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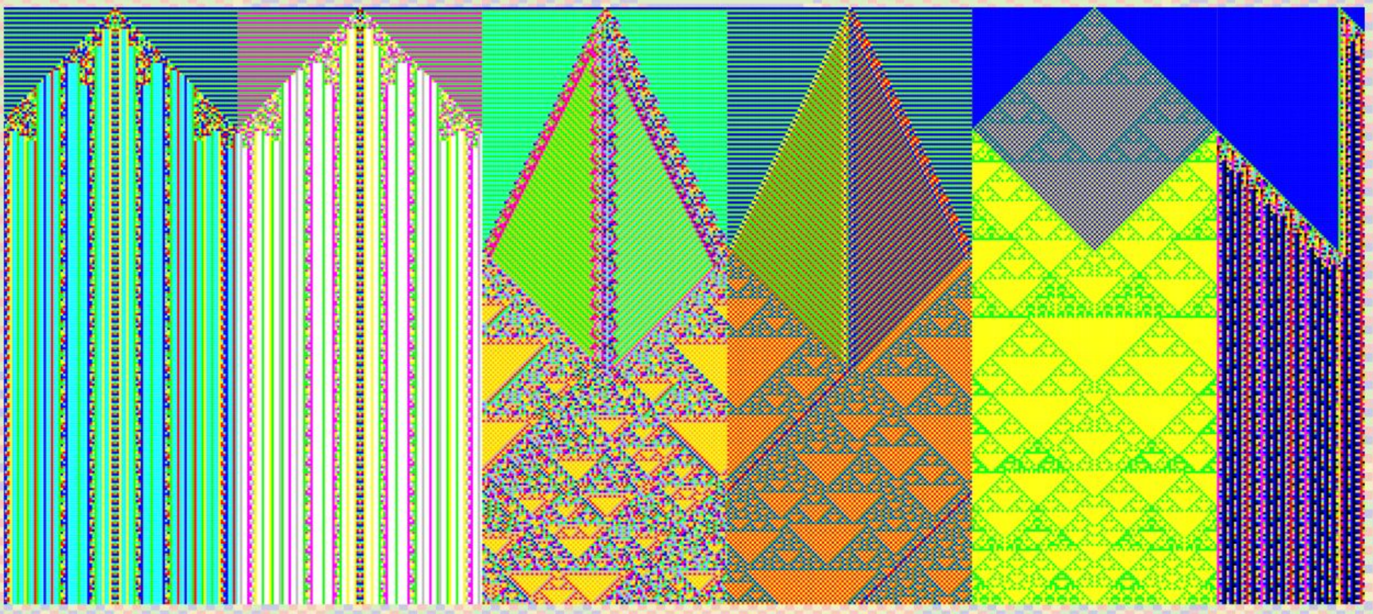

Second Asian Symposium on

CELLULAR AUTOMATA TECHNOLOGY

Indian Institute of Engineering Science and Technology, Shibpur, India

Glimpses of ASCAT 2022

ASCAT 2023

Second Asian Symposium on Cellular Automata Technology

Indian Institute of Engineering Science and Technology, Shibpur, India

02 - 04 March, 2023

Organized By

उत्तिष्ठत जाग्रत प्राप्य वरान् निबोधत
INDIAN INSTITUTE OF ENGINEERING SCIENCE AND TECHNOLOGY, SHIBPUR
भारतीय अभियांत्रिकी विज्ञान एवं प्रौद्योगिकी संस्थान, शिबपुर

Publisher

Springer

Springer AISC Series (ISSN: 2194-5357)

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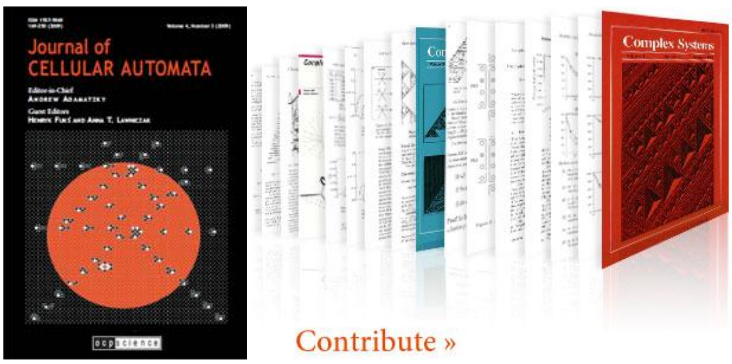

Message from Chief Patron

It is my great pleasure to pen a message for this second edition of the Asian Symposium on Cellular Automata Technology (ASCAT), which started its journey from our institute, the second oldest engineering institute, to be a platform for discussion and collaboration among scientists, academicians, and engineers for the development of Cellular Automata Technology. It highlights a brilliant accomplishment of India as a country in the vibrant research domain of cellular automata - an unconventional model of computation and one of the most emergent areas in natural computing. I am happy that two departments - the Department of Information Technology and the Department of Computer Science and Technology- play a pivotal role in organizing the “Second Asian Symposium on Cellular Automata Technology (ASCAT 2023)”. Both departments have vibrant research profiles in different research directions in synergy with cutting-edge research challenges, including Theoretical Computer Science in general and Cellular Automata in particular. I congratulate Prof. Biplab K. Sikdar and Dr. Sukanta Das for taking up the leading initiative as General Co-Chair and Technical Program Co-Chair this time. I hope this symposium will popularize research on unconventional computing among the academicians, scientists, and engineers of Asian countries and establish new international collaborations between Computer Scientists, Mathematicians, and Technologists in Asia and other parts of the world. I thank the eminent scientists who agreed to give invited talks and applaud individual authors for their salient contributions and the young scientists who participated in the Ph.D. Forum. I appreciate the efforts and contributions of Prof. Asit K. Das (Head, CST), Dr. Prasun Ghosal (Head, IT), and every faculty member and staff member, student, and participant in facilitating this event to be a successful one. I wish the conference all the success and encourage it to have a spirit of surpassing its accomplishment in the years to come.

Director
Indian Institute of Engineering Science and Technology, Shibpur

Message from General Chair

ASCAT 2023 is the second edition of the Asian Symposium on Cellular Automata Technology and an event of Cellular Automata India. It takes place at Indian Institute of Engineering Science and Technology (IIEST), Shibpur, on March 2-4, 2023 in hybrid mode. It is sponsored by IIEST, Shibpur, SPARC and SERB, Govt. of India. Fellowships for the financial assistance for Indian researchers and students, to attend the symposium, have been provided by SERB, Govt. of India.

Since the pioneering work of John von Neumann in 1950's, studies on cellular automata have been developing in diverse research areas ranging from theories and applications. Cellular automata are a model of discrete spatiotemporal systems, and hence they are applicable to wide varieties of natural and artificial systems, such as physical, biological, social, and parallel computing systems. The aim of ASCAT is to provide a place of exchanging ideas of theoreticians and engineers for creating novel theories and technologies on cellular automata.

ASCAT 2023 is proud to have Deepak Dhar, Alyssa M Adams, Katsunobu Imai, Ferdinand Peper, K. Ramachandra Rao, and Tim Otto Roth as invited speakers. This time ASCAT contains PhD Forum with nine talks. It is a new attempt for exchanging ideas of young scholars, and for advancing their research studies. A panel discussion on *Art, Mathematics and Computation*, and an exhibition on *Art of Cellular Automata* are also planned in ASCAT 2023. These will open a new vista on cellular automata, and will stimulate their technical developments. We believe all these activities in ASCAT 2023 will enhance future researches on cellular automata.

On this occasion, we express our gratitude to our Chief Patron, IIEST Officials, Sponsors, Publishers, Organizing Committee members, Volunteers and the Participants for ensuring the grand success of ASCAT 2023.

Biplab K Sikdar and Kenichi Morita
General Co-chairs

Message from Program Chair

A warm welcome to the second edition of the Asian Symposium on Cellular Automata Technology (ASCAT) series, going to be held during March 2-4, 2023. The series was started in 2022 under the aegis of SPARC (*Scheme for Promotion of Academic and Research Collaboration*), an initiative of the Ministry of Human Resource Development, Government of India, for the project titled "Exploring Cellular Automata Model for Hardware Security". SPARC continues to support the ASCAT 2023. This event is also sponsored by SERB (Science and Engineering Research Board), Government of India and is officially hosted by Indian Institute of Engineering Science and Technology, Shibpur (IIEST Shibpur), India in hybrid mode.

ASCAT aims to provide a premier platform for academicians and researchers to discuss the most recent advances and challenges of theory and applications of cellular automata. Since the late 1980's, the cellular automata have been used as excellent tools for providing solutions to the technological problems, particularly in the domain of VLSI Design and Test, Pattern Recognition and Classification, Security and Image Processing. Cellular Automata Technology includes all these issues and promises to provide solutions to many other technological challenges. Since technology cannot mature without a solid theoretical base, the ASCAT targets theoreticians and engineers to exchange their views and ideas.

We are indebted to our invited speakers, Tim Otto Roth, Deepak Dhar, Katsunobu Imai, Ferdinand Peper, K. Ramachandra Rao and Alyssa M Adams, who kindly accepted our invitation to deliver talks in ASCAT 2023. This time we have introduced a special session on *Beauty in Cellular Automata*, and a PhD Forum. An exhibition on *Art of Cellular Automata* is also being floated as a part of the special session. There was an open call for contribution in the exhibition. Apart from that, we also collected patterns for the exhibition. We are grateful to Mr. Amitabh Sengupta, a renowned artist, who kindly agreed to curate the exhibition. We are also thankful to Mihir Chakraborty, Tim Otto Roth, Subhasis Nibirh, Deepak Dhar and Amitabh Sengupta who kindly agreed to take part in a panel discussion on *Art, Mathematics and Computation.* For the PhD Forum, we have invited the Scholars who have completed their PhD program in the recent past or on the verge of completion, in the domain of cellular automata, to submit synopsis of their works. The synopsis of 9 PhD Scholars have been accepted for oral presentation.

ASCAT 2023 has received 30 submissions in total, out of which 21 submissions are for contributed talks, and fourteen among them were accepted for publication. We are thankful to the Program Committee members who have actively participated in the review process, and worked hard to select the best forteen papers for presentation. We also thank the authors for their contributions and hard work that make the event possible.

'*Cellular Automata India'*, a research group which was created during the pandemic, has played a leading role in making the event successful. We are thankful to the group. The group has organized a summer school in 2022, named where students as well as faculty members have participated. ASCAT 2023 has received six submissions as the outcome of the research work initiated during the school.

Finally, we would like to thank the members of the Organizing Committee, who have made it possible to organize the event physically after the pandemic. We are also grateful to the members of the departments of Information Technology, and Computer Science and Technology, IIEST Shibpur for extending their support towards the event.

We hope that you will enjoy the symposium. We welcome you once again to the ASCAT 2023!

Sukanta Das and Genaro J Martinez
Program Co-chairs

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ABOUT THE SYMPOSIUM

This is the second edition of the Asian Symposium on Cellular Automata Technology (ASCAT) to be held during March 02-04, 2023. The first edition of ASCAT (ASCAT 2022) was held during March 03-05, 2022 in online mode. ASCAT is the annual event of *Cellular Automata India*. This year, the symposium will be officially hosted in the campus of Indian Institute of Engineering Science and Technology, Shibpur (IIEST Shibpur), West Bengal, India. Target of the symposium is two-fold: to nurture the theories of cellular automata, and to explore the cellular automata as technology. The symposium is unique by its type - it does not look upon cellular automata as only mathematical tool, but also as technology.

