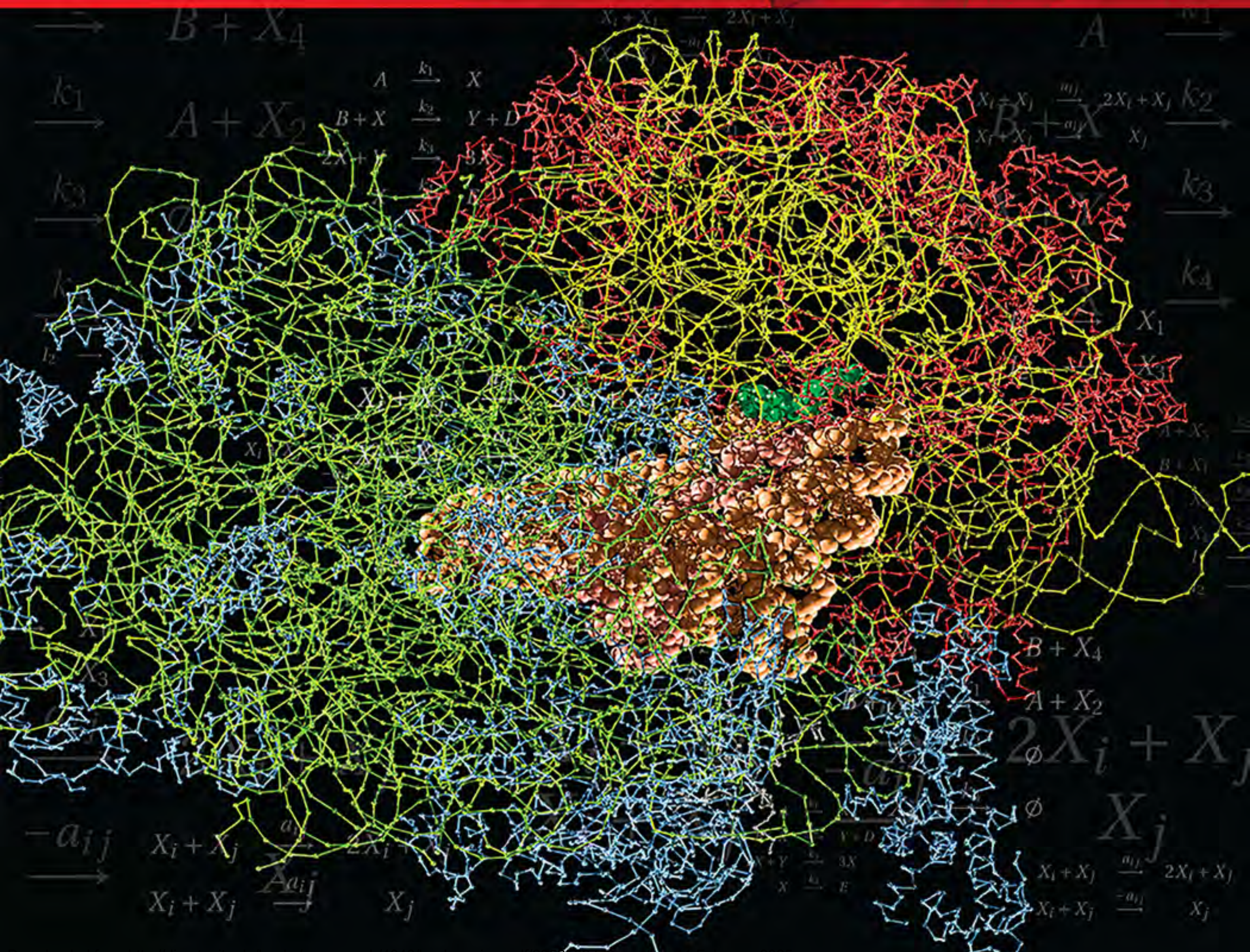
ARTIFICIAL CHEMISTRIES

WOLFGANG BANZHAF AND LIDIA YAMAMOTO



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The MIT Press
Cambridge, Massachusetts
London, England

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This book was set in New Times Roman using the LaTeX— Memoir class. Printed and bound in the United States of America.

Library of Congress Cataloging-in-Publication Data

Banzhaf, Wolfgang, 1955—

Artificial chemistries / Wolfgang Banzhaf and Lidia Yamamoto.

Includes bibliographical references and index.

ISBN 978-0-262-02943-8 (hardcover : alk. paper) 1. Biochemistry. 2. Molecular evolution. 3. Chemistry, Physical and theoretical. 4. Evolution (Biology) 5. Life—Origin. I. Yamamoto, Lidia. II. Title.

