set out in this book targets specifically the development of cognitive capabilities in humanoid robots. It identifies the necessary and hopefully sufficient conditions that must exist to allow this development. It has been created by bringing together insights from four areas: enactive cognitive science, developmental psychology, neurophysiology, and cognitive modelling. Thus, the roadmap builds upon what is known about the development of natural cognitive systems and what is known about computational modelling of artificial cognitive agents. In doing so, it identifies the essential principles of a system that can develop cognitive capabilities and it shows how these principles have been applied to the state-of-the-art humanoid robot: the iCub.

The book is organized as follows. Chapter 1 presents a conceptual framework that forms the foundation of the book. It identifies the broad stance taken on cognitive systems — emergent embodied systems that develop cognitive skills as a result of their action in the world — and it draws out explicitly the consequences of adopting this stance. Chapter 2 begins by discussing the importance of action as the organizing principle in cognitive behaviour, a theme that will recur repeatedly throughout the book. It then addresses the phylogeny of human infants and, in particular, it considers the innate capabilities of pre-natal infants and how these develop before and just after birth. Chapter 3 then details how these capabilities develop in the first couple of years of life, focussing on the interdependence of perception and action. In doing so, it develops the second recurrent theme of the book: the central role of prospective capabilities in cognition. Chapter 4 explores the neurophysiology of perception and action, delving more deeply into the way that the interdependency of perception and action is manifested in the primate brain. While Chapters 2 – 4 provide the biological inspiration for the design of an entity that can develop cognitive capabilities, Chapter 5 surveys recent attempts at building artificial cognitive systems, focussing on cognitive architectures as the basis for development. Chapter 6 then presents a complete roadmap that uses the phylogeny and ontogeny of natural systems as well as insights gained from computational models and cognitive architectures to define the innate capabilities with which the humanoid robot must be equipped so that it is capable of ontogenetic development. The roadmap includes a series of scenarios that can be used to drive the robot's developmental progress. Chapter 7 provides an overview of the iCub humanoid robot and it describes the use of the the roadmap in the realization of the iCub's own cognitive architecture. Chapter 8 concludes by setting out an agenda for future research and addressing the most pressing issues that will advance our understanding of cognitive systems, artificial and natural.

Dublin, Uppsala, and Ferrara
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David Vernon
Claes von Hofsten
Luciano Fadiga

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This book is based on the results of the RobotCub research project, the goal of which was to develop the iCub: an open and widely-adopted humanoid robot for cognitive systems research. This project was supported by the European Commission, Project IST-004370, under Strategic Objective 2.3.2.4: Cognitive Systems and we gratefully acknowledge the funding that made this research possible.

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Over one hundred people were involved in the creation of the iCub and it is impossible to acknowledge the contribution each made to the work that is described in this book. However, certain key individuals in each of the eleven institutes that participated in the research played a pivotal role is bringing the five year project to a successful conclusion. It is a pleasure to acknowledge their contributions.

Giulio Sandini, Italian Institute of Technology and University of Genoa, was the mastermind behind the project and he was the first to see the need for a common humanoid robot platform to support research in embodied cognitive systems and the benefits of adopting an open-systems policy for software and hardware development.

Giorgio Metta, Italian Institute of Technology and University of Genoa, inspired many of the design choices and provided leadership, guidance, and a level of commitment to the project that was crucial for its success.

Paul Fitzpatrick, Lorenzo Natale and Francesco Nori, Italian Institute of Technology and University of Genoa, together formed an indispensible team whose wide-ranging contributions to the software and hardware formed the critical core of the iCub.

José Santos-Victor and Alex Bernardino, IST Lisbon, set the benchmark early on with their design of the iCub head and their work on learning affordances, computational attention, gaze control, and hand-eye coordination.

Francesco Becchi, Telerobot S.r.l., provided the industry-strength knowhow which ensured that mechanical components of the iCub were designed, fabricated, assembled, and tested to professional standards.

Rolf Pfeifer, University of Zurich, provided inspiration for the tight relationship between a system's embodiment and its cognitive behaviour, a relationship that manifests itself in several ways in the the design of the iCub.

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Chapter 1
A Conceptual Framework for Developmental Cognitive Systems

1.1 Introduction

This book addresses the central role played by development in cognition. We are interested in particular in applying our knowledge of development in natural cognitive systems, i.e. human infants, to the problem of creating artificial cognitive systems in the guise of humanoid robots. Thus, our subject matter is cognition, development, and humanoid robotics. These three threads are woven together to form a roadmap that when followed will enable the instantiation and development of an artificial cognitive system. However, to begin with, we must be clear what we mean by the term cognition so that, in turn, we can explain the pivotal role of development and the central relevance of humanoid embodiment.

In the following, we present a conceptual framework that identifies and explains the broad stance we take on cognitive systems — emergent embodied systems that develop cognitive skills as a result of their action in the world — and that draws out explicitly the theoretical and practical consequences of adopting this stance.[1]

We begin by considering the operational characteristics of a cognitive system, focussing on the purpose of cognition rather than debating the relative merits of competing paradigms of cognition. Of course, such a debate is important because it allows us to understand the pre-conditions for cognition so, once we have established the role cognition plays and see why it is important, we move on to elaborate on these pre-conditions. In particular, we introduce the underlying framework of enaction which we adopt as the basis for the research described in this book.

By working through the implications of the enactive approach to cognition, the central role of development in cognition becomes clear, as do several other key issues such as the crucial role played by action, the inter-dependence of perception and action, and the consequent constructivist nature of the cognitive system's knowledge.

[1] This chapter is based directly on a study of enaction as a framework for development in cognitive robotics [385]. The original paper contains additional technical details relating to enactive systems which are not strictly required here. Readers who are interested in delving more deeply into enaction are encouraged to refer to the original.

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The framework of enaction provides the foundation for subsequent chapters which deal with the phylogeny and the ontogeny of natural cognitive systems — their initial capabilities and subsequent development — and the application of what we learn from these to the realization of an artificial cognitive system in the form of a humanoid robot.

1.2 Cognition

Cognitive systems anticipate, assimilate, and adapt. In doing so, they learn and develop [387]. Cognitive systems anticipate future events when selecting actions, they subsequently learn from what actually happens when they do act, and thereby they modify subsequent expectations and, in the process, they change how the world is perceived and what actions are possible. Cognitive systems do all of this autonomously. The adaptive, anticipatory, autonomous viewpoint reflects the position of Freeman and Núñez who, in their book *Reclaiming Cognition* [105], assert the primacy of action, intention, and emotion in cognition. In the past, however, cognition was viewed in a very different light as a symbol-processing module of mind concerned with rational planning and reasoning. Today, however, this is changing and even proponents of these early approaches now see a much tighter relationship between perception, action, and cognition (e.g. see [7, 214]).

So, if cognitive systems anticipate, assimilate, and adapt, if they develop and learn, the first question to ask is *why* do they do this? The subsequent question is *how* do they do it? The remainder of this section is devoted to the first question and the rest of the book addresses the latter.

The view of cognition taken in this book is that cognition is the process whereby an autonomous self-governing system acts effectively in the world in which it is embedded [237]. However, in natural systems, the latencies inherent in the neural processing of sense data are too great to allow effective action. This is one of the primary reasons a cognitive agent must anticipate future events: so that it can prepare the actions it may need to take. In addition, there are also limitations imposed by the environment and the cognitive system's body. To perform an action, one needs to have the relevant body part in a certain place at a certain time. In a dynamic environment that is constantly changing and with a body that takes time to move, this requires preparation and prediction. Furthermore, the world in which the agent is embedded is unconstrained and the sensory data which is available to the cognitive system is not only 'out-of-date' but it is also uncertain and incomplete. Consequently, it is not possible to encapsulate a priori all the knowledge required to deal successfully with the circumstances it will experience so that it must also be able to adapt, progressively increasing its space of possible actions as well as the time horizon of its prospective capabilities. It must do this, not as a reaction to external stimuli but as a self-generated process of proactive understanding. This process is what we mean by development. In summary, and as noted in the Preface, the position being set out in this book is that (a) cognition is the process by which an autonomous self-governing agent acts effectively in the world in which it is embedded, that (b) the dual purpose of cognition is to increase the agent's repertoire of effective actions and its power to anticipate the need for and outcome of future actions, and that (c) development plays an essential role in the realization of these cognitive capabilities.

We will now introduce a framework which encapsulates all these considerations.

1.3 Enaction

There are many alternative perspectives on cognition: what it is, why it is necessary, and how it is achieved. We have already argued that cognition arises from an agent's need to compensate for latencies in neural processing by anticipating what may be about to happen and by preparing its actions accordingly. So we can agree fairly easily what cognition is — a process of anticipating events and acting appropriately and effectively — and why it is necessary — to overcome the physical limitations of biological brains and the limitations of bodily movements operating in a dynamic environment. The difficulty arises when we consider how cognition is achieved. There are several competing theories of cognition, each of which makes its own set of assumptions. Here, we wish to focus on one particularly important paradigm — enaction — and pick out its most salient aspects in order to provide a sound theoretical foundation for the role of development in cognition [235, 236, 237, 238, 359, 380, 382, 381, 400] .

The principal idea of enaction is that a cognitive system develops it own understanding of the world around it through its interactions with the environment. Thus, enaction entails that the cognitive system operates autonomously and that it generates its own models of how the world works. When dealing with enactive systems, there are five key elements to consider [280, 373]:

1. Autonomy
2. Embodiment
3. Emergence
4. Experience
5. Sense-making

Autonomy is the self-maintaining organizational characteristic of living creatures that enables them to use their own capacities to manage their interactions with the world, and with themselves, in order to remain viable [61, 108]. This simply means that the system is entirely self-governing and self-regulating: it is not controlled by any outside agency and this allows it to stand apart from the rest of the environment and operate independently of it. That's not to say that the system isn't influenced by the world around it, but rather that these influences are brought about through interactions that don't threaten the autonomous operation of the system.

The second element of enaction is the idea of embodiment. For our purposes here, embodiment means that the system must exist in the world as a physical entity which can interact directly with the environment. This means the system can act on things in the world around it and they, in turn, can act on the system. These things can be inanimate objects or animate agents, cognitive or not. As it happens, there are some subtle distinctions which can be made about different types of embodiment and we will return to this topic later in the chapter in Section 1.4.

The element of emergence refers to the manner in which cognition arises in the system. Specifically, it refers to the laws and mechanisms which govern the behaviour of the component parts of the system. In an emergent system, the behaviour we call cognition arises from the dynamic interplay between the components and the laws and mechanisms we mentioned govern only the behaviour of the component parts; they don't specify the behaviour of the interplay between the components. Thus, behaviour emerges indirectly because of the internal dynamics. Crucially, these internal dynamics must maintain the autonomy of the system and, as we will see shortly, they also condition the experiences of the system through their embodiment in a specific structure.

Experience is the fourth element of enaction. This is nothing more than the cognitive system's history of interaction with the world around it: the actions it takes in the environment and the actions arising in the environment which impinge on the cognitive system. These interactions don't control the system (otherwise it wouldn't be autonomous) but they do trigger changes in the state of the system. The changes that can be triggered are *structurally determined*: they depend on the system structure, i.e. the embodiment of the self-organizational principles that make the system autonomous. This structure is also referred to as the system's phylogeny: the innate capabilities of an autonomous system with which it is equipped at the outset and which form the basis for its continued existence. The experience of the systems — its history of interactions — involving *structural coupling* between the system and its environment is referred to as its ontogeny.

Finally, we come to the fifth and, arguably, the most important element of enaction: sense-making. This term refers to the relationship between the knowledge encapsulated by a cognitive system and the interactions which gave rise to it. In particular, it refers to the idea that this emergent knowledge is generated by the system itself and that it captures some regularity or lawfulness in the interactions of the system, i.e. its experience. However, the sense it makes is dependent on the way in which it can interact: its own actions and its perceptions of the environment's action on it. Since these perceptions and actions are the result of an emergent dynamic process that is first and foremost concerned with maintaining the autonomy and operational identity of the system, these perceptions and actions are unique to the system itself and the resultant knowledge makes sense only insofar as it contributes to the maintenance of the system's autonomy. This ties in neatly with our view of cognition, the role of which is to anticipate events and increase the space of actions in which a system can engage. By making sense of its experience, the cognitive system is constructing a model that has some predictive value, exactly because it captures some regularity or lawfulness in its interactions. This self-generated model of the system's experience lends the system greater flexibility in how it interacts in the future. In other words, it endows the system with a larger repertoire of possible actions that allow richer interactions, increased perceptual capacity, and the possibility of constructing even better models that encapsulate knowlege with even greater predictive power. And so it goes, in a virtuous circle. Note that this

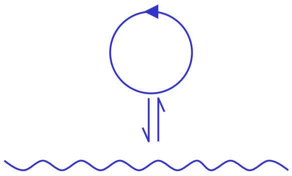

Fig. 1.1 Maturana and Varela's ideograms to denote structurally-determined autopoietic and organizationally-closed systems. The arrow circle denotes the autonomy, self-organization, and self-production of the system, the rippled line the environment, and the bi-directional half-lines the mutual perturbation — structural coupling — between the two.

sense-making and the resultant knowledge says nothing at all about what is really out there in the environment; it doesn't have to. All it has to do is make sense for the continued existence and autonomy of the cognitive system. Sense-making is actually the source of the term enaction. In making sense of its experience, the cognitive system is somehow bringing out through its actions — enacting — what is important for the continued existence of the system. This enaction is effected by the system as it is embedded in its environment, but as an autonomous entity distinct from the environment, through an emergent process of making sense of its experience. This sense-making is, in fact, cognition [108].

The founders of the enactive approach, Maturana and Varela, introduced a diagrammatic way of conveying the self-organizing and self-maintaining autonomous nature of an enactive system, perturbing and being perturbed by its environment [237]: see Fig. 1.1. The arrowed circle denotes the autonomy and self-organization of the system, the rippled line the environment, and the bi-directional half-arrows the mutual perturbation.

1.3.1 Enaction and Development

So what has all this to do with development? Our position in this book is that learning arises as a consequence of the interaction between the cognitive agent and the world around it, whereas development arises from learning through a process of interaction of the cognitive agent with itself. We remarked above that the process of sense-making forms a virtuous circle in that the self-generated model of the system's experience provides a larger repertoire of possible actions, richer interactions, increased perceptual capacity, and potentially better self-generated models, and so on. Recall also our earlier remarks that the cognitive system's knowledge is represented by the state of the system. When this state is embodied in the system's central nervous system, the system has much greater plasticity in two senses: (a) the nervous system can accommodate a much larger space of possible associations between system-environment interactions, and (b) it can accommodate a much larger space of potential actions. Consequently, the process of cognition involves the system modifying its own state, specifically its central nervous system, as it enhances its predictive capacity and its action capabilities. This is exactly what we mean by development. This generative (i.e. self-constructed) autonomous learning and development is one of the hallmarks of the enactive approach [280, 108].

Development, then, is identically the cognitive process of establishing and enlarging the possible space of mutually-consistent couplings in which a system can engage (or, perhaps more appropriately, which it can withstand without compromising its autonomy). The space of perceptual possibilities is predicated not on an absolute objective environment, but on the space of possible actions that the system can engage in whilst still maintaining the consistency of the coupling with the environment. These environmental perturbations don't control the system since they are not components of the system (and, by definition, don't play a part in the self-organization) but they do play a part in the ontogenetic development of the system. Through this ontogenetic development, the cognitive system develops its own epistemology, i.e. its own system-specific history- and context-dependent knowledge of its world, knowledge that has meaning exactly because it captures the consistency and invariance that emerges from the dynamic self-organization in the face of environmental coupling. Again, it comes down to the preservation of autonomy, but this time doing so in an every increasing space of autonomy-preserving couplings.

This process of development is achieved through self-modification by virtue of the presence of a central nervous system: not only does environment perturb the system (and vice versa) but the system also perturbs itself and the central nervous system adapts as a result. Consequently, the system can develop to accommodate a much larger space of effective system action. This is captured in a second ideogram of Maturana and Varela (see Fig. 1.2) which adds a second arrow circle to the ideogram to depict the process of development through self-perturbation and self-modification. In essence, development *is* autonomous self-modification and requires the existence of a viable phylogeny, including a nervous system, and a suitable ontogeny.

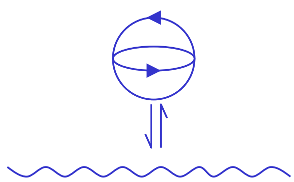

Fig. 1.2 Maturana and Varela's ideograms to denote structurally-determined autopoietic and operationally-closed systems. The diagram (denotes an organizationally-closed autonomous system with a central nervous system. This system is capable of development by means of self-modification of its nervous system, so that it can accommodate a much larger space of effective system action.

1.3.2 Enaction and Knowledge

Let us now move on to discuss in a little more detail the nature of the knowledge that an enactive cognitive system constructs. This knowledge is built on sensorimotor associations, achieved initially by exploration of what the world offers. However, this is only the beginning. The enactive system uses the knowledge gained to form new knowledge which is then subjected to empirical validation to see whether or not it is warranted (we, as enactive beings, imagine many things but not everything we imagine is plausible or corresponds well with reality). One of the key issues in cognition is the importance of internal simulation in accelerating the scaffolding of this early developmentally-acquired sensorimotor knowledge to provide a means to predict future events, to reconstruct or explain observed events (constructing a causal chain leading to that event), or to imagine new events [132, 144, 337]. Naturally, there is a need to focus on (re-)grounding predicted, explained, or imagined events in experience so that the system can *do* something new and interact with the environment in a new way. If the cognitive system wishes or needs to share this knowledge with other cognitive systems or communicate with other cognitive systems, it will only be possible if they have shared a common history of experiences and if they have a similar phylogeny and a compatible ontogeny.

In other words, the meaning of the knowledge that is shared is negotiated and agreed by consensus through interaction.