Hosted By:
Indian Institute of Engineering Science and Technology (IIEST), Shibpur
Howrah, West Bengal, India - 711103

In association with: Cellular Automata India

Webpage:
https://www.cellularautomata.in/ascat2023

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About Institute

Founded on 24 November 1856, the Indian Institute of Engineering Science and Technology, Shibpur is the 2nd oldest Engineering Institute of India. Undergoing 6 different names in its 163 years of heritage, it has nurtured some of the great engineers and technologists. IIEST is a public technical university recognized as an “Institute of National Importance” under MHRD. It is also one of the recognized institutes in the “Council of National Institutes of Technology”. IIEST is well recognized worldwide due to its huge alumni base and is reputed for offering high calibre students in every aspect of Engineering. IIEST Shibpur has sixteen academic departments, eight schools of excellence, and two multidisciplinary centers. It is also one of the premier institutes for carrying out research in India and its contributions are recognized all over the country. This place beholds a serene and calm environment which helps students to work more passionately towards their dreams and aspirations.

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Program Schedule of ASCAT 2023

Venue: M N Dastur Seminar Hall, IIEST Shibpur

(All Timings are in IST)

Day 1: 02 March 2023	
Morning Session	
09:00 - 09:30	Inauguration
09:30 - 10:00	Opening of Exhibition on Art of Cellular Automata
10:00 - 10:30	TEA BREAK
10:30 - 11:30	Invited Talk Title: A new kind of science – a new kind of art? Towards an aesthetics of complexity Speaker: *Tim Otto Roth, Conceptual Artist and Scholar, Germany*
11:30 - 13:00	Panel Discussion Title: Art, Mathematics, Computation Panelists: *Mihir Chakraborty, Jadavpur University* *Amitabh Sengupta, Artist* *Subhasis Nibirh, IIEST Shibpur* *Tim Otto Roth, Conceptual Artist* *Deepak Dhar, IISER Pune*
13:00 -14:30	LUNCH BREAK
Afternoon Session	
14:30 - 15:30	Invited Talk Title: On visualization of three-dimensional cellular automata and tilings with head-mounted display. Speaker: *Katsunobu Imai, Hiroshima University, Japan*
15:30 - 16:00	TEA BREAK
16:00 - 17:30	Contributed Talks (20 minutes each) • A Cellular Automata Based Clustering Technique for High-Dimensional Data — *Abhishek S, Mohammed Dharwish, Amit Das, and Kamalika Bhattacharjee* • Cellular Automata based Sentiment Analysis — *Elizabeth M J, Akash Kumar Panda, Parimal Pal Chaudhuri, and Raju Hazari* • Cellular Automata with Large Cycle Generator — *Sukanya Mukherjee and Sumit Adak* • A Cellular Automata Based Approach on Assessment of Thickness of Stratified Mineral Deposits — *Soumyadeep Paty, Sumit Adak, and Supreeti Kamilya*

Program Schedule of ASCAT 2023

Venue: M N Dastur Seminar Hall, IIEST Shibpur
(All Timings are in IST)

Day 2: 03 March 2023	
Morning Session	
09:30 - 10:30	**Invited Talk** Topic: Some Cellular Automata models studied in Physics Literature Speaker: *Deepak Dhar, IISER Pune, India*
10:30 - 11:00	TEA BREAK
11:00 - 13:00	**Contributed Talks (20 minutes each)** • Representation of Evolution of One-dimensional Homogeneous Cellular Automata Using Monoid Action — *Sreeya Ghosh and Sumita Basu* • Layered Cellular Automata and Pattern Classification — *Abhishek Dalai and Subrata Paul* • On Non-linear Maximal Length Cellular Automata — *Sumit Adak and Sukanya Mukherjee* • Analysis of One-Dimensional 4-State Cellular Automata Rules and DNA Evolutions. — *Arijit Ghosh, Suchitra Behera, Sagarika Padhi and Sudhakar Sahoo* • Design and Analysis of Regular Clock based 2:4 Decoder using T-Gate in QCA. — *Amit Kumar Pramanik, Sudipta Debnath, Jayanta Pal, and Bibhash Sen*
13:00 -14:30	LUNCH BREAK
Afternoon Session	
14:30 - 15:30	**Invited Talk** Title: Cellular Automata in vehicular traffic flow modelling Speaker: *K Ramachandra Rao, IIT Delhi, India*
15:30 - 16:00	TEA BREAK
16:00 - 17:30	**Contributed Talks (20 minutes each)** • Modeling Spread of Contagious Disease by Temporally Stochastic Cellular Automata — *Subrata Paul and Kamalika Bhattacharjee* • Genealogy Interceded Phenotypic Analysis (GIPA) of ECA Rules — *Rinkaj Goyal* • Isomorphism in Cellular Automata — *Sukanya Mukherjee, Vicky Vikrant, and Kamalika Bhattacharjee* • A cellular automaton model for language shift in Algeria — *Rezki Chemlal* • Cellular Automata based Simulation of Intergranular Fracture using Hexagonal Discretization — *Tarun Kumaar M K, Deeraj Harikrishnan, and P G Kubendran Amos*
18:30 - 21:30	**Cultural Program and Conference Dinner** Talk on *Moments of Legacies: Through the Prism of Lokayata* Speaker: Shaktinath Jha, Eminent Folklorist

Program Schedule of ASCAT 2023

Venue: M N Dastur Seminar Hall, IIEST Shibpur
(All Timings are in IST)

Day 3: 04 March 2023	
Morning Session	
09:30 - 10:30	**Invited Talk** **Topic: What Cellular Automata Tell Us About Life** *Speaker: Alyssa Adams, University of Wisconsin-Madison, United States*
10:30 - 11:00	TEA BREAK
11:00 - 13:00	**PhD Forum: Session 1 (20 minutes each)** ● Cyclic Properties of Cellular Automata — *Sukanya Mukherjee, Supervisor: Sukanta Das* ● Distributed Computing on Cellular Automata with Applications to Societal Problems — *Souvik Roy, Supervisor: Sukanta Das* ● Theory and Applications of Cellular Automata for Detection and Mitigation of Hardware Trojan Attacks Targeting Cache Performance in a Many-core System — *Suvadip Hazra, Supervisor: Mamata Dalui* ● Cellular Automata: Chaos, Convergence and Unification — *Supreeti Kamilya, Supervisor: Sukanta Das* ● Scalable circuit design scheme for parallel computing on an asynchronous cellular automaton — *Wenli Xu, Supervisor: Jia Lee*
13:00 -14:30	LUNCH BREAK
Afternoon Session	
14:30 - 15:30	**Invited Talk** **Title: Brownian Circuits: from Computation to Neural Networks** Speaker: *Ferdinand Peper, National Institute of Information and Communications Technology, Japan*
15:30 - 16:00	TEA BREAK
16:00 - 17:30	**PhD Forum: Session 2 (20 minutes each)** ● Chaos and Isomorphism in Cellular Automata — *Vicky Vikrant, Supervisor: Kamalika Bhattacharjee* ● Implementation of CBIR for Medical Images using Cellular Automata — *Rupashri Barik, Supervisor: Najma B. J Naskar* ● The rules L(p,q) — *Nassima Ait Sadi, Supervisor: Rezki Chemlal* ● Strictly periodic points of cellular automata with almost equicontinuous points — *Nacira Allaoua, Supervisor: Rezki Chemlal*
17:30 -18:00	Valedictory
18:00	ASCAT 2023 CLOSES

Invited Talks

Invited Talks

Title: A new kind of science – a new kind of art? Towards an aesthetics of complexity
Speaker: Tim Otto Roth, German conceptual artist, composer and scholar

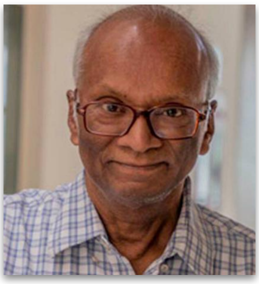
Abstract. With his seminal book Stephen Wolfram postulated "A New Kind of Science" for the mathematical model of cellular automata. Focusing a 'new kind of art' this paper changes perspective asking for a new aesthetics in a more philosophical sense. Here it reflects the power of the self-organization principle creating complexity based on a minimal set of conditions. Looking back to history, the complete discretization of space, time and state inherent to automata was considered in two complementary conceptual ways: On the one hand it was interpreted as a discrete "caricature" (Bossel 1994) of dynamical systems, especially of models based on continuous differential equations.On the other hand it was comprehended as a digital "calculating space" (Zuse 1969) representing more fundamental physics underlying existing physical models as for instance in quantum physics ('t Hooft 2015). In a more methodological sense, there are two complementary aesthetics reflecting cellular automata either visually or more inspired by music:
- The "morphological" approach practises a visual-formal analysis and classification of activity patterns revealing similarities to the use of visual analogies in art history.
- A musical approach works on a higher abstraction level. Here the behaviour of automata could be analyzed statistically and translated into more temporal patterns. In a special case, a meta behaviour can be highlighted as the composer Iannis Xenakis used it in a sequence of his piece "Horos" to switch instrumentation in case of certain cell configurations (Solomos 2005).
This aesthetic conceptualization finally ends up in the question, if there are visual patterns and sound sequences inherent to automata. Last but not least the automata aesthetics can be understood also as a plea for the arts switching from the simplicity of beauty towards the sublimity of complexity.

Title: Cellular Automata in vehicular traffic flow modelling
Speaker: K Ramachandra Rao, Indian Institute of Technology, Delhi

Abstract. This talk focuses on identifying Cellular Automata (CA) as one of the tools to model traffic flow. Beginning with the one of the earliest models by Nagel and Schreckenberg, we trace the journey of CAs and their applications in various contexts of traffic flow modelling. The moving traffic could comprise pedestrians and human driven vehicles. CAs recently are finding use in studying Connected and Autonomous Vehicles (CAV) and their influence on capacity and safety augmentation. Owning to their inherent simplicity and discreteness, they can be used at different levels of aggregation. It was found that by relaxing certain rules, CAs can be useful in modelling not only uninterrupted facilities such as main roads (Arterials/Expressways) but also interrupted facilities such as traffic lights. We try to highlight the effect of vehicle heterogeneity on traffic flow on urban arterials and junctions with traffic lights.

Title: Some cellular automaton models studied in physics literature
Speaker: Deepak Dhar, Indian Institute of Science Education and Research, Pune

Abstract. In this talk, I will describe some of the cellular automaton models that have been discussed in physics literature. The aim is to emphasize the diversity of the models, and the real world problems for which these serve as simple models. I will try to show, by examples, the questions of interest to



physicists, and the techniques used to determine these. I will start by discussing the box-ball system as a simple model showing "solitons". Then I discuss the abelian distributed processors model, and its special case the abelian sandpile model on a square lattice. The abelian group structure, characterization of the steady state, and the fat tail in the distribution of avalanches will be discussed. Lastly, I will discuss briefly some probabilistic cellular automata models for modelling relaxation of spins of a magnet, and epidemic spread. I will mention some recent work on stochastic predator-prey system called chase-escape percolation.

Title: On visualization of three-dimensional cellular automata and tilings with head-mounted display
Speaker: Katsunobu Imai, Hiroshima University, Higashi-Hiroshima, Japan

Abstract. We created a simulator using an AR-type head-mounted display for visualization of 3D cellular automata and tiling, and simulated various 3D CAs including life games. Using these simulators, we visualized a 3D version of Penrose tiling, one of the well-known quasiperiodic tiling.

Title: What Cellular Automata Tell Us About Life
Speaker: Alyssa M Adams, University of Wisconsin-Madison, United States

Abstract. Cellular automata have a long and rich history of being computational worlds where researchers can study the dynamics of living systems. While these worlds evolve according to relatively simple rules, the resulting state-space dynamics can be complex enough to be irreducible. This is ideal for studying aspects of living systems. Living systems are bound by the laws of physics (and chemistry), yet they cannot be described or predicted using these same laws. Instead, biology evolves according to emergent laws on different scales of spatial organization that continuously change over time. In this talk, I briefly overview the history of cellular automata being used to study living systems and then introduce modern approaches. I also summarize my current and recent work on using cellular automata to understand various aspects of life, including open-endedness and emergent functionality.

