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The Newsletter of the Autonomous Mental Development Technical Committee

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## Message from the Editor

Welcome to the first issue of the AMD TC Newsletter in 2007. I would like to thank IEEE CIS for funding this newsletter.

Featured in this issue is a dialog column guest-moderated by Pierre-Yves Oudeyer and Frédéric Kaplan and a kick-off statement by Minoru Asada: "Should robots develop as human infants do?" Researchers interested in this topic are welcome to submit a response (contact asada@jeap.org or shuqing.zeng@gm.com) by August 1, 2007. The length of each response must be between 300 and 500 words (including references) due to the page limitation of the Newsletter. Enjoy!

- Shuqing Zeng, Editor, IEEE CIS AMD Newsletter

## Committee News

- The Special Issue on Autonomous Mental Development in the IEEE Transactions on Evolutionary Computation co-edited by guest editors James McClelland, Psychology Department of Stanford University; Kim Plunkett, Department of Experimental Psychology of Oxford University; and Juyang Weng, Department of Computer Science and Engineering of Michigan State University, has appeared in vol. 11, no. 2, March 2007. A total of 8 papers have been published for the AMD Special Issue, including two survey articles, plus an editorial. The URL: http://ieeexplore.ieee.org/xpl/tocresult.jsp?isYear=2007&isnumber=4141050&Submit32=Go+To+Issue

- The Special Issue on Autonomous Mental Development in the International Journal of Humanoid Robotics, co-edited by guest editors Juyang Weng, Michigan State University; Brian Scassellati, Yale University; and Zhengyou Zhang, Microsoft Research, has completed the reviews and a total of 9 papers have been accepted. The issue is scheduled to appear in June 2007.

- IEEE ICDL 2007 once again attracted a large number of submissions from neurophysiologists, developmental psychologists, computer scientists and roboticists. The review process is under way, with decisions expected in the middle of May. The invited speakers, Professors Dautenhahn, Iriki, Johnson, and Shultz have confirmed their participation. Further updates, including the program will posted at http://www.icdl07.org

## Dialog Column

### Dialog: How can we assess open-ended development?

Pierre-Yves Oudeyer[1] and Frédéric Kaplan[2]
[1]Sony CSL Paris, [2]EPFL - CRAFT

One of the main goals of developmental robotics is to build machines that are able to learn new skills and to increase autonomously the complexity of their behaviour continuously during their whole life time. This has sometimes been termed autonomous mental development

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(Weng et al., 2001), ongoing emergence (Prince et al., 2003) or open-ended development (Oudeyer et al., 2007), and is related to the notion of task-independence: developmental robots shall not be programmed to achieve a prespecified practical task, but rather should permanently invent their own tasks. Motivation systems, and in particular intrinsic motivation systems, have been explored by researchers as a key dimension in this quest (Oudeyer et al., in press).

**Benchmarking**? But how can we assess scientifically these systems? How can we compare different systems? It seems that the development of an individual is the outcome of the interaction dynamics between its physical body, the properties of its environment, its cognitive and motivational biases and its personal history. Does this prevent any valid forms of benchmarking as each laboratory conducts experiments using differents robots, or on the contrary does this open interesting opportunities which are not available in human psychology, in which the body and environments cannot be changed for experimental purpose?

**Testing with new tasks?** Likewise, can we characterize the quality of a given intrinsic motivation system and the development that it allows? There are two potential ways of doing that. The first one is inspired from the field of human psychometrics (Michell, 1999), which has developped methods for tests and measurements for properties such as "general intelligence". The idea would be to let the robot develop autonomously for a while, and at some point to evaluate its skills on a number of specific tasks. But how do we choose these tasks? Wouldn't it always be possible to pick up new tasks on which it is always good and vice versa? How many tasks shall we choose? I sn't this kind of evaluation arbitrary and contradictory with the philosophy of task-independent development? Do we encounter the same kind of problems than for example the Stanford-Binet IQ test, and can we benefit from the experience of psychometrics?

