International Baccalaureate

Extended essay cover

SAMPLE B

Diploma Programme subject in which this extended essay is registered: Computer Science

(For an extended essay in the area of languages, state the language and whether it is group 1 or group 2.)

Title of the extended essay: Cellular Automata: A Perspective on Complexity

Candidate's declaration

If this declaration is not signed by the candidate the extended essay will not be assessed.

The extended essay I am submitting is my own work (apart from guidance allowed by the International Baccalaureate).

I have acknowledged each use of the words, graphics or ideas of another person, whether written, oral or visual.

I am aware that the word limit for all extended essays is 4000 words and that examiners are not required to read beyond this limit.

This is the final version of my extended essay.

Candidate's signature: ____________________ Date: 2-6-2009

IB Cardiff use only: **A:** 045086 **B:** ______

Supervisor's report

The supervisor must complete the report below and then give the final version of the extended essay, with this cover attached, to the Diploma Programme coordinator. The supervisor must sign this report; otherwise the extended essay will not be assessed and may be returned to the school.

Name of supervisor (CAPITAL letters) ______________________________

Comments

Please comment, as appropriate, on the candidate's performance, the context in which the candidate undertook the research for the extended essay, any difficulties encountered and how these were overcome (see page 13 of the extended essay guide). The concluding interview (viva voce) may provide useful information. These comments can help the examiner award a level for criterion K (holistic judgment). Do not comment on any adverse personal circumstances that may have affected the candidate. If the amount of time spent with the candidate was zero, you must explain this, in particular how it was then possible to authenticate the essay as the candidate's own work. You may attach an additional sheet if there is insufficient space here.

Andrew's initiative extended to the use of a Mcell program to help the simulations.

I have read the final version of the extended essay that will be submitted to the examiner.

To the best of my knowledge, the extended essay is the authentic work of the candidate.

I spent 4 hours with the candidate discussing the progress of the extended essay.

Supervisor's signature: ______________________ Date: 2/17/09

[redacted]

The IB Extended Essay

Candidate:
IB Class of 2009
Subject Area: Computer Science
Word Count: 3,956
Candidate Number: 119

Principal:
IB Coordinator:
Essay Supervisor:
Subject Mentor:

Cellular Automata: A Perspective on Complexity

Research Question:
How may cellular automata be used to simulate complex systems and structures, such as a replicating, evolving organism?

A -> 2

Abstract

Cellular automatons consist of grids of cells, each cell following a predefined rule (whether absurdly simple or extremely complex) in order to determine its state - a finite state machine. These come in many forms, ranging from grids coordinated by a global clock to fields in which each cell's update sequence is individually determined. Computer programs simulating such automata are commonly used to generate visual patterns, often for recreational or aesthetic purposes.

Although the study of such programs may initially seem to be an entirely trivial expedition, a closer examination of many automaton "rule sets" suggests that many of these programs can in fact produce results modeling highly complex systems, for example, a Universal Turing Machine, a device capable of computing any algorithm. ? This has the impact of suggested that given a sufficient quantity of time and patience, complexity may arise out of the mundane, that surprising emergent behavior may be far more common than previously thought.

I

Therefore, this exploration seeks to explore how several existing automaton rule sets give birth to intricate behavior, with a particular emphasis on the ability to generate an impression of simulated artificial life. Following that, it will go on to examine the feasibility of an automatic model of an organism and to also consider the possible impact of the properties of the cellular automaton across various fields.

J>1 it's not completely clear ho
this research will be
carried out.