When there are two or more cognitive agents involved, interaction is a shared activity in which the actions of each agent influence the actions of the other agents engaged in the same interaction, resulting in a mutually constructed pattern of shared behaviour [275]. Again, Maturana and Varela introduce a succinct diagrammatic way of of conveying this coupling between cognitive agent and the development it engenders [238]: see Fig. 1.3. Such mutually-constructed patterns of complementary behaviour is also emphasized in Clark's notion of joint action [64]. Thus, explicit meaning is not necessary for anything to be communicated in an interaction, it is simply important that the agents are mutually engaged in a sequence of actions. Meaning emerges through shared consensual experience mediated by interation. The research programme encapsulated in this roadmap is based on this foundational principle of interaction. The developmental progress of imitation follows tightly that of the development of other interactive and communicative skills,

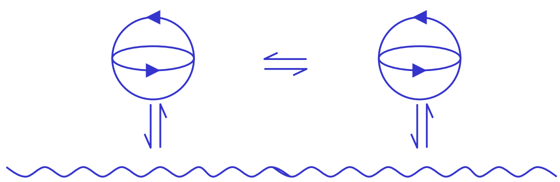

Fig. 1.3 Maturana and Varela's ideogram to denote the development engendered by interaction between cognitive systems

such as joint attention, turn taking and language [268, 350, 377]. Imitation is one of the key stages in the development of more advanced cognitive capabilities.

1.3.3 Phylogeny and Ontogeny: The Complementarity of Structural Determination and Development

Let us summarize: enaction entails two complementary processes: (a) phylogenetically-dependent structural determination, i.e. the preservation of autonomy by a process of self-organization which determines the relevance and meaning of the system's interactions, and (b) ontogenesis, i.e. the increase in the system's predictive capacity and the enlargement of its action repertoire through a process of generative model construction by which the system develops its understanding of the world in which is it embedded. Ontogenesis results in development: the generation of new couplings effected by the self-modification of the system's own state, specifically its central nervous system. This complementarity of structural determination — phylogeny — and development — ontogeny — is crucial. Cognition is the result of a developmental process through which the system becomes progressively more skilled and acquires the ability to understand events, contexts, and actions, initially dealing with immediate situations and increasingly acquiring a predictive or prospective capability. Prediction, or anticipation, is one of the two hallmarks of cognition, the second being the ability to learn new knowledge by making sense of its interactions with the world around it and, in the process, enlarging its repertoire of effective actions. Both anticipation and sense-making are the direct result of the developmental process. This dependency on exploration and development is one of the reasons why the artificial cognitive system requires a rich sensory-motor interface with the environment.

1.4 Embodiment: The Requirements and Consequences of Action

Cognitive systems as described above are intrinsically embodied and embedded in their environment in a situated historical developmental context [370]. Furthermore, as we have already noted, the system's physical embodiment plays a direct constitutive role in the cognitive process [383, 204, 111]. But what exactly is it to be embodied? One form of embodiment, and clearly the type envisaged by proponents of the enactive systems approach to cognition, is a physically-active body capable of moving in space, manipulating its environment, altering the state of the environment, and experiencing the physical forces associated with that manipulation [367]. But there are other forms of embodiment. Ziemke introduced a framework to characterise five different types of embodiment [413, 414]:

1. *Structural coupling* between agent and environment in the sense that a system can be perturbed by its environment and can in turn perturb its environment.
2. *Historical embodiment* as a result of a history of structural coupling;

3. *Physical embodiment* in a structure that is capable of forcible action;
4. *Organismoid embodiment*, i.e. organism-like bodily form (e.g. humanoid or rat-like robots);
5. *Organismic embodiment* of autopoietic living systems.

These five types are increasingly more restrictive. Structural coupling entails only that the system can influence and be influenced by the physical world. Historical embodiment adds the incorporation of a history of structural coupling to this level of physical interaction so that past interactions shape the embodiment. Physical embodiment is most closely allied to conventional robot systems, with organismoid embodiment adding the constraint that the robot morphology is modelled on specific natural species or some feature of natural species. Organismic embodiment corresponds to living beings.

To repeat again, the fundamental idea underpinning embodiment is that the morphology of the system is actually a key component of the systems dynamics. The morphology of the cognitive system not only matters, it is a constitutive part of the cognitive process and cognitive development depends on and is shaped by the form of the embodiment. There is, however, an important consequence of this. In a system that only satisfies the minimal requirements of embodiment, there is no guarantee that the resultant cognitive behaviour will be in any way consistent with human models or preconceptions of cognitive behaviour. Of course, this may be quite acceptable, as long as the system performs its task adequately. However, if we want to ensure compatibility with human cognition, then we have to admit the stronger version of embodiment and adopt a domain of discourse that is the same as the one in which we live: one that involves physical movement, forcible manipulation, and exploration, and perhaps even human form [50]. Why? Because when two cognitive systems interact or couple, the shared consensus of meaning — the systems' common epistemology — will only be semantically similar (have similar meaning) if the experiences of the two systems are compatible: phylogenetically, ontogenetically, and morphologically consistent [237]. Consequently, the approach to cognition we are advocating here requires that the cognitive system be embodied in a very specific sense: that it should lie in the organismoid space of embodied cognitive systems and, further still, that it should lie in the humanoid subspace of the organismoid space.

Apart from the morphology and phylogeny of the cognitive system, this also has strong implications for the development of the cognitive system. Specifically, the ontogeny of the system must follow the development of natural (human) systems. We will deal with this in considerable depth in Chaps. 3 and 6 but it should be noted here that this development follows a general path that begins with actions that are immediate and have minimal prospection, and progresses to much more complex actions that bring forth much more prospective cognitive capabilities. This involves the development of perception-action coordination, beginning with head-eye-hand coordination, progressing through manual and bi-manual manipulation, and extending to more prospective couplings involving inter-agent interaction, imitation, and (gestural) communication. As we will see in Chap. 3, this development occurs in both the innate skills with which phylogeny equips the system and in the acquisition of new skills that are acquired as part of the ontgenetic development of the systems. As we have noted already, it is the ontogenetic development which provides for the greater prospective abilities of cognitive systems.

1.5 Challenges

The adoption of an enactive approach to cognitive systems poses many challenges. We highlight just a few in the following.

The first challenge is the identification of the phylogenetic configuration and the ontogenetic processes. Phylogeny — the evolution of the system configuration from generation to generation — determines the sensory-motor capabilities that a system is configured with at the outset and that facilitate the system's innate behaviours. Ontogenetic development — the adaptation and learning of the system during its lifetime — gives rise to the cognitive capabilities that we seek. To enable development, we must somehow identify a minimal phylogenetic state of the system. In practice, this means that we must identify and effect perceptuo-motor capabilities for the minimal behaviours that ontogenetic development will subsequently build on to achieve cognitive behaviour.

The requirements of real-time synchronous system-environment coupling and historical, situated, and embodied development pose another challenge. Specifically, the maximum rate of ontogenetic development is constrained by the speed of coupling (i.e. the interaction) and not by the speed at which internal processing can occur [400]. Natural cognitive systems have a learning cycle measured in weeks, months, and years and, while it might be possible to condense these into minutes and hours for an artificial system because of increases in the rate of internal adaptation and change, it cannot be reduced below the time-scale of the interaction. You cannot short-circuit ontogenetic development because it is the agent's own experience that defines its cognitive understanding of the world in which it is embedded. This has serious implications for the degree of cognitive development we can practically expect of these systems.

Development implies the progressive acquisition of anticipatory capabilities by a system over its lifetime through experiential learning. Development depends crucially on the motives which underpin the goals of actions. The two most important motives that drive actions and development are social and exploratory. There are at least two exploratory motives, one focussing on the discovery of novelty and regularities in the world, and one focussing on the potential of one's own actions. A challenge that faces all developmental embodied robotic cognitive systems is to model these motivations and their interplay, to identify how they influence action, and thereby build on the system's phylogeny through ontogenesis to develop every-richer cognitive capabilities.

Our goal in this book is to address these issues by borrowing heavily from the neurosciences and from developmental psychology, using them to guide us in identifying the necessary phyologeny, the progression of ontogenetic development, the balance between the two, and the factors that drive the ontogenetic development. We consider these in detail in the next three chapters.

1.6 Summary

We conclude the chapter with a summary of the principal requirements for the development of cognitive capabilities that are implied by the adoption of the enactive system stance on cognition.

A cognitive system must support two complementary processes: structural determination and development. Structural determination acts to maintain the autonomous operational identity of the system through a process of self-organizing perception and action provided by the system phylogeny. The phylogeny also provides the mechanisms for development through a process of self-modification which functions to extend the system's repertoire of possible actions and expand its anticipatory time-horizon.

The phylogeny must be capable of allowing the system to act on the world and to perceive the effects of these actions. The phylogeny must have a rich array of sensorimotor couplings and it must have a nervous system that modifies itself to facilitate the construction of an open-ended space of action-perception mappings built initially on the basis of sensorimotor associations or contingencies.

The phylogeny must allow the system to generate knowledge by learning affordances: to interpret a perception of something in its world as affording the opportunity for the system to act on it in a specific way with a specific outcome (in the sense of changing the state of the world).

The phylogeny must have some facility for internal simulation to accelerate the scaffolding of early sensorimotor knowledge and to facilitate prediction of future events, the reconstruction of observed events, and the imagination of possible new events. The phylogeny must facilitate the grounding of the simulation in action to establish its worth and thus either discard the experience or use it to enhance the system's repertoire of actions and its anticipatory capability.

Finally, the phylogeny must embody social and exploratory motives to drive development. These motives must enable the discovery of novelty and regularities in the world and the potential of the sytem's own actions.

Chapter 5
Computational Models of Cognition

Having looked at the development of cognitive abilities from the perspective of psychology and neuroscience, we now shift our sights to recent attempts at building artificial cognitive systems. In the following, we will focus on cognitive architectures rather than on specific cognitive systems. We do this because cognitive architectures are normally taken as the point of departure for the construction of a cognitive system and they encapsulate the various assumptions we make when designing a cognitive system. Consequently, there are many different types of cognitive architecture. To provide a framework for our survey of cognitive architectures, we must first address these assumptions and we will do this by beginning our discussion with an overview of the different paradigms of cognition. We have already discussed one approach to cognition in Chap. 1 — enaction — and we will take the opportunity here to position enaction within the overall scheme of cognition paradigms. With the differences between the different paradigms of cognition established, we can then move on to discuss the importance of cognitive architectures and survey the cognitive architecture literature, classifying each architecture according to its paradigm and highlighting the extent to which each architecture addresses the different characteristics of cognition. We will make this survey as complete as possible[1] but we will emphasize those architectures that are intended to be used with physical robots and those that provide some developmental capability. On the basis of this review of cognitive architectures — both general characteristics and specific instances — we will conclude with a summary of the essential and desirable features that a cognitive architecture should exhibit if it is to be capable of forming the basis of a system that can autonomously develop cognitive abilities.

5.1 The Three Paradigms of Cognition

Broadly speaking, there are three distinct approaches to cognition: the *cognitivist* approach, the *emergent systems* approach, and *hybrid* approaches [63, 382, 387] (see Fig. 5.1).

[1] The survey of cognitive architectures is an updated and extended version of a survey that appeared in [387].

D. Vernon et al.: A Roadmap for Cogn. Develop. in Humanoid Robots, COSMOS 11, pp. 81–99.
springerlink.com

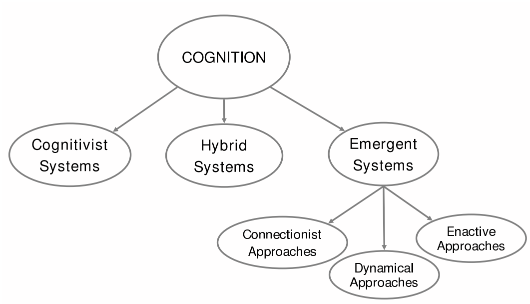

Fig. 5.1 The cognitivist, emergent, and hybrid paradigms of cognition

Cognitivist approaches correspond to the classical view that cognition is a form of symbolic computation [298]. Emergent systems approaches view cognition as a form of self-organization [195, 370]. Emergent systems embrace connectionist systems, dynamical systems, and enactive systems. Hybrid approaches attempt to blend something from each of the connectionist and emergent paradigms. Although cognitivist and emergent approaches are often contrasted purely on the basis of symbolic computation, the differences are much deeper [387, 384]. We can contrast the cognitivist and emergent paradigms on fourteen distinct characteristics:[2]

1. computational operation,
2. representational framework,
3. semantic grounding,
4. temporal constraints,
5. inter-agent epistemology,
6. embodiment,
7. perception,
8. action,
9. anticipation,
10. adaptation,
11. motivation,
12. autonomy,
13. cognition,
14. philosophical foundation.

Let us look briefly at each of these in turn (see Table 5.1 for a synopsis of the key issues).

Computational Operation

Cognitivist systems use rule-based manipulation of symbol tokens, typically but not necessarily in a sequential manner.

[2] These fourteen characteristics are based on the twelve proposed by [387] and augmented here by adding two more: the role of cognition and the underlying philosophy. The subsequent discussion is also an extended adaptation of the commentary in [387].

Emergent systems exploit processes of self-organization, self-production, self-maintenance, and development, through the concurrent interaction of a network of distributed interacting components.

Representational Framework

Cognitivist systems use patterns of symbol tokens that refer to events in the external world. These are typically the descriptive[3] product of a human designer and are usually, but not necessarily, punctate rather than distributed.

Emergent systems representations are global system states encoded in the dynamic organization of the system's distributed network of components.

Semantic Grounding

Cognitivist systems symbolic representations are grounded through percept-symbol identification by either the designer or by learned association. These representations are accessible to direct human interpretation.

Emergent systems ground representations by autonomy-preserving anticipatory and adaptive skill construction. These representations only have meaning insofar as they contribute to the continued viability of the system and are inaccessible to direct human interpretation.

Temporal Constraints

Cognitivist systems are atemporal and are not necessarily entrained by the events in the external world.

Emergent systems are entrained and operate synchronously in real-time with events in its environment.

Inter-agent Epistemology

For cognitivist systems an absolute shared epistemology between agents is guaranteed by virtue of their positivist view of reality; that is, each agent is embedded in an environment, the structure and semantics of which are independent of the system's cognition.

The epistemology of emergent systems is the subjective agent-specific outcome of a history of shared consensual experiences among phylogentically-compatible agents.

Embodiment

Cognitivist systems do not need to be embodied, in principle, by virtue of their roots in functionalism (which holds that cognition is independent of the physical platform in which it is implemented [105]).

Emergent systems are intrinsically embodied and the physical instantiation plays a direct constitutive role in the cognitive process [383, 204, 111].

Perception

In cognitivist systems, perception provides an interface between the absolute external world and the symbolic representation of that world. The role of perception os to abstract faithful spatio-temporal representations of the external world from sensory data.

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[3] Descriptive in the sense that the designer is a third-party observer of the relationship between a cognitive system and its environment so that the representational framework is how the designer sees the relationship.

In emergent systems, perception is an agent-specific interpretation of perturbations of the system by the environment.

Action

In cognitivist systems, actions are causal consequences of symbolic processing of internal representations.

In emergent systems, actions are perturbations of the environment by the system, typically to maintain the viability of the system.

Anticipation

In cognitivist systems, anticipation typically takes the form of planning using some form of procedural or probabilistic reasoning with some a priori model.

Anticipation in the emergent paradigm requires the system to visit a number of states in its self-constructed perception-action state space without commiting to the associated actions.

Adaptation

For cognitivism, adaptation ususally implies the acquisition of new knowledge.

In emergent systems, adaptation entails a structural alteration or re-organization to effect a new set of dynamics. Adaptation can take the from of either learning or development.

Motivation

In cognitivist systems, motives provide the criteria which are used to select the goal to adopt and the associated actions.

In emergent systems, motives encapsulate the implicit value system that modulate the system dynamics of self-maintenance and self-development, impinging on perception (through attention), action (through action selection), and adaptation (through the mechanisms that govern change), such as enlarging the space of viable interaction.

Autonomy

Autonomy[4] The cognitivist paradigm does not necessarily entail autonomy. The emergent paradigm does since cognition is the process whereby an autonomous system becomes viable and effective through a spectrum of homeostatic processes.

Cognition

In the cognitivist paradigm, cognition is the rational process by which goals are achieved by reasoning with symbolic knowledge representations of the world in which the agent operates.

In the emergent paradigm, cognition is the dynamic process by which the system acts to maintain its identity and organizational coherence in the face of environmental perturbation. Cognition entails system development to improve its anticipatory capabilities and extend it space of autonomy-preserving actions.

[4] There are many possible definitions of autonomy, ranging from the ability of a system to contribute to its own persistence [40] through to the self-maintaining organizational characteristic of living creatures — dissipative far-from equilibrium systems — that enables them to use their own capacities to manage their interactions with the world, and with themselves, in order to remain viable [61].

Table 5.1 A comparison of cognitivist and emergent paradigms of cognition; refer to the text for a full explanation (adapted from [387] and extended)

The Cognitivist Paradigm vs. **the Emergent Paradigm**		
Characteristic	**Cognitivist**	**Emergent**
Computational Operation	Syntactic manipulation of symbols	Concurrent self-organization of a network
Representational Framework	Patterns of symbol tokens	Global system states
Semantic Grounding	Percept-symbol association	Skill construction
Temporal Constraints	Atemporal	Synchronous real-time entrainment
Inter-agent epistemology	Agent-independent	Agent-dependent
Embodiment	No role implied: functionalist	Direct constitutive role: non-functionalist
Perception	Abstract symbolic representations	Perturbation by the environment
Action	Causal consequence of symbol manipulation	Perturbation by the system
Anticipation	Procedural or probabilistic reasoning	Traverse of perception-action state space
Adaptation	Learn new knowledge	Develop new dynamics
Motivation	Criteria for goal selection	Increase space of interaction
Autonomy	Not entailed	Cognition entails autonomy
Cognition	Rational goal-achievement	Self-maintenance and self-development
Philosophical Foundation	Positivism	Phenomenology

Philosophical Foundations
The cognitivist paradigm is grounded in positivism [105].
The emergent paradigm is grounded in phenomenology [108, 386].