QD415.B24 2015

572—dc23

2014046071

10 9 8 7 6 5 4 3 2 1

artificial, *a.*, contrived by art rather than nature: ”artificial flowers”;

http://www.thefreedictionary.com/artificial, accessed 2014

Made or produced by human beings rather than occurring naturally, typically as a copy of something natural.

https://www.google.ca, accessed 2014

chemistry, *n.*, a branch of physical science that studies the composition, structure, properties and change of matter, [from Greek: $\chi\eta\mu\epsilon\iota\alpha$],

http://en.wikipedia.org/wiki/Chemistry, accessed 2014

The investigation of substances, their properties and reactions, and the use of such reactions to form new substances.

http://www.oxforddictionaries.com/definition/english/chemistry, accessed 2014

CONTENTS

PREFACE

The field of Artificial Life (ALife) is now firmly established in the scientific world. A number of conference series have been founded, books and edited volumes have been written, journals are being published, and software has taken up the philosophy of Artificial Life. One of the original goals of the field of Artificial Life, the understanding of the emergence of life on Earth, however, has not (yet) been achieved. It has been argued that, before life could emerge on the planet, more primitive forms of self-organization might have been necessary. So just as life likely was preceded by a prebiotic phase of the organization of macromolecules, perhaps Artificial Life would gain from the introduction of models explicitly studying chemical reaction systems. It is from this motivation that artificial chemistries were conceived.

Artificial chemistries (ACs) have been around for more than two decades. Perhaps sometimes in disguise, they have been a fascinating topic for scientist of numerous disciplines, mathematicians and computer scientists foremost among them. From the term itself we can glean that they are not primarily meant to produce new materials, but rather new interactions. The interactions between molecules are to be man-made, and the molecules themselves might be artificial, or even virtual. As a consequence, the results of artificial chemistries can be found in the virtual world, e.g. in certain multiagent systems, or in the real world, in the form of new (artificial) reaction systems.