**Complexity measures vs qualitative description.** The second possibility would be to try to characterize development by the properties of its trajectory rather than by its end point. This would amount to evaluate how much the complexity of its behaviour has increased. But what measure of complexity shall we use? There are many such measures in the literature, which are often not mutually consistent. Moreover, complexity has been argued to be a property of the relation between the observer and the observee, rather than an inherent property of the observee. If this is so, shall we not borrow instead from developmetal psychology methods of observation and verbal description ? We could study the development of a robot in terms of stages, and admit right from the beginning that the definition of a stage might be subjective. In other words, do we have to choose between subjectivity and arbitrariness?

**What duration for experiments?** A last issue about the evaluation of intrinsic motivation systems and open-ended development is the length of robotic experiments. As stated in the beginning, the goal is to allow the increase of skills on an extended period of time. But, to our knowledge, all existing experiments in the field have a maximum duration of one day. This is clearly not an extended period of time. Does this bias the evaluation of our systems? How crucial are longer experiments? How to achieve them?

**Reference**

Weng, J., McClelland J., Pentland A., Sporns O., Stockman I., Sur M., and Thelen E. (2001) *Autonomous mental development by robots and animals*, Science, vol. 291, pp. 599-600.

Prince, C. and Helder, N. and Hollich, G. (2005) Ongoing Emergence: *A Core Concept in Epigenetic Robotics*. In Berthouze, Luc and Kaplan, Frédéric and Kozima, Hideki and Yano, Hiroyuki and Konczak, Jürgen and Metta, Giorgio and Nadel, Jacqueline and Sandini, Giulio and Stojanov, Georgi and Balkenius, Christian, Eds.

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Proceedings Fifth International Workshop on Epigenetic Robotics: Modeling Cognitive Development in Robotic Systems 123, pages pp. 63-70, Nara, Japan.
Oudeyer, P.-Y., Kaplan, F., and Hafner, V. (2007). *Intrinsic motivation systems for autonomous mental development*. IEEE Transactions on Evolutionary Computation, 11(2), DOI: 10.1109/TEVC.2006.890271.
Michell, J. (1999). *Measurement in Psychology*. Cambridge: Cambridge University Press.

## Reply to Dialog: "How can we assess open-ended development?"


### Open Ended Robotics Contest - aka the Dilbert Grand Challenge

Dan Burfoot[1] and Max Lungarella[2]
[1]Dept. of Mechano-Informatics, [2]JST ERATO Asada Synergistic Intelligence Project, The University of Tokyo, Japan

In answering the question of how to evaluate developmental robotic systems, we can make an analogy to the unique challenge faced by software developers. When designing software the immediate requirements are often easily accomplished. The problem is that new requirements may appear in the future. Thus a good design should allow the system to be easily adapted to meet future requirements with a minimum of additional effort. We can see that good software developers share intellectual ground with developmental roboticists. The emphasis in both fields is on simplicity, adaptivity, and modularity, rather than on narrow functionality. Indeed, one could say that the paradigm of the developmental robotics is the adaptive "software development paradigm" pushed to the ultimate limit.

To illustrate this limit, imagine a scene from a Dilbert cartoon. The deranged project managers tell the hapless software engineers to solve the following problem: "One year from now we will need a high quality software system," they say, "but we don't currently know any of the requirements." Although this seems like a ridiculous demand, it is in fact a deep intellectual challenge, and an almost exact parallel to the goals of developmental robotics. Researchers in the field have worked on building intelligent systems that can learn on their own, or through interaction with humans or other robots. Ideally, such systems should achieve goals that are unspecified at the time of their creation (much like in developing children). Unfortunately, we are not at the level of true general-purpose robots yet, so we are often forced to evaluate and compare systems on the basis of intrinsically meaningless tasks. To borrow from the language of statistical learning, the robots built for these tasks tend to overfit the data.

To rectify this dilemma, we propose the Dilbert Grand Challenge, a robotics competition like RoboCup or the DARPA Grand Challenge, where the tasks are not specified in advance but defined only a few weeks before the challenge takes place. The tasks should not be exceptionally difficult but should span a diverse range of activities, e.g. hitting a baseball with a bat, searching a building for a red beach ball, or stacking up some blocks. We might not be overly impressed by a robot that could perform any of these tasks, if it was designed for them. However, we should be impressed if a robot can perform these tasks if it was not specifically designed to do so. Again borrowing from the terminology of statistical learning, we would say the robot can generalize from the training (designer-defined) tasks to the test (referee-defined) tasks.