5.1.1 The Cognitivist Paradigm

Cognitivism holds that cognition is achieved by computations performed on internal symbolic knowledge representations whereby information about the world is abstracted by perception, and represented using some appropriate symbolic data-structure, reasoned about, and then used to plan and act in the world. The approach has also been labelled by many as the *information processing* (or symbol manipulation) approach to cognition [230, 272, 136, 291, 197, 382, 370, 195] In most cognitivist approaches concerned with the creation of artificial cognitive systems, the symbolic representations are the descriptive product of a human designer. This is significant because it means that they can be directly accessed and understood or interpreted by humans and that semantic knowledge can be embedded directly into and extracted directly from the system. Cognitivism makes the positivist 'the world we perceive is isomorphic with our perceptions of it as a geometric environment' [343]. In cognitivism, the goal of cognition is to reason symbolically about these representations in order to effect the required adaptive, anticipatory, goal-directed, behaviour. Typically, this approach to cognition will deploy an arsenal of techniques including machine learning, probabilistic modelling, and other techniques in an attempt to deal with the inherently uncertain, time-varying, and incomplete nature of the sensory data that is being used to drive this representational framework. However, this doesn't alter the fact that the representational structure is still predicated on the descriptions of the designers. In cognitivist systems, the instantiation of the computational model of cognition is inconsequential: any physical platform that supports the performance of the required symbolic computations will suffice. This divorce of operation from instantiation is known as functionalism.

5.1.2 The Emergent Paradigm

In the emergent paradigm, cognition is the process whereby an autonomous system becomes viable and effective in its environment. It does so through a process of self-organization through which the system is continually maintaining its operational identity through moderation of mutual system-environment interaction and co-determination [237]. Co-determination implies that the cognitive process determines what is real or meaningful for the agent: the agent constructs its reality (its world and the meaning of its perceptions and actions) as a result of its operation in that world. Thus, cognitive behaviour is sometimes defined as the automatic induction of an ontology: such an ontology will be inherently specific to the embodiment and dependent on the system's history of interactions, i.e., its experiences. Thus, for emergent approaches, perception is concerned with the acquisition of sensory data in order to enable effective action [237] and is dependent on the richness of the action interface [124]. Sandini et al. have argued that cognition is also the complement of perception [329]. Perception deals with the immediate and cognition deals with longer timeframes. Thus cognition reflects the mechanism by which an agent compensates for the immediate nature of perception and can therefore adapt to and anticipate environmental action that occurs over much longer timescales. That is, cognition is intrinsically linked with the ability of an agent to act prospectively: to operate in the future and deal with what might be, not just what is. In contrast to the cognitivist approach, many emergent approaches assert that the primary model for cognitive learning is anticipative skill construction rather than knowledge acquisition and that processes which both guide action and improve the capacity to guide action while doing so are taken to be the root capacity for all intelligent systems [61]. While cognitivism entails a self-contained abstract model that is disembodied in principle, the physical instantiation of the systems plays no part in the model of cognition [383, 384]. In contrast, emergent systems are intrinsically embodied and the physical instantiation plays a pivotal role in cognition. They are neither functionalist nor positivist.

5.1.3 The Hybrid Paradigm

Considerable effort has also gone into developing approaches which combine aspects of the emergent systems and cognitivist systems [124, 125, 126]. Typically, hybrid systems exploit symbolic knowledge to represent the agent's world and logical rule-based systems to reason about this knowledge in order to achieve goals and select actions while at the same time using emergent models of perception and action to explore the world and build these representations. Hybrid systems still use representations and representational invariances but these representations are constructed by the system itself as it interacts with and explores the world rather than through a priori specification or programming. Thus, objects are represented as 'invariant combinations of percepts and responses where the invariances (which are not restricted to geometric properties) need to be learned through interaction rather than specified or programmed a priori' [124]. Thus, just like emergent systems, the agent's ability to understand the external world is dependent on its ability to flexibly interact with it and interaction is an organizing mechanism that drives a coherence of association between perception and action. Thus, hybrid systems are in many ways consistent with emergent systems while still exploiting programmer-centred representational frameworks (for example, see [277]).

5.1.4 Relative Strengths

The foregoing paradigms have their own strengths and weaknesses, their proponents and critics, and they stand at different stages of scientific maturity. The arguments in favour of emergent systems are compelling but the current capabilities of cognitivist systems are actually more advanced.

Several authors have provided detailed critiques of the various approaches. These include, for example, Clark [63], Christensen and Hooker [62], and Crutchfield [72].[5]

Christiansen and Hooker argued [62] that cognitivist systems suffer from three problems: the symbol grounding problem, the frame problem (the need to differentiate the significant in a very large data-set and then generalize to accommodate new data),[6] and the combinatorial problem. These problems are one of the reasons why cognitivist models have difficulties in creating systems that exhibit robust sensorimotor interactions in complex, noisy, dynamic environments. They also have difficulties modelling the higher-order cognitive abilities such as generalization, creativity, and learning [62]. According to the Christensen and Hooker, and as we have remarked on several occasions, cognitivist systems are poor at functioning effectively outside narrow, well-defined problem domains.

Emergent systems should in theory be much less brittle because they emerge — and develop — through mutual specification and co-determination with the environment, but our ability to build artificial cognitive systems based on these principles is actually very limited at present. To date, dynamical systems theory has provided

[5] The following is abstracted from [387].

[6] In the cognitivist paradigm, the frame problem has been expressed in slightly different but essentially equivalent terms: how can one build a program capable of inferring the effects of an action without reasoning explicitly about all its perhaps very many non-effects? [338].

more of a general modelling framework rather than a model of cognition [62] and has so far been employed more as an analysis tool than as a tool for the design and synthesis of cognitive systems [251, 62]. The extent to which this will change, and the speed with which it will do so, is uncertain. Hybrid approaches appear, to some at least, to offer the best of both worlds: the adaptability of emergent systems (because they populate their representational frameworks through learning and experience) but the advanced starting point of cognitivist systems (because the representational invariances and representational frameworks don't have to be learned but are designed in). However, it is unclear how well one can combine what are ultimately highly antagonistic underlying philosophies. Opinion is divided, with arguments both for (e.g. [63, 72, 123]) and against (e.g. [62]).

Clark suggests that one way forward is the development of a form of 'dynamic computationalism' in which dynamical elements form part of an information-processing system [63]. This idea is echoed by Crutchfield [72] who, whilst agreeing that dynamics are certainly involved in cognition, argues that dynamics per se are "not a substitute for information processing and computation in cognitive processes" but neither are the two approaches incompatible. He holds that a synthesis of the two can be developed to provide an approach that does allow dynamical state space structures to support computation. He proposes 'computational mechanics' as the way to tackle this synthesis of dynamics and computation. However, this development requires that dynamics itself needs to be extended significantly from one which is deterministic, low-dimensional, and time asymptotic, to one which is stochastic, distributed and high dimensional, and reacts over transient rather than asymptotic time scales. In addition, the identification of computation with digital or discrete computation has to be relaxed to allow for other interpretations of what it is to compute.

It might be opportune to remark at this point on the dichotomy between cognitivist and emergent systems. As we have seen, there are some fundamental differences these two general paradigms — the principled disembodiment of physical symbol systems vs. the mandatory embodiment of emergent developmental systems [384], and the manner in which cognitivist systems often preempt development by embedding externally-derived domain knowledge and processing structures, for example — but the gap between the two shows some signs of narrowing. This is mainly due (i) to a fairly recent movement on the part of proponents of the cognitivist paradigm to assert the fundamentally important role played by action and perception in the realization of a cognitive system; (ii) to the move away from the view that internal symbolic representations are the only valid form of respresentation [63]; and (iii) to the weakening of the dependence on embedded a priori knowledge and the attendant increased reliance on machine learning and statistical frameworks both for tuning system parameters and the acquisition of new knowledge both for the representation of objects and the formation of new representations. However, cognitivist systems still have some way to go to address the issue of true ontogenetic development with all that it entails for autonomy, embodiment, architecture plasticity, and system-centred construction of knowledge mediated by exploratory and social motivations and innate value systems.

5.2 Cognitive Architectures

Any cognitive system is inevitably going to be complex. Nonetheless, it is also the case that it will exhibit some degree of structure. This structure is often encapsulated in what is known as a cognitive architecture.

Although used freely by proponents of the cognitivist, emergent, and hybrid approaches to cognitive systems, the term *cognitive architecture* originated with the seminal cognitivist work of Newell et al. [270, 271, 326]. Consequently, the term has a very specific meaning in this paradigm where cognitive architectures represent attempts to create unified theories of cognition [55, 271, 7], i.e. theories that cover a broad range of cognitive issues, such as attention, memory, problem solving, decision making, learning, from several aspects including psychology, neuroscience, and computer science. Newell's Soar architecture [211, 326, 220, 222], Anderson's ACT-R architecture [6, 7], Sun's CLARION architecture [362, 363], and Minsky's *Society of Mind* [254] are all candidate unified theories of cognition.

Since unified theories of cognition are concerned with the computational understanding of human cognition, cognitivist cognitive architectures are also concerned with human cognition [271, 364]. There is an argument that that the term cognitive architecture should be reserved for systems that model human cognition, suggesting that the term "agent architecture" as a better term to refer to general intelligent behaviour, including both human and machine cognition [407]. However, it has become common-place to use the term cognitive architecture in this more general sense, both in the cognitivist and emergent paradigms, so we will use it in this generic sense throughout the book on the understanding that a cognitive architecture may entail different requirements and characteristics, depending on the approach being discussed. Consequently, we will begin by considering exactly what a cognitive architecture does entail in the two different approaches: cognitivist and emergent. Following that, we will consider the necessary and desirable features of a cognitive architecture before embarking on a survey of specific cognitive architectures.

5.2.1 The Cognitivist Perspective on Cognitive Architectures

In the cognitivist paradigm, the focus in a cognitive architecture is on the aspects of cognition that are constant over time and that are independent of the task [128, 214, 217, 309]. In Sun's words [364]:

> "a cognitive architecture is a broadly-scoped domain-generic computational cognitive model, capturing the essential structure and process of the mind, to be used for broad, multiple-level, multiple-domain analysis of behaviour."

Since cognitive architectures represent the fixed part of cognition, they cannot accomplish anything in their own right and need to be provided with or acquire knowledge to perform any given task. A cognitivist cognitive architecture is a generic computational model that is neither domain-specific nor task-specific. It is the knowledge which populates the cognitive architecture that provides the requisite specificity. This combination of a given cognitive architecture and a particular knowledge set is generally referred to as a *cognitive model*.

In most cognitivist systems the knowledge incorporated into the model is normally determined by the human designer, although there is an increasing use of machine learning to augment and adapt this knowledge [217, 364].

A cognitive architecture specifies the overall structure and organization of a cognitive system, including the essential modules, the essential relations between these modules, and the essential algorithmic and representational details within these modules [364]. The architecture specifies the formalisms for knowledge representations and the types of memories used to store them, the processes that act upon that knowledge, and the learning mechanisms that acquire it. Typically, it also provides a way of programming the system so that intelligent systems can be instantiated in some application domain [214].

A cognitive architecture plays an important role in computational modelling of cognition in that it makes (or should make) explicit the initial set of assumptions upon which that model is founded. Sun notes that these assumptions can be derived from several sources: biological or psychological data, philosophical arguments, or ad hoc working hypotheses inspired by, e.g., neurophysiology, psychology, or computational models [364]. A cognitive architecture also provides a comprehensive framework for developing these ideas further.

5.2.2 The Emergent Perspective on Cognitive Architectures

For emergent approaches to cognition, which focus on development from a primitive state to a fully cognitive state over the life-time of the system, the architecture of the system is equivalent to its phylogenetic configuration: the initial state from which it subsequently develops. With emergent approaches, the need to identify an architecture arises from the intrinsic complexity of a cognitive system and the need to provide some form of structure within which to embed the mechanisms for perception, action, adaptation, anticipation, and motivation that enable the ontogenetic development over the system's life-time. It is this complexity that distinguishes an emergent developmental cognitive architecture from, for example, a connectionist robot control system that typically learns associations for specific tasks [186]. Again, the cognitive architecture of an emergent system corresponds to the innate resources and capabilities that are endowed by the system's phylogeny and which don't have to be learned but of course which may be developed further. These resources facilitate the system's ontogensis. They represent the initial point of departure for the cognitive system and they provide the basis and mechanism for its subsequent autonomous development, a development that may impact directly on the architecture itself. As we have stated already, the autonomy involved in this development is important because it places strong constraints on the manner in which the system's knowledge is acquired and by which its semantics are grounded (typically by autonomy-preserving anticipatory and adaptive skill construction) and by which an inter-agent epistemology is achieved (the subjective outcome of a history of shared consensual experiences among phylogenetically-compatible agents); see Table 5.1.

The presence of innate capabilities in an emergent system does *not* imply that the architecture is necessarily functionally modular, i.e. that the cognitive system is comprised of distinct modules each one carrying out a specialized cognitive task. If a modularity is present, it may be because it develops this modularity through experience as part of its ontogenesis or epigenesis rather than being prefigured by the phylogeny of the system (e.g. see Karmiloff-Smith's theory of representational redescription, [189, 190]). Even more important, it does not necessarily imply that the innate capabilities are hard-wired cognitive skills as suggested by nativist psychology (e.g. see Fodor [98] and Pinker [292]).[7] At the same time, neither does it necessarily imply that the cognitive system is a blank slate, devoid of any innate cognitive structures as posited in Piaget's constructivist view of cognitive development [290];[8] at the very least there must exist a mechanism, structure, and organization which allows the cognitive system to be autonomous, to act effectively to some limited extent, and to develop that autonomy.

Finally, since the emergent paradigm sits in opposition to the two pillars of cognitivism — the dualism that posits the logical separation of mind and body, and the functionalism that holds that cognitive mechanisms are independent of the physical platform [105] — it is likely that the architecture will reflect in some way the morphology of the physical body of which it is embedded and of which it is an intrinsic part.

It is worth pausing here to note that the cognitivist and emergent perspectives differ somewhat on this issue of innate structure. While in an emergent system, the cognitive architecture *is* the innate structure, it is not necessarily so with a cognitivist system. Sun contends that "an innate structure can, but need not, be specified in an initial architecture" [363]. He argues that an innate structure does not have to be specified or involved in the computational modelling of cognition and that architectural detail may indeed result from ontogenetic development. However, he concedes that non-innate structures should be avoided as much as possible and that we should adopt a minimalist approach: an architecture should include only minimal structures and minimal learning mechanisms which should be capable of "bootstrapping all the way to a full-fledged cognitive model".

5.2.3 Desirable Characteristics of a Cognitive Architecture

In his *Desiderata for Cognitive Architectures* [363], Sun identifies several desirable features of a cognitive architecture. These are

1. Ecological realism;
2. Bio-evolutionary realism;

[7] More recently, Fodor [99] asserts that modularity applies only to local cognition (e.g. deciding to take a ride on your bicycle) but not global cognition (e.g. planning to train for the Race Across America).

[8] Piaget founded the constructivist school of cognitive development whereby knowledge is not implanted a priori (i.e. phylogenetically) but is discovered and constructed by a child through active maniulation of the environment.

3. Cognitive realism;
4. Inclusivity of prior perspectives.[9]

The key idea behind *ecological realism* is that a cognitive architecture should focus on allowing the cognitive system to operate in its natural environment, engaging in "everyday activities". This means it has to be able to deal with being embodied and the attendant natural constraints on its actions and perceptions. It also means that the architecture has to deal with many concurrent and often conflicting goals with many environmental contingencies. Since human intelligence evolved from the capabilities of earlier primates, *bio-evolutionary realism* asserts that a cognitive model of human intelligence should be reducible to a model of animal intelligence. *Cognitive realism* means that a cognitive architecture should capture the essential characteristics of human cognition as we understand them from the perspective of psychology, neuroscience, and philosophy. Finally, the design of a cognitive architecture should include *prior perspectives* and capabilities. In other words, new models should draw on, subsume, or supercede older models.

Sun also elaborates on the behavioural and cognitive characteristics which should ideally be captured by a cognitive architecture and exhibited by a cognitive system.

From a behavioural perspective, a cognitive system should act and react without employing excessively complicated conceptual representations and extensive computation devoted to working through alternative strategies. That is, the system should behave in a "direct and immediate" manner. Furthermore, a cognitive system should operate sequentially, one step at a time, in a temporally-extended sequence of actions. This leads naturally to the characteristic of gradually-learned routine behaviours, typically acquired through a process of trial-and-error adaptation.

From the perspective of cognitive characteristics, Sun suggests that a cognitive architecture should comprise two distinct types of process: one explicit, the other implicit. The explicit processes are accessible and precise whereas the implicit ones are inaccessible and imprecise. Furthermore, there should be a synergy borne of interaction between these two types of process. There are, for example, explicit and implicit learning processes and these interact. The most important type of learning in a cognitive architecture is what Sun refers to as bottom-up learning whereby implicit learning is followed by explicit learning. In Sun's own work [362, 364], implicit processes operate on connectionist representations and implicit processes on symbolic representations. Thus, he adopts a strong hybrid approach to cognitive architectures. Finally, Sun argues for a form of modularity in a cognitive architecture so that some cognitive faculties are specialized and separate, either as functionally-encapsulated modules or as physically — neurophysiologically — encapsulated modules.

Langley, Laird, and Rogers [217] catalogue nine functional capabilities that should be exhibited by an ideal cognitive architecture. Although they focus mainly on cognitivist cognitive architectures in their examples, the capabilities they discuss also apply for the most part to emergent systems. The nine capabilities are:

1. Recognition and Categorization;
2. Decision Making and Choice;

[9] Sun refers to this inclusivity as "eclecticism of methodologies and techniques" [363].

3. Perception and Situation Assessment;
4. Prediction and Monitoring;
5. Problem Solving and Planning;
6. Reasoning and Belief Maintenance;
7. Execution and Action;
8. Interaction and Communication;
9. Remembering, Reflection, and Learning.

Let's look at each of these in turn.

Recognition and Categorization: A cognitive architecture must be able to recognize objects, situations, and events as instances of known patterns and it must be able to assign them to broader concepts or categories. A cognitive architecture should be able to learn new patterns and categories, modify existing ones, either by direct instruction or by experience.