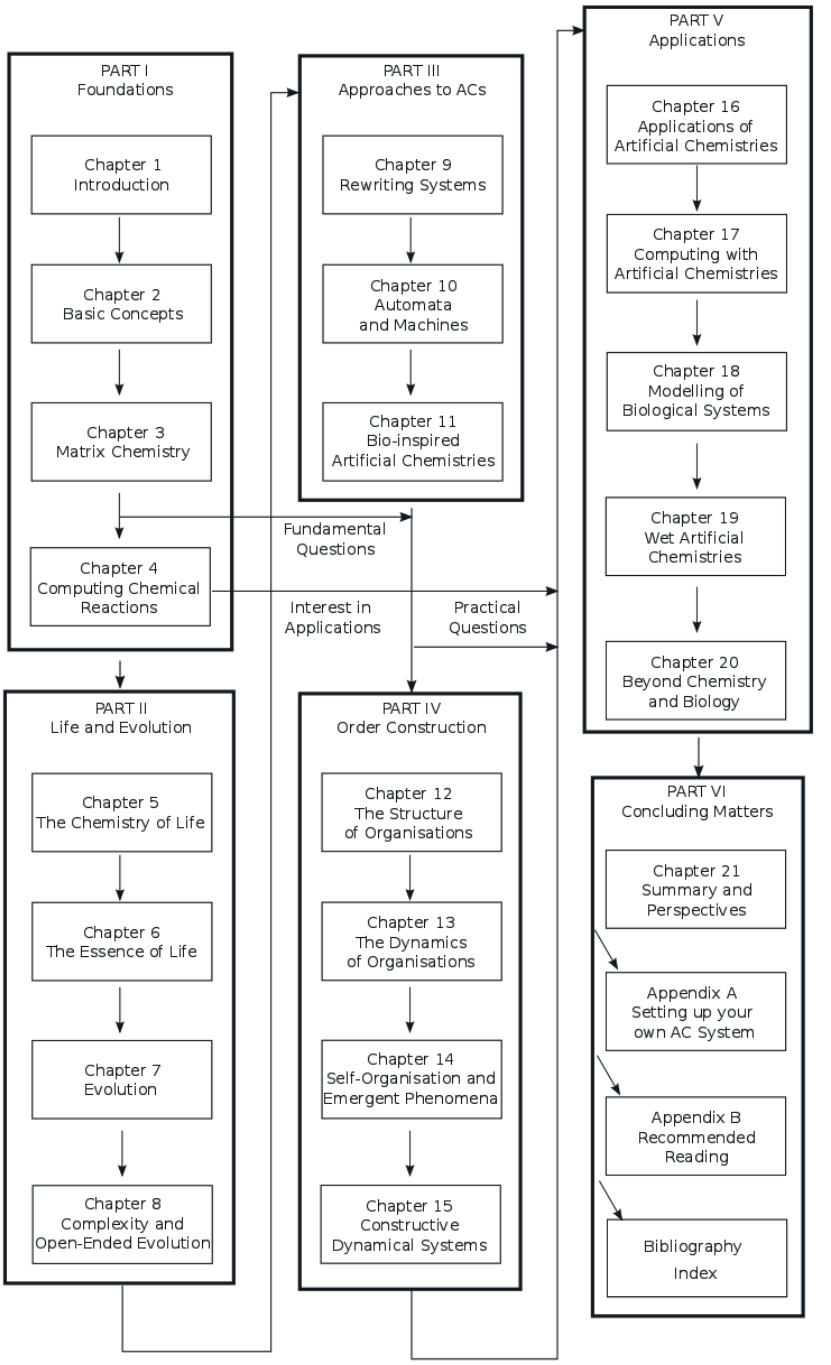
Book Overview

This book will provide an introduction and broad overview of this still relatively young field of artificial chemistries (ACs). The field is highly interdisciplinary, touching chemistry, biology, computer science, mathematics, engineering, and even physics and social sciences to a certain extent. Therefore, we have tried to make the book as accessible as possible to people from these different disciplines. We assume that the reader has some basic knowledge of mathematics and computer algorithms, and we provide a general introduction to the concepts of chemistry and biology that are most often encountered in ACs.

The book will start with a gentle introduction, discuss different examples of artificial chemistries from different areas proposed in the literature, and then delve into a deeper discussion of both theoretical aspects of ACs and their application in different fields of science and technology. An appendix will offer a hands-on example of an AC toolkit ready for the reader to implement his or her own artificial chemistry on a computer.

This book is divided into the following parts:

- Part I holds introductory chapters, with chapter 1 discussing the relation to Artificial Life and other roots of the field, chapter 2 offering a more general methodological introduction,



and chapter 3 exposing, by way of example, key problems that will reappear throughout the book. Chapter 4 gives an introduction to the algorithms applied to chemical reactions, which are also used in ACs.

- Part II, on life and evolution, then steps back for some time to briefly review important aspects of Biology: Chapter 5 discusses the relation between life and chemistry, chapter 6 delves into the essence of life and its origins, chapter 7 reviews the basic mechanisms of evolution and their relation to ACs, and chapter 8 discusses the issue of complexity growth and openness of evolution, a topic that attracts much interest from AC and ALife researchers.

- Part III, Approaches to Artificial Chemistries, is dedicated to a discussion of different Artificial Chemistries introduced in the literature of the last two decades and classifies them into groups: Rewriting Systems (chapter 9) include ACs where the transformation of molecules during "chemical" reactions is dictated by rules that rewrite the contents of these molecules. Automata and Machines (chapter 10) cover ACs that operate in a similar way as a computer with a processor, a memory, and some registers. Bio-inspired ACs (chapter 11) take inspiration from various biological processes, such as the way enzymes operate on DNA molecules.

- Part IV, on order construction, comprises chapters 12 to 15, which expose fundamental questions of how order can emerge. Central to this part of the book is the concept of *chemical organization*, a closed and self-maintaining set of chemicals. Chemical organization theory formalizes this concept and is the topic of chapters 12 and 13. Chapter 12 (co-authored with Pietro Speroni di Fenizio) elaborates on how the structure of organizations can be formalized. Chapter 13 undertakes first steps into the dynamics of organizations. Chapter 14 discusses self-organization and emergent phenomena, which play a key role in ACs. Chapter 15 wraps up with an exposure of constructive dynamical systems, systems that are able to produce novelty and thereby to create new organizations.

- Part V, on applications, returns to reality and is dedicated to a discussion of a broad range of AC applications: Chapter 16 introduces some selected applications; chapter 17 looks at how artificial chemistries can be used for computing; chapter 18 discusses how ACs can be used for the modeling of systems in biology; chapter 19 reports on synthetic life and wet chemical computers; and chapter 20 discusses implementations in different media ranging from mechanical to social systems.

- Part VI concludes the book with a summary chapter (chapter 21), followed by some further suggested reading, and an appendix that introduces a Python toolkit for implementing ACs.

Given the interdisciplinary nature of this book, readers with different backgrounds might find interest in different parts of the book. For instance, readers familiar with chemistry and biology might prefer to skip chapter 5. Readers interested in more fundamental questions will certainly enjoy part IV of the book, while a more practically oriented readership might wish to focus on the application areas in part V. At any time readers should feel free to set up their own AC simulation system. In order to help with that process, we have provided an easy-to-follow guide in the appendix, with code written in Python.