The Dilbert Grand Challenge will be a way of evaluating and comparing the learning or generalization ability of robotic systems - robots that perform well on the Challenge are much more likely to be able to adapt to other tasks, some of which might have practical value. The contest might also provide grounds for defining, exploring and

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hopefully validating design principles for developmental systems, a crucial step en route to the formulation of theory of development in natural and artificial systems.

## Reply to Dialog: "How can we assess open-ended development?"


### Measuring skill stability and integration in developing robots

Christopher G. Prince and Nathan A. Helder
Department of Computer Science,
University of Minnesota Duluth, Duluth, MN, USA

Human children typically develop. Robots do not. We are caught in a situation where we are attempting to create robotic software, hardware, and environmental conditions to produce psychological development in robots and also simultaneously working on methods to assess that development. In this dialog, we consider the latter.

Dynamical systems theory suggests that development in human children proceeds in alternating periods of unstable and then stable behavior, and that the unstable behavior enables the child to seek new self-organizing patterns of behavior (Schöner & Dineva, 2007; Thelen & Smith, 1998). Additionally, in many cases, the new stable behavior is presumably different and/or more complex in some ways than the earlier behaviors. This suggests that means for measuring robotic psychological development needs to consider at least two issues:

1) measurement of behavioral stability versus instability, and
2) measurement of behavioral complexity.

The idea of stability versus instability has intuitive appeal. It seems obvious that in order for a given psychological development to in fact constitute a development it must be stable or lasting over a period of time. Presumably also must be reliably produced in some prescribed circumstances. If a child couldn't walk more than a few steps or couldn't reliably name objects, their skill with walking or naming wouldn't be particularly stable and hence we really wouldn't think of them as having developed those skills. Furthermore, there are quantitative means by which dynamic stability can be assessed (e.g., Buzzi & Ulrich, 2004; Nehmzow, 2003). Quantitative measures of the periods of stability and instability in the behavior of developmental robots would take us closer to our goals of demonstrating development in robots, perhaps enabling segmentation of the behavior of a developing robot, over time, to determine which behaviors occur before and after a particular development.

Behavioral complexity also has intuitive appeal. It seems obvious that in order to achieve walking or object naming behaviors, an infant must first develop (and stabilize) certain other precursor skills to be used as functional units (Berthouze & Goldfield, to appear). In considering behavioral complexity, we are focusing on qualitative changes (as opposed to quantitative changes, e.g., Adolph, et al., 2003) such as the onset of walking or naming. In these cases, it seems that a new skill emerges that draws from earlier skills. In our view, it is this integration process that characterizes qualitative developmental changes and is what needs improved assessment in robotic systems (Prince, et al., 2005). Furthermore, while the issue of assessing individual developments (or emergent behaviors, e.g., Deguet, et al., 2006) is important, if a robotic system is exhibiting a series of developments (i.e., open-ended development or ongoing emergence), then as long as the later skills build upon the earlier skills, a net increase in system adaptation should have occurred.

**Reference**

Adolph, K. E., Vereijken, B., & Shrout, P. E. (2003). *What changes in walking and why?* Child Development, 74, 475-497.

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Berthouze, L. & Goldfield, E. C. (to appear). *Assembly, tuning, and transfer of action systems in infants and robots.* Special issue of journal Infant and Child Development.
Buzzi, U. H. & Ulrich, B. D. (2004). *Dynamic stability of gait cycles as a function of speed and system constraints.* Motor Control, 8, 241-254.
Deguet, J., Demazeau, Y., & Magnin, L. (2006). *Elements about the emergence issue: A survey of emergence definitions*. Complexus, 3, 24-31.
Nehmzow, U. (2003). *Quantitative analysis of robot-environment interaction-towards "scientific mobile robotics."* Robotics and Autonomous Systems, 44, 55-68.
Prince, C. G., Helder, N. A., & Hollich, G. J. (2005). *Ongoing emergence: A core concept in epigenetic robotics*. Proceedings of The Fifth International Workshop on Epigenetic Robotics: Modeling Cognitive Development in Robotic Systems, Nara, Japan, July 22-24, 2005 (pp. 63-70).