Title: Brownian Circuits: from Computation to Neural Networks
Speaker: Ferdinand Peper, National Institute of Information and Communications Technology, Kobe, Hyogo, Japan

Abstract. Brownian circuits use the fluctuations of signals, implemented by tokens, to drive computation. They have been shown to significantly reduce the required complexity of circuits or platforms implementing these circuits, such as Cellular Automata. The original model of Brownian circuits eyed computation models in which operations on individual tokens are at the core. This paper discusses models in which collections of tokens are used as signals in Brownian circuits, in particular neural networks. We show how previously proposed Brownian circuit primitives can be employed to implement neural functionality,

Contributed Talks

Contributed Talks

Title: A Cellular Automata Based Clustering Technique for High-Dimensional Data

Author: Abhishek S, Mohammed Dharwish, Amit Das and Kamalika Bhattacharjee

Abstract. The paper reports an *efficient* clustering technique for high-dimensional data using cycles of reversible finite cellular automata (CAs). As any arbitrary cellular automaton (CA) is not useful for maintaining less intra-cluster and high inter-cluster distance essential for an effective clustering, first the candidate CA rules have been identified based on theoretical properties of *information flow and self-replication*. Three stages of hierarchical clustering are incorporated over the encoded real dataset with any number of features. Because of the inherent parallelism of our algorithm, its running time is polynomial to the number of objects in the dataset which avoids the limitations of the existing CA-based clustering techniques. With respect to various standard benchmark performance metrics,our algorithm is at par with the other existing algorithms.

Title: Cellular Automata based Sentiment Analysis

Author: Elizabeth M J, Akash Kumar Panda, Parimal Pal Chaudhuri and Raju Hazari

Abstract. Analyzing the opinion of human beings such that there is continued development as per individual's needs is one of the primary objectives of sentiment analysis. To understand the perception of customer's reviews and their opinions, the data retrieved are organized in a structured manner. There is always room for people's reviews and feedback in all elds of society. So, if we are able to distinguish whether those opinions are positive, negative, or neutral then the services of various resources can improve significantly. This paper focuses on the use of cellular automata to determine the sentiments from the reviews as positive or negative. Our approach produces 92.44% of accuracy for the sentiment tweets dataset by using various parameters which are extracted from the cycle length values generated by elementary cellular automata without using any kind of pre-trained language models.

Title: Cellular Automata with Large Cycle Generator

Author: Sukanya Mukherjee and Sumit Adak

Abstract. This paper presents an efficient mechanism on the design of n-cell reversible cellular automaton which can produce a cycle of a given length k where n is “near optimal”. Here, we develop an operator which allows to design a cellular automaton of size n1+n2 having length lcm(ℓ1, ℓ2) by using two cellular automata of sizes n1 and n2 having cycle lengths ℓ1 and ℓ2 respectively. Our approach is to apply a stochastic method to synthesize cellular automata having large cycles in their configuration spaces, and then apply the operator repeatedly on these cellular automata to design the target automaton. We show that this is an optimization problem, and then apply a novel biologically inspired algorithm to solve the problem.

Title: A Cellular Automata Based Approach on Assessment of Thickness of Stratified Mineral Deposits

Author: Soumyadeep Paty, Sumit Adak and Supreeti Kamilya

Abstract. There has always been a large contribution of mineral industry to a nation’s economical growth. Various characteristics of mineral deposits, such as grade, thickness and density are estimated by different geostatistical methods like krigging, copula, distance weighting and conditional simulation methods. Two popular distance weighting methods are inverse distance and inverse squared distance weighting methods. In the present work, we estimate thickness of stratified deposit that is, coal seam.

The results obtained by directly applying inverse distance method and inverse squared distance method are shown in the paper. Two cellular automata (CAs) with rules as the inverse distance weighting and inverse squared distance weighting are used in the study to estimate thickness of the coal seam. It is observed that the use of CA in the estimation gives similar result as the other geostatistical estimation methods. However, cellular automata greatly simplifies the techniques of estimation and provides output in lesser time. The time taken by directly applying the distance weighting methods and the CAs are provided in the paper.

Title: Representation of Evolution of One-dimensional Homogeneous Cellular Automata Using Monoid Action

Author: Sreeya Ghosh and Sumita Basu

Abstract. Evolution of a cellular automaton (CA) is governed by the global transition function of the CA. The set of all possible global transition functions of a homogeneous cellular automaton forms a monoid. In this paper we have explored some of the properties of the action of a monoid on a set. Further we could use the properties of monoid action studied here to represent evolution of a one-dimensional homogeneous cellular automaton.

Title: Layered Cellular Automata and Pattern Classification

Author: Abhishek Dalai and Subrata Paul

Abstract. This paper proposes a new kind of cellular automaton (CA) model, where every cell's update is divided into two layers. The CA employs a single rule in the first layer, but the system is influenced by some outside noise in the second layer. The lower layer (layer 0) rule is represented by f, whereas the upper layer (layer 1) rule is represented by g (noise rule). This type of cellular automata is named as Layered Cellular Automata (LCAs). The dynamical behavior of these CAs has been studied to identify the LCAs which converge to a fixed point from any seed. Finally, this kind of CA is used to construct a two-class pattern classifier, and assess the effectiveness in comparison to existing pattern classification techniques.

Title: On Non-linear Maximal Length Cellular Automata

Author: Sumit Adak and Sukanya Mukherjee

Abstract. This paper explores *non-linear maximal length cellular automata*. We show that a cellular automaton (CA) having a *blocking word* in the information flow of that automaton can never be a maximal length CA. In addition, the notion of *isomorphism* of cellular automata is applied to devise a decision algorithm for finding non-linear maximal length CA using linear maximal length cellular automaton.

Title: Analysis of One-Dimensional 4-State Cellular Automata Rules and DNA Evolutions

Author:Arijit Ghosh, Suchitra Behera, Sagarika Padhi and Sudhakar Sahoo

Abstract. The main purpose of this research article is to analyse the different mutation rules applied in DNA sequences that are characterized by their State Transition diagrams (STDs) and Space-Time diagrams like Cellular Automata (CA). These set of rules evolved from the DNA constituents of nucleotide bases that is Adenine, Thymine, Cytosine and Guanine generating a huge number of patterns. Various colour patterns are generated using python programming and their mutation behaviours are characterised by their STDs. The **256** rules are classified into **5** different classes based on the number of nucleotides fixed or varying in the rule definition. Similar looking STDs are grouped to form equivalence classes and their graph theoretic properties have been studied. The impact of Space-Time diagrams to study point mutations and amino acid sequences is highlighted. A hybrid architecture has been proposed which combines a non-deterministic automaton and a deterministic CA rule for point mutation. For analysing the dynamics of amino acid sequences **4**-state **3**-neighbourhood CA rules have been characterised with the help of reflection, conjugation and conjugate-reflection operators. The results obtained from our study will help in analysing the CA rules and other base-**2** and base-**4** dynamical systems.

Title: Design and Analysis of Regular Clock based 2:4 Decoder using T-Gate in QCA

Author: Amit Kumar Pramanik, Sudipta Debnath, Jayanta Pal and Bibhash Sen

Abstract. The CMOS technology experiences enormous challenges in digital logic design due to its lower device density and greater power dissipation. Quantum-dot-cellular automata (QCA) has emerged as one of the most suitable alternatives to overcome the flaws. The fundamental component of QCA is the cell, each containing two electrons within it. A majority gate can realize the basic gates, whereas a T-gate is capable of producing NAND and NOR logic. On the other side, regular clocking has a significant impact on QCA in realizing efficient and reliable circuits. This article proposes a novel design of 2-to-4 decoder circuit embedding with the regular clocking scheme. The T-Gate logic is utilized for the proposed design. The efficacy of the proposed design is investigated in respect of cost, fault-tolerant capability, and energy dissipation. The experimental result verifies the efficacy of that proposed design compared to the previous designs.

Title: Modeling Spread of Contagious Disease by Temporally Stochastic Cellular Automata

Author: Subrata Paul and Kamalika Bhattacharjee

Abstract. This paper proposes a new variant of CA called *Non-uniform Temporally Stochastic Cellular Automata* (NTSCAs) as a natural choice for modeling spread of any highly contagious deadly virus that can cause an epidemic/pandemic like situation. This work also introduces the concept of *distant neighbor* to model the transmission of virus over a long distance which happens through travel of asymptotic careers via flights. A set of properties are identified which represent the essence of this spread. These properties are incorporated into the NTSCA using *flow of information* and *partial blocking* of information to synthesize the perfect rules satisfying the nature of any specific deadly virus as well as the mutation of the viruses and also the precautionary steps employed at times. As a case study, COVID-19 is successfully simulated using these CAs and matched with real-time data.

Title: Genealogy Interceded Phenotypic Analysis (GIPA) of ECA Rules

Author: Rinkaj Goyal

Abstract. This study demonstrates an alternative ECA rules classification using information-theoretic measures with 88 minimal representatives of ECA rules. It proposes using entropy-time diagrams (variation in BiEntropy values with time) to compare ECAs behavior, where two configurations may correspond to the same approximate information content despite their visual differences in the space-time diagrams. The genotype of an ECA rule, which is perceived as the amount of information processed, is captured through four proposed measures, i.e., DiffEntropy (DE), SimConfigOrdered (SCO), SimConfigImmediate (SCI), and SimConfigFluctuation (SCF). By clustering the temporal sequences of

entropy values of different rules using dynamic time warping (DTW), a Genealogy Interceded Phenotypic Analysis (GIPA) of 88 ECA rules is proposed. This study is restricted to synchronous ECA with periodic boundary conditions.

Title: Isomorphism in Cellular Automata

Author: Sukanya Mukherjee, Vicky Vikrant and Kamalika Bhattacharjee

Abstract. Two cellular automata (CAs) are said to be isomorphic if their respective configuration transition diagrams are isomorphic. In this paper, we propose two schemes to determine the set of CAs that are isomorphic to any given cellular automaton (CA). Our first procedure works by permutation of the states of a set of cell positions of the CA. This methodology can be applied to generate $(d!)^n - 1$ isomorphic cellular automata each of which will maintain the same neighborhood as the given n-cell d-state CA. Whereas, our second procedure does an exchange of the cells at different positions; we show that the isomorphic cellular automata generated in this manner may have larger neighborhood than the input CA, depending on the range of cell positions exchanged. An extensive experimentation has been done to establish the efficacy of our schemes.

Title: A cellular automaton model for language shift in Algeria

Author: Rezki Chemlal

Abstract. Intragranular fracture is the propagation of a crack along the weakened grain boundaries of a material. It can lead to catastrophic material failure and is often caused by hostile environmental influences such as high stresses. Such cracking is quite challenging to model in a conventional theoretical manner so atomistic models are often employed as an ideal tool for the study of fracture mechanisms in metallic materials. The uniqueness of cellular automata lies in its ability to generate a temporally varying dynamic system based on few straightforward local rules. This work compares the results of conventional square discretization against the relatively unexplored hexagonal discretization of the domain in the modelling of a polycrystalline microstructure. The propagation and widening of intergranular fracture in the generated microstructure are then simulated using an asynchronous secondary transition function. The morphology of the obtained crack is altered by the parameters of the secondary function till the characteristic wedge shape observed in molecular dynamics-based simulations is obtained. Furthermore, in polycrystalline microstructures, the model is capable of navigating triple junctions with the aim of maximizing grain misorientation to lower the energy of the system. Thus, the model may have potential applications as a path-finding algorithm outside the field of materials science.

Title: Cellular Automata based Simulation of Intergranular Fracture using Hexagonal Discretization

Author: Tarun Kumaar M K, Deeraj Harikrishnan and P G Kubendran Amos

Abstract. We are interested in developing a language shift model in the case of Algerian using 2 dimensional cellular automata. Our model takes in account 4 languages : Amazigh, Arabic, French and English. We use a particular coding of cell states in order to measure the social pressure towards the use of English or Amazigh language. In this paper we detail the model and give some insights about its dynamical properties.