Personal Remarks by Wolfgang Banzhaf

I first became involved with artificial chemistries when I discovered an interest in self-replicating structures. Von Neumann's proof that self-replicating machines are possible, together with the "Game of Life" rules for cellular automata, exerted an enormous influence on me. While those ideas had been established in the 1950s and 1970s, respectively, Artificial Life as a concept took another decade to arrive. At that time I was a freshly minted theoretical physicist, with lots of ideas and no way to realize them.

What is the essence of life? How is it that the molecules in our bodies are replaced every so often, yet we consider ourselves the same, regardless of which molecules are doing their heavy lifting within our bodies? Surely, it could not be the material constitution of our bodies that would make us alive? It was in this context that I began reading books and articles about organization, self-organization, and the processes of life. I realized that below the wonderful phenomena of real life there was a huge machinery of chemical and physical processes, all the time providing the raw material and energy gradients, the driving forces, and the constraints necessary for life to exist.

Following the lead of others, and together with my students, I started to develop notions of artificial chemistry, which at the same time were reinforced and further developed by a whole group of researchers fascinated by Life.

When MIT Press approached me and asked whether I would like to write a book about the topic of artificial chemistries, I was hesitant at first. In a field so new and inhomogeneous as this, how could one hope to find a thread and to provide a concise discussion of the major ideas without sacrificing many of the potentially valuable avenues that are being explored as one writes them down? Fascination with the topic, however, prevailed over caution, and it is in this exploring spirit that we hope you receive this book. It is not intended to discourage any effort in this field — just the opposite, we hope to convey some of this fascination, and to draw as many of you as possible into this field, if you have not yet been dedicated to the cause: to understand life, in all its forms, and therefore ultimately, to understand where we come from.

Personal Remarks by Lidia Yamamoto

When I was invited to help write this book, I felt of course very honored and excited, but at the same time I also felt very scared by the scale of the challenge ahead of me. My enthusiasm finally won over my fear, and I decided to leap at this chance.

Writing this book was a big learning experience for me. Our collaboration was a great pleasure and a source of inspiration for me. This book represents about four years of our joint effort. As I had feared, I was quickly overwhelmed by the huge amount of information that I had to synthesize into a coherent and mature overview of this still burgeoning field. My goal was to make this book as accessible as possible, remembering the person I was when I first came into artificial chemistries, all the questions I had and for which I couldn't find easy answers, and all the questions that I even didn't know how to formulate. One of my past advisors once said that I am a walking question mark. Indeed.

In this book we tried to bring answers to those questions, even if most of the answers consist in saying that no firm answer is currently known, at least we tried to point the reader to the places where people are looking for the answers. We hope that this will stimulate many more people into finding the answers, and then contribute to the progress in the field.

It quickly became apparent that we had to achieve much more than just a big survey of the field of artificial chemistries. This was an opportunity to finally put together the fundamental concepts needed to understand and work with artificial chemistries, the main motivations and rationale behind the work done so far, and where we should be heading from now on. This was a daunting possibility, and perhaps the main value of the book. I don't know if we have attained this ambitious goal; the readers will tell us. However, I think the book at least made a big leap in this direction, although we might not be fully there yet.

Acknowledgments

We are indebted to many people: Bob Prior, executive editor at MIT Press, first planted the idea to consider the plan for a book on artificial chemistries seriously. Susan Buckley, associate acquisition editor at MIT Press, regularly (and patiently) checked in to ask about the status of the book, Christopher Eyer took over from her and helped in the later stages of getting the book draft ready. Katherine Almeida accompanied the production of the book with unfailing diligence.

Over the years, we worked with many individuals (students, colleagues and collaborators) on various aspects of artificial chemistries: Jens Busch, Pierre Collet, Peter Dittrich, Burkard Eller, Mark Hatcher, Christian Lasarczyk, Bas Straatman, Thomas Meyer, Daniele Miorandi, Hilmar Rauhe, Pietro Speroni di Fenizio, Christian Tschudin, Roger White, and Jens Ziegler. We also had many discussions with colleagues in the community who in various ways helped to shape our thinking about Artificial Chemistries or read parts of the book and gave feedback: Mark Bedau, Ernesto Costa, Rene Doursat, Harold Fellermann, Christoph Flamm, Walter Fontana, James Foster, Martin Hanczyc, Stuart Kauffman, Jan Kim, Krzysztof Krawiec, Julian Miller, Una-May O'Reilly, Steen Rasmussen, Hiroki Sayama, Peter Schuster, Lee Spector, Peter Stadler, Brian Staveley, Susan Stepney, Yasuhiro Suzuki, and Hiroshi Tanaka. We gratefully acknowledge the rich and inspiring interactions we had with them all.