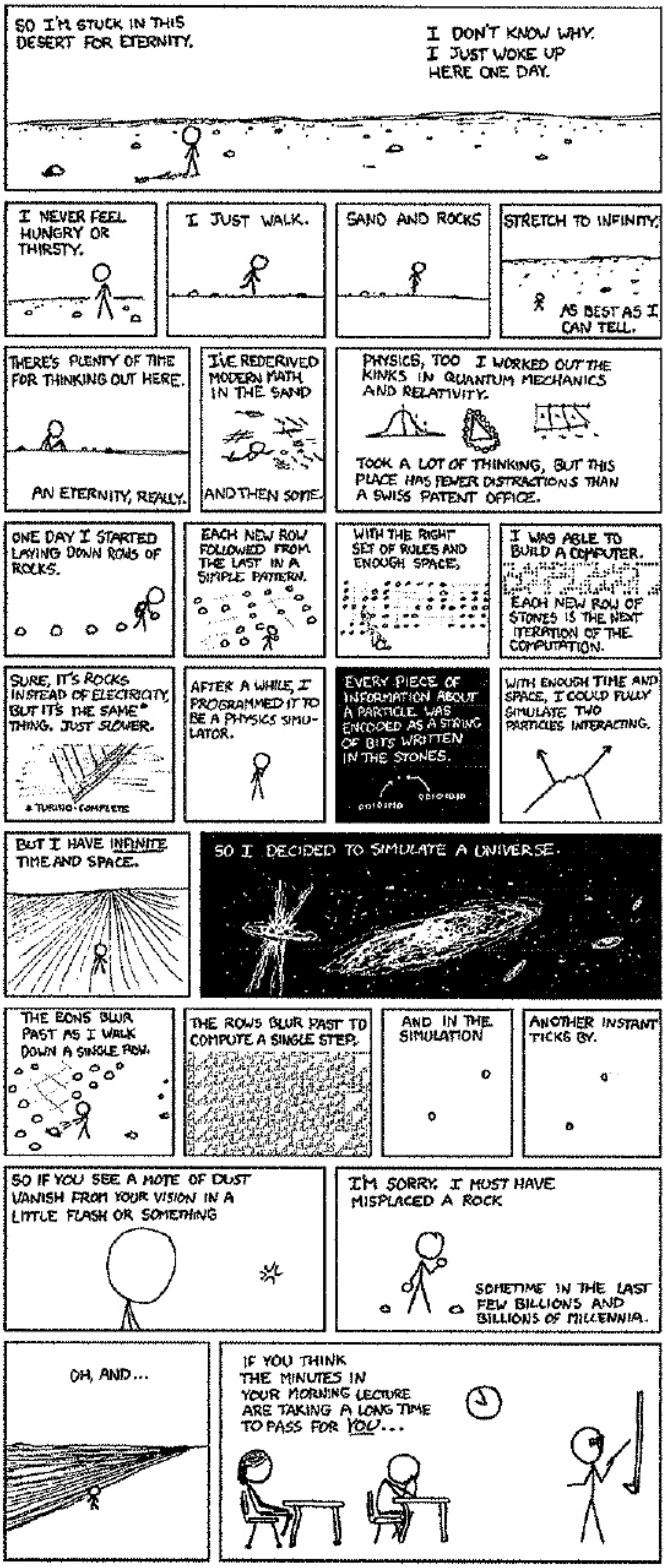


Figure 1: Image retrieved from www.xkcd.com

?

Table of Contents

Introduction

Cellular automata are large groups of interacting finite state machines.

The most commonly known example is perhaps Conway's Game of Life, a "game" in which a large, sometimes infinite, sometimes toroidal two-dimensional grid of two-state machines ("cells") is set in which each machine follows a common rule: a cell is/becomes if and only if "live" if two or three of its immediate neighbors (counted in directions both orthogonally and diagonally[1]) are also "live"; the cells are processed simultaneously in "ticks". Despite the simplicity of the rules shown, this particular automaton is known to have formed the building blocks for intricate, far more complex devices; for example, one particular arrangement of "live" and "dead" cells will form an oscillating structure that continually outputs other oscillators, that themselves translate away from the host (Figure 2). In fact, almost every arrangement of live cells seems to eventually generate a mass of oscillators, moving or static (1).

not sho

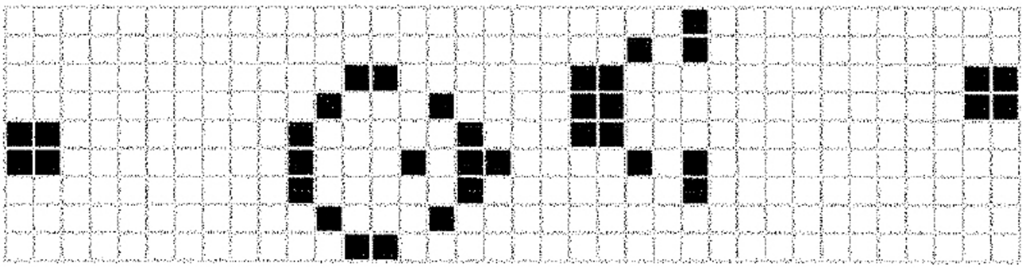


Figure 2 : The "Gosper Gun"

The behavior shown in Conway's game seems not to be a unique phenomenon, but instead seems to be a common feature among several other "rule sets" of automata.