PhD Forum

Cyclic Properties of Cellular Automata

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Humans have been intrigued about natural phenomena from time immemorial. Any untutored event instigates them to deduce some inference rationally. It is a common observation that most systems are in a continuous process of aging that leads to their decay and wear out with time. However, this concept of aging seems relative to the perspective of view. For example, the Sun and the solar system are constantly aging and shall eventually die out, but to a general observer these are stable.

Many of the efforts in natural science have been earmarked to categorize systems based on whether they seem stable or in flux relative to us. These mainly rely on some models that mathematically capture the essential features of the physical systems [1]. Let us consider the example of heat flow. The second law of thermodynamics states that heat never spontaneously flows from colder body to warmer body; thus the process of heat flow is *irreversible*. On the other hand, formulation of the energy conservation law in terms of forces between indivisible elements of the bodies establishes Newtonian mechanics as fundamentally *time-reversible*; mathematically, such transformation is *bijective*. Most natural phenomena are reversible when observed from the microscopic viewpoint.

Many physical phenomena (such as traffic flow, forest fire, growth of cancer cells) can be expressed as many-body systems. Here, instead of considering individual elements, the system is considered as a collection of components distributed over space and evolving in time through local interactions amongst themselves [2]. Often, these interactions can be represented by a set of rather simple rules that captures the evolution of a component based on its neighbors. Cellular automaton (CA) is one of the modeling tools introduced in this context to provide a simple description of the complex natural systems.

A Cellular Automaton (CA) consists of a grid of elements termed as *cells*; a cell has a discrete *state* and the cell's state space is finite. The collection of states of all cells at a time step is called as *configuration*. CA evolves in discrete time and space. The state of a cell gets updated over time steps based on a *rule*, which is a *computable* local transition function on the states of the cell and its neighbors. In other words, the rules modify synchronously the state of each cell according to its state and those of the adjacent cells. A CA with m-neighborhood architecture represents that a cell updates its state based on the state values of its m-neighbors (including the cell itself). Thus, in every time step, a configuration transits to its *next configuration* by applying a rule to every cell of CA; the former configuration is said to be the predecessor of the latter. A configuration is said to be *reachable* if it has at least one predecessor. Classically, a CA follows the same rule at all cells (*uniform* CA) but recently there has also been a focus on *non-uniform* CA that follows different rules at different cells.

The above principles make the design of CAs quite intuitive and ingenious to model natural phenomena [3], [4], [5]. The aspect of reversibility of most natural phenomena can be mimicked by *reversible* CA, a class of CA that preserves information [6]. The study of reversible CA was initiated by Hedlund [7] and Richardson [8]. The field of reversibility of finite CA has gained immense popularity over the last few years [9], [10], [11], [12].

In a reversible CA, every configuration is reachable. Clearly, the transition function of such a CA must be bijective, so that its inverse exists. Traditionally, CAs are defined over infinite lattice with infinite configurations. In practice, however, one can not work with an infinite lattice; thus the lattice size (number of cells) has to be *finite*. If a CA has n number of cells, we call such CA as n-cell CA and in other words, we can say that the *size* of the CA is n. In a reversible CA of finite size, every configuration can be reached from itself and thus *cycles* are formed; elseways, some configurations do not belong to any cycle and such a CA is termed as *irreversible* CA. Therefore, the configuration space of any reversible CA of finite size represents cyclic space. Many physical systems can be modeled by such cyclic spaces; for example, determining the steady state or dynamic equilibrium of a natural process in thermodynamics can be modeled using cyclic spaces. In this dissertation, we study the *cyclic behavior of finite* 1*-dimensional three neighborhood binary CAs with null boundary condition*.

Motivation and Objectives of the Dissertation

During evolution, a CA hops from one configuration to another configuration; thus a sequence (or path) of configurations can be formed where a particular configuration in the sequence is reachable from any configuration appearing before it in the sequence. This brings the notion of a decision problem - *Configuration REachability Problem* (CREP). Given a source configuration and a destination configuration, the goal of CREP is to decide whether the destination configuration is reachable from the source one. CREP is undecidable for

1-dimensional infinite CAs [13]; so researchers considered this problem for finite CAs [13], [14] where CREP is shown to be PSPACE-complete [13]. It has also been shown that CREP is NP-intermediate for the CAs with additive rules [14]. However, all works on CREP focus on the uniform CAs only, this motivates us to study CREP for non-uniform CAs in this dissertation.

The special case of CREP with the same source and destination configurations confirms the existence of a cycle in CA configuration space. Similarly, in a reversible CA, the existence of a path among a set of given l configurations establishes the presence of a cycle of length at least l. However, CREP is computationally demanding, impelling us to find the *cycle structure* of CA through some alternate mechanisms. If a CA generates μ_1 cycles of length l_1, μ_2 cycles of length l_2, and so on, then the cycle structure of that CA is $[\mu_1(l_1), \mu_2(l_2), \cdots]$. The cycle structure of a CA is a well studied problem (see [15], [16], [17]), with both theoretical interests and applications [9], [16], [18]. CAs with large length cycles are in demand for generating Pseudo-random patterns, to test VLSI circuits (see [9], [16]) etc., CAs which have cycles of equal length are used in block cipher generation [18]. All these works about cycle structure focus on linear CAs only. In a more recent work [19], both linear and non-linear CAs have been considered for the following problems: (i) a decision algorithm to figure out whether a given CA configuration belongs to a cycle or not of the input CA; (ii) the total number of configurations that belong to the cycles of a CA; (iii) synthesis of CAs with only *point state attractors* (cycles of length one) which have great contributions in pattern recognition. However, [19] mainly covers irreversible CAs, and reversible CAs have not been explored to a great extent. Moreover, though a small piece of work is done on the cyclic properties of non-linear CAs, till date, no method is available for evaluating the cycle structures of an arbitrary non-linear CA. This dissertation aims to devise some strategies which compute the cycle structures of both irreversible and irreversible non-linear CA efficiently.

Note that the problem of finding the cycle structure of a CA explained above returns a summarized representation of CA cyclic space. The converse problem is equally appealing and challenging, where the aim is to deduce some properties of a CA given its cycle structure. To this effect, we focus on the cyclic space of reversible cellular automata and characterize the cyclic spaces of CAs and categorize the CAs into different classes.

Our next objective is to study the lengths of cycles of cellular automata. There has been a theoretical challenge since late 1980s to the CA community to get the maximum possible cycle length for a CA. Prior works have addressed this problem by considering the *maximal length* CAs (a CA that can generate a cycle of length $2^n - 1$ where the CA has n number of cells) [16], [20]. It has already been seen that maximal length CAs are mainly non-uniform linear CAs, and generation of maximal length CAs is related to primitive polynomials. The maximum degree of available binary primitive polynomial known till date is limited (see [21]). Moreover, the complexity of generating the primitive polynomial is exponential. Hence, given the inherent hardness, we can only resort to finding near optimal solution for the problem, with the objective that the *displacement* (difference from the optimal solution) of the attained near optimal solution should be as small as possible. Formally, any CA that generates a cycle of length $l \in \mathbb{N}$ is of size at least $n = \lfloor log_2 l \rfloor + 1$; thus our objective is to find a binary reversible CA of size $n+\delta$, with δ as small as possible, that generates a cycle of length at least l. Furthermore, we want to observe a practical applicability of such CAs as Pseudo-random Number Generators (PRNGs).

One of the well-known general purpose PRNGs is *Mersenne Twister* and its variants [22] where the period length is a *Mersenne* prime. Similar cycles can also be generated by a maximal length CA of size n, where the corresponding cycle length $2^n - 1$ is prime, that is a Mersenne prime. Hence maximal length CAs can be used as a special category of prime generator - Mersenne prime generator. However, if the CA is not a maximal length, then the cycle length, if it is a prime, can not be a Mersenne prime, but some other primes. This observation steers us to think whether a CA is capable of generating a cycle of arbitrary prime length. We also explore if there exists a collection of CAs of size n which can generate cycles of lengths of all possible primes in between 2^{n-1} and $2^n - 1$.

Recall that in a cellular automaton (CA), the configurations within a cycle are reachable from one another, whereas the configurations of different cycles are not reachable. A *cluster* also establishes an intrinsic connection among the objects. This connectivity indicates us to think reversible cellular automata (CAs) as natural clustering tools. Therefore, a reversible CA can act as a function that maintains a bijective mapping among the configurations which are reachable or connected and gathers similar objects (configurations) into same cluster (cycle). Clustering can be viewed as an optimization problem where a trade-off between two facets - *limited* number of clusters and less *intra-cluster* distances among the target objects (the values for any particular feature of the objects in a cluster are close) exists. Therefore, our objective is to design CA based clustering such that CA has limited number of cycles and the configurations inside a cycle represent related objects.

CONTRIBUTIONS OF THE DISSERTATION

Our contributions in this dissertation are listed below.

- We employ reachability tree as a characterization tool of CA. By developing theories on reachability tree, we can decide for some selective cases whether a given configuration is reachable from itself or not (in this dissertation we consider the special case of CREP where the source and destination configurations are same).
- Using the reachability tree, we design a mechanism for computing the cycle structure of a CA by filtering out configurations that do not belong to any cycle. This scheme performs well for irreversible CA, but is computationally intensive for reversible CAs.

- To address the above issue, in the reachability tree, we capture the *resemblance* among the *subtrees* based on which we decide whether to traverse a particular subtree or not. To this effect, we introduce the concept of *blocks*. This dissertation introduces a new notion of *partial cycle structure* which evaluates the numbers of cycles along with their lengths of a subtree or a collection of subtrees. By detecting the resemblance among the subtrees and using the partial cycle structures, we infer that not all nodes in the reachability tree need to be explored, resulting in increased efficiency of our algorithm for evaluating the cycle structure of a reversible cellular automaton.
- We characterize the cyclic spaces of finite reversible cellular automata based on which we categorize those CAs broadly into two classes - *reducible* and *irreducible*. Further, reducible CAs are sub-categorized into *strictly reducible* and *weakly reducible* cellular automata. In this chapter, we introduce the notion of *isomorphic* CAs based on their cycle structures. Given a cyclic structure, we show efficient mechanisms of identifying the category of the CA.
- To design a binary n-cell CA that generates a cycle of length at least $l \in \mathbb{N}$ such that n is as small as possible, the following contributions are summarized.
  - A stochastic method has been developed to synthesize CAs with *large* cycles. We introduce an n-cell CA as *large length cycle* CA if the CA generates a cycle of length l where $l > 2^{n-1}$.
  - An operator has been proposed which operates over two CAs of sizes n_1, n_2 and forms a new CA of size $n_1 + n_2$.
  - An evolutionary strategy has been developed to obtain near optimal CA for a given length of cycle. The novelty of this scheme is that it reduces not only the displacement, but also generates the best solution efficiently.
- We use the large length cycle CAs generated from the above mentioned stochastic process as a source of randomness and report a generalized scheme of using these CAs as window-based pseudo-random number generators. We have empirically tested these PRNGs for randomness using Diehard, TestU01 and NIST as the testbeds.
- We also demonstrate that irreducible CAs of size n can act as prime number generator for an arbitrary prime number in the range $[2^{n-1}, 2^n - 1]$.
- We report an *iterative* strategy which can generate *desired* number of clusters on demand. This work presents the performance analysis of our proposed cycle based clustering algorithm on some real datasets taken from ML repository. We also compare our proposed algorithm with some traditional benchmark clustering algorithms like *centroid based clusterings*, *hierarchical clusterings* [23], [24]. Our results indicate that, performance of our CA-based clustering technique is at least as good as the best known clustering algorithm existing today.

