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Combining Learning, Regulatory, and Developmental Mechanisms for Evolving Intelligent Systems

Technical Report 31-031

The LEAD AI Project

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Version 1.1 Original Document 15/10/91

Abstract: This paper outlines a novel approach to the development of mechanisms intended to support the growth and development of systems that subsequently adapt and evolve. Recently developed learning, memory, and timing mechanisms will be incorporated into a new set of developmental mechanisms that embody the foundations of all types of adaptive behavior, so that these may then be used to literally grow (in software) new adaptive systems with a structural and behavioral complexity approaching that of biological organisms. A notable aspect of this approach is that it will not attempt to directly improve particular characteristics of the final structure of each generation of a system. Instead, it will tend to produce a generalised enhancement of final structure by refining the coordinated operation of developmental mechanisms while they are subject to environmental influences.

Acknowledgments: This work was supported by the Laboratory for Concurrent Computing Systems. The principal author would also like to thank John G. Wallace for his support and encouragement. Correspondence concerning this paper should be addressed to Brendan L. Rogers, Laboratory for Concurrent Computing Systems, Swinburne Institute of Technology, P. O. Box 218, Hawthorn, Victoria 3122, Australia.

The Learning, Evolution, Adaptation, and Development (LEAD) Artificial Intelligence (AI) Project.

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Technical Report 31-031
Version 1.0, October 1991

Abstract

This paper outlines a novel approach to the development of mechanisms intended to support the growth and development of systems that subsequently adapt and evolve. Recently developed learning, memory, and timing mechanisms will be incorporated into a new set of developmental mechanisms that embody the foundations of all types of adaptive behavior, so that these may then be used to literally grow (in software) new adaptive systems with a structural and behavioral complexity approaching that of biological organisms. A novel aspect of this approach is that it will not attempt to directly improve particular characteristics of the final structure of each generation of a system. Instead, it will tend to produce a generalised enhancement of final structure by refining the coordinated operation of developmental mechanisms while they are subject to environmental influences.

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Introduction

It is proposed to extend the new low-level associative learning, memory, and timing mechanisms recently developed by Rogers (1991) to also include the self-regulating and self-adapting processes which direct the growth and development of an individual (ontogeny), and the evolution of a species (phylogeny).

That some functional relationship exists between ontogeny and phylogeny is undeniable, though the precise nature and extent of this relationship has, since the time of Aristotle (384BC-322BC) (e.g., Aristotle, 1965), been the subject of considerable interest and debate, with particularly influential theories emerging from the late 19th century (Darwin, 1859; Haeckel, 1866; Lamarck, 1873). A neoDarwinian theory, in which inherited random variation and environmental selection is proposed to support phylogeny, is currently enjoying popular acceptance. However, an undercurrent of unease exists within the scientific community, with many doubting that this mechanism is able on its own to account for coordinated developmental changes, or the total degree of constructive phylogenic change that has occurred in the time that was available (e.g., Crawford & Marsh, 1989; Frazzetta, 1975; Ho & Saunders, 1979; Hoyle & Wickramasinghe, 1980; Rattray Taylor, 1983; Russell, 1945; Szent-Gyorgyi, 1977; Waddington, 1975; Whyte, 1965).

Darwin himself sought an additional directive process whereby environmental interaction could directly produce phylogenetic adaptation, repeatedly stating that natural selection worked cooperatively with the influence of environmental *conditions of existence* (Darwin, 1859). Darwin (1868, 1875) subsequently put forward his own *provisional theory of pangenesis*, in which he suggested that every cell in the body contained minute particles called *gemmules* that registered changes within the cell in response to new conditions and, by circulating in the blood stream to reach the gonads, passed these changes on to the offspring. Darwin was searching for a mechanism by which environmental forces could stimulate change, which was later acted on by environmental selection. (Ghiselin (1975) discusses the rational of pangenesis in some detail.)

However, the subsequent failure to find such gemmules, and the popular acceptance of random mutation and natural selection as a sufficiently powerful driving and directing force in its own right, led to the demise of pangenesis. Although Darwin failed to develop a convincing mechanism, he repeatedly emphasised the importance of some type of learning and memory process that responded to environmental conditions and subsequently altered development (Crawford & Marsh, 1989, pp. 19-22).

