Note from the Editor

Mark A. Bedau

There is a misimpression in some quarters that artificial life concerns just building and studying computational systems. This is certainly one of artificial life's central aims, perhaps even the one that has occupied the most people and generated the most attention. And contemporary artificial life was born because of the new role that computer experiments play today in the study of complex systems, alongside the traditional twin partners of theory and experiment. But computational investigations certainly do not exhaust artificial life. This should be clear from reading the "Instructions to Authors" printed inside the back cover of each issue, but it is worth elaborating a little.

If we let *soft* artificial life refer to computer simulations or other purely digital constructions that exhibit lifelike behavior, then we should also recognize two other activities: *hard* artificial life, which produces hardware implementations of lifelike systems, and *wet* artificial life, which involves the creation of lifelike systems from biochemical substances in the laboratory. These activities are often interconnected, of course, as when computer simulations are used to guide and instruct hardware efforts or wet experiments in the laboratory. But soft, hard, and wet artificial life are united at a deeper and more important level. They all focus on the essential rather than the contingent features of living systems, and they all employ the constructive methodology of studying life by synthesizing lifelike processes in artificial systems. These synthetic methodologies help artificial life focus on essential rather than contingent properties of living systems, because they provide wide scope for exploring the full range of possible life forms.

Although this journal publishes research in all three branches of artificial life (for some recent examples, see [7, 8, 16]), wet artificial life has been in the minority. This essentially reflects simply the relatively small number of submissions in wet artificial life, and this in turn is almost certainly the result in part of the relatively long lead time of wet artificial life experimentation. Nevertheless, I strongly suspect that wet artificial life will be the source of especially exciting scientific innovations in the next five years. If so, the center of gravity in artificial life will inevitably shift toward the experimental biochemical pole, and the coverage of this journal will shift accordingly. With this in mind, I chose the cover of this volume to depict an experimental result in wet artificial life (for more details, see [5]), and I want here to bring the readers of this journal up to date on some current work in wet artificial life (with a bias toward what I know best).

The holy grail of wet artificial life is to create artificial cells out of biochemicals [15]. Such artificial cells would be microscopic, autonomously self-organizing and self-replicating entities built from simple organic and inorganic substances. Although artificial, for all intents and purposes they would be alive, for they would spontaneously organize and repair themselves, grow and reproduce, and ultimately evolve and adapt in an open-ended fashion. If one could make artificial cells from scratch, especially using materials or methods that are not employed by natural forms of life, one would have dramatic proof that one grasps the essential molecular foundations of living systems.

Nobody has yet created an artificial cell, but research aimed at this goal is actively under way. Two main approaches are being pursued. The human genome pioneer J. Craig Venter and the Nobel Prize winner Hamilton Smith recently publicized their intention to create a certain kind of artificial cell, with support from the US Department of Energy [4]. Venter and Smith are using a top-down strategy that starts by simplifying the genome of the simplest existing cell with the smallest genome: *Mycoplasma genitalium* [3, 6]. Once that is accomplished, they plan to remove the genetic material from an existing *Mycoplasma* bacterium, replace it with a man-made minimal genome, and then coax the resulting entity to express its synthetic DNA. This top-down approach has the virtue that it can simply borrow the biological wisdom embodied in *Mycoplasma* biochemistry. It has the corresponding disadvantage that its insights will be limited by those same evolutionary contingencies.

The other approach is bottom-up. It starts with nonliving materials and builds physiochemical systems with more and more lifelike properties. Szostak, Bartell, and Luisi [17] and Pohoril and Deamer [14] have each presented bottom-up strategies that are strongly inspired by the lipid bilayer membranes and RNA chemistry found in existing cells. Lipid vesicles have been shown to grow and reproduce in the laboratory [18]. The main challenge of this bottom-up strategy is that there is no known chemical path for the self-sustenance and reproduction of RNA that is sufficiently complex to encode the minimal molecular functions needed by an artificial cell. Rasmussen et al. [16] have proposed a simpler bottom-up approach in which PNA chemistry [11] replaces RNA chemistry and lipid micelles replace vesicles. Rasmussen's artificial cell in essence would be a lipid micelle into which metabolic and genetic molecules stick, rather than a watery broth of such molecules enclosed by a lipid bilayer membrane. This nicely illustrates how wet artificial life might reshape the boundaries of how we conceive of life. An even more dramatic reconception of possible artificial cells might come from a new European research project on *programmable artificial cell evolution* (PACE). Funded by the European Commission in the IST-FET section of the 6th Framework Program with a total volume of €8,500,000, this project aims to create the foundation for a new generation of embedded information technology using programmable, self-assembling artificial cells [12]. These evolvable complex information systems will be programmed using artificial selection of embodied chemical systems. Any artificial cells that arise from this process would be unconstrained by the historical contingencies of existing life forms.