Decision Making and Choice: Since a cognitive architecture exists to support the actions of a cognitive agent, it must provide a way to identify and represent alternative choices and then decide which are the most appropriate and select an action for execution. Again, an ideal cognitive architecture should be able to improve its decisions through learning.

Perception and Situation Assessment: A cognitive architecture must have some perceputal capacity and, since a cognitive agent typically has limited computational resources, it must have an attentive capacity to decide how to allocate these resources and to detect what is immediately relevant.

Prediction and Monitoring: A cognitive architecture should have some mechanism to predict future situations and events, typically based on an internal model of the cognitive agent's environment. Ideally, a cognitive architecture should have a mechanism to learn these models from experience and improve them over time.

Problem Solving and Planning: To achieve goals, a cognitive architecture must have some capability to plan actions and solve problems. A plan requires some representation of a partially-ordered sequence of actions and their effects. Problem solving differs from planning in that it may also involve physical change in the agent's world. As always, an ideal cognitive architecture should be able to deploy learning to support both planning and problem solving.

Reasoning and Belief Maintenance: The knowledge that complements a cognitive architecture constitutes the agent's beliefs about itself and its world, while planning is focussed on using this knowledge to effect some action and achieve a desired goal. The cognitive architecture should also have a reasoning mechanism which allows the cognitive system to draw inferences from these beliefs, either to maintain the beliefs or to modify them.

Execution and Action: Langley, Laird, and Rogers highlight the fact that "cognition occurs to support and drive activity in the environment". Consequently, a cognitive architecture must have some mechanism to represent and store motor skills that can be used in the execution of an agent's actions. As before, an ideal cognitive architecture will have some way of learning these motor skills from instruction or experience.

Interaction and Communication: A cognitive architecture should be able to communicate with other agents so that they can obtain and share knowledge. This may also require a mechanism for transforming the knowledge from internal representations to a form suitable for communication.

Remembering, Reflection, and Learning: Langley, Laird, and Rogers remark that it may also be useful for a cognitive archtitecture to have additional capabilities which are not strictly necessary but which may improve the operation of the cognitive agent. These are referred to as meta-management functions [347] and they are concerned with remembering (storing and recalling) the agent's cognitive experiences and with reflecting on them, for example, to explain decisions, plans, actions in terms of the cognitive steps that led to them. They include also a form of learning that is capable of generalizing from specific experiences of the cognitive system.

These nine capabilities are advocated by others, e.g. Sun who identifies at least twelve similar requisite functionalities in a cognitive architecture: perception, categorization, multiple representations, multiple types of memory, decision making, reasoning, planning, problem solving, meta-cognition, communication, action control and execution, and several types of learning (which will often be embedded in the other functional capabilities) [364]. Sun also notes that very few cognitive architectures support these functionalities fully. He stresses the importance of the interconnectivity between these processes and the dynamic interaction that arises as the cognitive system experiences and acts in its environment. In Sun's words: "we need to strive for complex[10] cognitive architectures that capture dynamics of cognition through capturing its constituent elements."

Langley, Laird, and Rogers conclude their paper by highlighting a number of challenges in cognitive architecture research [217]. These include mechanisms for selective attention, processes for categorization, support for episodic memory and processes to reflect on it, support from multiple knowledge representation formalisms, the inclusion of emotion in cognitive architectures to modulate cognitive behaviour, and the impact of physical embodiment on the overall cognitive process, including the agent's internal drives and goals.

Sun too identifies several challenges in designing cognitive architectures [364]. He warns of the perils of designing excessively-complicated models. A cognitive architecture should involve only what is "minimally necessary". Like Einstein, who believed "a scientific theory should be as simple as possible, but no simpler", Sun advocates that a cognitive architecture should be well constrained with as few parameters as possible, without compromising its broad-based domain-generic objectives [364]. He also notes that the validation of cognitive architectures poses a major but essential challenge and he highlights the need to guard against over-stating the case for any particular architecture: "as in any other scientific fields, painstakingly detailed work needs to be carried out before sweeping claims can be made" [364].

In designing a cognitive architecture, Sloman and his co-workers advocate a three-step process [138]. First, the requirements of the architecture should be

[10] Complex, but not excessively complex: see the second-next paragraph.

identified, partly through an analysis of several typical scenarios in which the eventual agent would demonstrate its competence. These requirements are then used to create an *architecture schema*: "a task and implementation independent set of rules for structuring processing components and information, and controlling information flow". This schema leaves out much of the detail of the final design choices, detail which is finally filled in by an instatiation of the architecture schema in a cognitive architecture proper on the basis of a specific scenario and its attendant requirements.

While not specifically targetting cognitive architectures, Krichmar et al. identify six design principles for systems that are capable of development [203, 206, 204]. Although they present these principles in the context of their brain-based devices, most are directly applicable to emergent systems in general. First, they suggest that the architecture should address the dynamics of the neural element in different regions of the brain, the structure of these regions, and especially the connectivity and interaction between these regions. Second, they note that the system should be able to effect perceptual categorization: i.e. to organize unlabelled sensory signals of all modalities into categories without a priori knowledge or external instruction. In effect, this means that the system should be autonomous and, as noted by Weng [394], p. 206, a developmental system should be a model generator, rather than a model fitter (e.g. see [278]). Third, a developmental system should have a physical instatiation, i.e. it should be embodied, so that it is tightly coupled with its own morphology and so that it can explore its environment. Fourth, the system should engage in some behavioural task and, consequently, it should have some minimal set of innate behaviours or reflexes in order to explore and survive in its initial environmental niche. From this minimum set, the system can learn and adapt so that it improves[11] its behaviour over time. Fifth, developmental systems should have a means to adapt. This implies the presence of a value system (i.e. a set of motivations that guide or govern it development). These should be non-specific (in the sense that they don't specify what actions to take) modulatory signals that bias the dynamics of the system so that the global needs of the system are satisfied: in effect, so that its autonomy is preserved or enhanced. Such value systems might possibly be modelled on the value system of the brain: dopaminergic, cholinergic, and noradrenergic systems signalling, on the basis of sensory stimuli, reward prediction, uncertainty, and novelty. Krichmar et al. also note that brain-based devices should lend themselves to comparison with biological systems.

5.2.4 A Survey of Cognitive Architectures

For the remainder of the chapter, the term cognitive architecture will the taken in the general and paradigm non-specific sense. By this we mean the minimal configuration of a system that is necessary for the system to exhibit and develop cognitive capabilities and behaviours: the specification of the components in a cognitive system, their function, and their organization as a whole.

[11] Krichmar et al. say 'optimizes' rather than 'improves'.

Appendix A contains a synopsis of twenty cognitive architectures spanning the cognitivist, emergent, and hybrid paradigms. The cognitive architectures surveyed are Soar, EPIC, ACT-R, ICARUS, ADAPT, GLAIR, and CoSy Architecture Schema (cogntivist); Autonomous Agent Robotics, Global Workspace, I-C SDAL, SASE, Darwin, Cognitive-Affective (emergent); and HUMANOID, Cerebus, Cog: Theory of Mind, Kismet, LIDA, CLARION, PACO-PLUS (hybrid). This survey is adapted from [387] and extended to bring it up to date by including the GLAIR, CoSy Architecture Schema, Cognitive-Affective, LIDA, CLARION, PACO-PLUS cognitive architectures.

Table 5.2 shows a comparison of the twenty architectures surveyed vis-à-vis a subset of the fourteen characteristics of cognitive systems which we discussed in Sect. 5.1. We have omitted the first five and last two characteristics — Computation Operation, Representational Framework, Semantic Grounding, Temporal Constraints, and Inter-agent Epistemology, Cognition, and Philosophical Foundation — because these can be inferred directly by the paradigm in which the system is based: cognitivist, emergent, or hybrid. The seven remaining characteristics — embodiment, perception, action, anticipation, adaptation, motivation, and autonomy — are crucial for enactive cognitive systems which we are adopting as our framework for development, as discussed in Chap. 1.

Table 5.2 reveals a number of interesting points.

The cognitivist cognitive architectures typically address only a subset of the seven characteristics. Only one — GLAIR [339] (see Sect. A.1.6) — addresses autonomy, only one — CoSy Architecture Schema [137, 138] (see Sect. A.1.7) — addresses motivation, and only one — ADAPT [30] (see Sect. A.1.5) — makes any strong commitment to embodiment. To an extent, this is not surprising, given the functionalist and dualist foundation of cognitivism: a mind that is divorced in principle from its body doesn't need to worry about embodiment, survival and the preservation of autonomy, or the motivations that modulate that autonomy-preserving process. Most of the cognitivist architectures do address perception, action, anticipation, and adaptation, although it is significant that only ICARUS [60, 213, 214, 215, 216] (see Sect. A.1.4) addresses adaptation in the strong sense that entails development through the creation of new representational frameworks or models. In the specific case of ICARUS, the cognitive architecture can learn hierarchically-structured skills to solve new problems.

All of the emergent cognitive architectures address most of the seven characteristics. Three of the seven architectures surveyed address all seven. Again, this is not surprising, given the foundations of the emergent paradigm in self-organizing autonomy-preserving embodied systems. All address embodiment, perception, action, and autonomy to a lesser or greater extent. They differ in whether or not they target anticipation and adaptation. Only the Global Workspace cognitive architecture [335, 336, 337, 338] (see Sect. A.2.2) and the Cognitive-Affective schema [264, 415] (see Sect. A.2.6) address anticipation in depth and only the SASE architecture [394, 395, 393] (see Sect. A.2.4) and the Cognitive-Affective schema [264, 415] (see Sect. A.2.6) address adaptation in a strong manner. The Global Workspace architecture uses internal simulation of interaction with the environment

Table 5.2 Cognitive architectures vis-à-vis the seven of the fourteen characteristics of cognitive systems. Key: '×' indicates that the characteristic is strongly addressed in the architecture, '+' indicates that it is weakly addressed, and a space indicates that it is not addressed at all in any substantial manner. A '×' is assigned under the heading of Adaptation only if the system is capable of development (in the sense of creating new representational frameworks or models) rather than simple learning (in the sense of model parameter estimation). Adapted from [387] and extended to bring it up to date by including the GLAIR, CoSy Architecture Schema, Cognitive-Affective, LIDA, CLARION, PACO-PLUS cognitive architectures.

Cognitive Architecture	Embodiment	Perception	Action	Anticipation	Adaptation	Motivation	Autonomy
Cognitivist							
Soar				+	+		
Epic		+	+	+			
ACT-R		+	+	+	+		
ICARUS		+	+	+	×		
ADAPT	×	×	×	+	+		
GLAIR		+	+		+		+
CoSy		+	+		+	+	
Emergent							
AAR	×	×	×			+	×
Global Workspace	+	+	+	×		×	×
I-C SDAL	+	+	+	+	+	×	×
SASE	×	×	×	+	×	×	×
Darwin	×	×	+		+	×	×
Cognitive-Affective	×	×	×	×	×	×	×
Hybrid							
HUMANOID	×	×	×	+	+	+	
Cerebus	×	×	×	+	+		
Cog: Theory of Mind	×	×	×	+			
Kismet	×	×	×			×	
LIDA	+	+	+	×	×	+	+
CLARION		+	+	×	×	+	+
PACO-PLUS	×	×	×		×		

to effect anticipation and planning, with action selection being modulated by affective motivation mechanisms. Significantly, it is the concurrent operation of the components / sub-systems of the cognitive architecture as they compete for access to a global workspace that governs the behaviour of the system, with the resultant behaviour emerging as a sequence of states arising from their interaction. It is noteworthy that, reflecting contemporary thinking in neuroscience, in the Cerebus cognitive architecture [170, 171] (see Sect. A.3.2) each of these components / sub-systems maintains its own separate and limited representation of the world and the task at hand: different motor effectors need different sensory inputs, derived in different ways, and differently encoded in ways that are particular to different effectors. On the other hand, the SASE cognitive architecture incorporates explicit self-modification by monitoring and altering its own state, specifically to generate models and predict the outcome of actions. In essence, this is a sophisticated process of homeostasis, or self-regulation, which preserves the autonomy of the system while allowing it to operate effectively in its environment. The Cognitive-Affective cognitive architecture schema adopts a similar approach, but extends it by proposing a spectrum of homeostasis. Different levels of cognitive function and behavioural complexity are brought about by different levels of emotion, ranging from reflexes, through drives, to emotions and feelings, each of which is linked to a homeostatic autonomy-preserving self-maintenance process, ranging from basic metabolic processes, through reactive sensorimotor activity, associative learning and prediction, to interoception and internal simulation of behaviour prior to action.

The hybrid cognitive architectures fall somewhere in between the cognitivist and emergent cognitive architectures in the extent to which they address the seven characteristics. LIDA [17, 103, 104, 106, 299] (see Sect. A.3.5) CLARION [362, 363, 364] (see Sect. A.3.6) and PACO-PLUS [201] (see Sect. A.3.7) are the only hybrid cognitive architectures that address adaptation in the developmental sense. LIDA addresses anticipation and adaptation by deploying transient and consolidated episodic memories of past experiences and procedural memory of associated actions and outcomes. Adaptation occurs when sensory-derived perceptions re-combine with associated recalled episodic memories and are either incorporated into the episodic memory as a new experience or are used to reinforce existing experiences. Selected episodic memories are used to recall associated actions and likely outcomes from the procedural memory for subsequent execution. Both anticipation and adaptation are effected in CLARION by observing the outcome of a selected action and updating bottom-level reinforcement learning in a connectionist representation and a top-level rule-based update in a symbolic representation. In addition, rule-based actions are either generalized or refined, depending on the outcome. In a similar way, the PACO-PLUS cognitive architecture also learns from observations. In particular, PACO-PLUS autonomously learns co-joint object-action affordances by exploration, selecting an action and observing the effects of these actions on the objects in the robots environment.

5.3 Summary

We conclude the chapter with a summary of the principal requirements for the design of a cognitive architecture which adheres to the emergent paradigm of cognition and, in particular, to the enactive systems approach. Such a cognitive architecture must be capable of supporting the development of cognitive capabilities, as well as adequately addressing the seven characteristics of embodiment, perception, action, anticipation, adaptation, motivation, and autonomy discussed in the previous sections. These requirements derive from a consideration of both the generally-desirable characteristics of cognitive architectures discussed in Sect. 5.2.3 and the features of specific cognitive architectures surveyed in Sect. 5.2.4.

A cognitive architecture should have the following characteristics.

1. A minimal set of innate behaviours for exploration and survival (i.e. preservation of autonomy) [203, 206, 204].
2. A value system — a set of task non-specific motivations — that guides or governs development [203, 206, 204].
3. An attentional mechanism [217].
4. Learning from experience the motor skills associated with actions [217].
5. A spectrum of self-regulating autonomy-preserving homeostatic processes (ranging from basic metabolic processes, through associative learning and prediction, to interoception and internal simulation) associated with different levels of emotion (ranging from reflexes, through drives, to emotions and feelings) resulting in different levels of cognitive function and behavioural complexity [264, 415] (Cognitive-Affective) and [394, 395, 393] (SASE).
6. Anticipation and planning based on internal simulation of interaction with the environment [335, 336, 337, 338] (Global Workspace).
7. Action selection modulated by affective motivation mechanisms [335, 336, 337, 338] (Global Workspace).
8. Separate and limited representations of the world and the task at hand in each component / sub-system [170, 171] (Cerebus)
9. Transient and consolidated (generalized) episodic memories of past experiences [17, 103, 104, 106, 299] (LIDA).
10. Procedural memory of actions and outcomes associated with episodic memories [17, 103, 104, 106, 299] (LIDA).
11. Learning based on comparison of expected and observed outcomes of selected actions, resulting in either generalization or refinement of the associated action [362, 363, 364] (CLARION).
12. Learning co-joint object-action affordances by exploration [201] (PACO-PLUS).
13. Hierarchically-structured representations for the acquisition, decomposition, and execution of action-sequnce skills [60, 213, 214, 215, 216](ICARUS).
14. Concurrent operation of the components / sub-systems of the cognitive architecture so that the resultant behaviour emerges as a sequence of states arising from their interaction as they compete and co-operate [335, 336, 337, 338] (Global Workspace).

In the next chapter, we turn our attention to integrating these requirements with those derived from our study of psychology and neurophysiology in previous chapters.

Appendix A
Catalogue of Cognitive Architectures

This appendix contains a catalogue of twenty cognitive architectures drawn from the cognitivist, emergent, and hybrid traditions, beginning with some of the best known cognitivist ones. Table A.1 lists the cognitive architectures surveyed.

Table A.1 The cognitive architectures surveyed in this appendix. This survey is adapted from [387] and extended to bring it up to date by including the GLAIR, CoSy Architecture Schema, Cognitive-Affective, LIDA, CLARION, PACO-PLUS cognitive architectures. The architectures are treated in order, top-to-bottom and left-to-right (*i.e.* cognitivist first, then emergent, and finally hybrid).

Cognitivist	**Emergent**	**Hybrid**
Soar	AAR	HUMANOID
EPIC	Global Workspace	Cerebus
ACT-R	I-C SDAL	Cog: Theory of Mind
ICARUS	SASE	Kismet
ADAPT	DARWIN	LIDA
GLAIR	Cognitive-Affective	CLARION
CoSy		PACO-PLUS

A.1 Cognitivist Cognitive Architectures

A.1.1 The Soar Cognitive Architecture

The Soar system [211, 326, 220, 222] is Newell's candidate for a Unified Theory of Cognition [271] and, as such, it is an architypal cognitivist cognitive architecture (as well as being an iconic one).It is a production (or rule-based) system[1] that operates in a cyclic manner, with a production cycle and a decision cycle. It operates as follows. First, all productions that match the contents of declarative (working) memory fire. A production that fires may alter the state of declarative memory and cause other productions to fire. This continues until no more productions fire. At this point, the decision cycle begins in which a single action from several possible actions is selected. The selection is based on stored action preferences. Thus, for each decision cycle there may have been many production cycles. Productions in Soar are low-level; that is to say, knowledge is encapsulated at a very small grain size.