In the late 19th and early 20th centuries, other researchers advocated memory processes suggested to be based upon vibrations and wave motions, electric potentials, and chemical processes (Gould, 1977, pp. 96-97). Although some of the advocated processes appeared remotely possible at the time, all of them suffered a similar demise to pangenesis for similar reasons.

The rediscovery at the turn of this century of Mendel's work on inheritence, and then the discovery of the structure of DNA and its role in protein synthesis, provided a firm and apparently simple mechanistic basis for neoDarwinian selection, leading to its currently fortified position. However, as the apparent complexity of DNA function slowly unfolds, its operation as a hierarchical associative mechanism capable of environmentally directed adaptation is beginning to appear to be potentially feasible.

The proposed research approach involves the production of a functioning mechanism which supports the processes of ontogeny and phylogeny, in the form of a regulating and developing associative learning mechanism that parallels the possible (and at this time somewhat speculative) role of DNA and its associated regulatory systems within both the nucleus and the cytoplasm of eukaryotic cells. The general aim is to produce adaptive behavior which compares favorably with that of biological systems, and although similar types of basic mechanistic interaction are to be employed, no attempt will be made to precisely model the actual underlying biological mechanisms as these are highly intricate and largely unknown.

Previous Research

A new real time psychological model of associative conditioning, temporal generalisation and discrimination, and multistage memory, in the form of a functioning biologically-relevant artificial neural network element of unusually large mechanistic and behavioral complexity, has recently been developed by Rogers (1991).

The resulting system was referred to as the Associative Conditioning Element (ACE), and is a fully functioning system whose behavior has been simulated on a digital computer and compared with empirical results from animal experiments in order to assess its performance.

Computer simulation results have been generated to support the claims that ACE successfully produces a wider breadth of classical conditioning, memory, and timing behavior than any other existing functional neuronal model (Rogers, 1991), and more faithfully matches empirical results for each type of behavior that it produces than more restricted models (e.g., Sutton & Barto, 1981; Barto & Sutton, 1985; Desmond & Moore, 1988; Gluck & Thompson, 1987; Grossberg & Schmajuk, 1989; Kehoe, 1988; Klopf, 1987; Rescorla & Wagner, 1972).

ACE incorporates several newly developed subsystems, the most notable of which is the Neural Multiprocess Memory Model (NMMM). The NMMM integrates associative short-term, medium-term, and long-term memory, and a particularly powerful adaptive associability memory that automatically determines the most appropriate learning rate based upon past experience.

Although highly specific comparisons have been made using data from individual animal experiments, the behavior addressed by ACE is so fundamental, and of such general utility, that it is produced by creatures ranging from insects and molluscs to mammals, and will be directly applicable to the proposed research.

Proposed Research Approach

In biological systems, regulatory mechanisms that are near equilibrium underly all maintenance of form, while ontological development is supported by a succession of active regulatory mechanisms in nonequilibrium. In other words, the developmental progression from fertilised egg to adult, and the adaptive maintenance of adult form, are mechanistically defined in terms of regulatory processes. Organisms are dynamic systems that support life cycles, cell cycles, cell organelle cycles, and metabolic cycles of enzyme synthesis and degradation (Bonner, 1974).

In contrast, man-made systems are usually defined in terms of their static structural end-state as some form of plan, blueprint, or technical specification. When attempting to unravel the organisation and operation of biological systems this emphasis upon specification in terms of final structure and content is usually maintained, with the result that the ensuing immensity of detail and complexity becomes overwhelming. Biological systems would therefore be more appropriately veiwed in terms of their underlying regulatory mechanisms, though this is initially more difficult because developmental processes are less readily revealed by empirical analysis than the structural or behavioral interdependencies that exist at a given stage of development.