---

[1] Called a "Moore neighborhood"

It is here that we may begin to wonder if this strange ability may be used to implement far more complex systems, that cellular automata may be used as an example of emergent behavior to model and emulate greater things. Specifically, can a cellular automaton simulate some sort of reproducing, evolving organism - may one create a structure that can reproduce and evolve?

The course of investigation will pass through three different automaton rule sets in order to obtain an idea of the feasibility of such a simulation. Trivial replicators, such as an automaton involving a cell converting its immediate neighbors to itself without any semblance of more complicated behavior, and asynchronous (the cells do not operate on a shared clock) automata are ignored for this expedition.

neither the context or the importan
of the RQ is clearly shown.
B -> i

Case Studies

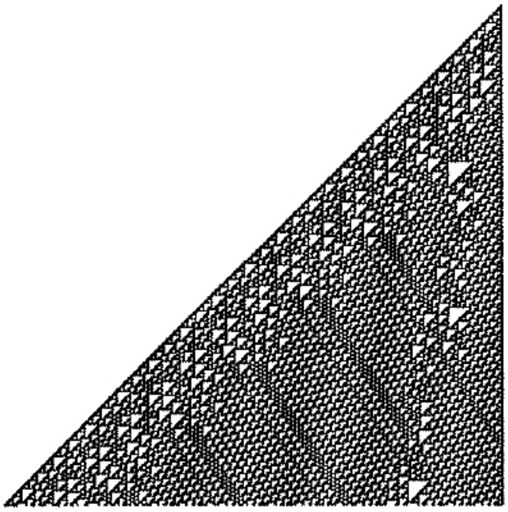
We may further examine some of the sets producing complex behavior using three case studies: the one-dimensional two-state automata used by Wolfram in *A New Kind of Science*, the self-replicating loops fashioned by Christopher Langton, and the massive universal constructor and copier specified by von Neumann. The studies are arranged in order of simple to complex (in terms of the number of states required for each ruleset).

Terminology

- Cell - in grid-based automaton, the term for the finite state machine residing in each grid point
- Finite state machine - a model object whose behavior consists of a finite number of states and transitions between said states
- Rule set - the deterministic pseudocode for the program by which all of the finite state machine in a particular automaton operate, serves as a method of distinguishing different automata.
- Step/Tick - the global update timer, each tick sees all of the cells in the automaton updated in regard to the rule set being applied to the results of the previous update (for the first step, the initial starting arrangement)

Case 1: Wolfram's 1-D Automata

The one-dimensional two-state "elementary" automata featured by Stephen Wolfram offer an interesting jumping-off point into the world of simple programs generating complex results. In this simulation, the "world" consists of a one-dimensional line, in which the state of a cell is determined by the states of its neighbors and itself from the previous tick. Since there are relatively few possible rule sets in such a setting, each possible rule set is assigned a number from zero to two hundred and fifty-five. When placed onto a two-dimensional sheet showing many steps, some rule sets generate interesting patterns, others do not; an example lies in Figure 3 (2).



progressio

Figure 3: Rule 110, starting from a single live cell

which is?

What is interesting is that the automatons given by Wolfram seem to have many unique qualities; for example, one, rule 30, seems to exhibit properties similar to that of a pseudorandom number generator, and thus could be yet another tool in the field of cryptography (3). Another rule set, rule 110, has drawn attention as a possible method to implement a universal Turing Machine, therefore conclusively demonstrating that given time and effort, the simple may model the complex (4). All in all, the elementary cellular automata serve to hark the coming of structures in more complex rule sets.

— but none of this is show

Case 2: Langston's Loops

While the aforementioned one-dimensional automatons described by Wolfram are interesting, none bear any resemblance, at least to the human eye, to any known life form. However, another automaton offers some interest in this area.