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Distributed Computing on Cellular Automata with Applications to Societal Problems

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INTRODUCTION

When we see a group of birds sweeps across the sky or a trail patterns of ants forage for food, we use to think that there is a leader in the system. As if, the patterns of birds are determined by the dictates of the bird at the front and the other birds follow the instruction, and the queen ant at the front leads and the rest of the worker ants follow. This is the trivial thinking procedure we are associated with. But is it true?

> "Each bird in the flock follows a set of simple rules, reacting to the movements of the birds nearby it. Orderly flock patterns arise from these simple, local interactions. None of the birds has a sense of the overall flock pattern. The bird in front is not a leader in any meaningful sense - it just happens to end up there. The flock is organized without an organizer, coordinated without a coordinator." – M. Resnick, 1994 [1].

In natural systems, the decisions are not determined by some centralized authority but by local interactions among decentralized components. The journey of scientific development has always been fascinated by nature and its wonders. But question remains, why the thinking procedure of human being is oriented towards "leader" after observing a group of birds or a trail patterns of ants?

A possible explanation can be, the presence of centralized authority is everywhere in our capitalist patriarchal society. That is, starting from the smallest unit - 'family' to the largest unit - 'nation' and 'state', the decisions are determined by some centralized authority in the society. Though, the thought process of scientific development was affected by centralized philosophy imposed by society, the fascination for nature has always guided the scientific journey towards decentralized one.

In computation, the people seem to have strong attachments to centralized ways of thinking. Starting from the modern computer era (40's), the mathematical model of computation heavily relies on Turing machine [2], [3] where computation is governed by a central tape 'head'. In implementation part, (John) von Neumann architecture of general purpose computer is also governed by a 'central processing unit'. Starting from the very first computers (Z3, ENIAC etc.) to todays' most modern smartphones seem to have connection with the centralized approach. At some deep level, when people see patterns in the world (like a group of birds), they often assume that there is some type of centralized control (a leader of the group of birds).

In another part of the story, from the end of the first half of 20^{th} century, a new approach has started to come in scientific studies; which after questioning so called Cartesian analytical approach, says that interconnections among the elements of a system, be it physical, biological, artificial or any other, greatly effect the behavior of the system. In fact, according to this approach, knowing the parts of a system, one can not properly understand the system as a whole. In physics, David Bohm [4] is one of the advocates of this approach. This approach is adopted in psychology by Jacob Moreno [5], which later gave birth of a new branch of science, named Network Science. During this time, however, a number of models, respecting this approach, have started to be proposed; many of these are bio-inspired and offer parallel and distributed decentralized computing. Cellular Automata (CAs) emerged as one of the most important developments in this regard. In computation, the concept of decentralization have been popularized after the development of first widespread distributed systems - local-area network, such as Ethernet [6], [7]. After the 'paradigm shift' introduced by so called distributed system 'Internet', the ideas about decentralization penetrated more deeply, spread more widely and has emerged as a theme in almost every domain of human activity.

A distributed system is a collection of networked but independent computing elements which communicate and coordinate their actions only by message passing. From process point of view, a distributed system can be considered as a collection of spatially separated process which communicate among themselves by only message passing. Thus the processes in the system interact only with their neighbors to perform a computational task. In a distributed computing framework, there are no central entity to control or look after the computation. The elements/processes of a distributed computation can be distinguishable by unique identities (ID). However, a system with distinguishable unique identities (non-anonymous system) requires a central entity to assign unique IDs to the processes. This violates the very essence of distributed control. Therefore, a distributed system should be inherently anonymous [7], [8]. A number of formal models have already been proposed for distributed systems [9], [10], [11], which provide several insights of the systems. However, for distributed computing framework, cellular automata (CAs) can always be a natural choice because of their built-in parallelism.

MOTIVATION AND OBJECTIVE OF THE THESIS

The objective of this thesis is to explore computational ability of decentralized computational model, in particular, distributed computing on cellular automata (CAs). A cellular automaton (CA) is defined over a regular grid, each cell of which consists of a finite automaton that interacts with its neighbors to go to its next state [12]. The beauty of a CA is, simple local interaction produces a (global) complex behavior. Some even claim that nature is a quantum information processing system [13] where CA is the way by which nature does this processing [14], [15]. One of the pioneering works on CAs was in fact initiated to utilize CAs as models of concurrency and distributed systems [16]. In the literature, the CAs have also been utilized to solve few distributed systems problems as computational tasks, for example see [16], [17]. Here, one of the property of CA is anonymous cells. The cells in CA are not associated with any cell numbers. Therefore, the CAs have been utilized not only to solve computational problems in the field of distributed systems but also to solve the anonymous instance of problems as a computational task. In this dissertation, we explore the computation ability of CAs to solve anonymous instance of following well-establish distributed system problems:

- Distributed mutual exclusion problem; and
- Distributed spanning tree problem.

Further, the computations in CAs are performed in a distributed fashion on a spatially extended grid. However, practically, breaking the deep commitment to centralized ways of thinking is not a one step effortless approach. The reflection of centralized idea also present in many well establish decentralized systems from many abstract perception. Like, in the society, the notion of class-struggle can not able to fully capture the independence in terms of caste, gender etc. This presence of centralized ideas is also true for cellular automata. Classically, the CAs are synchronous where all cells change their state simultaneously at discrete time steps. This synchronous approach assumes the presence of a global clock to ensure all cells are updated together. However, the presence of global clock might be an unrealistic assumption if the model is intended to represent a living natural system or distributed system where there is no evidence for the presence of such global clock. Moreover, in cellular automata, no delay in information sharing among the neighboring cells is considered. However, this assumption is not generally true for natural complex and distributed systems where information sharing (non-uniform) delay cannot generally be ignored. Moreover, sometimes in natural complex and distributed systems, messages are lost, which makes the system non-deterministic. In the literature, few researchers have proposed different asynchronous updating scheme to break these centralized approach [18], [19]. In this dissertation, we study following notions of non-uniformity in CAs from real-time distributed system - societal problem modeling prospective.

- (Fully) asynchronous updating scheme in cellular automata; and
- Delay-sensitive updating scheme with delay and probabilistic loss of information perturbation in cellular automata.

CONTRIBUTION OF THE THESIS

In view of the above objective, we have undertaken this research. The main outcomes of the research activities are summarized as following:

- Distributed mutual exclusion problem as a CA computational task is defined. A theorem is reported which depicts the impossibility result for distributed mutual exclusion problem by a 1-$\mathcal{D}$ CA under periodic boundary condition considering all possible initial configurations.
- A classification is reported on all possible valid initial configuration to explore the possibility of solving distributed mutual exclusion problem by a CA under periodic boundary condition.
- For some classes of initial configurations, a CA based solution for the problem is reported. The notion of non-uniform neighborhood (i.e. 4-neighborhood left/right skewed neighborhood) is used during the construction of the CAs. However, for some classes of initial configurations, the impossibility result is also reported.
- Distributed spanning tree problem in the domain of cellular automata is introduced. To do so, the relationship between grid graphs and configurations of CAs is reported.
- A cellular automaton is developed to compute the spanning tree of a given (grid) graph which requires $\mathcal{O}(n \log n)$ time. Here, n is the number of nodes in the given graph.
- The basins of attraction of elementary cellular automata under fully asynchronous updating scheme is explored from natural complex (physical, social) system modeling prospective.
- The new notion of cloud behavior in the convergence dynamics of ACAs is introduced. We get a new classification of convergent ACA rules – eccentric cloud, partially eccentric cloud, and deterministic cloud system based on the notion of the cloud behavior.
- The similarity of cloud behavior with natural clouds across the sky, election model of parliamentary democratic system, and electron cloud around nucleus is discussed.
- The new notion of hidden configuration in the reversible dynamics of ACAs is introduced. We get a new classification of recurrent ACA rules – fully exposed recurrent rule and partially exposed recurrent rule based on the notion of hidden configuration.
- A new class of cellular automata, named delay-sensitive cellular automata is introduced from natural complex modeling prospective.

- The effect of (non-uniform) delay and probabilistic loss of information during information sharing between neighbors in the dynamics of elementary cellular automata and Game of Life is presented.
- The wide variety of phase transition results for elementary cellular automata under delay-sensitive updating scheme is reported using statistical experimental approach. The similarity and dissimilarity of phase transition results with other various asynchronous updating scheme is discussed.
- To understand the reason of different phase transition behavior, the delay-sensitive updating scheme is explored at microscopic level for few example ECAs rules.
- The abrupt change in phase due to the effect of delay perturbation for Game of Life is reported.
- In a societal application, the potential of elementary cellular automata along with delay sensitivity to model the dynamics of communal riot is explored.
- The physical significant of probabilistic loss of information and delay perturbation with the presence of anti-riot population and organizational presence of communal forces is discussed.
- The generative behavior of elementary cellular automata under delay-sensitive updating scheme is reported to model the rioting dynamics. According to the generative behavior, a classification of elementary cellular automata is reported to identify the appropriate ECAs for modeling riot dynamics.
- The cellular automata based communal riot model is verified by a recent event of riot that occurred in Baduria of West Bengal, India. For this study, the propagation dynamics of Baduria riot is reported from media reports and field interviews.

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Theory and Applications of Cellular Automata for Detection and Mitigation of Hardware Trojan Attacks Targeting Cache Performance in a Many-core System

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The growing demand for parallelism in application programs has resulted in an increase in the number of processing cores in many-core Integrated Circuits (ICs). Due to the globalization of integrated circuits, the IC vendors' control on fabricated chips is decreasing day by day. Most of the many-core processor companies outsource ICs from different third-party vendors to minimize future design challenges, meet the aggressive target of time-to-market and reduce cost. Even if in-house engineers are involved in the IC design process, it is impossible to audit individual's work as there are a huge number of engineering experts involved in the process. This opens up a door for various security threats like integration of poor-quality components, overproducing of a device, and malicious modification of ICs in the untrustworthy foundry.

Such malicious alteration/modification in IC design without changing its main functionality is referred to as Hardware Trojan (HT) [1]. An HT can cause a chip's undesired functional behavior, like degradation of system performance and leakage of confidential information [2].

Two broadly used methods exist for detecting HT(s) are: logic testing and side-channel analysis [1]. Besides conventional methods, researchers are also focusing on developing unconventional techniques. Although HT countermeasures are not capable to safeguard against all possible forms of attacks, researchers are still finding promising avenues to work with. Hence, unconventional solution, such as Cellular Automata (CA) based solution for detection and mitigation of HT(s), has been explored. CA, as a powerful modeling tool, has long been received attention from researchers of diverse fields - VLSI circuit testing [3], cryptography [4], and authentications [5], etc. The continual quest for more scalability, robustness and versatility of CA based models to study physical systems around us have forced researchers to explore wide variety of CA based models. Modeling physical systems, inherently irreversible in nature, involves a special class of irreversible CA. Here, we explore properties of irreversible CA to model solutions for HT attacks in the context of multi-core processors' cache systems. Theory of irreversible CA has been developed that exhibits its power in the potential application domain.

Here, we have analyzed HT from both - the attacker's and defender's point of view with the final aim to thwart the attack and build a secure system. From an attacker's perspective, we aim to design stealthy HT(s) that can be hosted in a real-time many-core system and cause severe degradation in system performance due to the HT payload. Furthermore, from a defender's perspective, we target to design effective defense mechanisms to safeguard the system. Here, we have considered Cellular Automata (CA) as one of the potential tool that can be employed for successful detection and mitigation of the modeled Trojans.