## Reply to Dialog: "How can we assess open-ended development?"

### Once is not enough

Paul Fitzpatrick, LIRA Lab, University of Genova, Italy

Oudeyer and Kaplan enumerate some of the factors involved in development: 1) The robot's physical body. 2) The properties of its environment. 3) Its cognitive and motivational biases. 4) Its personal history.

These factors should affect development in relevant and appropriate ways. To some extent, we can test for this. We can measure to what degree the following desirable properties hold as we vary a factor, such as the robot's environment: 1) Plasticity: is behavior affected by variation we consider relevant? 2) Robustness: is behavior unaffected by variation we consider irrelevant? 3) Adaptivity: is the effect of variation on behavior appropriate? "Relevance" and "appropriateness" are task-dependent notions. Testing for them needs to be done in the context of a task or set of tasks. We should also measure how task-general a system is: Generality: for what range of tasks is an acceptable level of plasticity, robustness, and adaptivity demonstrated? This is the robot's "niche".

We are in fact in a better position to make such tests than experimental psychologists are, since we can make snapshots of our subject's "brains", and then run a battery of experiments on them starting repeatedly from that snapshot. This lets us test the effect of variation in a very systematic and controlled way. For example, we could evaluate object familiarization this way, and tease out the sensitivity of a robot to object features versus interference from extraneous factors such as lighting conditions. How much variation should we test with? Enough to justify (or refute) the hypothesis that the subject is capable of development within a given niche. The outcome of a single short session with a robot is of limited value. Since developmental systems are complex, there is a high burden of proof to be met before they become the simplest hypothesis available to explain a set of observations. We need to systematically evaluate plasticity, robustness, adaptivity, and generality in the face of variation, in order to experimentally distinguish truly developmental systems from more parsimonious explanations.

Unlike infant research, we can have some direct understanding of what is going on inside a robot's "head", and don't necessarily need indirect testing paradigms such as looking-time experiments. But relying on this carries a danger of introducing interpretation bias. Ideally, tests on robots would be comparable to tests on infants or animals, if only to simplify interdisciplinary collaboration and facilitate cross-fertilization of ideas. In the RobotCub project [1], a consortium of roboticists, neuroscientists, and experimental psychologists are working together to develop an open humanoid platform for cognition research. Our experimental psychologists are creating

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test scenarios based on what is known of early infant development, to evaluate the looking and reaching performance of our iCub robot. Whether these scenarios will generalize beyond our platform remains to be seen, but this or similar efforts could be useful building-blocks for assessing development.

[1] Sandini, G., Metta, G., and Vernon, D. 2004. "RobotCub: An Open Framework for Research in Embodied Cognition", Proceedings of IEEE-RAS/RSJ International Conference on Humanoid Robots (Humanoids 2004), pp. 13-32.

## Reply to Dialog: "How can we assess open-ended development?"

### Three Broad Themes for Testing Machines

Charlie Kemp, Health Systems Institute, The Wallace H. Coulter Department of Biomedical Engineering at Georgia Tech and Emory University

How can we assess open-ended development? Pierre-Yves Oudeyer and Frederic Kaplan have asked a fascinating and important question. For the field of autonomous mental development (AMD) to succeed, objective standards for assessing performance will be required.

**Bio Benchmarking.** Arguably, the only examples we have of successful AMD are found in biology. As such, a plausible approach to assessing open-ended development is to benchmark artificial systems against the performance of model organisms, such as humans. Human psychometrics fit into this framework, but more generally, protocols found within developmental psychology, developmental biology, and related sciences can serve as standards for evaluation. Researchers have made progress along these lines and conferences such as ICDL support this approach.

With the strictest interpretation of this approach, researchers would build artificial infants and assess these artificial infants using experiments designed for human infants. Ultimately the artificial infants will differ from human infants, so researchers must select which aspects of human infants to emulate. The developmental robotics community places a premium on full systems that operate within the real world. This has the advantage of enabling the artificial systems to develop within the same world as the biological systems. Unfortunately, it also implies that the artificial systems must operate in real time with a real body, which is a bottleneck for conducting experiments. It is currently impractical for researchers to wait a year while a robot develops, and building hundreds of robots in order to conduct experiments in parallel offers little solace. Simulation in conjunction with real robots seems inevitable.