One final brief note on the essential properties of living systems. The articles on embodied robotics in the present special double issue discuss themes including intelligence, cognition, agency, and mental representation. One might doubt whether these issues have any important connection with life, but a broader view suggests keeping an open mind. A long-standing puzzle about life is whether it is intrinsically connected with the mind [1]. Is it just an accident that all life forms have various kinds of what one could call "mental" capacities (sensitivity to the environment, abilities to communicate, etc.), and that the relative sophistication of these mental capacities seems to correspond to and explain the relative sophistication of those forms of life? Aristotle saw a deep unity between life and mind, and many in artificial life today are sympathetic [2, 9, 10, 13]. (See also vol. 10, no. 3 of this journal.) The work in the present volume can in time contribute to the ultimate resolution of the puzzle about the essential connection between life and mind.

References

1. Bedau, M. A. (1998). Four puzzles about life. *Artificial Life*, *4*, 125–140.

2. Beer, R. D. (1990). *Intelligence as adaptive behavior: An experiment in computational neuroethology.* Boston: Academic Press.

3. Fraser, C. M., Gocayne, J. D., White, O., Adams, M. D., Clayton, R. A., Fleischmann, R. D., Bult, C. J., Kerlavage, A. R., Sutton, G., Kelley, J. M., Fritchman, J. L., Weidman, J. F., Small, K. V., Sandusky, M., Fuhrmann, J., Nguyen, D., Utterback, T. R., Saudek, D. M., Phillips, C. A., Merrick, J. M., Tomb, J.-F., Dougherty, B. A., Bott, K. F., Hu, P.-C., Lucier, T. S., Peterson, S. N., Smith, H. O., Hutchison, C. A., III, & Venter, J. C. (1995). The minimal gene component of *Mycoplasma genetalium*. *Science*, *270*, 397–403.

4. Gillis, J. (2002). Scientists planning to make new form of life. *Washington Post*, November 21, A01.

5. Hanczyc, M. M., Fujikawa, S. M., & Szostak, J. W. (2003). Experimental models of primitive cellular compartments: Encapsulation, growth, and division. *Science*, *302*, 618–622.

6. Hutchison, C. A., III, Peterson, S. N., Gill, S. R., Cline, R. T., White, O., Fraser, C. M., Smith, H. O., & Venter, J. C. (1999). Global transposon mutagenesis and a minimal *Mycoplasma* genome. *Science*, *286*, 2165–2169.

7. Lehman, N. (2004). Assessing the likelihood of recurrence during RNA evolution in vitro. *Artificial Life*, *10*, 1–22.

8. Luisi, P. L., Stano, P., Rasi, S., & Mavelli, F. (2004). A possible route to prebiotic vesicle reproduction. *Artificial Life*, *10*, 297–308.

9. Maturana, H. R., & Varela, F. J. (1980). *Autopoiesis and cognition: The realization of the living.* Dordrecht, The Netherlands: Reidel.

10. Maturana, H. R., & Varela, F. J. (1987). *The tree of knowledge: The biological roots of human understanding*, revised edition (1992). Boston: Shambhala.

11. Nielsen, P., Egholm, M., Berg, R. H., & Buchardt, O. (1991). Sequence-selective recognition of DNA by strand displacement with a thymine-substituted polyamide. *Science*, *254*, 1497–1500.

12. PACE (programmable artificial cell evolution). http://134.147.93.66/bmcmyp/Data/PACE/Public. (Accessed November 2004).

13. Parisi, D., Nolfi, N., & Cecconi, F. (1992). Learning, behavior, and evolution. In F. Varela & P. Bourgine (Eds.), *Towards a practice of autonomous systems* (pp. 207–216). Cambridge, MA: Bradford Books/MIT Press.

14. Pohorille, A., & Deamer, D. (2002). Artificial cells: Prospects for biotechnology. *Trends in Biotechnology*, *20*, 123–128.

15. Rasmussen, S., Chen, L., Deamer, D., Krakauer, D. C., Packard, N. H., Stadler, P. F., & Bedau, M. A. (2004). Transitions from nonliving and living matter. *Science*, *303*, 963–965.

16. Rasmussen, S., Chen, L., Nilsson, M., & Abe, S. (2003). Bridging nonliving and living matter. *Artificial Life*, *9*, 269–316.

17. Szostak, J. W., Bartel, D. P., & Luisi, P. L. (2001). Synthesizing life. *Nature*, *409*, 387–390.

18. Walde, P., Wick, R., Fresta, M., Mangone, A., & Luisi, P. L. (1994). *Journal of the American Chemical Society*, *116*, 11649–11654.