However, in man-made systems the opportunity exists to begin with the development of new regulatory mechanisms, and then to assess these in terms of the systems they produce, which have the potential to be as detailed and diverse as biological systems. A similar type of approach has recently been explored in the domain of "fractals", in which relatively simple developmental rules have been used to generate structures or processes which emulate the rich character of natural counterparts. When viewed at appropriate scales, particular trees, root systems, and primitive plants such as lichens, mosses, and sea weeds, are able to be closely modelled by fractals. Other natural formations or processes modelled by fractals with varying degrees of correspondence include cloud boundaries, mountain skylines, coastlines, forked lightning, electrodeposition, flow through porous media, and to a limited extent the growth of neurons and blood vessels (Avnir, 1989; Ball, 1986; Falconer, 1990;

Fleischmann, Tildesley, & Ball, 1989; Mandelbrot, 1982; Peitgen & Richter, 1986; Pietronero, 1989; Pietronero, & Tosatti, 1986; Shlesinger, Mandelbrot, & Rubin, 1984). However, while the general philosophy behind fractals is somewhat analogous to that underlying the proposed research, currently available fractal models are far too limited to be directly applied to this work.

The proposed approach will therefore invlove the creation of new developmental rules and regulatory mechanisms. These will be responsible for the development of dynamically evolving functioning systems that, via interaction with their environment, learn to improve both their behavior (during the lifetime of the system) and their structure (over successive generations). The proposed approach therefore represents a synthesis of developmental theories, regulatory mechanisms, and the more established field of associative learning in which the Laboratory for Concurrent Computing Systems is establishing a growing active involvement (i.e. the Previous Research outlined above).

It is proposed here that regulatory mechanisms and their relative rates and interdependencies be expressed as associative relationships, which are in turn subject to associative learning mechanisms. It is further proposed that associative learning would occur during the unfolding ontogenetic process, with each regulatory mechanism responding to feedback that is spatially and temporally contiguous to its deployment. Associatively learned adaptations in regulatory processes would then be passed onto the next generation (by a process somewhat analogous to reverse transcription), where they are subsequently expressed as changes in the relative rate, extent, or timing of regulatory processes actively involved in the development of the next generation. Even subtle developmental alterations in ontogeny are capable of producing dramatic changes in final form or function, and may well be capable of supporting most aspects of phylogeny (Gould, 1977). This learning process is intended to support the accommodation of changing environmental conditions into the structure of the system, and to provide an internal momentum of continuously refining developmental processes that produce new coordinated combinations of structural mechanisms.

Mechanisms developed within ACE other than those directly concerned with basic associative learning, and which were previously intended to account for behavioral phenomena only, will also be directly applied to developmental processes. For example, mechanisms within ACE that enable it to generalise and discriminate in the time domain will be employed to adaptively control the sequence and duration of these adaptive developmental processes.

Furthermore, the new adaptive associability mechanism developed within ACE will provide a highly specific means of selectively extending phylogeny in directions previously found to result in favorable coordination between internal developmental processes and external environmental influences. This is somewhat analogous to the concept that the mutation rates of genes within eukaryotic cells are not uniform, and that special control genes exist which selectively determine the mutation rates of the other genes (Layzer, 1980; Kimura, 1967; Cox, 1970). However, the proposed research approach suggests that random gene mutation may be supplemented, or even replaced, by an ordered associative learning mechanism; and that modification of the rate of this learning (i.e. changes in associability) may also be subject to another specific nonrandom mechanism. Since prototypes for both of these mechanisms have already been developed within ACE (Rogers, 1991), it is primarily only the application of these (formerly) behavoral mechanisms to ontogenetic and phylogentic processes that is speculative.

One unavoidable consequence of defining systems in terms of their developmental mechanisms instead of their final state, is that it becomes more difficult to independently specify fine details of the system's structure and content, particularly in regard to complex neural hardware. Even though the use of developmental mechanisms may lead to the formation of a very intricate and detailed system, the greatly condensed representational format has difficulty in accommodating large numbers of highly specific exceptions. In nature this deficiency appears to be supplemented by incorporating neural circuits (and corresponding behavior) of relatively limited initial specificity, which are preprogrammed to support more specific types of adaption as a result of environmental interaction, and subsequently to produce more specific and appropriate behavior.

The relationship between initial instinctive behavior, and more specific learned behavior acquired as a result of environmental experience gained during performance of this instinctive behavior, has been studied in creatues ranging from insects to humans in the field of ethology (Lorenz, 1981; Gould, 1982). It is intended to use a similar relationship between instinctive and learned behavior to supplement the limited specificity of developmental mechanisms in the proposed research.

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