**Abstract AMD.** As an alternative approach to assessing AMD, we might seek to develop a new science that abstracts away from the details of biological systems and applies to domains beyond common ecological niches. Even in the best cases, robotics researchers must pick and choose which aspects of biological systems they will emulate, and developmental roboticists seem destined to run more trials in simulation than they do in the real world. Given this seemingly inescapable abstraction in both the embodied system and the world in which it operates, perhaps we should more directly pursue abstraction. What characteristics must a domain have in order to support non-trivial open-ended development? Could true AMD exist in flatland? Can human societies be modeled as systems that exhibit AMD? What characteristics constitute AMD? Can common characteristics such as stages of development, schema, hierarchies of behavior, intrinsic motivation, curiosity, intention, self-recognition, and trajectories of increasing complexity be meaningfully formalized as part of a unified theory? If so, this theory would be likely to lead to objective ways of assessing open-ended development.

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**Developmental Robots for Better Living.** At the other extreme of evaluation, we might look for practical applications with which to evaluate open-ended development. If a robot exhibiting open-ended development could measurably enhance our lives, it would in some ways be the most satisfying assessment of all.

## Reply to Dialog: "How can we assess open-ended development?"


### What is it like to be a developmental robot?

Doug Blank, Jim Marshall, and Lisa Meeden

Imagine that you have set out to create an autonomous, task-independent, open-ended developmental robotics system. Perhaps your robot is designed to learn about its world by paying attention to novel or surprising events, which differ somehow from what it expects to see. By focusing on the discrepancies between its erroneous expectations and what really happens, the robot begins to learn to improve its predictions. However, imagine also that as the robot learns to better anticipate its immediate environment, it is also designed to lose interest in it, become "bored", and seek out novel situations. Suppose that you had succeeded in your goal of creating such a system; would you know it? What would you measure? How would you know that the system was not simply failing to learn to predict?

We doubt that it is possible to know for sure whether one has succeeded, because there may be nothing meaningful to measure. Of course, we don't think we have succeeded yet (although we have built a proof-of-concept of the above ideas [1]). But the point is that we do not believe that there could be a measure of success; therefore, you won't even know when you are on the right track. The problem is that a truly autonomous developmental system, having grown up on its own, free from human perceptual and physiological constraints, would be completely alien to us. Its behavior need not conform to our notions of intelligence.

This limitation could not be overcome through detailed study of the robot's internal workings. We might understand everything about it at the microscopic level, but still not understand its mental structures, its motivations, or its general level of intelligence. In essence, its "self" would only make sense to itself, from within---it would not be understandable from the outside. One might attempt to use some type of information-theoretic metric to objectively measure the complexity of the system's behavior or internal structures. However, without a subjective understanding of the system's inner self-perspective, it would be impossible to differentiate meaningful information content from random noise.

Does this place developmental robotics outside the realm of science? We don't think so. On the contrary, we believe that this dilemma highlights and elucidates problems that have existed for millennia in defining and measuring intelligence. Allowing development to occur in a completely unconstrained way may lead to systems that we can't relate to. Sure, this might be a fascinating example of an alien intelligence, very interesting in its own right, but one that is of no use to us. Instead, we may need to impose some boundaries and limitations on the developmental process or the environment, in order to ensure that (adapting Nagel's phrase [2]), our developmental systems become something it is like something human to be. If we do that, then it would be appropriate to apply the same kinds of intelligence metrics that we apply to ourselves.

The question then becomes: can we force an autonomous, task-independent, open-ended developmental robotics system down a particular anthropomorphic path? Such a research agenda may, at least, be measurable. However,

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such constraints may also squelch the very power of open-ended development.

**Reference**
[1] Marshall, J., Blank, D., and Meeden, L. "An emergent framework for self-motivation in developmental robotics," International Conference on Development and Learning, 2004.
[2] Nagel, T., "What is it like to be a bat?" The Philosophical Review, 83:435-50, 1974.