"Langton's loops" offer a perspective into the use of cellular automata to simulate genetic codes. Each loop is composed of outer and inner sheaths surrounding a circulating ring of genetic material. The structure replicates by expressing its genome into a growth "arm", with the sequence of states in the gene determining the length of the arm. Upon reaching its maximum length, the arm bends; this process is then repeated until the arm intersects with itself, at which point it disconnects from the parent into a new loop, an exact clone of the original (Figure 4). Should a loop become completely surrounded by others, its growth arm will collapse, disrupting replication of the gene and "killing" the landlocked loop. As a result, the growth rate of a population of living loops is not exactly exponential, it is somewhat less; furthermore, the presence of any sort of finite environment will eventually result in a coral of no living loops. (5)

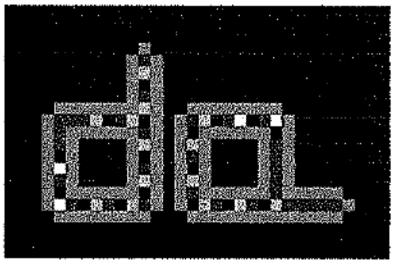


Figure 4: Two growing loops

What is interesting about Langton's loop is that the cells contain genetic codes - therefore, it may seem that the automaton could be adapted to provide a crude simulation of evolution, although the model has the disadvantage of its genotype being equivalent with its phenotype. Indeed, there exist attempts

there's really no atte
to explain or analyse

to implement such a system, with names ranging from SDSR[2] loops (in which dead cells disappear) to Evoloops (in which loop genomes are allowed some modification) to Sexyloops (in which genomes can be transferred between loops).

As a model for artificial life, Langton's loops are rather limited simulations. Namely, the loops are limited to only two traits (which also happen to be their only non-reproductive outputs) - size and response to collosions. Therefore, any simulation of evolution will tend to play out with the generation of smaller and ever smaller structures (since such may "squeeze" between larger ones). In addition, barring a miraculous once-in-a-lifetime chimerical event involving the collision of many loops in an auspicious order, the loops will not gain any complexity in terms of structure in the process of replication, they are, and will stay, square rings containing a flow of genetic material.

unconvinci
use of lang

Hence, Langton's loops seem to be a curious interpretation of the growth of a little-mutating, budding, microorganism.

- just a description
- no comp. sci.
- no data / algorithms / v

Case 3: Von Neumann's Universal Copier and Constructor

For the purpose of demonstrating universal construction and replication abilities, none stands out more than the purely logical von Neumann machine. When implemented in a cellular automaton environment, the machine attempts to demonstrate "logical universality[3], constructability[4], construction universality[5], self-reproduction[6], and evolution[7]". (6) While the machine exists primarily as a set of rules describing a machine and writing arm feeding off of a tape (greatly resembling some sort of ribosome), there have been several implementations of von Neumann's constructor, such as that given by Pesavento, as seen in Figure 55 (7).