Many of our colleagues were so friendly to allow us to reproduce figures from their own work. We have acknowledged these permissions in the appropriate places, but want to express our gratitude here as well to Erwan Bigan, Aaron Clauset, Mark Hatcher, Martin Hanczyc, Simon Hickinbotham, Sandeep Krishna, Thomas Miconi, Robert Pennock, Hiroki Sayama, Peter Stadler, and Sébastien Verel.

This book was typeset in LaTeX's Memoir class and counted upon various tools from the free software and open source communities, including Python, Gnuplot, Inkscape, OpenOffice and many more. We would like to express our sincere gratitude to these developer communities.

W.B. would like to cordially thank his wife Pia for her interest and continuous encouragement in the process of writing this book. L.Y. wishes to thank her husband Pascal for his unconditional support, encouragement, and sacrifices that were essential to her successful contribution to this extensive book writing effort. Both of us are indebted to Pierre Collet from the University of Strasbourg, who kindly provided us with the academic infrastructure needed to pursue part of this project. Finally, we both owe many apologies to our families and friends who were too often neglected on the way toward completion of this project.

Wolfgang Banzhaf, St. John's, Newfoundland, Canada
Lidia Yamamoto, Brussels, Belgium
February 25, 2015

Part I

Foundations

Information should be generated from information just as organisms from organisms.

STANISLAW LEM, SUMMA TECHNOLOGIAE, 1964

CHAPTER 1

INTRODUCTION

The study of Artificial Chemistries (ACs) originated from the efforts to understand the origins of life. Similarly to how Artificial Life studies models of "life as it could be," artificial chemistries propose and study various models of chemical reactions as they could be imagined. In real chemistry, reactions happen when a set of molecules (the reactants) come into contact in such a way that some of the bonds between their atoms are broken and other bonds are formed, rearranging the atoms into the final products of the reaction. There are a vast number of different ways to rearrange atoms into valid molecular structures. In artificial chemistries, this combinatorial space of possible structures is extended beyond pure chemistry: one is allowed to "play god" and invent his or her own rules to determine how objects interact to produce other objects. In an abstracted sense, we mean by chemical reaction in an artificial chemistry the transformation and sometimes the new generation of objects in combinatorial spaces. In this general notion, artificial chemistries can be considered tools that study the dynamics of systems of interacting objects in these combinatorial spaces. A surprisingly broad set of natural and man-made systems and phenomena fall under this class, from chemistries to even economies. As such, artificial chemistries have become a field of interest to a number of different research and engineering disciplines.

The strength of artificial chemistries draws from the fact that they offer tools for an examination of both quantitative and qualitative phenomena. The concentration or frequency of occurrence of some particular agents (chemical types) offers a window into the quantitative world, while the particular types of agents being under consideration allow a qualitative picture to develop, e.g. a new type of agents appears for the first time, or some types start cooperating (e.g., by supporting reactions that produce each other). In the same way that real chemistry is concerned with both qualitative and quantitative aspects, by measuring concentrations of reacting substances and by analyzing newly developed substances, artificial chemistry is concerned with observing the concentrations of collections of objects and with the analysis of their internal properties.

Stanislaw Lem, the famous Polish philosopher, literary critic and author, has wonderfully summarized the key idea of this field by suggesting the symbols of mathematics as the basic objects of consideration. In one of his most influential books, *Summa Technologiae*, meant as a summary (both review and outlook) on the technology humans have developed, much as Thomas Aquinas summarized the status and perspectives of theology in the Middle Ages in his famous *Summa Theologiae*, Lem stated:

> "Information should be generated from information just as organisms from organisms. The pieces should fertilize each other, they should be crossed over, they should be mutated, that is, varied to a small degree, but also to a larger degree by radical changes not known in genetics. This could perhaps happen in some vessels where reactions between "information-carrying molecules" take place, molecules that carry information in a similar way as chromosomes carry the features of organisms."

So the problem Lem envisioned at the core of this new discipline was, how to set up a system akin to a chemistry, with the interacting objects being symbols like numbers. And Lem already correctly identified the need for a combinatorial approach, by envisioning molecules — today one would say macromolecules — akin to DNA chromosomes. Finally, another aspect of his view on these reactions of information-carrying molecules is an evolutionary approach, something that became well known in the meantime under the term "evolutionary algorithm" or "genetic algorithm." We shall later come back to this notion, but will now concentrate on the proposition of mathematical symbols as reactants, as it is one of the representations for artificial chemistries. Instead of mathematical operations being executed on symbols without connection to a material world, however, in an artificial chemistry, operations include a notion of material. For example, two symbols from the set of the natural numbers, say "5" and "6" as being part of an addition, $5+6$, would actually be two representatives of type "5" and "6" respectively, that would not form a symbolic equation

$$5+6=11, \tag{1.1}$$

but instead would perform a quasi-chemical reaction that leads to a new product, "11," in the following form

$$5+6 \rightarrow 11. \tag{1.2}$$

As such, a new symbol, "11" would be produced by this reaction, and the arguments of the addition operation would disappear due to them now being contained in the new product.[1] In a sense, these particular representatives of the symbol types "5" and "6" would be consumed by the reaction. This is indeed a very materialistic understanding of the symbols, with an assumption of conservation of matter behind the consumption of the original symbols.