One important aspect of the decision process concerns a process known as *universal sub-goaling*. Since there is no guarantee that the action preferences will be unambiguous or that they will lead to a unique action or indeed any action, the decision cycle may lead to an 'impasse'. If this happens, Soar sets up an new state in a new problem space — sub-goaling — with the goal of resolving the impasse. Resolving one impasse may cause others and the sub-goaling process continues. It is assumed that degenerate cases can be dealt with (*e.g.* if all else fails, choose randomly between two actions). Whenever an impasse is resolved, Soar creates a new production rule which summarizes the processing that occurred in the sub-state in solving the sub-goal. Thus, resolving an impasse alters the system super-state, *i.e.* the state in which the impasse originally occurred. This change is called a result and becomes the outcome of the production rule. The condition for the production rule to fire is derived from a dependency analysis: finding what declarative memory items matched in the course of determining the result. This change in state is a form of learning and it is the only form that occurs in Soar, *i.e.* Soar only learns new production rules. Since impasses occur often in Soar, learning is pervasive in Soar's operation.

[1] A production is effectively an IF-THEN condition-action pair. A production system is a set of production rules and a computational engine for interpreting or executing productions.

A.1.2 EPIC — Executive Process Interactive Control

EPIC [196] is a cognitive architecture that was designed to link high-fidelity models of perception and motor mechanisms with a production system. An EPIC model requires both knowledge encapsulated in production rules and perceptual-motor parameters. There are two types of parameter: standard or system parameters which are fixed for all tasks (*e.g.* the duration of a production cycle in the cognitive processor: 50 ms) and typical parameters which have conventional values but can vary between tasks (*e.g.* the time required to effect recognition of shape by the visual processor: 250 ms).

EPIC comprises a cognitive processor (with a production rule interpreter and a working memory), and auditory processor, a visual processor, an oculo-motor processor, a vocal motor processor, a tactile processor, and a manual motor processor. All processors run in parallel. The perceptual processors simply model the temporal aspects of perception: they don't perform any perceptual processing *per se*. For example, the visual processor doesn't do pattern recognition. Instead, it only models the time it takes for a representation of a given stimulus to be transferred to the declarative (working) memory. A given sensory stimulus may have several possible representations (*e.g.* colour, size, ...) with each representation possibly delivered to the working memory at different times. Similarly, the motor processors are not concerned with the torques required to produce some movement; instead, they are only concerned with the time it takes for some motor output to be produced after the cognitive processor has requested it.

There are two phases to movements: a preparation phase and an execution phase. In the preparation phase, the timing is independent of the number of features that need to be prepared to effect the movement but may vary depending on whether the features have already been prepared in the previous movement. The execution phase is concerned with the timing for the implementation of a movement and, for example, in the case of hand or finger movements the time is governed by Fitt's Law.

Like Soar, the cognitive processor in EPIC is a production system in which multiple rules can fire in one production cycle. However, the productions in EPIC have a much larger grain size than Soar productions.

Arbitration of resources (*e.g.* when two tasks require a single resource) is handled by 'executive' knowledge: productions which implement executive knowledge do so in parallel with productions for task knowledge.

A.1.3 ACT-R — Adaptive Control of Thought - Rational

The ACT-R [6, 7] cognitive architecture is a widely-regarded candidate for a unified theory of cognition. It focusses on modular decomposition and offers a theory of how these modules are integrated to produce coherent cognition. The architecture comprises five specialized modules, each devoted to processing a different kind of information (see Figure A.1). There is a vision module for determining the identity and position of objects in the visual field, a manual module for controlling hands, a declarative module for retrieving information from long-term information, and a goal module for keeping track of the internal state when solving a problem. Finally, it also has a production system that coordinates the operation of the other four modules. It does this indirectly via four buffers into which each module places a limited amount of information.

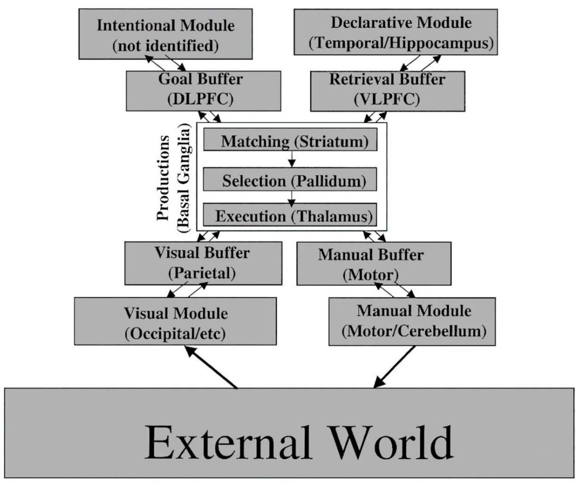


Fig. A.1 The ACT-R Cognitive Architecture (from [7])

ACT-R operates in a cyclic manner in which the patterns of information held in the buffers (and determined by external world and internal modules) are recognized, a single production fires, and the buffers are updated. It is assumed that this cycle takes approximately 50 ms.

There are two serial bottle-necks in ACT-R. One is that the content of any buffer is limited to a single declarative unit of knowledge, called a 'chunk'. This implies that only one memory can be retrieved at a time and indeed that a single object can be encoded in the visual field at any one time. The second bottle-neck is that only one production is selected to fire in any one cycle. This contrasts with both Soar and

EPIC both of which allow many productions to fire. When multiple production rules are capable of firing, an arbitration procedure called conflict resolution is activated.

Whilst early incarnations of ACT-R focussed primarily on the production system, the importance of perceptuo-motor processes in determining the nature of cognition is recognized by Anderson *et al.* in more recent versions [55, 7]. That said, the perceptuo-motor system in ACT-R is based on the EPIC architecture [196] which doesn't deal directly with real sensors or motors but simply models the basic timing behaviour of the perceptual and motor systems. In effect, it assumes that the perceptual system has already parsed the visual data into objects and associated sets of features for each object [6]. Anderson *et al.* recognize that this is a short-coming, remarking that ACT-R implements more a theory of visual attention than a theory of perception, but hope that the ACT-R cognitive architecture will be compatible with more complete models of perceptual and motor systems. The ACT-R visual module differs somewhat from the EPIC visual system in that it is separated into two sub-modules, each with its own buffer, one for object localization and associated with the dorsal pathway, and the other for object recognition and associated with the ventral pathway. Note that this sharp separation of function between the ventral and dorsal pathways has been challenged by recent neurophysiological evidence which points to the interdependence between the two pathways [316, 314]. When the production system requests information from the localization module, it can supply constraints in the form of attribute-value pairs (*e.g.* colour-red) and the localization module will then place a chunk in its buffer with the location of some object that satisfies those constraints. The production system queries the recognition system by placing a chunk with location information in its buffer; this causes the visual system to subsequently place a chunk representing the object at that location in its buffer for subsequent processing by the production system. This is a significant idealization of the perceptual process.

The goal module keeps track of what the intentions of the system architecture (in any given application) so that the behaviour of the system will support the achievement of that goal. In effect, it ensures that the operation of the system is consistent in solving a given problem (in the words of Anderson *et al.* "it maintains local coherence in a problem-solving episode").

On the other hand, the information stored in the declarative memory supports long-term personal and cultural coherence. Together with the production system, which encapsulates procedural knowledge, it forms the core of the ACT-R cognitive system. The information in the declarative memory augments symbolic knowledge with subsymbolic representations in that the behaviour of the declarative memory module is dependent of several numeric parameters: the activation level of a chunk, the probability of retrieval of a chunk, and the latency of retrieval. The activation level is dependent on a learned base level of activation reflecting its overall usefulness in the past, and an associative component reflecting its general usefulness in the current context. This associative component is a weighted sum of the element connected with the current goal. The probability of retrieval is an inverse exponential function of the activation and a given threshold, while the latency of a chunk that is retrieved (*i.e.* that exceeds the threshold) is an exponential function of the activation.

Procedural memory is encapsulated in the production system which coordinates the overall operation of the architecture. Whilst several productions may qualify to fire, only one production is selected. This selection is called conflict resolution. The production selected is the one with the highest utility, a factor which is a function of an estimate of the probability that the current goal will be achieved if this production is selected, the value of the current goal, and an estimate of the cost of selecting the production (typically proportional to time), both of which are learned in a Bayesian framework from previous experience with that production. In this way, ACT-R can adapt to changing circumstances [55].

Declarative knowledge effectively encodes things in the environment while procedural knowledge encodes observed transformations; complex cognition arises from the interaction of declarative and procedural knowledge [6]. A central feature of the ACT-R cognitive architecture is that these two types of knowledge are tuned in specific application by encoding the statistics of knowledge. Thus, ACT-R learns sub-symbolic information by adjusting or tuning the knowledge parameters. This sub-symbolic learning distiguishes ACT-R from the symbolic (production-rule) learning of Soar.

Anderson *et al.* suggest that four of these five modules and all four buffers correspond to distinct areas in the human brain. Specifically, the goal buffer corresponds to the dorsolateral pre-frontal cortex (DLPFC), the declarative module to the temporal hippocampus, the retrieval buffer (which acts as the interface between the delarative module and the production system) to the ventrolateral pre-frontal cortex (VLPFC), the visual buffer to the parietal area, the visual module to the occipital area, the manual buffer to the motor system, the manual module to the motor system and cerebellum, the production system to the basal ganglia. The goal module is not associated with a specific brain area. Anderson *et al.* hypothesize that part of the basal ganglia, the striatum, performs a pattern recognition function. Another part, the pallidium, performs a conflict resolution function, and the thalamus controls the execution of the productions.

Like Soar, ACT-R has evolved significantly over several years [6]. It is currently in Version 6.0.

A.1.4 The ICARUS Cognitive Architecture

The ICARUS cognitive architecture [60, 213, 214, 215, 216] follows in the tradition of other cognitivist architectures, such ACT-R, Soar, and EPIC, exploiting symbolic representations of knowledge, the use of pattern matching to select relevant knowledge elements, operation according to the conventional recognize-act cycle, and an incremental approach to learning. In this, ICARUS adheres strictly to Newell's and Simon's physical symbol system hypothesis [272] which states that symbolic processing is a necessary and sufficient condition for intelligent behaviour. However, ICARUS goes further, asserting that mental states are always grounded in either real or imagined physical states, and *vice versa* that problem-space symbolic operators always expand to actions that can be effected or executed. Langley refers to this as the *symbolic physical system* hypothesis. This assertion of the importance of action and perception is similar to recent claims by others in the cognitivist community such as Anderson *et al.* [7].

There are also some other important difference between ICARUS and other cognitivist architectures. ICARUS distinguishes between concepts and skills, and devotes two different types of representation and memory for them, with both long-term and short-term variants of each. Conceptual memory encodes knowledge about general classes of objects and relations among them whereas skill memory encodes knowledge about ways to act and achieve goals. ICARUS forces a strong correspondence between short-term and long-term memories, with the short-term structured being specific instances of the long-term structures. These instances are triggered on the basis of the contents of another short-term memory — a perceptual buffer — which contains a description of physical entitites that correspond to the output of sensors. Furthermore, ICARUS adopts a strongly hierarchical organization for its long-term memory, with conceptual memory directing bottom-up inference and skill memory structuring top-down selection of actions.

Langley notes that incremental learning is central to most cognitivist cognitive architectures, in which new cognitive structures are created by problem solving when an impasse is encountered. ICARUS adopts a similar stance so that when an execution module cannot find an applicable skill that is relevant to the current goal, it resolves the impasse by backward chaining. ICARUS differs from other cognitivist cognitive architectures in that it focusses on the origin of hierarchical skill-based structures which Langley suggest arise incrementally from problem-solving behaviour. Like many other cognitivist cognitive architectures such as Soar and ACT-R, ICARUS maintains a commitment to a unified theory of cognition that is consistent with human capabilities.

The ICARUS execution cycle operates as follows. First, the perceptual buffer is updated. These structures are compared with the long-term concept memory and those that match are instantiated in the short-term concept memory as beliefs. The ICARUS long-term concept memory is organized as a lattice structure, with primitive concepts at the lowest level and more complex composite concepts at successively higher levels. Equally, instances of every level of matching concept are created in the short-term memory, provided they have support in the perceptual buffer. The short-term skill memory is then examined to determined which skill should be considered for execution, based on its current goals. To ensure that this execution does not degenerate into a simple stimulus-response behaviour, ICARUS uses a global persistence parameter to evaluate possible contenting skills for execution. The higher the persistence factor, the greater the system's bias for selecting the skills it chose on the previous cycle.

The skill memories, both short-term and long-term, are organized as hierarchical structures of primitive and non-primitive skills. Primitive skills comprise an action sequence, the concepts that must hold to initiate the skill, and a description of the resultant state should the skill be executed. Non-primitive skills specify how to decompose the skill further and a description of the concepts that will be achieved upon successful execution of the skill. A recent version of ICARUS [216] provides an extension which allows the architecture to compose skills to solve new problems and to store them, *i.e.*, to learn new skills. To date, ICARUS has not yet been used with a physical robot although it is the stated intention of Langley *et al.* to do so [216].

A.1.5 ADAPT — A Cognitive Architecture for Robotics

Some authors, e.g. Benjamin *et al.* [30], argue that existing cognitivist cognitive architectures such as Soar, ACT-R, and EPIC, don't easily support certain mainstream robotics paradigms such as adaptive dynamics and active perception. Many robot programs comprise several concurrent distributed communicating real-time behaviours and consequently these architectures are not suited since their focus is primarily on "sequential search and selection", their learning mechanisms focus on composing sequential rather than concurrent actions, and they tend to be hierarchically-organized rather than distributed. Benjamin *et al.* don't suggest that you cannot address such issues with these architectures but that they are not central features. They present a different cognitive architecture, ADAPT — Adaptive Dynamics and Active Perception for Thought, which is based on Soar but also adopts features from ACT-R (such as long-term declarative memory in which sensori-motor schemas to control perception and action are stored) and EPIC (all the perceptual processes fire in parallel) but the low-level sensory data is placed in short-term working memory where it is processed by the cognitive mechanism. ADAPT has two types of goals: task goals (such as 'find the blue object') and architecture goals (such as 'start a schema to scan the scene'). It also has two types of actions: task actions (such as 'pick up the blue object') and architectural actions (such as 'initiate a grasp schema'). While the architectural part is restricted to allow only one goal or action at any one time, the task part has no such restrictions and many task goals and actions — schemas — can be operational at the same time. The architectural goals and actions are represented procedurally (with productions) while the task goals and actions are represented declaratively in working memory as well as procedurally.

A.1.6 The GLAIR Cognitive Architecture

GLAIR (Grounded Layered Architecture with Integrated Reasoning) [339] is three-layer cognitive architecture comprising a low-level Sensori-Actuator Layer (SAL), a mid-level Perceputo-Motor Layer (PML), and a high-level Knowledge Layer (KL). The SAL controls the sensors and the hardware effectors. The PML is divided into three sublayers which are, from bottom to top, the PMLc layer which encapsulates the sensors and the effectors in the robot's repertoire of behaviours, the PMLb which acts as an interface with the PMLa, and the PMLa itself which serves to ground the symbolic knowledge in the KL in perceptions and actions. The KL represents the beliefs of the agent and it is at this layer that reasoning, planning, and act selection are effected.

GLAIR is a strongly cognitivist architecture, advocating both mind-body dualism (*i.e.* the logical separation of mind and body) and and functionalism (cognitive mechanisms are independent of the physical platform [105]), *viz.*: "The KL constitutes the mind of the agent; the PML and SAL, its body. However, the KL and PMLa layers are independent of the implementation of the agent's body, and can be connected, without modification, to a hardware robot or to a variety of software-simulated robots or avatars".

The KL is the core of the architecture insofar as it grew out of earlier work on knowledge representation and reasoning, in particular logic-based, frame-based, and network-based representations. It supports metaproposition (propositions about propositions) as well as forward and backward reasoning and bidirectional inference by treating the KL representation as a propositional graph and traversing it accordingly. According to its developers, GLAIR's focus on reasoning differentiates it from other cognitive architectures that are driven primarily by problem-solving or goal-achievement. Reflecting GLAIR's heritage as an interactive natural language understanding system, it operates using a sense-reason-act cycle whereby a natural language utterance is input, analyzed in the context of current beliefs, and a natural language utterance expressing the resultant proposition is output. The output proposition depends on whether the input utterance is a statement, a question, or a command (in which case, the output proposition will represent a new belief, an answer to the question, or an act to be performed.)

GLAIR distinguishes between different types of acts: external, internal (mental), and control acts. This act is composed of an action and zero or more arguments. An agent may perform an act, or it may have propositions about acts, or it may have a policy about an act, *i.e.* a specification of the circumstances under which reasoning leads to an act. Thus, a GLAIR agent "performs an act, believes a proposition, and adopts a policy". External acts either sense or affect the agent's environment (which can be real, virtual, or simulated). *No external acts are predefined in GLAIR and they must be supplied by the designer of the agent.* Mental acts affect the agent's beliefs and policies. Control acts determine the overall functioning of the reasoning system.

In principle, GLAIR agents are able to reason about themselves by including a term that refers to the agent itself but providing GLAIR agents with knowledge of the actions they are currently performing above the level of primitive actions is the subject of further research. Similarly, while the KL contains delarative knowledge and procedural knowledge for carrying out pre-defined acts, GLAIR does not yet have the capability to learn these procedural representations. Finally, when attempting to achieve a goal, a GLAIR agent selects an act in the belief that it will lead to the achievment of that goal. However, GLAIR agents don't yet have the ability to formulate these beliefs by reasoning about the effects of various acts or by observing the effects of its acts. In other words, GLAIR doesn't yet learn to anticipate the outcome of its actions.

A.1.7 CoSy Architecture Schema

Sloman and his co-workers advocate splitting the design of a cognitive architecture into three steps: the analysis of several scenarios to identify the principal requirements, the creation of an architecture schema, and the instantiation of the architecture schema in a scenario-specific cognitive architecture design [137, 138]. The architecture schema addresses the organization of information and processing components and the control of information flow among them in a task and implementation independent manner. In other words, the architecture schema identifies the general shape of an architecture suitable for a relatively broad class of scenarios but leaves the details to a subsequent scenario-specific design phase.