---

[2] Structurally Dissolvable Self-Reproducing

[3] Capable of performing any arbitrary algorithm not stretching

[4] Capable of assembly by another automaton

[5] Capable of constructing any other automaton, namely a set of cells

[6] Capable of cloning itself

[7] Capable of changes in runtime and complexity over time and generations

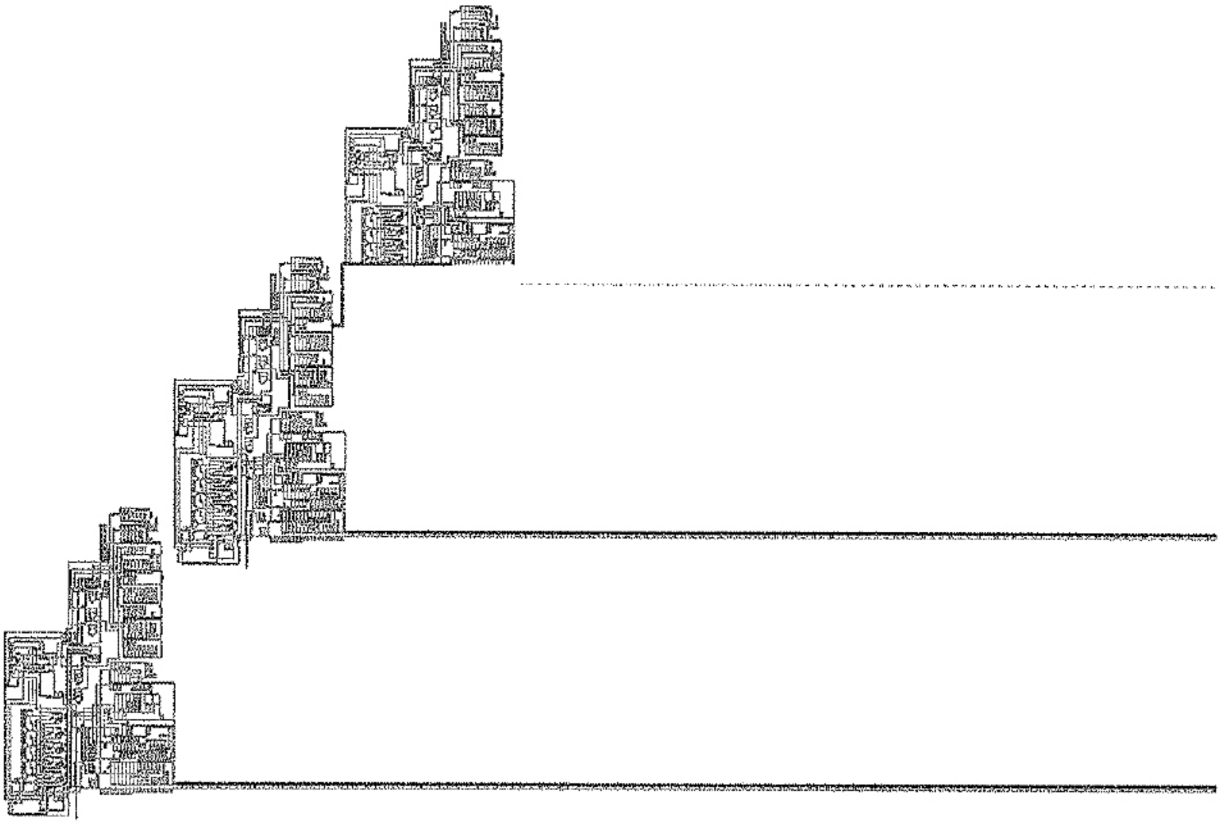


Figure 5: Three generations of the Nobili-Pesavento self-replicator

Although the automaton is thus capable of constructing and modeling "anything", such comes at the cost of exorbitant initial complexity and fragility. Calculations for time required for a new generation often lie in a range with 10^9 as a minimum magnitude (7). In addition, the machine does not have any sort of method of dealing with errors in the tape, it blindly copies them. While interesting and necessary for universality, this causes any implementation of evolution on the machine to most likely destroy it without any fruitful result.

Interestingly, given the availability of sufficient computing power, it may be possible that large numbers of constructors reading mutated tapes may happen to come across more efficient or hardy devices - a literal interpretation of a genetic algorithm to find an ideal answer.

Evaluation

The three different rule sets examined suggest that while it may be possible to accurately model an evolving, replicating organism via the use of cellular automata, the means to do so currently lie in but yet out of reach due to the immense complexity required to design such a device, as simple rules still require favorable starting positions in order to initiate any desirable behavior. As seen with Langton's loop, there exist easier means of creating such phenomena, but these smaller arrangements seem to always sacrifice some element: Langton gives up structural versatility.

evidence for th

As mentioned in the post-word to the discussion of von Neumann's universal constructor, perhaps a method to design such an organism could be to design a rule set implementing a nondeterministic genetic algorithm. Alternately, one could use an automaton to simulate such an organism living aboard a virtual reality simulation powered by a Turing-Equivalent process, or one could just design a sufficiently complicated rule set that *each cell* is such an organism or some other complex actor[8]. Of the two options, the genetic algorithm appears to be cleaner to implement, while the each-cell-an-organism approach seems too complex to justify using on an automaton level, unless one be modeling herds of such creatures.

Hence, it is likely that although useful, cellular automata are best used to process events involving large numbers of discrete actors, since some objects may ironically be in the position at which the cell structure needed to simulate such a thing would be more complex than the item itself. On the other hand, given the right "neighborhood" selections, cellular automata could excel in the field of mass prediction and modeling, given that each actor in the actual event may be simulated by a finite state machine.

once again, th
no justification
any of these
statements

---

[8] Things resembling this were once known as "boardgames"

Impact

We may try to evaluate the impact of the emergent behavior witnessed in cellular automata across various fields using the traditional IB categories.

Areas of Knowledge

Although the field of automata most strongly relates to its parent mathematical sciences, it also seems to show an effect in other fields, particularly the natural sciences.

Mathematics/Computer Science

The existence of simple rule sets capable of matching Turing Machines suggests that the limit as to what can compute may be far lower than previously thought.