In real chemistry, of course, there is a backward reaction as well, which would translate into a possible decay of "11" into the two constituents "5" and "6":

$$11 \rightarrow 5+6. \tag{1.3}$$

Both forward and backward reactions in chemistry are governed by the kinetics of a particular reaction process. The kinetics determines the speed of the reactions based on the concentrations

[1] Note that this understanding of an operation is much closer to computer operations than the structural understanding of mathematics.

of reactants and on rate coefficients stemming from energy considerations. For our toy arithmetic chemistry above, it is an interesting question whether it would be possible to formulate a mathematics based on such processes. It would probably entail to assume an infinite resource of symbols of any particular type, and perhaps the assumption that the kinetic constants for all possible reactions are exactly equal. If we would relax the latter assumption, would we end up with a different mathematics?

To recapitulate: The gist of artificial chemistry is that a set of (possibly abstract) objects is allowed to interact and produce other (sometimes new) objects. The observation of those systems would then give a hint at their potential for producing regularity, fault-tolerance, and innovation. What we will need to define for an artificial chemistry is therefore objects, rules for their interactions, and an "experimental" system where we can let them react.

In real chemistry, both the objects and their rules of interaction are given by nature, the former being atoms of chemical elements or collections of atoms of elements in the form of assemblages called molecules, the latter in being nature's laws of chemical reactions. Variability can be introduced in choosing the conditions for the reaction vessel, its geometry and environmental parameters (pressure, temperature, flow, etc.). The reaction laws cannot be tampered with, however, and in most cases the objects are known beforehand.

Contrast that to artificial chemistries: Everything is free to be varied, certainly the reaction vessel and its parameters, but then also the laws of interaction between objects and even the objects themselves. For instance, the objects could be shares of companies, held by a trader on the New York Stock Exchange. Reactions could be the buying and selling of shares through the trader, based on an exchange of money. And the reaction vessel could be the market, with its particular conditions, e.g., price level, amount of shares on offer, economic climate, and so on.

One key feature of both artificial and real chemistry is that not all reactions between objects are equally likely to happen or even possible. Some are simply not allowed on energetic reasons, for instance (if there is a notion of energy), some others are not possible based on other constraints of the system under consideration. If there is no acceptable prize, shares will simply not be sold or bought by the trader in the example mentioned before, despite a hypothetical offer. So no reaction takes place, what is sometimes called "elastic collision," from the notion that objects have come close, even to the point where they encountered each other, but the constraints didn't allow a reaction to happen. The objects are non-reactive, and will not form compounds, or produce anything new.

In general, artificial chemistries follow their natural counterpart in studying interactions between two objects. If there are more objects participating in an overall reaction, a separation into a number of two-object reactions is often used to build the overall reaction. This follows from a principle of physics: A collision between two particles is much more likely than a simultaneous collision of several particles together. This simplest form of interaction is also able to capture reactions with more partners, since two-body interactions can be concatenated with other two-body interactions to provide an overall result.

Real chemistry is, of course, about more than just single two-body interactions. A huge number of reactions are possible in principle, and only energetically disfavored. This produces a patterning of objects, with some being more abundant than others. Thus the study of abundances and the energy kinetics of reactions is a key element of chemistry, as it determines these patterns. In artificial chemistries, energy considerations have only started to enter studies recently. In principle, abstract interactions can be formulated without recurrence to energy, a freedom that many researchers in artificial chemistries have made use of. The observation of abundance

patterns, however, is a central part of all artificial chemistries, since it provides the information necessary to judge which interactions produce which objects in the system under study.