Based on scenarios for a hypothetical robotic assistant which can interact with a family in a home environment, which can learn about and alter its world through physical actions, which can engage in linguistic discourse, and which can perform household tasks, Sloman *et al.* introduce the CoSy Architecture Schema which forms the basis of subsequent (outline) architecture instantiations [138] as well as a software toolset to effect this instantiation [137]. Because this schema is based on scenarios which focus on the robot behaviour, such a schema is neither a unified theory of cognition or general theory of mind (as many other cognitivist cognitive architectures are) nor is it a general schema which can be used to describe *any* cognitive architecture, such as Sloman's CogAff schema [347].

The CoSy Architecture Schema is based on three general requirements: that the architecture schema should support interaction in a dynamic world, that it should enable the integration of information from several sources, and that it should facilitate goal-directed behaviour with multiple goals. These requirements mean that the architecture schema must provide mechanisms for relating information from different sources, for dealing with inconsistencies, and for allowing global motives to influence processing throughout the system. Furthermore, since the target robot system is intended to have several individual capabilities or competences, the schema must allow for multiple specialized representations for each competence or sub-system. Furthermore, these must update asynchronously and concurrently in the target architecture. Sloman *et al.* claim that this focus on concurrent modular processing distinguishes the CoSy Architecture Schema from many other existing architectures which are "essentially monolithic in their styles of processing" [138].

Based on these requirements, the CoSy Architecture Schema comprises a separate subarchitecture for each competence. Each subarchitecture is derived from a common template (to be described below) and all subarchitectures are loosely-coupled to avoid complex interdependencies. Typically, there are subarchitectures for motor control, vision, planning, linguistic communication, spatio-temporal memory, and so on. Each subarchitecture comprises a set of processing components connected to a local subarchitecture-specific working memory which can be written to only by the subarchitecture processes and by a single global process (the goal manager).

The information in each subarchitecture and in the architecture schema as a whole is controlled by goals. These goals are generated by the system as it operates and interacts with its environment. There are two types of goal. Global goals, which require coordination across two or more subarchitectures, and local goals, which originate in and are particular to a given subarchitecture.

The knowledge encapsulated in each subarchitecture is defined by a subarchitecture-specific ontology: "a structured description of the kinds of information that the cognitive system can process from either internal or external sources" [138]. Relationships between entities in these ontologies are defined by a set of general ontologies. These general ontologies define knowledge at global level. They deal with knowledge that is independent of competence and related to general architecture issues such as global goals, planning, and reasoning. The implementation of these ontologies is not specified.

Since the CoSy Architecture Schema comprises many concurrent processing components, the issue of coordination and control is an important issue. In the CoSy Architecture Schema, control is effected by the global goal manager. It is achieved by requiring each component to announce its intention to perform some processing by posting a goal for approval. Each subarchitecture has a task manager process with determines whether or not that local goal should be adopted. This decision can also be made by the global goal manager based on the current global goals for the entire system.

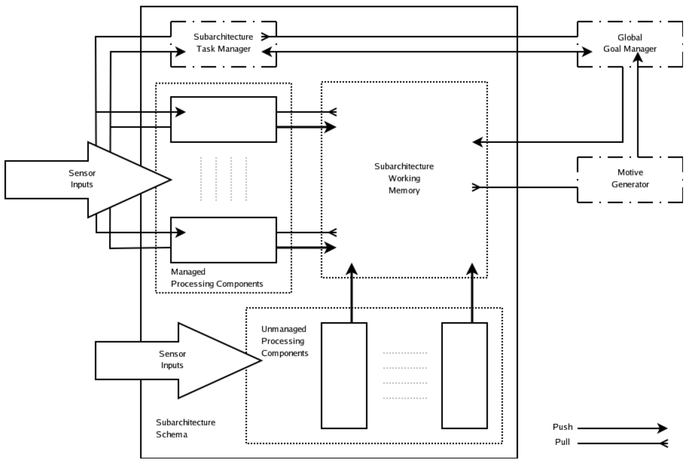


Fig. A.2 The CoSy Architecture Schema: template subarchitecture (from [138])

A template for a subarchitecture is shown in Figure A.2. Each subarchitecture comprises the following four components:

1. *Subarchitecture Working Memory* which holds the results of the processes in that subarchitecture;
2. *Subarchitecture Task Manager* which decided which of the subarchitecture's local goals is to be adopted;
3. A set of *Unmanaged Processing Components* which typically serve the systems sensor inputs and which can run *without* posting a goal for approval;
4. A set of *Managed Processing Components* which monitor the working memory for information that they can process and which post a local goal when they can process that information.

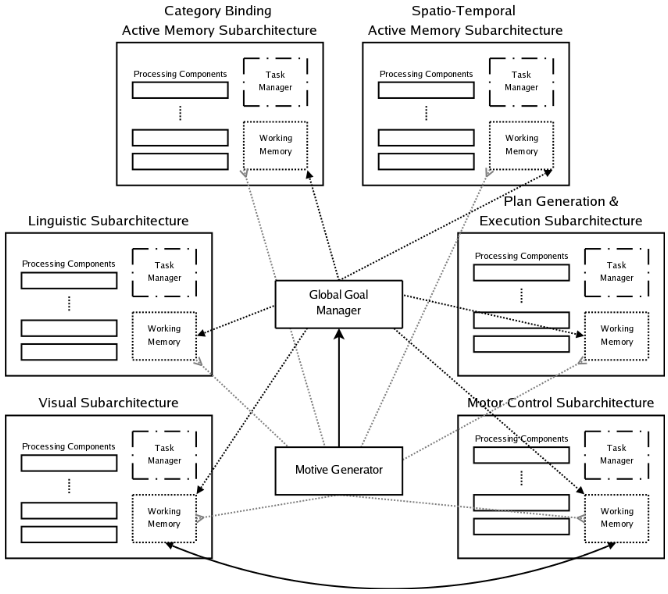


Fig. A.3 The CoSy Architecture Schema: Example architecture instatiation with six subarchitectures, the Global Goal Manager, and the Motive Generator (from [138]).

Apart from a specific subarchitecture for each competence, there are three global components: the *Motive Generator*, the *Global Goal Manager*, and the *General Memory* (see Figure A.3). The motive generator monitors the working memory in every subarchitecture looking for information which may be able to trigger processing in a different subarchitecture. When it finds such information, it posts a global goal for the whole architecture. This global goal is then considered by the global goal manager (the manner in which the global goals are adopted is not specified). Once a global goal is adopted, it writes information to the working memory of the appropriate subarchitecture which will in turn cause a component in the subarchitecture to post a local goal and start a chain of local processing. The general memory stores long-term knowledge about anything that is relevant to the control of the overall instantiated architecture schema, *e.g.* beliefs, goals, etc. Again, no specific structure for this general memory is proposed in [138].

Ultimately, the CoSy Architecture Schema is a cognitivist rule-based schema for the design of cognitive architectures focussing on the effective coordination of multiple concurrent asynchronously-updating sub-systems, achieved through a combination of local and global moderation of goal-oriented processing and through the sharing and integration of knowledge among these sub-systems. The manner in which these goals are acquired or how knowledge is generated is not specified. Learning is not specifically addressed in the schema although it is evident that a capacity for learning is envisaged to be incorporated in some of the processing components in one or more of the competence subarchitectures.

A.2 Emergent Cognitive Architectures

A.2.1 Autonomous Agent Robotics

Autonomous agent robotics (AAR) and behaviour-based systems represents an emergent alternative to cognitivist approaches. Instead of a cognitive system architecture that is based on a decomposition into functional components (*e.g.* representation, concept formation, reasoning), an AAR architecture is based on interacting *whole* systems. Beginning with simple whole systems that can act effectively in simple circumstances, layers of more sophisticated systems are added incrementally, each layer subsuming the layers beneath it. This is the subsumption architecture introduced by Brooks [49]. Christensen and Hooker [62] argue that AAR is not sufficient either as a principled foundation for a general theory of situated cognition. One limitation includes the explosion of systems states that results from the incremental integration of sub-systems and the consequent difficulty in coming up with an initial well-tuned design to produce coordinated activity. This in turn imposes a need for some form of self-management, something not included in the scope of the original subsumption architecture. A second limitation is that it becomes increasingly problematic to rely on environmental cues to achieve the right sequence of actions or activities as the complexity of the task rises. AAR is also insufficient for the creation of a comprehensive theory of cognition: as the subsumption architecture can't be scaled to provide higher-order cognitive faculties (it can't explain self-directed behaviour) and even though the behaviour of an AAR system may be very complex it is still ultimately a reactive system.

Christensen and Hooker note that Brooks has identified a number of design principles to deal with these problems. These include motivation, action selection, self-adaption, and development. Motivation provides context-sensitive selection of preferred actions, while coherence enforces an element of consistency in chosen actions. Self-adaption effects continuous self-calibration among the sub-systems in the subsumption architecture, while development offers the possibility of incremental open-ended learning.

We see here a complementary set of self-management processes, signalling the addition of system-initiated contributions to the overall interaction process and complementing the environmental contributions that are typical of normal subsumption architectures. It is worth remarking that this quantum jump in complexity and organization is reminiscent of the transition from level one autopoietic systems to level two, where the central nervous system then plays a role in allowing the system to perturb itself (in addition to the environmental perturbations of a level 1 system).

A.2.2 A Global Workspace Cognitive Architecture

Shanahan [335, 336, 337, 338] proposes a biologically-plausible brain-inspired neural-level cognitive architecture in which cognitive functions such as anticipation and planning are realized through internal simulation of interaction with the environment. Action selection, both actual and internally simulated, is mediated by affect. The architecture is based on an external sensori-motor loop and an internal sensori-motor loop in which information passes though multiple competing cortical areas and a global workspace.

In contrast to manipulating declarative symbolic representations as cognitivist architectures do, cognitive function is achieved here through topographically-organized neural maps which can be viewed as a form of analogical or iconic representation whose structure is similar to the sensory input of the system whose actions they mediate.

Shanahan notes that such analogical representations are particularly appropriate in spatial cognition which is a crucial cognitive capacity but which is notoriously difficult with traditional logic-based approaches. He argues that the semantic gap between sensory input and analogical representations is much smaller than with symbolic language-like representations and, thereby, minimize the difficulty of the symbol grounding problem.

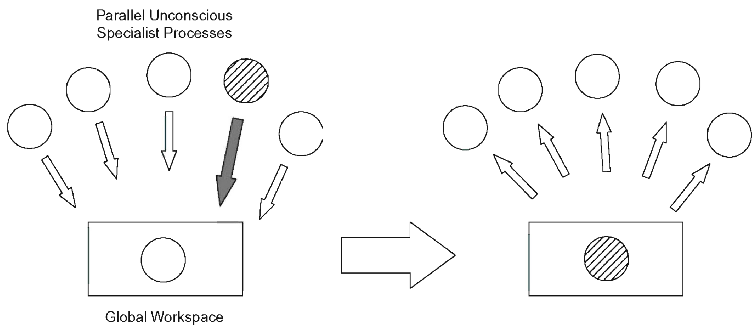


Fig. A.4 The Global Workspace Theory cognitive architecture: 'winner-take-all' coordination of competing concurrent processes (from [337])

Shanahan's cognitive architecture is founded also upon the fundamental importance of parallelism as a constituent component in the cognitive process as opposed to being a mere implementation issue. He deploys the *global workspace* model [15, 16] of information flow in which a sequence of states emerges from the interaction of many separate parallel processes (see Figure A.4). These specialist processes compete and co-operate for access to a global workspace. The winner(s) of the competition gain(s) controlling access to the global access and can then broadcast information back to the competing specialist processes. Shanahan argues that this type of architecture provides an elegant solution to the frame problem.

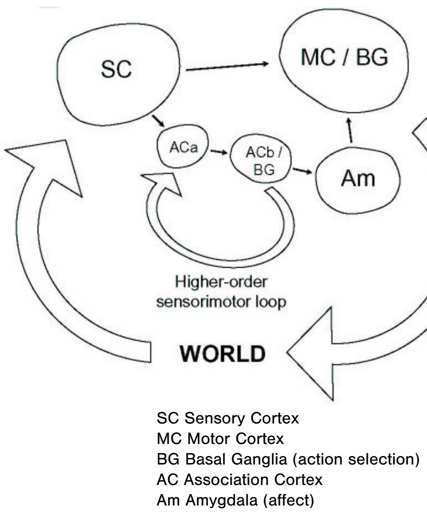


Fig. A.5 The Global Workspace Theory cognitive architecture: achieving prospection by sensori-motor simulation (from [337])

Shanahan's cognitive architecture is comprised of the following components: a first-order sensori-motor loop, closed externally through the world, and a higher-order sensori-motor loop, closed internally through associative memories (see Figure A.4). The first-order loop comprises the sensory cortex and the basal ganglia (controlling the motor cortex), together providing a reactive action-selection sub-system. The second-order loop comprises two associative cortex elements which carry out off-line simulations of the system's sensory and motor behaviour, respectively. The first associative cortex simulates a motor output while the second simulates the sensory stimulus expected to follow from a given motor output. The higher-order loop effectively modulates basal ganglia action selection in the first-order loop via an affect-driven amygdala component. Thus, this cognitive architecture is able to anticipate and plan for potential behaviour through the exercise of its "imagination" (*i.e.* its associative internal sensori-motor simulation). The global workspace doesn't correspond to any particular localized cortical area. Rather, it is a global communications network.

The architecture is implemented as a connectionist system using G-RAMs: generalized random access memories [3]. Interpreting its operation in a dynamical framework, the global workspace and competing cortical assemblies each define an attractor landscape. The perceptual categories constitute attactors in a state space that reflects the structure of the raw sensory data. Prediction is achieved by allowing the higher-order sensori-motor loop to traverse along a simulated trajectory in that state space so that the global workspace visits a sequence of attractors. The system has been validated in a Webot [252] simulation environment.

A.2.3 Self-directed Anticipative Learning

Christensen and Hooker propose a new emergent interactivist-constructivist (I-C) approach to modelling intelligence and learning: self-directed anticipative learning (SDAL) [61]. This approach falls under the broad heading of dynamical embodied approaches in the non-cognitivist paradigm. They assert first the primary model for cognitive learning is anticipative skill construction and that processes that both guide action and improve the capacity to guide action while doing so are taken to be the root capacity for all intelligent systems. For them, intelligence is a continuous management process that has to support the need to achieve autonomy in a living agent, distributed dynamical organization, and the need to produce functionally coherent activity complexes that match the constraints of autonomy with the appropriate organization of the environment across space and time through interaction. In presenting their approach they use the term "explicit norm signals" for the signals that a system uses to differentiate an appropriate context performing an action. These norm signals reflect conditions for the (maintenance) of the system's autonomy (*e.g.* hunger signals depleted nutritional levels). The complete set of norm signals is termed the norm matrix. They then distinguish between two levels of management: low-order and high-order. Low-order management employs norm signals which differentiate only a narrow band of the overall interaction process of the system (*e.g.* a mosquito uses heat tracking and CO_2 gradient tracking to seek blood hosts). Since it uses only a small number of parameters to direct action, success ultimately depends on simple regularity in the environment. These parameters also tend to be localized in time and space. On the other hand, high-order management strategies still depend to an extent on regularity in the environment but exploit parameters that are more extended in time and space and use more aspects of the interactive process, including the capacity to anticipate and evaluate the system's performance, to produce effective action (and improve performance). This is the essence of self-directedness. "Self-directed systems anticipate and evaluate the interaction process and modulate system action accordingly". The major features of self-directedness are action modulation ("generating the right kind of extended interaction sequences"), anticipation ("who will/should the interaction go?", evaluation ("how did the evaluation go?"), and constructive gradient tracking ("learning to improve performance").

A.2.4 A Self-Affecting Self-Aware (SASE) Cognitive Architecture

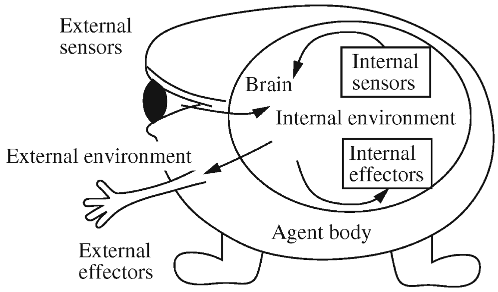


Fig. A.6 The Self-Aware Self-Effecting (SASE) architecture (from [393])

Weng [394, 395, 393] introduced an emergent cognitive architecture that is specifically focussed on the issue of development, by which he means that the processing accomplished by the architecture is not specified (or programmed) *a priori* but is the result of the real-time interaction of the system with the environment including humans. Thus, the architecture is not specific to tasks, which are unknown when the architecture is created or programmed, but is capable of adapting and developing to learn both the tasks required of it and the manner in which to achieve the tasks. In this sense, even through Weng's architecture is not a cognitivist one, his use of the term is very faithful to the meaning of *cognitive architecture* as it was originally intended when it was introduced originally in the cognitivist paradigm. That is, it represents the underlying infrastructure for a cognitive system, specifically those aspects of a cognitive agent that are constant over time and independent of the task [128, 214, 309].

Weng refers to his architecture as a Self-Aware Self-Effecting (SASE) system (see Figure A.6). The architecture entails an important distinction between the sensors and effectors that are associated with the environment (including the system's body and thereby including proprioceptive sensing) and those that are associated with the system's 'brain' or central nervous system (CNS). Only those systems that have explicit mechanisms for sensing and affecting the CNS qualify as SASE architectures. The implications for development are significant: the SASE architecture is configured with no knowledge of the tasks it will ultimately have to perform, its brain or CNS are not directly accessible to the (human) designers once it is launched, and after that the only way a human can affect the agent is through the external sensors and effectors. Thus, the SASE architecture is very faithful to the emergent paradigms of cognition, especially the enactive approach: its phylogeny is fixed and it is only through ontogenetic development that the system can learn to operate effectively in its environment.