The automata could also have applications in research - one could presumably construct a grid of evolving cells as a genetic method of developing sophisticated algorithms to solve particular problems (8). In addition, there should exist automata that may be used as ciphers for encoding messages, thus adding another tool to the arsenal of cryptography. (3) Furthermore, there appears to be research into automata in which each cell is individually "tick"ed, has an infinite number of states, and/or lies in a continuous, rather than discrete, grid (9).

Natural sciences

The field of digital physics is constructed around the belief that the universe may be the result or the process of a great computation, calculated as if it were a truly Cyclopean cellular automaton - therefore, all events, from the nuclear decay to supernovae, are scripted to happen and always will happen as a result of the computation continuously updating the universe - even the infamous uncertainty effect is the result of one part of the process trying to view another. However, this area does not give any conclusive proof for or against the existence of a computable world, so its "popularity" seems to be a matter of fashion. Figure 1, on the fourth page, takes a whimsical view of this idea (10) (11).

Regardless of the computing state of the universe, cellular automatons should prove useful for modeling physical process involving large numbers of "dumb" actors, such as the growth of crystals or the coordination of swarms of relatively simple nanometer-scale machines. (2)

Human sciences

The field of economics may be strongly affected by the use of cellular automata, as these programs would allow means of simulating the behavior of market players (each one a cell) and the flow of monetary resources from one hand to another on a massive scale, rather than just examining the relationship between two players - a system that may produce extremely precise and accurate approximations, but does not scale well to thousands and millions and billions of market participants.

History

The field of cellular automata, even when bundled into digital physics, probably will have little effect on the study of history, as even if one could somehow reverse the flow of time and reconstruct the past, one would still have to decipher events and minds. Furthermore, the amount of information gathering needed for such an endeavor of reconstruction is already harnessed - in a form best known as the study of history.

Arts

Seeing that as cellular automata can often generate complex patterns from simple rules, one could possibly imagine a form of aesthetic display in which the artists sift through countless amounts of possible rule sets in order to find one that generates a pleasing result when given a certain input - this parallels the current popularity of flame fractals, a similar process (in decision of the human, not in rendering of the image), although somewhat cleaner (grids of finite state machines tend to be unpredictable given differing rule sets and initial activation circumstances[9], one would require an immense amount of foresight and grasp of emergent behavior).

Ethics

This particular area could be particularly affected by the appearance of digital physics, which suggests that all one knows and all one believes, and even the ability to change such, is quite literally determined by their setting. This also reignites those believing in determinism, thus inciting more arguments about free will and the lack of or need for moral responsibility that ensues. Interestingly, the implications of the universe as an automaton seem to mesh with the beliefs of four-dimensionalism, with step and tick replacing past and future. (12)

Ways of Knowing

Although the automaton may have great effects on the various areas of knowledge, its effect on the core routes of knowledge are more muted and less visible.

Emotion

The idea that so much can be modeled through cold impersonal computations is likely to be repulsive to the emotional mind, much like the common depiction of the mind and its feelings as nothing more than simple chemical processes (or computations on a giant grid…). On the other hand, the advent of say, digital physics, could bolster the impression of the world as a mysterious place of self-organizing behavior powered by mysterious algorithms, thus perhaps lending room for some form of mysticism and awe at the scale of life.

Language

The faculty of language is not likely to be shredded by the introduction of automata, other than the introduction of new words into the common lexicon or professional jargon. This is probably due to the

---

[9] For example, one initial cell sequence, consisting of alternating "lives" and "deads", can turn the infamously pseudorandom rule 30 elementary cellular automaton into a field consisting entirely of parallel lines.

fact that cellular automata currently have no foreseen ability to analyze the diction and tone and flow of the various human tongues, although the implementation of better text-to-speech and vice-versa systems somehow using cellular automatons could be a remote possibility.

Sensory perspection

A major concern is that cellular automata may, in fact, not really be accurate models of many different systems, but that instead patterns observed in much computations are only random bits that the human mind happens to believe is, for example, a leaf; that the famous examples of models already known are in actuality extraordinary cases or of confirmation bias. However, sensory resemblance to a particular object is often stimulus enough (and sometimes even useful enough too), and thus the unknowing humans keep researching automata despite the presence of such doubts.