## Synthesis of the responses

### From proximal to distal assessment methods in developmental robotics: routes and prospects

Pierre-Yves Oudeyer and Frédéric Kaplan

Burfoot and Lungarella explain that one of the desired features of a developmental robot is to be able to adapt to and achieve new tasks which were unknown by its designers. Then they propose to organize the Dilbert Grand Challenge as a way to benchmark and compare developmental robots. A few weeks before the challenge, a battery of tasks to be solved by the same robot is defined by the referees. Burfoot and Lungarella propose that the ability to adapt rapidly a robot to all these tasks at the same time will be a measure of their open-endedness. This is for sure an interesting evaluation strategy to explore, but we think it also raises a number of questions. First of all, wouldn't it be even more interesting to define the new tasks to be solved only the day of the challenge and preventing all manual engineer intervention? Indeed, it seems to us that another fundamental feature of a developmental robot is that it should be autonomous and so shall not need any manual tuning when faced to new problems. Second, how will the tasks be chosen? Developmental trajectories depend crucially on morphological and cognitive biases, and it is very probable that different robots become both very skillful in very different domains, and it might be difficult to prepare a set of tasks that will take this into account.

Prince and Helder describe a different route to open-ended development assessment. As we suggested in our questions, they propose to focalize the study on the properties of the developmental trajectory rather than on the study of the capacities of the robots at the end of experiments. In particular, they identify two crucial properties that characterize human infant development and shall be used to evaluate developmental robots: 1) the sequencing and alternation of periods of stability and instability in behavior (which correspond to developmental stages and transitions); 2) the increase of behavioural complexity as new stages arise. Nevertheless, it should be noted that the measurement of these properties is far from trivial and still requires a lot of research.

Kemp goes in the same direction, arguing that the classic methods of study of existing developmental systems, i.e. biological creatures and humans in particular, should probably be the reference for the study of developmental robots. This includes in particular experimental protocols found in developmental psychology and developmental biology. Practically, a way to do this would be to assess developing robots using experiments designed for human infants. But Kemp points out that a big obstacle to resolve is time: modeling human infant development and using corresponding experimental practices will necessarily lead to month-long or even year-long experiments. In this case, the possibility to replicate experiments and statistical significance is a problem.

Resonating to this, Fitzpatrick insists that experiments should be systematic and replicated many times if one wants to state general properties of a given developmental system. Moreover, he argues that true understanding of what is going on involves the detailed study of the particular role of morphology, environmental constraints, cognitive biases and personal history on each of the following dimensions of development: plasticity, robustness, adaptivity

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and generality. Like Kemp, he proposes to use experimental setups designed in collaboration with infant development specialists. But we would agree with Kemp that because of the inherent time constraint of using real robots, there is probably an inevitable and crucial role to be played by simulation (in spite of the relevant criticisms that roboticists can have against simulations).

Blank, Marshall and Meeden present a potential theoretical obstacle to assessing developing robots. Indeed, having very different morphological and cognitive constraints than humans, it would be possible that robots develop complex and organized skills so different from human skills that we would not be able to detect structure or analyze them, even looking into the details of their artificial neural architectures. Basically, their intelligence could potentially not relate at all to ours. If one wants to use the tools that psychology, and science in general, has built to measure human intelligence and development, then the big research challenge becomes to try to introduce human-inspired constraints in the robot so that if would follow an anthropomorphic developmental path.

All these approaches to the assessment of open-ended development in robot are as a matter of fact "proximal". They debate about methods to measure how well a robot is able to learn autonomously and continuously new skills of increasing complexity. But if we take a step back and consider the "distal" goals that researchers have when they try to build developmental robots, we might come to different kinds of assessment. For example, as Kemp notes, one of the objectives of developmental robotics is to be able to build robots that can become well integrated into the social human world, and for example establish affective relationships with humans. Wouldn't it be relevant to assess developmental robots in those terms? Another orthogonal objective of developmental robotics is to contribute, through the building of machines and models, to a better understanding of human development. Thus, it could be interesting to assess how much influence a given artificial developmental system (or class of systems) has had in debates and theories in developmental psychology. Of course, this assessment would take longer, but we believe it would be of high relevance.