I. Methodology

In a real-time many-core system, three potential areas have been identified for insertion of HT(s) - the coherence mechanisms, memory transactions and replacement policies. In order to investigate the relevant research works in the concerned field, a comprehensive survey on HT attacks on many-core systems have been reported in this work. We have performed modeling of different types of HT attacks, their payload evaluation and devised the relevant detection and/or mitigation techniques. For payload evaluation, we have used the Multi2sim [6] simulation framework. In the current research, we have employed an unconventional solution, Cellular Automata (CA), to devise effective detection and mitigation techniques for HT(s). Relevant CA theory has been developed. The overall organization of the work elements has been depicted in Fig. 1.

Chapter 1 formally introduces the problem addressed in the research work. In order to investigate the relevant research works in the concerned field, a comprehensive survey on Hardware Trojan attacks on Many-core systems has been reported in chapter 2. In Chapter 3, a comprehensive study on 3-neighborhood CA with 2-state per cell is presented. A graph-based tool called Next State RMT Transition Diagram (NSRTD) is developed to analyze the state transition behavior

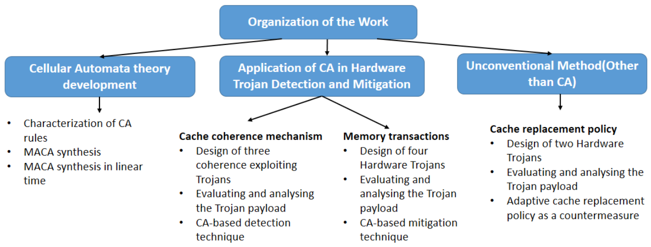

Fig. 1. Organization of the Work Elements.

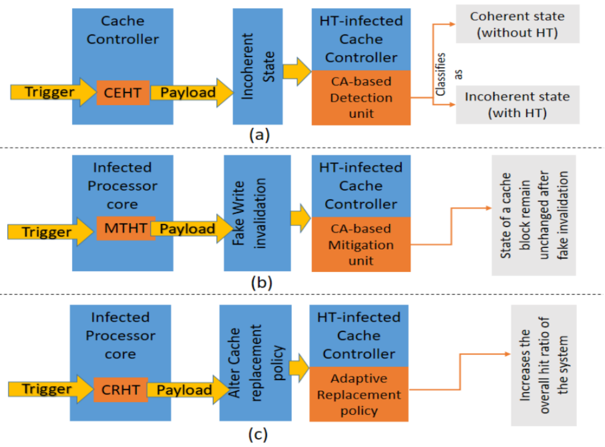

Fig. 2. (a) Coherence Exploiting (CE) Hardware Trojans, (b) Memory Transaction inducing (MT) Hardware Trojans, (c) Cache Replacement policy affecting (CR) Hardware Trojans.

of non-uniform CA with fixed points. Methodologies are proposed for synthesizing Single Length Cycle Multiple Attractor CA (MACA) with a specified number of fixed point(s) and are further improved to ensure a linear time synthesis mechanism.

In Chapter 4, we investigate the coherence exploiting HT attacks. Here, we have proposed three stealthy HT models that affect the coherence mechanism within the cache system of a many-core processor by arbitrarily modifying the state of a cache line, which may leave the cache line's state as incoherent as shown in Fig. 2 . Due to this type of Trojan, execution time of the system increases by 142%. A CA based detection mechanism which can detect the presence of such HT by classifying between coherent (desirable) states and incoherent (undesirable) states (resulted due to the HT payload) has been designed which ensure 100% detection accuracy. A similar kind of solution has been proposed in [7] to detect incoherency in cache line states caused due to faults in hardware logic in a CMPs system. Our CA-based detection unit require 97% less area than the solution proposed in [7].

The memory transaction inducing HT(s) continuously inject read/write invalidate requests to slow down the system has been discussed in Chapter 5. Here, we have considered four different HT attacks on memory transactions. These memory transactions may cause a significant decrease in system performance (power consumption of the system increases by 117%) by evicting valid cache lines and causing spurious invalidation broadcasts. Even malicious HT activity has the potential to convert an upper level cache hit for a cache line into a cache miss, which would then trigger a DoS attack. These types of attacks, in turn, drastically increase lower-level memory traffic. Such HT(s) are very insidious in nature so as to evade detection. A CA based coherence state machine has been designed to filter out HT induced fake invalidations from the original ones (Fig. 2 (b)) and achieve 100% mitigation efficiency but require 17.50% more area than conventional one. The proposed mitigation technique can also mitigate the Trojan effect of coherence exploiting HT(s) by 100% with write operation and 68.75% with read operation by non-infected core.

HT model targeting the cache replacement policy, degrades system performance by intervening in the cache replacement policy has been discussed in Chapter 6. Here, two different HT models have been proposed. One of the proposed HT affects the Least Recently Used (LRU) cache replacement policy by evicting the most recently used block instead of the least recently used one and the other affects the Least Frequently Used (LFU) cache replacement policy by evicting the most frequently used block instead of the least frequently used one. Evaluation of the HT payload shows significant impact on the system performance as hit ratio of the infected core decreases by 8.52%. The proposed adaptive replacement techniques (Fig. 2(c)) mitigate the HT effect by adaptively switching between the LRU(LFU) and MRU(MFU) replacement policies thereby increasing the hit ratio of the infected core by 7.46%.

II. Conclusion

HT has emerged as a potential security attack targeting ICs and components. It poses severe challenges to operational reliability and integrity. Here, we analyze HT(s) from both attackers' and defenders' perspectives. Three potential areas of HT insertion are identified. The special class of irreversible CA is utilized to safeguard the system from HT attacks. However, the study initiated may be extended in future for exploring other HT models, and devising the CA based solutions for designing secure systems.

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Cellular Automata: Chaos, Convergence and Unification

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The research work primarily deals with two opposite behaviors - divergence and convergence of one dimensional cellular automaton (CA). The convergence problem that we deal with here is - given a CA, decide whether all the configurations of the CA converge to a single fixed point. This problem is classically known as nilpotency problem. Such CAs are known as nilpotent cellular automata (CAs) or single attractor CAs (SACAs).

This work first targets to study chaos in classical CAs as well as in non-uniform / hybrid CAs. Adding an information to a cell, how the information flows to its left or right direction is measured in the study. The probabilistic measurement decides whether one cell communicates with another. Depending on the communication among cells, a binary relation called *communication relation*, over the set of cells is defined for classical as well as non-uniform CAs. It is shown that the relation has to be an equivalence relation to make a CA chaotic. The equivalence relation among the cells form an equivalence class, termed as communication class. The communication gets interrupted for the existence of *blocking word*. Therefore identifying blocking word in order to predict chaos is a necessary step, which is reported in the work. Based on the communication class and blocking word, parametrization technique is shown for classical as well as hybrid CAs. Note that, different cells may use different rules in a non-uniform CA. Therefore, it is difficult to establish a parametrization technique in non-uniform CAs. The work develops a parameter for classical or uniform CAs that shows better result than any of the existing parameters, at least for elementary CAs. On the other hand, parameter developed for a non-uniform CA shows promising result in predicting the behavior of the CA. It is found out from the study that the parameter developed for a non-uniform CA is a generalized version of the parameter developed for classical CA. A number of experimental results are shown in the study, that establish superiority of the proposed parameter over existing parameters for classical CAs.

The opposite behavior of chaos is the convergence. The work studies a special type of convergence problem of CAs where all the configurations of a CA converge to a single fixed point only (nilpotency problem). However, the study tries to predict the nilpotent CAs for uniform as well as non-uniform cases. Identification of fixed point is possible for both the cases. However, the study fails to identify the multi-length cycles in a CA that is defined over infinite lattice size. Therefore, the study is done on finite non-uniform CAs. In particular, the study considers non-uniform ECAs where the cells are Wolfram's rules. Even though nilpotency is decidable in finite CAs, it becomes challenging to distinguish such CAs when CA size is too large. There are only 256 elementary rules while studying convergence of classical CAs. However, there are 256^n number of non-uniform ECAs of length n. Hence it is difficult to search an SACA from this huge number of non-uniform CAs when n is large. Moreover, even for a given non-uniform CA with length n, it takes exponential time to analyze whether it is an SACA if n is very large. In this work, we analyze and synthesize SACAs by developing algorithms that take constant time to determine an SACA, in average case. A characterization tool, called *reachability tree* is used for the study.

Finally, the work deals with the simulation of non-uniform CAs by uniform CAs. It can be seen that any non-uniform CA can be simulated by a uniform one. A bijective function ψ is developed that maps the rules and states of a given non-uniform CA to the states of the proposed uniform CA. However, the number of states of the uniform CA becomes greater than that of the non-uniform CA where we keep the neighborhood same. Our target is also to reduce the number of states of the uniform CA and check how much we can reduce the number of states of a uniform CA that can simulate a given non-uniform CA. For that we use the function ψ as non-bijective. It can be observed from the study that every non-uniform CA can be simulated by uniform CAs, whereas, there are some uniform CAs that do not simulate any non-uniform CA (with at least two rules in the rule set) by the given construction.

Scalable circuit design scheme for parallel computing on an asynchronous cellular automaton

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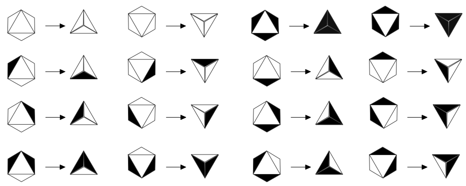


Fig. 1. List of transition rules of the TPCA R_8.

Researches on cellular automata (CAs) often attempts at configuring logic circuits in the cell spaces, in order to prove that they have the same computational power as logic circuits or Turing machines. Such Turing-universality, however, sounds not enough to capture the intrinsic characteristics of massive parallelism in cellular automata [1]. For 2D synchronous CAs, their Turing-universality usually coincides with the intrinsic universality, because they are able to construct the whole class of Boolean circuits which implicitly enables an effective scheme to simulate any other synchronous CAs. In [2], a triangular partitioned cellular automaton (TPCA) is proposed which construct all reversible logic circuits in the two-dimensional cellular space, and hence, it holds an intrinsic universality in simulating all reversible CAs [3]. On the other hand, asynchronous cellular automata (ACAs) allow cells to be updated independently at random times [4, 5], whereby they need more complex constructions to achieve the same level of universality as their synchronous counterparts. For example, the ACA model in [6] has the minimal complexity so far in implementing a Turing machine notwithstanding, it can only construct a partial class of asynchronous circuits, thereby lack of the ability to realize the full functionalities of logic circuits.

This paper aims to explore a stronger universality of the ACA in [6] beyond the Turing completeness, which is achieved by proving the ACA is capable of simulating the TPCA in [2] through time-space rescaling. The TPCA is a synchronous CA defined by $R_8 = (\mathcal{Z}^2, \{0,1\}^3, f_R, (0,0,0))$ where each cell is partitioned into three sub-cells that are in one-to-one correspondence with the cell's neighbors, and every sub-cell takes a state from a binary set $\{0,1\}$. The local function $f_R : \{0,1\}^3 \rightarrow \{0,1\}^3$, can be described in terms of the transition rules given in Fig. 1. In addition, Fig. 2(1) illustrates a configuration of R_8 in which a local pattern representing a signal will move along the path to conduct logic operations.

Likewise, the ACA with von Neumann neighborhood in [6] can be defined by $A_4 = (Z^2, N_{von}, \{0,1,2,3\}, f_4, 0)$, which takes four cell states per each cell that are described by □, ■, ■ and ⊠, respectively. Also, the local function f_4 is described in terms of 38 transition rules given in [6]. In A_4, a straight path is simply a continuous cells in state 0 on which a signal is represented by the pattern in Fig. 3(1). The pattern in Fig. 3(2) is used to turn a signal's direction to the left or right in the cellular space. Moreover, A_4 is capable of implementing three basic elements of asynchronous circuits [6], as shown in Fig. 4.