The concept of self-aware self-effecting operation is similar to the level 2 autopoietic organizational principles introduced by Matura and Varela [237] (*i.e.* both self-production and self-development) and is reminiscent of the recursive self-maintenant systems principles of Bickhard [40] and Christensen's and Hooker's interactivist-constructivist approach to modelling intelligence and learning: self-directed anticipative learning (SDAL) [61]. Weng's contribution differs in that he provides a specific computational framework in which to implement the architecture. Weng's cognitive architecture is based on Markov Decision Processes (MDP), specifically a developmental observation-driven self-aware self-effecting Markov Decision Process (DOSASE MDP). Weng places this particular architecture in a spectrum of MDPs of varying degrees of behavioural and cognitive complexity [395]; the DOSASE MDP is type 5 of six different types of architecture and is the first type in the spectrum that provides for a developmental capacity. Type 6 builds on this to provide additional attributes, specifically greater abstraction, self-generated contexts, and a higher degree of sensory integration.

The example DOSASE MDP vision system detailed in [394] further elaborates on the cognitive architecture, detailing three types of mapping in the information flow within the architecture: sensory mapping, cognitive mapping, and motor mapping. It is significant that there is more than one cognitive pathway between the sensory mapping and the motor mapping, one of which encapsulates innate behaviours (and the phylogenetically-endowed capabilities of the system) while the other encapsulates learned behaviours (and the ontogenetically-developed capabilities of the system). These two pathways are mediated by a subsumption-based motor mapping which accords higher priority to the ontogenetically-developed pathway. A second significant feature of the architecture is that it facilitates what Weng refers to as "primed sensations" and "primed action". These correspond to predictive sensations and actions and thereby provide the system with the anticipative and prospective capabilities that are the hallmark of cognition.

The general SASE schema, including the associated concept of Autonomous Mental Development (AMD), has been developed and validated in the context of two autonomous developmental robotics systems, SAIL and DAV [396, 397, 394, 395].

A.2.5 Darwin: Neuromimetic Robotic Brain-Based Devices

Kirchmar *et al.* [203, 204, 205, 206, 207, 334] have developed a series of robot platforms called Darwin to experiment with developmental agents. These systems are 'brain-based devices' (BBDs) which exploit a simulated nervous system that can develop spatial and episodic memory as well as recognition capabilities through autonomous experiential learning. As such, BDDs are a neuromimetic approach in the emergent paradigm that is most closely aligned with the enactive and the connectionist models. It differs from most connectionist approaches in that the architecture is much more strongly modelled on the structure and organization of the brain than are conventional artificial neural networks, *i.e.* they focus on the nervous system as a whole, its constituent parts, and their interaction, rather than on a neural implementation of some individual memory, control, or recognition function.

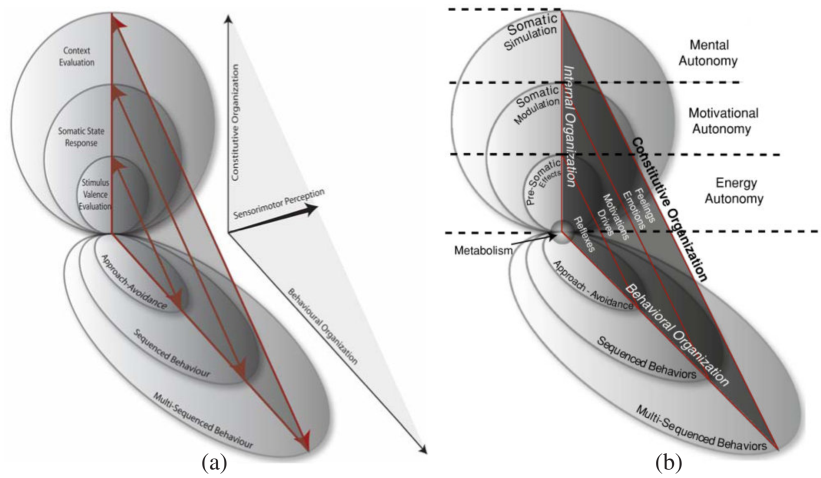
The principal neural mechanisms of the BDD approach are synaptic plasticity, a reward (or value) system, reentrant connectivity, dynamic synchronization of neuronal activity, and neuronal units with spatiotemporal response properties. Adaptive behaviour is achieved by the interaction of these neural mechanisms with sensorimotor correlations (or contingencies) which have been learned autonomously by active sensing and self-motion.

Darwin VIII is capable of discriminating reasonably simple visual targets (coloured geometric shapes) by associating it with an innately preferred auditory cue. Its simulated nervous system contains 28 neural areas, approximately 54,000 neuronal units, and approximately 1.7 million synaptic connections. The architecture comprises regions for vision (V1, V2, V4, IT), tracking (C), value or saliency (S), and audition (A). Gabor filtered images, with vertical, horizontal, and diagonal selectivity, and red-green colour filters with on-centre off-surround and off-centre on-surround receptive fields, are fed to V1. Sub-regions of V1 project topographically to V2 which in turn projects to V4. Both V2 and V4 have excitatory and inhibitory reentrant connections. V4 also has a non-topographical projection back to V2 as well as a non-topographical projection to IT, which itself has reentrant adaptive connections. IT also projects non-topographically back to V4. The tracking area (C) determines the gaze direction of Darwin VIII's camera based on excitatory projections from the auditory region A. This causes Darwin to orient toward a sound source. V4 also projects topographically to C causing Darwin VIII to centre its gaze on a visual object. Both IT and the value system S have adaptive connections to C which facilitates the learned target selection. Adaptation is effected using the Hebbian-like Bienenstock-Cooper-Munroe (BCM) rule [41]. From a behavioural perspective, Darwin VIII is conditioned to prefer one target over others by associating it with the innately preferred auditory cue and to demonstrate this preference by orienting towards the target.

Darwin IX can navigate and categorize textures using artificial whiskers based on a simulated neuroanatomy of the rat somatosensory system, comprising 17 areas, 1101 neuronal units, and approximately 8400 synaptic connections.

Darwin X is capable of developing spatial and episodic memory based on a model of the hippocampus and surrounding regions. Its simulated nervous system contains 50 neural areas, 90,000 neural units, and 1.4 million synaptic connections. It includes a visual system, head direction system, hippocampal formation, basal forebrain, a value/reward system based on dopaminegic function, and an action selection system. Vision is used to recognize objects and then compute their position, while odometry is used to develop head direction sensitivity.

A.2.6 The Cognitive-Affective Architecture



(a) (b)

Fig. A.7 The cognitive-affective enactive architecture: (a) The Enactive Organizational Constraints Hierarchy (from [264]) in which increasing constitutive organizational complexity facilitates increasing levels of stimulus evaluation and appraisal in maintaining the constitutive autonomy of the system, accompanied by an associated increase in adaptivity. These levels are directly coupled, by sensorimotor perception, to increasing complexity along the behavioural organization axis; (b) The Cognitive-Affective Architecture Schematic (from [415]) refines this by showing a single spectrum of constitutive organization brought about by the recruitment of a progression of emotions, from reflexes, through drives and motivations, to emotions-proper and feelings. Each level in the constitutive organization is associated on the Internal Organization axis with an increasing level of homeostatic autonomy-preserving self-maintenance, ranging from basic metabolic processes through reactive sensorimotor activity (pre-somatic effects), associative learning and prediction (somatic modulation), to interoception and internal simulation of behaviour prior to action. Equally, each level in the constitutive organization is associated on the Behavioural Organization axis with an increasing level of complexity in behaviour, ranging from approach-avoidance, sequenced behaviours, and multi-sequenced behaviours.

Ziemke and his co-workers have developed a schema for an enactive cognitive architecture [264, 415] that explicitly addresses the role of emotion in a cognitive system. Based on the architecture and physiology of the mammalian brain, they refer to it both as a schema for an “Enactive Organizational Constraints Hierarchy” [264] and a “Cognitive-Affective Architecture Schematic” [415]. It is a schema in the sense that it identifies the principal characteristics of the architecture without providing a detailed design of the component parts of the architecture and the dynamics of their interaction. However, to complement the schema, they also propose a design process called *holistic-reductionism* which focusses on the interdependencies of the components rather than on the identification of independent functional modules, as is normally the case with architecture design. Any modularity in the system, they argue, emerges from the interdependence of the embodied cognitive processes rather than by phylogenetic pre-specificiation.

The key idea in holistic reductionism is to consider first a minimally-cognitive agent which is impaired by de-cortication of selected cognitive functions and then to incrementally re-corticate the agent, allowing progressively greater cognitive capabilities to emerge. Thus, the methodology is to realize a minimal, but complete and viable, autonomous system and then develop it through re-cortication. Targetting an initial de-corticated system allows one to focus on the essential requirements of autonomous self-maintenance through essential metabolic homeostatic processes. These processes can be perturbed when interacting with the world in which the system is embedded and "the well-being of the agent, specified in terms of disruption and the effort required to re-assert metabolic norms provides the basis of motivation" [264]. The autonomy of the agent is effected through a hierarchy of homeostatic self-regulatory processes, each of which exploits a progression of associated emotions, ranging from basic reflexes linked to metabolic regulation, through drives and motivations, to emotions-proper and feelings linked to "higher" cognitive functions. This follows closely Damasio's hierarchy of levels of homeostatic regulation [73]. Thus, "the emotional aspect of cognition, providing motivation and value to an otherwise neutral world, ... is a fundamental part of the make-up of and organism with respect to sensorimotor learning" [264]. When extending the autonomy — and cognitive capabilities — of the system by re-cortication, Ziemke emphasizes that "new elements of the extended model must integrate with the existing model through modulation and not by functional replacement, or by modular extension" [264].

The Enactive Organizational Constraints Hierarchy (see Fig. A.7 (a)) traverses two dimensions: (i) Constitutive Organization and (ii) Behavioural Organization. The former refers to the system's internal dynamics as it maintains its integrity — its autonomy — in the face of perturbation by various stimuli. At the core of this space there is metabolic homeostatic self-regulation. This extends, as re-cortication proceeds, to stimulus valence evaluation, somatic state response, and content evaluation, each level offering increasing organizational complexity, an increasing degree of decoupling between stimulus and response, and an increasing degree of appraisal and associated adaptivity. Each level in the constitutive organization dimension is matched by an associated level in the behavioural organization dimension: approach-avoidance, sequenced behaviour, and multi-sequenced behaviour, respectively. Thus, the behavioural organization dimension is coupled by sensorimotor perception to the constitutive organizational dimension. A later version of the architecture [415], the Cognitive-Affective Architecture Schematic, reflects this coupling by referring to a single space of constitutive organization which is viewed from two perspectives: internal organization and behavioural organization (see Fig. A.7 (b)).

The spectrum of constitutive organization is realized by the recruitment of a progression of emotions, from reflexes, through drives and motivations, to emotions-proper and feelings. Each level in the constitutive organization is associated on the Internal Organization axis with an increasing level of homeostatic autonomy-preserving self-maintenance, ranging from basic metabolic processes through reactive sensorimotor activity (pre-somatic effects), associative learning and prediction (somatic modulation), to interoception and internal simulation of behaviour prior to action. Equally, each level in the constitutive organization is associated on the Behavioural Organization axis with an increasing level of complexity in behaviour, ranging from approach-avoidance, sequenced behaviours, and multi-sequenced behaviours.

The key idea under-pinning the Cognitive-Affective Architecture is that different levels of cognitive function and behavioural complexity are associated with, and are brought about by, different levels of emotion, each linked to affective homeostatic processes ranging from reflexes right through to internal simulation.

A.3 Hybrid Cognitive Architectures

A.3.1 A Humanoid Robot Cognitive Architecture

Burghart *et al.* [54] present a hybrid cognitive architecture for a humanoid robot. It is based on interacting parallel behaviour-based components, comprising a three-level hierarchical perception sub-system, a three-level hierarchical task handling system, a long-term memory sub-system based on a global knowledge database (utilizing a variety of representational schemas, including object ontologies and geometric models, Hidden Markov Models, and kinematic models), a dialogue manager which mediates between perception and task planning, an execution supervisor, and an 'active models' short-term memory sub-system to which all levels of perception and task management have access. These active models play a central role in the cognitive architecture: they are initialized by the global knowledge database and updated by the perceptual sub-system and can be autonomously actualized and reorganized. The perception sub-system comprises a three-level hierarchy with low, mid, and high level perception modules. The low-level perception module provides sensor data interpretation without accessing the central system knowledge database, typically to provide reflex-like low-level robot control. It communicates with both the mid-level perception module and the task execution module. The mid-level perception module provides a variety of recognition components and communicates with both the system knowledge database (long-term memory) as well as the active models (short-term memory). The high-level perception module provides more sophisticated interpretation facilities such as situation recognition, gesture interpretation, movement interpretation, and intention prediction.

The task handling sub-system comprises a three-level hierarchy with task planning, task coordination, and task execution levels. Robot tasks are planned on the top symbolic level using task knowledge. A symbolic plan consists of a set of actions, represented either by XML-files or Petri nets, and acquired either by learning (*e.g.* through demonstration) or by programming. The task planner interacts with the high-level perception module, the (long-term memory) system knowledge database, the task coordination level, and an execution supervisor. This execution supervisor is responsible for the final scheduling of the tasks and resource management in the robot using Petri nets. A sequence of actions is generated and passed down to the task coordination level which then coordinates (deadlock-free) tasks to be run at the lowest task execution (control) level. In general, during the execution of any given task, the task coordination level works independently of the task planning level.

A dialogue manager, which coordinates communication with users and interpretation of communication events, provides a bridge between the perception sub-system and the task sub-system. Its operation is effectively cognitive in the sense that it provides the functionality to recognize the intentions and behaviours of users.

A learning sub-system is also incorporated with the robot currently learning tasks and action sequences off-line by programming by demonstration or tele-operation; on-line learning based on imitation are envisaged. As such, this key component represents work in progress.

A.3.2 The Cerebus Architecture

Horswill [170, 171] argues that classical artificial intelligence systems such as those in the tradition of Soar, ART-R, and EPIC, are not well suited for use with robots. Traditional systems typically store all knowledge centrally in a symbolic database of logical assertions and reasoning is concerned mainly with searching and sequentially updating that database. However, robots are distributed systems with multiple sensory, reasoning, and motor control processes all running in parallel and often only loosely coupled with one another. Each of these processes maintains its own separate and limited representation of the world and the task at hand and he argues that it is not realistic to require them to constantly synchronize with a central knowledge base.

Recently, much the same argument has been made by neuroscientists about the structure and operation of the brain. For example, evidence suggest that space perception is not the result of a single circuit, and in fact derives from the joint activity of several fronto-parietal circuits, each of which encodes the spatial location and transforms it into a potential action in a distinct and motor-specific manner [316, 314]. In other words, the brain encodes space not in a single unified manner — there is no general purpose space map — but in many different ways, each of which is specifically concerned with a particular motor goal. Different motor effectors need different sensory input: derived in different ways and differently encoded in ways that are particular to the different effectors. Conscious space perception emerges from these different pre-existing spatial maps.

Horswill contends also that the classical reasoning systems don't have any good way of directing perceptual attention: they either assume that all the relevant information is already stored in the database or they provide a set of actions that fire task-specific perceptual operators to update specific parts of the database (just as, for example, happens in ACT-R). Both of these approaches are problematic: the former fall foul of the frame problem (the need to differentiate the significant in a very large data-set and then generalize to accommodate new data) and the second requires that the programmer design the rule based to ensure that the appropriate actions are fired in the right circumstances and at the right time; see also similar arguments by Christensen and Hooker [62].

Horswill argues that keeping all of the distinct models or representations in the distributed processes or sub-systems consistent needs to be a key focus of the overall architecture and that is should be done without sychronizing with a central knowledge base. They propose a hybrid cognitive architecture, Cerebus, that combines the tenets of behaviour-based architectures with some features of symbolic AI (forward- and backward-chaining inference using predicate logic). It represents an attempt to scale behaviour-based robots (*e.g.* see Brooks [49] and Arkin [11]) without resorting to a traditional central planning system. It combines a set of behaviour-based sensory-motor systems with a marker-passing semantic network and an inference network. The semantic network effects long-term declarative memory, providing reflective knowledge about its own capabilities, and the inference network allows it to reason about its current state and control processes. Together they implement the key feature of the Cerebus architecture: the use of reflective knowledge about its perceptual-motor systems to perform limited reasoning about its own capabilities.

A.3.3 Cog: Theory of Mind

Cog [51] is an upper-torso humanoid robot platform for research on developmental robotics. Cog has a pair of six degree-of-freedom arms, a three degree-of-freedom torso, and a seven degree-of-freedom head and neck. It has a narrow and wide angle binocular vision system (comprising four colour cameras), an auditory system with two microphones, a three-degree of freedom vestibular system, and a range of haptic sensors.

As part of this project, Scassellati has put forward a proposal for a Theory of Mind for Cog [333] that focusses on social interaction as a key aspect of cognitive function in that social skills require the attribution of beliefs, goals, and desires to other people.

A robot that possesses a theory of mind would be capable of learning from an observer using normal social signals and would be capable of expressing its internal state (emotions, desires, goals) though social (non-linguistic) interactions. It would also be capable of recognizing the goals and desires of others and, hence, would be able to anticipate the reactions of the observer and modify its own behaviour accordingly.

Scassellati's proposed architecture is based on Leslie's model of Theory of Mind [221] and Baron-Cohen's model of Theory of Mind [25] both of which decompose the problem into sets of precursor skills and developmental modules, albeit in a different manner. Leslie's Theory of Mind emphasizes independent domain specific modules to distinguish (a) mechanical agency, (b) actional agency, and (c) attitudinal agency; roughly speaking the behaviour of inanimate objects, the behaviour of animate objects, and the beliefs and intentions of animate objects. Baron-Cohen's Theory of Mind comprises three four modules, one of which is concerned with the interpretation of perceptual stimuli (visual, auditory, and tactile) associated with self-propelled motion, and one of which is concerned with the interpretation of visual stimuli associated with eye-like shapes. Both of these feed a shared attention module which in turn feed a Theory of Mind module that represents intentional knowledge or 'epistemic mental states' of other agents.

The focus Scassellati's Theory of Mind for Cog, at least initially, is on the creation of the precursor perceptual and motor skills upon which more complex theory of mind capabilities can be built: distinguishing between inanimate and animate motion and identifying gaze direction. These exploit several built-in visual capabilities such as colour saliency detection, motion detection, skin colour detection, and disparity estimation, a visual search and attention module, and visuo-motor control for saccades, smooth-pursuit, vestibular-ocular reflex, as well as head and neck movement and reaching. The primitive visuo-motor behaviours, *e.g.* for finding faces and eyes, are based on embedded motivational drives and visual search strategies.