### Call For Responses

#### Should robots develop as human infants do?

Minoru Asada, JST ERATO Asada Synergistic Intelligence Project (www.jeap.org)
Graduate School of Engineering, Osaka University, asada@jeap.org

The question is intended not including physical development but focusing on mental development although there could be a tight connection between them. Most people may answer "NO" because of so much difference between robots and human infants in many aspects. But, actually, to what extent do we understand the human infant developmental process? Paterson et al. [1] says "Recent advances in cognitive neuroscience have allowed us to begin investigating the development of both structure and function in the infant brain. However, despite the rapid evolution of technology, surprisingly few studies have examined the intersection between brain and behaviour over the first years of life."

"Cognitive Developmental Robotics" (hereafter, CDR) [2] aims at providing new understanding of human development by building cognitive developmental robots. CDR consists of the design of self-developing structures inside the robot's brain, and the environmental design: how to set up the environment so that the robots embedded therein can gradually adapt themselves to more complex tasks in more dynamic situations. Therefore, the development of perception, behavior, motivation and their relationships are important issues in CDR (see [3] for more recent one).

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The recent review of the human infant development of structure and function by Paterson et al. [1] reveals the followings:

1) The state of the infant brain, both in terms of structure and function, cannot and should not be derived from the adult brain. Areas involved in the development of a function are not the same as those required for its maintenance.
2) In face processing subcortical areas are recruited early in development but later a wider network is involved.
3) The developmental progression of joint attention, from responding to initiating is paralleled by the shift in the localisation of attentional mechanisms from the posterior to the anterior of the brain. As control of attention moves to more frontal areas, the infant is able to begin to modulate their own attention as well as engaging the attention of others more effectively and thus becomes a more effective social partner.

As long as we concentrate on the development of a single cognitive function assuming that other functions have already matured, we do not think that the change of the functions in physical modules is needed as the learning proceeds. However, if we challenge to simultaneously develop multiple cognitive functions of robots that actually happen in the human infant brain, we may have different aspects of the development: the development of one cognitive function may trigger the development of the other or the development of all functions affect each other. Since the brain areas are limited (the resource bounded condition), sharing, change or shift of cognitive functions among physical areas can be considered for their efficient use during the developmental process. Rather, it might be necessary for mutual development. Therefore, we may need a more structure in CDR so that these processes can be autonomous if we consider the development of multiple cognitive functions together as human infants do.

**Reference**

[1] Sarah J. Paterson, Sabine Heim, Jennifer Thomas Friedman, Naseem Choudhury, and April A. Benasich. Development of structure and function in the infant brain: Implications for cognition, language and social behaviour, Neuroscience and Biobehavioral Reviews 30 (2006) 1087.1105
[2] Minoru Asada, Karl F. MacDorman, Hiroshi Ishiguro, and Yasuo Kuniyoshi. Cognitive developmental robotics as a new paradigm for the design of humanoid robots. Robotics and Autonomous System, 37:185-193, 2001.
[3] Minoru Asada, Koh Hosoda, Yasuo Kunioshi, Hiroshi Ishiguro, Toshio Inui, and Ken Nishimura. Synergistic intelligence: Approach to human intelligence through understanding and design of cognitive development. In The 5th International Conference on Development and Learning (ICDL'06), 2006.

# Glossary

**Genomic equivalence:** The zygote has the ability to give rise to every type of cell in the adult body. This property of a cell is called totipotent. Stem cells are primal cells that retain the ability to renew themselves through cell division (mitosis) and can differentiate into a wide variety of specialized cell types. Stem cells are capable of asymmetric division, meaning that its two daughter cells are different. For example, one is the new stem cell, and the other is a transit-amplifying cell. However, with differentiation, there is generally no irreversible change in the genome within each cell. During the process of mitosis (cell division) that takes place in the nucleus of a dividing cell, the entire set of DNA is replicated so that each daughter cell has the entire set of DNA, with only a few exceptions (e.g., adult blood cells, which lose the nucleus). This fundamental principle of developmental biology is known as genomic equivalence. In other words, no genetic information is lost from the nuclei of cells as they pass through the early stages of embryonic development. This principle has some deep computational implications to a biologically plausible developmental program. *Provided by Juyang Weng*.