Although very often energy does not play a constraining role in artificial chemistries, constraints in general are considered and easily implementable. They are called filter conditions, and are included as one step in the process of calculating a reaction product in the algorithm that implements an artificial chemistry. Thus, an artificial chemistry might allow a reaction product to be generated, but not to be released into the pool of objects. It is filtered out before it enters the pool. An example might help to explain this point: Suppose again, we have an artificial chemistry of natural numbers. This time, however, reactions are chosen to be the division of numbers. So two elements of the pool of objects, say an "8" and a "4," might collide and react. In this case, we have

$$8 : 4 \rightarrow 2 \tag{1.4}$$

The first complication here arises from the fact that, mathematically speaking, the arguments of the division operator are not commutable, i.e., it makes a difference whether we divide "8" by "4" or "4" by "8." This asymmetry in the application of the division produces a conceptual difficulty for artificial chemistries, since chemical reactions are symmetrical. Two reactants "A" and "B" will react to the same product, regardless of their order of writing in the equation. We can evade this difficulty for now by simply saying that always the larger of the two numbers will be divided by the smaller. So, the operation ":" that we wrote in equation 1.4 really is not just a division, but a sorting of the numbers, followed by a division. Suppose now that we are interested in a particular feature of numbers, namely their divisibility, and that we want to restrict reactions to those that produce only natural numbers. This is the aforementioned filter condition, in that we determine that if a number "a" does not divide a number "b," and produces a natural number, then this reaction is not allowed. We say, the reaction is an elastic collision. Technically, we can still let the division happen, but then need to prohibit the result from getting back into the pool of objects. For instance,

$$8 : 5 \rightarrow \emptyset \tag{1.5}$$

despite the fact that, in principle, "8" divided by "5" could be calculated as "1.6." This filter condition is not the same as trying to make sure that the operation of division stays within the allowed set of natural numbers. Such a strategy would, for instance, be represented by the division with subsequent choice of the next integer. In our example above, the result would be "2" since "1.6" is closer to "2" than to "1."

As we can see from this example, performing a reaction can be more than a simple mathematical operation, it can be an entire program or algorithm being executed prior to the production of the result, and another program being executed after the production of the result, to check whether the result is indeed allowed by the constraints of the system. In principle, even a certain degree of randomness can be injected into this process, for example, by allowing a result to enter the pool only based on the cast of a dice.

In this sense, the expressive power of artificial chemistries is larger than that of their natural counterparts, since they allow arbitrary constraints to be implemented, not to speak of the objects and interactions which also can be chosen with relative freedom.

Suppose now that we have determined the types of objects and the rules of interaction of such a system of objects, together with the general method for producing reactions. We already said that by observing the development of abundances of objects over time, we can start to discern one dynamics from another and find ways to characterize the objects and their interactions. If we had a full classification of objects and looked at each of them separately, what could we

learn from these? We can ask questions like: Which of the objects is stable, i.e., will not be replaced by others through reactions? Which subset of objects is stable in its appearance, and is produced in large numbers? Which interactions produce which patterns of abundances? What is the influence of initial conditions on the outcome? Generally speaking, we can ask questions relating to the nondynamic ("static") character of the artificial chemistry under study. In simple cases, all reactions can be exhaustively listed and put into a reaction matrix. But we can also ask questions relating to the dynamic character of the AC, e.g., how abundances develop under which conditions, etc. Many of the simpler Artificial Chemistries being studied will have a notion of equilibrium, just as it happens in real chemistry. In other words, after some time the dynamics will reach a steady state, upon which not very much will happen, or no qualitative changes will occur any more in the behavior of the system.

While we can learn a lot from these kinds of studies, artificial chemistries really come into their own when we start discussing the production of new molecules, new entities that never before had appeared in the reaction vessel ("pool"), whose production happens for the first time in a single event. For that to happen, it is important that the set of objects is not fully known to us from the outset, which means that reactions can only be defined implicitly, or that at least the number of knowable objects is much greater than the number of realized objects. We can see from here how important it is to consider combinatorial spaces, spaces that are very large, yet not necessarily populated to the full extent. So only a subgroup of artificial chemistries will be able to exhibit such events, namely those based on combinatorial spaces, because only there is the number of possible different objects much greater than the number of existing objects.

Once a new object appears, it has the chance to participate in subsequent interactions. If these interactions, now having a new participant, produce new results again, we might even get a whole slew of new objects in a very short time, some of which might be produced repeatedly, some others of which only intermittently, soon to disappear again. Yet through this process, the system as a whole might move to a different equilibrium state. So while the emergence of a new object has suddenly thrown the system out of balance, a new, different balance might be established through the integration and with the help of the new object.

The innovation potential, therefore, that can be part of an artificial chemistry is extremely interesting in that the establishment of an artificial chemistry is one of the very few methods with which we can conceptualize and study the emergence of novelty and of qualitative changes to a system in a simulation environment. For a long time, novelty has eluded the grasp of exact Science and could be treated only qualitatively. Here, finally, is a method that allows to study the phenomenon in a model, and to determine the conditions under which innovation thrives.