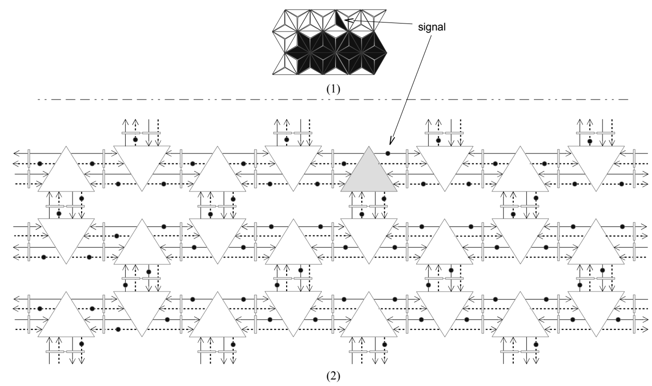


Fig. 2. (1) A local configuration of R_8 and (2) a circuit scheme for implementing the configuration.

In order to simulate R_8 via A_4, we transform each cell in R_8 into modules that can accomplish the logic function of the cell. To this end, Fig. 5 provides two modules, called UT and DT, each of which can work as a cell in R_8. Accordingly, Fig. 2(2) illustrates a circuit scheme in which each UT (DT) module uniquely works as a cell in Fig. 2(1) and is connected to three DT (resp. UT) modules in the neighborhood, in accordance with the uniform cellular structure of R_8. In particular, communications between each pair of connected modules will be done by exchanging signals between them, which is intermediated by a special module, called Synchronizer in Fig. 5(3). The Synchronizer is used to keep the two modules process the signals in a lockstep way, for the sake of simulating the synchronized transitions of their corresponding cells in R_8.

Furthermore, both the UT and DT modules in Fig. 5 can be decomposed into the three elements in Fig. 4, whereby they can be constructed in A_4 as shown in Fig. 6a and Fig. 6b, respectively. As a result, simulation of the synchronous TPCA R_8 can be accomplished by partitioning the cell space of the ACA A_4 into blocks of cells, and then embedding a circuit in either Fig. 6a or Fig. 6b into each block to emulate the state transitions of one cell in R_8. The ACA A_4, therefore,

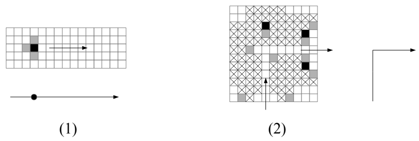


Fig. 3. Configurations representing (1) a signal in A_4 and (2) a Turn component

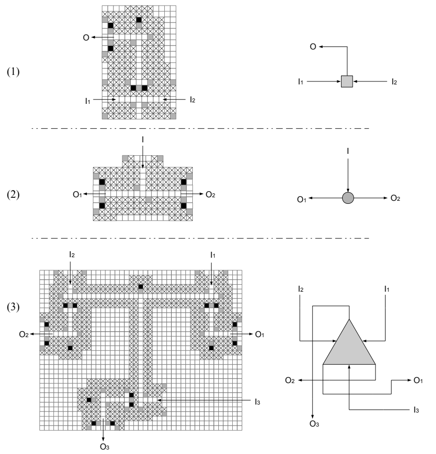


Fig. 4. Configurations representing (1) Merge (2) Fork and (3) Tria elements

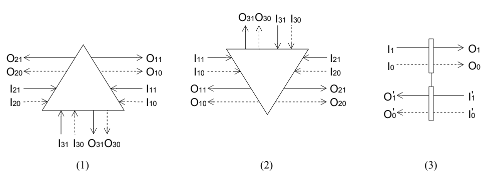
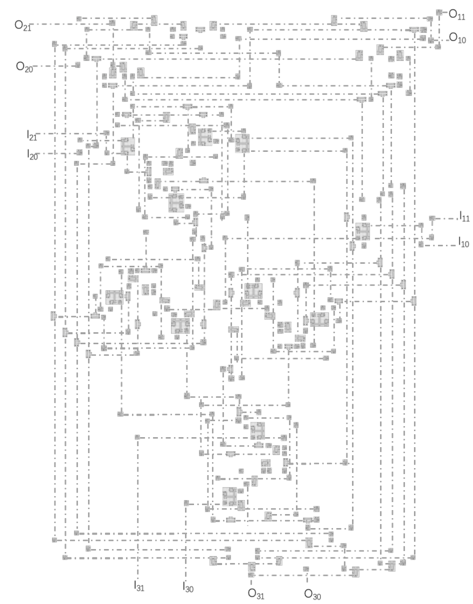


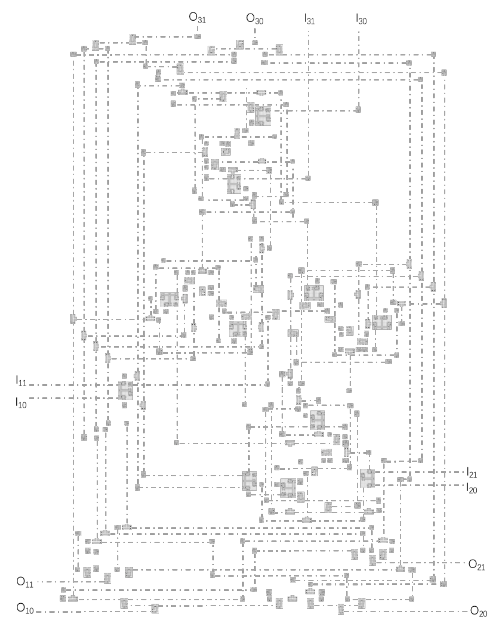
Fig. 5. (1) UT module, (2) DT module and (3) Synchronizer.

not only holds the Turing universality, but also have identical computational power as the intrinsically universal CA R_8. According to the rules, we have split a part of UT and verified the validity of its calculation on the simulator.

In summary, embedding logic circuits into cellular automaton is an effective scheme to conduct universal computations on CAs. The main result of this paper manifests that to achieve equivalent universality in parallel computing with synchronous CAs, it seems no need to implement the whole class of asynchronous circuits, which might suggest a further reduction of the complexity of the universal ACA in [6] by decreasing the number of elements used to simulate synchronous CAs.



(a) Configuration representing UT module in A_4.



(b) Configuration representing DT module in A_4.

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Chaos and Isomorphism in Cellular Automata

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I. Introduction

Cellular automata are discrete dynamical systems that produce complex global behavior using simple local computation [1]–[4]. The configuration of a cellular automaton (CA) evolves with time. We have studied the global property that is chaos and isomorphism in cellular automata. Using the space-time diagram and chaotic parameters, we analyze the chaotic behavior with different states d=2 to d=10. Also, we classify isomorphism using two rule extraction schemes.

II. Problem statement - 1

Increasing the number of states from 2 to 10 effectively increases the randomness quality. So, by changing the number of states, we may get CA-based PRNGs suitable for our application. There are $10^3 = 1000$ different neighborhood combinations when using the 3-neighborhood, 10-state CA rule. Therefore, it is difficult to write down a rule that contains all of these possibilities. Even with the shortened form, we still required an algorithm to obtain the CA rule [1], [3]. Furthermore, because there are so many potential rules, it is almost hard to thoroughly search the CA rule space for CAs that are good in terms of unpredictability but simple to define.

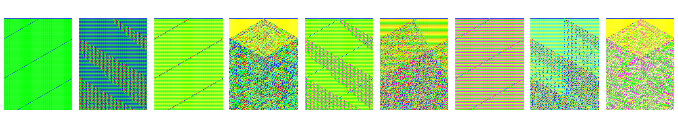
Definition 1: A cellular automata rule $R : S^3 \to S$ is of first degree, if the rule can be represented in the following form: $R(x, y, z) = (c_0xyz + c_1xy + c_2xz + c_3yz + c_4x + c_5y + c_6z + c_7) \pmod{d}$. Here, d is the number of states of the CA and x, y, z are the three neighbors of each cell where $x, y, z \in S$. As, we are using modular arithmetic, each constant $c_i \in \mathbb{Z}_d$ = {0, 1, $\cdots$, d-1}.

A. Methodology

Using a greedy approach, we select those CAs that have a flow of information in one direction, no non-trivial fixed point attractor, and trivial configurations that cannot be reached from other non-trivial configurations. Nevertheless, our essential requirement is that such a CA has to be simple to represent and interact with. This is the reason we present First Degree Rules for the study of chaos in cellular automata. We use two chaotic parameters [2] to study the chaotic behavior of these CAs.

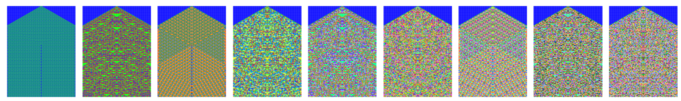
B. Result

A small amount of information added to one cell has an impact on nearby cells and gradually spreads across the composition. Due to this circumstance, CA is an attractive choice for a PRNG. Information can flow in two directions – left and right. The following figures show the analysis with respect to d of some selected rules with the help of Space-Time Diagram. Here, we are considering n=101, with initial configuration as 0^{50} 10^{50}.



(a) 2 (b) 3 (c) 4 (d) 5 (e) 6 (f) 7 (g) 8 (h) 9 (i) 10

Fig. 1: Rule $\langle \mathbf{0,0,0,1,1,0,0,1} \rangle$, $d = 2$ to 10



(a) 2 (b) 3 (c) 4 (d) 5 (e) 6 (f) 7 (g) 8 (h) 9 (i) 10

Fig. 2: Rule $\langle \mathbf{0,0,0,1,1,1,1,0} \rangle$, $d = 2$ to 10

For some rules, CA behaviour does not change with the update in d; whereas, for some CAs, the CA may become less chaotic (even periodic) for some d. Following table shows the chaotic parameter values of selected rules for d=2 to d=10.

C. Discussion

Using the chaotic parameter over Wolfram's class III rules, we choose those first degree CAs for which randomness will never decrease with d when we test from d=2 to d=10. These CAs are used as window-based PRNG. They are comparable with and superior to the best PRNGs that are currently available. Our next target is to investigate chaotic CA classes for random number generators.

D. Key result

1. Our scheme works for any d-state m-neighborhood CAs by properly choosing the parameters. We studied the first degree CA with the Z and P chaotic parameters. Some selected rules give almost the same results. We have compared the randomness quality of the PRNGs using existing bench- mark testbeds. It is observed that performance of these CAs are at par with the existing good PRNGs.
2. We are studying the convergence of CA with the chaotic parameters and space-time diagram. By increasing the value of chaotic parameters we get the randomness whereas by decreasing the chaotic parameter value we can get the convergence of the rules. Our target is to analyze first degree CAs from d=2 to 10 and identify the best CAs which are always convergent irrespective of any d.

III. Problem statement - 2

To discover a few inherent properties of CAs to decide whether the given non-uniform cellular automata are isomorphic. Also, classify the ECA as having the same isomorphism.

Definition 2: The two cellular automata are said to be isomorphic if their configurations evolve in the similar way. A configuration is said to be reachable if it has some predecessor configuration; otherwise, the configuration is non-reachable [5]. Let G be a CA and C be the configuration space. Let $G(x) = y$ and $G(z)$ is not equal to x where y is reachable configuration and y is reachable from x; Now, c is not reachable from any configuration z. Therefore, x is non-reachable. In finite CA, every configuration ultimately reaches to some cycle. The configuration which is used to form a cycle, is called a cyclic configuration. The length of a cycle is determined by the number of cyclic configurations it possesses. The configuration which is not cyclic, is called as acyclic. The cycle structure of a CA is the collection of the number of cycles along with their lengths. If all the configurations of a CA are cyclic, then such CA is reversible; otherwise, the CA is irreversible. Let G_1 and G_2 be two ECAs of same size having same configuration space C. G_1 and G_2 and are said

TABLE I: Chaotic parameter for selected rules

Class III	**P value from d=2 to d=10**								
PARAMETERS	2	3	4	5	6	7	8	9	10
0,0,0,1,1,1,1,0	[0.5, 1.0]	[0.6666667, 1.0]	[0.6666667, 1.0]	[0.8, 1.0]	[0.7, 1.0]	[0.85714287, 1.0]	[0.78571445, 1.0]	[0.8333333, 1.0]	[0.8111111, 1.0]
0,0,0,1,1,0,0,1	[0.5, 1.0]	[0.6666667, 1.0]	[0.6666667, 1.0]	0.8, 1.0]	[0.7, 1.0]	[0.85714287, 1.0]	[0.78571445,1.0]	[0.8333333, 1.0]	[0.8111111, 1.0]

to be isomorphic if there exists a bijective mapping $\pi : C \rightarrow C$ such that $G_1(x) = y$ if and only if $G_2(\pi(x)) = \pi(y)$ where $\forall x, y \in C$. It is very challenging to figure out π and not much work has been found on the isomorphism in cellular automata. Thus we are motivated to find some intrinsic properties of cellular automata which play the instrumental role in deciding isomorphism in CAs.