A.3.4 Kismet

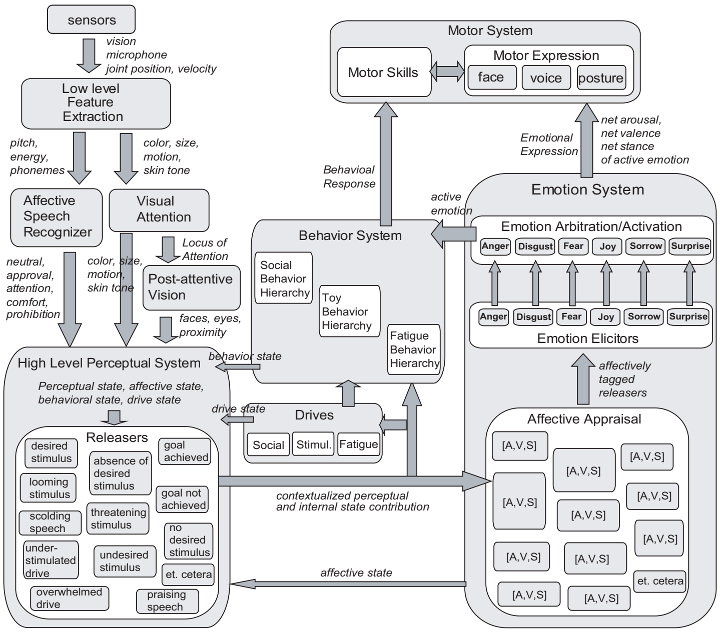


Fig. A.8 The Kismet cognitive architecture (from [46])

The role of emotion and expressive behaviour in regulating social interaction between humans and robots has been examined by Breazeal using an expressive articulated anthropomorphic robotic head called Kismet [45, 46]. Kismet has a total of 21 degree-of-freedom, three to control the head orientation, three to direct the gaze, and fifteen to control the robots facial features (*e.g.* eye-lids, eyebrows, lips, and ears). Kismet has a narrow and wide angle binocular vision system (comprising four colour cameras), and two microphones, one mounted in each ear. Kismet is designed to engage people in natural and expressive face-to-face interaction, perceiving a natural social cues and responding through gaze direction, facial expression, body posture, and vocal babbling.

Breazeal argues that emotions provide an important mechanism for modulating system behaviour in response to environmental and internal states. They prepare and motivate a system to respond in adaptive ways and serve as reinforcers in learning new behaviour, and act as a mechanism for behavioural homeostasis. The ultimate goal of Kismet is to learn from people though social engagement, although Kismet does not yet have any adaptive (*i.e.* learning or developmental) or anticipatory capabilites.

Kismet has two types of motivations: drives and emotions. Drives establish the top-level goals of the robot: to engage people (social drive), to engage toys (stimulation drive), and to occasionally rest (fatigue drive). The robot's behaviour is focussed on satiating its drives. These drives have a longer time constant compared with emotions and they operate cyclically: increasing in the absence of satisfying interaction and diminishing with habituation. The goal is to keep the drive level somewhere in a homeostatic region between under stimulation and over stimulation. Emotions — anger & frustration, disgust, fear & distress, calm, joy, sorrow, surprise, interest, boredom — elicit specific behavioural responses such as complain, withdraw, escape, display pleasure, display sorrow, display startled response, re-orient, and seek, in effect tending to cause the robot to come into contact with things that promote its "well-being" and avoid those that don't. Emotions are triggered by pre-specified antecedent conditions which are based on perceptual stimuli as well as the current drive state and behavioural state.

Kismet has five distinct modules in its cognitive architecture: a perceptual system, an emotion system, a behaviour system, a drive system, and a motor system (see Figure A.8).

The perceptual system comprises a set of low-level processes which sense visual and auditory stimuli, perform feature extraction (*e.g.* colour, motion, frequency), extract affective descriptions from speech, orient visual attention, and localize relevant features such as faces, eyes, objects, *etc.*. These are input to a high level perceptual system where, together with affective input from the emotion system, input from the drive system and the behaviour system, they are bound by *releaser* processes 'that encode the robot's current set of beliefs about the state of the robot and its relation to the world. There are many different kinds of releasers, each of which is 'hand-crafted' by the system designer. When the activation level of a releaser exceeds a given threshold (based on the perceptual, affective, drive, and behavioural inputs) it is output to the emotion system for appraisal. Breazeal says that 'each releaser can be thought of as a simple "cognitive" assessment that combines lower-level perceptual features with measures of its internal state into behaviorally significant perceptual categories' [46]. The appraisal process tags the releaser output with pre-specified (*i.e.* designed-in) affective information on their arousal (how much it stimulates the system), valence (how much it is favoured), and stance (how approachable it is). These are then filtered by 'emotion elicitor' to map each AVS (arousal, valence, stance) triple onto the individual emotions. A single emotion is then selected by a winner-take-all arbitration process, and output to the behaviour system and the motor system to evoke the appropriate expression and posture.

Kismet is a hybrid system in the sense that it uses quintessentially cognitivist rule-based schemas to determine, *e.g.*, the antecedent conditions, the operation of the emotion releasers, the affective appraisal, *etc.* but allows the system behaviour to emerge from the dynamic interaction between these sub-systems.

A.3.5 The LIDA Cognitive Architecture

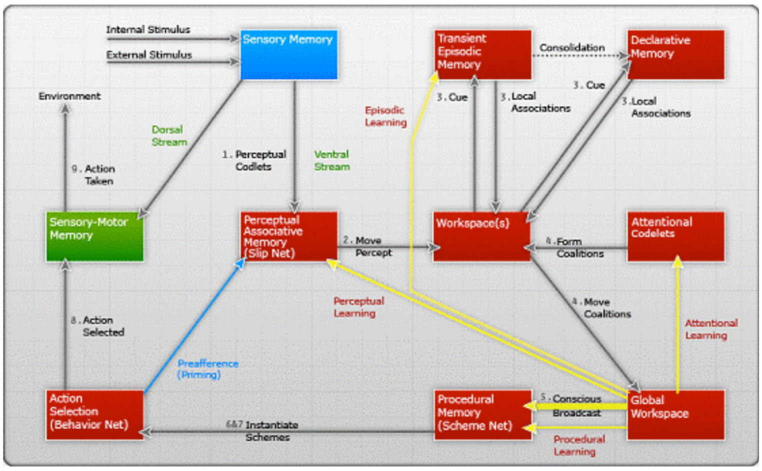


Fig. A.9 The LIDA cognitive cycle (from [17])

LIDA (Learning Intelligent Distribution Agent) is a hybrid cognitive architecture which combines features of both symbolic cognitivist and connectionist approaches [17, 103, 104, 106, 299]. It deploys several modules and processes to effect attention, action selection, and learning. The operation of LIDA is based around the concept of an atomic cognitive action-perception cycle. Each cycle comprises three phases: understanding, attending, and action selection (see Figure A.9).

The understanding phase involves sampling or sensing the environment and then it "makes sense" of its current situation by updating its representation of external sensory-derived features and internally-generated features of the agent's world comprising objects, categories, relations, events, and situations. These features are stored in a sensory memory module and a perceptual memory module, respectively.

The attending phase decides what aspect of the current situation model requires attention. This attentional process uses a mechanism adapted from Global Workspace Theory [15, 16] whereby each portion of the model competes for attention by being moved to a global workspace where a single portion of this model is selected. This portion is then broadcast back to the rest of the system. The contents of the broadcast yields a set of potential actions which are then subjected to a further competition in the subsequent action selection phase.

The initial representation of the current situation resulting from the understanding phase is stored in the perceptual memory. This is used by the workspace module to access transient and declarative episodic memories of events. Both episodic memories use these inputs to recall associatively past experiences. These recalled perceptual events are re-assembled with the current percept and past percepts in the global workspace to generate a new model. This completes the understanding phase.

Portions of this model then compete for attention in a Global Workspace Theory winner-take-all competition. The winning portion is then broadcast globally to all other modules in the architecture. This completes the attending phase of the cycle.

The primary recipient of the broadcast is a procedural memory module which stores templates of possible associated actions and outcomes, and a measure of the likelihood of the outcome occuring. Templates that match best with the broadcast data are then passed together with templates from previous cycles to the action selection mechanism which chooses a single action for execution. The algorithms for implementing the selected action are stored in a sensorimotor memory.

LIDA uses computational versions of feelings and emotions (*i.e.* feelings with cognitive content) to modulate the operation of the action selection, attention, and learning. A representation of particular feelings are incorporated into the perceptual memory and are associated with the object representation. These are propagated though the system as part of the understanding, attending, and actions selection processes.

Learning in LIDA takes two forms: *instructionalist* (whereby new experiences are incorporated into the LIDA representation) and *selectionist* (whereby existing experiences are reinforced in the LIDA representation). Learning impacts on the three primary memories in LIDA: the perceptual memory, the episodic memory, and the procedural memory.

LIDA has only been partially implemented and, in particular, the learning aspects have not yet been completed.

A.3.6 The CLARION Cognitive Architecture

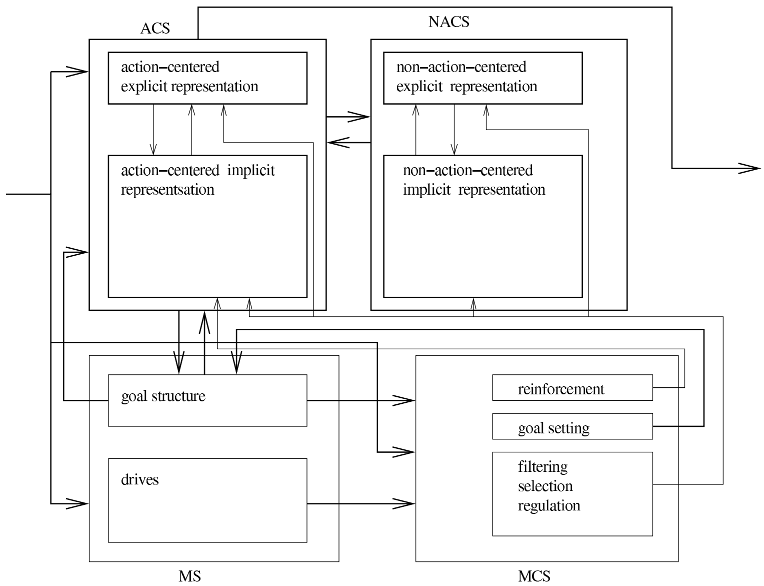


Fig. A.10 The CLARION hybrid cognitive architecture (from [364]). ACS stand for the action-centered subsystem, NACS for the non-action-centred subsystem, MS for the motivational subsystem, and MCS for the meta-cognitive subsystem. All four subsystems have two types of representation: implicit (connectionist) and explicit (symbolic).

CLARION [362, 363, 364] is an architypal hybrid cognitive architecture, deploying both connectionist and symbolic representations. It comprises four subsystems:

1. An action-centred subsystem (ACS);
2. A non-action-centred subsystem (NACS);
3. A motivational subsystem (MS);
4. A meta-cognitive subsystem (MCS).

All four subsystems have two levels of knowledge representation: an implicit connectionist bottom level and an explicit symbolic top level. The implicit and explicit levels interact and cooperate both in action selection and in learning.

The action-centred subsystem controls both external physical movements and internal “mental” operations. Given some observational state, i.e. a set of sensory features, the bottom level evaluates the desirability of all possible actions. The desirability is learned by reinforcement learning using the Q-Learning algorithm [392]. At the same time, the top level identifies possible actions from a rule network, again based on the observed sensory features. The bottom-level and top-level action are compared and the most appropriate top-level action is selected and executed. The outcome of the action is observed and the associated sensory features are used in the bottom-level reinforcement learning process. The top-level rules are also updated on the basis of the action outcome. The bottom level comprises several modules of small neural networks, each adapted to a distinct sensory modality or task. These modules can be developed by the system based on experience (*i.e. though ontogenesis*) or they can be specified *a priori* and hard-wired into the cognitive architecture (*i.e. as the system phylogeny*). The implicit bottom level and the explicit top level representations interact to effect bottom-up learning. This operates as follows. If an action selected by the bottom level is successful, then the system extracts an explicit rule that corresponds to the sensory features and the selected action, and adds the rule to its top level rule network. Subsequently, the system verifies the extracted rule and, depending on whether the outcome is successful or unsuccessful, the rule is either generalized (made more universal and applicable to other situations) or refined (made more specific and exclusive of the current situation), respectively. In this way, the CLARION cognitive architecture is able to effect autonomous generation of explicit conceptual structures by exploiting implicit knowledge acquired by trial-and-error learning. CLARION can also effect top-down learning by integrating externally-provided knowledge in the form of explicit rule-based conceptual structures and assimilating these into the bottom level implicit representation.

The non-action-centred subsystem maintains the system's general knowledge, again both in implicit connectionist form and explicit symbolic form. The implicit bottom level uses associative memory networks whereas the explict top level encodes knowledge as a network of nodes, each node corresponding to an entity-specific chunk comprising an entity identifier (*e.g.* *table*) and a vector of feature dimensions / feature value pairs (*e.g.* (*size*, *large*) ... (*colour*, *white*)). The feature values are represented by nodes in the bottom level associative memory. Chunks are linked associatively. Like the action-centred subsystem, both bottom-up and top-down learning can take place in the non-action-centred subsystem.

The motivational subsystem provides the drive and feedback signals that influence the system's perceptions and actions. It provides the action-centered subsystem with goals derived from low-level drives concering physiological needs (*e.g.* need to avoid boredom) and high-level drives (*e.g.* desire for imitation of other people) which can be either primary hard-wired or secondary derived drives.

The meta-cognitive subsystem monitors and governs the overall behaviour of the cognitive system to improve cognitive performance, *e.g.* by setting goals and by setting essential parameter values.

A.3.7 The PACO-PLUS Cognitive Architecture

PACO-PLUS [201] is three-level hybrid cognitive architecture for a six-degree-of-freedom robot manipulator. The architecture comprises a low-level sensorimotor robot-vision layer, a mid-level memory layer, and high-level symbolic planning layer. The system learns object-action associations by exploring its environment. These representations are used to plan and execute sequences of actions. Unexpected errors that occur during exploration or plan execution are used to improve future performance after taking corrective action at the appropriate level, *e.g.* withdrawing the end-effector at the sensorimotor level, re-inspection of the objects in the environment at the memory level, or plan reformulation at the planning level.

The sensorimotor level is responsible for low-level robot control, camera control, and the acquisition of visual and haptic perceptual data. Visual information from a high-resolution binocular stereo rig is encapsulated at this level in a number of representations, the richest being a 3D contours. This contour data is used to identify an appropriate grasping strategy for a two-finger gripper based on pre-defined associations between grasp configurations and parts of an object. Haptic data is captured from a torque sensor on the wrist of the gripper. In its present state of development, the PACO-PLUS architecture uses a limited repertoire of object and grasp configuration representations based primarily on 3-D eliptical contours.

The memory level provides a co-joint Object Action Complexes (OACs) representation. In essence, an OAC implmements a form of affordance [118] whereby the object and the actions that the object affords the robot in terms of its ability to manipulate it are represented as a single entity. These affordances are learned autonomously by the robot. The initial grasp affordances that are hardwired in the sensorimotor level are elaborated by active exploration of the object by poking, grasping, or re-orienting it in the robot gripper. This yields a full three-dimensional visual representation of the object shape. Knowledge of the motion of the robot's arm during this exploratory phase is used to simplify the object segmentation problem and to integrate the multiple views of the object into a single 3D representation. Symbolic labels are attached to objects once the temporal consistency of the sensed data is validated.

The planning level constructs actions plans to achieve pre-specified goals. The planner uses a high-level abstract symbolic model of the robot's environment based on an extension of the STRIPS language [95]. This model specifies the objects in the environment, their properties, and the actions that can be executed on those objects. Objects are represented simply by symbolic labels linked to the memory level OAC representations. Object and robot properties are specified by predicates and functions, such as $ingripper(x)$: the robot has grasped the object x in its gripper. Similarly, actions are represented in a high-level abstract manner as functions, such as $graspA - table(x)$ which corresponds to a grasp action directed at object x using grasp configuration A. It is the responsibility of the memory and sensorimotor levels to translate these symbolic action specifications into low-level motor control signals. The plans are constructed using PKS ("Planning with Knowledge and Sensing") [285, 286], a planner that can operate with incomplete information, using a generalization of STRIPS [95]. Plans can be straightforward sequences of actions or they can include conditional branching based on the outcome of sensing actions. In this way, the planning level incorporates a form of reasoning on possible outcome of actions. It executes a plan by feeding the action primitives to the lower levels. Feedback from the lower levels allow the planning level to update its model of the state of the environment. This feedback allows the architecture to replan in the event of unexpected outcomes or invoke a some remedial action such as acquiring higher resolution scene representations.

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A Roadmap for Cognitive Development in Humanoid Robots

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A Roadmap for Cognitive Development in Humanoid Robots

This book addresses the central role played by development in cognition. The focus is on applying our knowledge of development in natural cognitive systems, specifically human infants, to the problem of creating artificial cognitive systems in the guise of humanoid robots. The approach is founded on the three-fold premise that (a) cognition is the process by which an autonomous self-governing agent acts effectively in the world in which it is embedded, (b) the dual purpose of cognition is to increase the agent's repertoire of effective actions and its power to anticipate the need for future actions and their outcomes, and (c) development plays an essential role in the realization of these cognitive capabilities. Our goal in this book is to identify the key design principles for cognitive development. We do this by bringing together insights from four areas: enactive cognitive science, developmental psychology, neurophysiology, and computational modelling. This results in roadmap comprising a set of forty-three guidelines for the design of a cognitive architecture and its deployment in a humanoid robot. The book includes a case study based on the iCub, an open-systems humanoid robot which has been designed specifically as a common platform for research on embodied cognitive systems.

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