It will be no surprise that, together with novelty, the question of complexity growth will play an important role in artificial chemistries. Is it possible to set up systems in a way that they are open to grow in complexity? Where does this complexity growth ultimately come from, and what are the conditions under which it thrives? How does complexity growth relate to novelty in these systems? These fascinating questions are suddenly open for a closer examination using simulation tools in an artificial chemistry. Admittedly, simulated systems might look artificial, yet there is a chance to find valuable answers that can be transferred to more realistic, perhaps even to real systems.

The condition that needs to be fulfilled for innovation to be a constitutive part of a system is that the number of possible different types of objects, N, in a system is much larger than the number of existing objects (of any type), M, or

$$N \gg M. \tag{1.6}$$

This condition will ensure that there is always enough possibility for innovation. How can such a condition become a constituting part of a system? There might be systems where this is just a natural condition that can be fulfilled under most any circumstances. Or it might be that this is a particular corner of the system space in which these conditions prevail. We are of the opinion that nature can be considered to realize systems that most naturally allow innovation to occur. The very fact that macromolecular chemistry, and carbon-based macromolecular chemistry in particular, allows the assembly of molecules like beads on a strand virtually guarantees a combinatorial explosion of system spaces and thus conditions proliferating innovation.

Even simple systems such as those that can be constructed from using sequences or strings of binary numbers "0" and "1," the most basic of all number representations, already possess the power to produce novelty in the above sense. Let's just explore for a moment how easy that is. Suppose we consider the memory system of a modern computer with a storage capacity of a terabyte as our reaction system. Suppose now that we fill this storage with strings of binary numbers of length 100, i.e., each of our strings is 100 bits long. You can't put a lot of information into 100 bits, as we all know. Given that each packet of data traversing the Internet holds at least 160 bits, such a string could not even hold a single e-mail packet. Yet there are $2^{100} \simeq 10^{30}$ different strings of length 100 bits. Filling the entire terabyte of storage with strings will allow us to store 8×10^{10} strings of this length. Since there are, however, that number of different strings available, even if we would allow every string to be only held once, only one out of every 10^{19} possible strings would be in the storage. Thus, the combinatorial space of binary strings is essentially empty. Had we required that strings need to be there in multiple copies, an even smaller proportion of all possible strings could have been realized, providing tremendous potential for novelty. Would there be a mechanism in place which allowed strings to be replaced by other strings, with an occasional variation incorporated in the process, we would naturally expect the emergence of strings never seen before.

One of the key driving questions for the field of Artificial Life has been how life emerged in the first place. Origin-of-life research is closely related to the earlier question: How did qualitative change happen and a nonliving system suddenly transform itself into a living one? We have argued previously, that while this is an important question, perhaps one stands to learn a lot from studying artificial chemistries first, before asking about the origin of life. Indeed, there exist many "origin" questions for which Artificial Chemistries might have lessons to teach. Origin of language, origin of consciousness, origin of human society, origin of, you name it, are questions that target a very special, innovative event in their respective systems. These are fascinating questions as they tie the dynamics of their underlying system to qualitative changes these systems undergo at certain key junctions in their development.

Beyond the simulation realm, with the progress in natural and material sciences, it now becomes feasible to set up chemistries that can be called artificial, i.e., man-made chemistries, that heretofore were not possible or realized in nature. Simple examples close to the border with biochemistry are systems where additional amino acids are used to produce "artificial proteins," or where more than four nucleotides are used to create an "artificial genetic code." Many similar ideas are presently being examined, which can be subsumed under the general term "wet artificial chemistries." This term stems from the idea that most of the artificial chemistries are used to model lifelike systems, which in reality are systems in a wet environment. Note that innovation in these wet artificial chemistries is based on the exploration of novel combinations of atoms leading to new chemical compositions that were not known before, but which still obey the same universal laws as natural chemistry. In contrast to virtual or "in silico" artificial chemistries, the laws of chemistry here cannot be tampered with. Nonetheless, the potential of such new

chemistries is enormous: from new materials to synthetic biology, enabling perhaps totally new forms of “wet artificial life” based on a different genetic code or fueled by different metabolic processes. A new technology based on such engineered living entities opens up a whole new range of applications, and of course also raises numerous ethical issues.

Applications of artificial chemistries range from astrophysics to nanoscience, with intermediate stops at social and economic systems. At a certain level of abstraction human societies can be considered artificial chemistries. Models have been built that encapsulate these ideas and predict collective behavior of groups of individuals. On a more elementary level we can look at social behavior and study social interactions in AC-type models. Observation and imitation would be important aspects of such studies, since they allow social norms to develop and to be reinforced.

It remains to be seen how far the paradigm is able to carry. For the time being, many systems can be looked at from this point of view, and potentially new insights might be gained by a thorough modeling and treatment as an artificial chemistry. In the next chapter, we will look at a very simple embodiment of an AC, but first we need to understand some principles of modeling and simulation in general.

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