Reason

The power of reason, already apparently the (semiofficial) dominant player of the ways of knowing, is likely to be bolstered via the use of automata to model various objects - it serves to further declare that reason can not only understand, but also simulate and recreate all. In other words, the advancement of cellular automata as models may serve to heighten the idea that reason generates tangible results greater than that of any of the other ways of knowing, an opinion already elevated by modern science and philosophy. Therefore, cellular automata's influence will be similar to that of what was once called natural philosophy.

Conclusion

This exploration probably could have been improved by discussing the author's own attempts to implement the sort of organism described, however, this was omitted due to concerns for space and relevancy, in addition to academic usefulness.[10]

---

[10] Additional editing is a quite obvious remark to make. ?

All in all, the author feels that the results of this exploration suggest that cellular automata do indeed simulate complex systems, but that the effectiveness of such simulations may vary depending on the object to be simulated and the rule set being used for the simulation. However, should a breakthrough of mass awareness be discovered in the use of cellular automata for the simulation of natural phenomena or for art, that the fallout from such should be immense in the categories bound to the different sciences.

H → O

Works Cited

1. **Silver, Stephen A.** Life Lexicon. [Online] 2006. [Cited: September 2, 2008.] http://www.argentum.freeserve.co.uk/lex.htm.

2. **Wolfram, Stephen.** *A New Kind of Science.* Canada : Wolfram Media, Inc., 2002. ISBN 1-57955-008-8.

3. *Cryptography with Cellular Automata.* **Wolfram, Stephen.** s.l. : Crypto '85 Proceedings, Lecture Notes in Computer Science, 1986.

4. *Universality in Elementary Cellular Automata.* **Cook, Matthew.** 1, Champaign, IL : Complex Systems, 2004, Vol. 15.

5. **Cameron, J. Scott.** *An Overview Of Artificial Life with A Focus On Genetic Algorithm and Genetic Programming.* Wooster, Ohio : The College of Wooster, 2000-2001.

6. **Von Neumann, John.** *Theory of Self-Reproducing Automata.* Urbana and London : University of Illinois Press, 1966.

7. *An Implementation of von Neumann's Self-Reproducing Machine.* **Pesavento, Umberto.** Cambridge, MA : MIT - Artificial Life, 1995, Vol. 2.

8. *Evolving Cellular Automata with Genetic Algorithms: A Review of Recent Work.* **Mitchell, Melanie, Crutchfeld, James P. and Das, Rajarshi.** Moscow : In Proceedings of the First International Conference on Evolutionary Computation and Its Applications, 1996.

9. *Evolution in Asynchronous Cellular Automata.* **Nehaniv, C. L.** Cambridge, MA : Artificial Life, 2002, Vol. 8.

10. **Zuse, Konrad.** *Calculating Space.* Cambridge, MA : MIT Press (Project MAC), 1970.

11. **Rucker, Rudy.** *The Lifebox, the Seashell, and the Soul.* s.l. : Thunder's Mouth Press / Avalon Publishing Group, 2005. ISBN 1-56025-722-9.

12. **Rea, Michael C.** Four Dimensionalism. [book auth.] Michael J. Loux and Dean W. Zimmerman. *The Oxford Handbook of Metaphysics.* Oxford : Oxford University Press, 2005.

13. **Ceruzzi, Paul E.** *A History of Modern Computing.* Cambridge, MA : MIT Press, 2000.

14. **Shalizi, Cosma.** Cellular Automata. [Online] 2007. [Cited: August 28, 2008.] http://cscs.umich.edu/~crshalizi/notebooks/cellular-automata.html.

15. *Pattern Formation without Favored Local Interactions.* **Wissner-Gross, Alex.** 4, s.l. : Journal of Cellular Automata, Vol. 1.

works cited = bibliogra

used [illegible]
but not
cited?

Assessment form (for examiner use only)

Candidate session number	**0**	**0**	

Assessment criteria

		Achievement level First examiner	maximum	Second examiner
A	research question	2	2	
B	introduction	1	2	
C	investigation	1	4	
D	knowledge and understanding	1	4	
E	reasoned argument	1	4	
F	analysis and evaluation	1	4	
G	use of subject language	2	4	
H	conclusion	0	2	
I	formal presentation	3	4	
J	abstract	1	2	
K	holistic judgment	2	4	
	Total out of 36	15		

Name of first examiner: ______________________ Examiner number: __________
(CAPITAL letters)

Name of second examiner: ______________________ Examiner number: __________
(CAPITAL letters)