A. Methodology

In our work, we use a reachability tree, which is a rooted and edge-labeled binary tree that decides the reachable and non-reachable configurations of CA. This tool is used to develop some properties of isomorphism in cellular automata. We are extracting the isomorphic CA using an exchanging the cells at different positions and permutation of the states of a set of cell positions scheme.

Property1: Two CAs G_1 and G_2 are said to be isomorphic if both be reversible or both be irreversible but the converse is not always true. If Property1 is not satisfied by the given G_1 and G_2, then they are not isomorphic. Therefore, we test the reversibility of the given nonuniform CAs (using an algorithm of O(n)) and if we find that G_1 is reversible CA and G_2 is irreversible CA, then they are not isomorphic. Let (10, 150, 90, 20) and (2, 150, 90, 20) are given CAs. Here, (10, 150, 90, 20) is reversible CA but (2, 150, 90, 20) is irreversible CA as 2 can not be the first rule of any reversible CA. So, They are not isomorphic. As Property1 is a necessary condition to decide isomorphism in cellular automata, we need to figure out some more properties on CAs when G_1 and G_2 both be reversible or both be irreversible. Now, in reversible CAs, as all configurations are cyclic, for deciding isomorphism, we need to check whether they have the same number of cycles along with the same lengths.

Property2: Let G_1 and G_2 be reversible cellular automata. They are said to be isomorphic iff both the CAs have the same cycle structure, as shown in Fig. 3. Here, (9, 142, 165, 65) and (6, 232, 90, 20) are isomorphic CAs as they have the same cycle structure [2(1),1(3), 1(11)]. To study the isomorphism in irreversible CAs, other than cycle structures of those CAs, the count of acyclic configurations play an instrumental role.

Property3: Let G be a CA of size n. In the reachability tree of that CA, if k^i denote the number of non-reachable edge(s) at the level i of that tree, then the total number of non reachable configurations(s) of that CA is $\sum_{i=0}^{n-1} k^i \times 2^{n-1-i}$

Property4: Let G_1 and G_2 be irreversible cellular automata. They are said to be isomorphic if both the CAs have the same number of non-reachable configurations but the converse is not always true. If Property-4 is not satisfied by the given G_1 and G_2, then they are not isomorphic. To check the count of non-reachable configurations, we should use the reachability tree as a tool. Here, (1, 135, 92, 5) and (10, 60, 86,20) are not isomorphic cellular automata as they have a total number of non reachable configurations 3 and 4 respectively. But, (54, 25, 211, 155) and (73, 118, 57, 187) are isomorphic CAs as they have cycle length of 6, count of acyclic configurations and orientation of both CA are same (see Fig. 3).

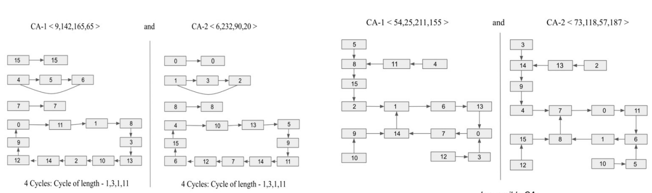


Fig. 3: Isomorphic Reversible and Irreversible CA

1) Equivalence Relation: Isomorphism is reflexive, symmetric, transitive, and therefore an equivalence.

2) Synthesis: We are using permutation of the states of a set of cell positions and exchanging the cells at different positions procedures to extract the isomorphic Rules.

TABLE II: Sample result from Juan Carlos Lopez classification to state map under periodic Boundary Condition

Juan Carlos Lopez	**Periodic Boundary Condition n=4 to n=8**				
Periodic Boundary Condition n=4	n=4	n=5	n=6	n=7	n=8
2,16,191,247	{2}{16}{191,247}	N	N	N	N
8,64,239,253	{8}{64}{239,253}	{8,64}{239,253}	{8,64}{239,253}	{8,64,}{239,253}	{8,64,} {239,253}
90,105,150,165	{90,105,150,165}	N	{90,105,150,165}	{90} {105,150}{165}	N

B. Sample result

Using the equivalence properties, we were able to maintain the isomorphism for our n-length uniform cellular automata when synthesizing them using the exchanging of cell states. Exchanging the cells at different positions- d^n set of isomorphic rules, where n is the cell length and d is the state of the CA. In the table below, we compare the n=4 to n=8 under Periodic boundary condition to the Lopez isomorphic class [6] under periodic boundary conditions. Some sample results shown below showing isomorphic classes.

C. Discussion

We have introduced two procedures exchanging the cells at different positions and permutation of the states of a set of cell positions to extract the isomorphic rules under periodic and null boundary conditions. An interesting problem to study in future is to find the exact count of partitions for a given CA size.

D. Key result

1. We studied the two greedy approaches (i) permutation of the states of a set of cell positions (ii)exchanging the cells at different positions. Using these procedures we will study the isomorphic classification of cellular automata under different boundary conditions.
2. Our future work will be to find the inverse CA for reversible cases as part of isomorphic classification.

ACKNOWLEDGMENTS

We are grateful to Prof. Sukanta Das, and Dr. Sukanya Mukherjee for mentoring the work on isomorphism in Cellular Automata.

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Implementation of CBIR for Medical Images using Cellular Automata

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I. Introduction

Content-based image retrieval (CBIR) [1] is a technique for searching images that balance the conventional text-based retrieval of images by exercising visual features, like color, texture, and shape, considering the search criteria. CBIR is used for retrieving same types of images from image databases, based on automated feature extraction methods. CBIR helps medical practitioners to identify same type of medical images through looking back into the previous cases during diagnosis.

Cellular automata (CA) [2] have a major application in image processing due to its two-dimensional matrix structure and transition rules. CA are considered as computational model, which has a finite number of cells and it comprises of a grid of cells. As digital images are represented by two-dimensional array, so 2D CA is suitable among the various structures of CA, for performing different operations on medical images. The transition rules of CA can be used as transformation function for processing an image.

Cellular Automata based Edge Detection - In CBIR, different features of imaging modalities can be extracted using image segmentation techniques. Proposed cellular automata-based image segmentation technique extracts the region of interest (ROI) through a semiautomatic or automatic process from medical images. Edge

detection is a primitive tool for the machine vision systems which may help in image segmentation. An edge is a zone of demarcation between two different regions according to some measure of homogeneity. In general, edge can be denoted as the borderline between contrasting regions in image whereas specifically it can be defined as abrupt local change in brightness. Popovici and Popovici [3] addressed one efficient edge detection technique. In this approach the differences of states between the pixels in its neighborhood and the reference pixel has been considered following Von-Neumann concept. The rule is represented as:

$$v_{c+} = \begin{cases} v_c, \text{ if } |v_i - v_c| > \epsilon, \text{ for all } i \in N_c \\ 0, \ otherwise \end{cases}$$

where, v_i is the intensity of i^{th} neighborhood cell and v_c represents the value of central cell c and v_{c+} is the intensity values of next state. The mentioned approach has been applied to detect brain tumor and bone fracture.

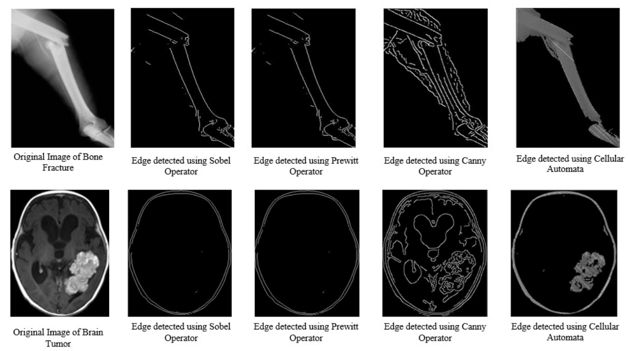

Fig. 1. Transformed Images using CA based Edge Detection.

Fig. 1 shows the comparison among the conventional methods of edge detection (Sobel, Prewitt, Canny Edge Detector) and the edge detection approach based on Cellular Automata. It has been observed that the CA based approach produces better results and the computed peak signal-to-noise ratio (PSNR) is higher than the obtained PSNR value using other edge detection methods. PSNR is used to compute peak signal-to-noise ratio of images and it is measured in terms of decibel(dB). It helps to measure the quality improvement between the original and a modified image. The higher value of PSNR indicates better in quality of the reconstructed image and here the PSNR obtained for the CA based approach is 29.659 dB for the brain images and 31.295 dB for the sample bone image.

Cancer Detection using Cellular Automata based Image Segmentation- Considering CA based image segmentation [4] to a greater extent work has been done and one automated system has been implemented that can detect brain tumor, breast tumor and lung cancer from different medical image modalities like X-ray or Computed Tomography (CT). It is helpful to identify the area of abnormalities where the mass is being developed. After enhancing the quality of input X-ray or CT image, Moore neighborhood concept of Cellular Automata has been applied as transition rule for separating the growth of mass from its background found in different organs. One central cell has been taken in consideration and it is subtracted from all of its eight adjacent cells. Value of the reference cell to be replaced with 0 if all these differences are less than the chosen threshold otherwise the value of central cell will remain unchanged. Depending on the input image threshold value has been chosen. Then the obtained image has been inverted and finally image binarization has been performed to obtain the segmented image.

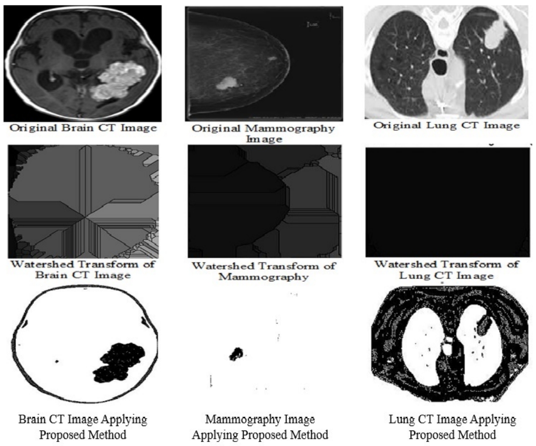

Fig. 2. Transformed Images using CA based Image Segmentation.

Fig. 2 illustrates that the transformed images obtained applying CA based segmentation technique has a good clarity than Watershed Transform approach for detecting brain tumor, breast tumor and lung cancer. Henceforth, applying CA Segmentation Rules here the growth of mass has been detected and segmented from its background. Applying Moore neighborhood concept of CA, one image segmentation technique has been implemented and applied on different medical image modalities like X-ray or Computed Tomography (CT) of different organs for detecting tumors in brain, breast, and lung, etc. It results fine, continuous, and clear area of abnormal growth of mass has been segmented.

COVID-19 detection System with CA based approach - Cellular Automata (CA) is very much efficient technique for Bio-medical images in terms of computation time and clarity. Extending the above concept an automated system for COVID-19 detection [5] has been implemented for detecting coronavirus infection in chest and it produces effective results with 93% of accuracy in case of detecting novel Coronavirus in human being. The transformed images have been scaled with a size of 256×256 and have been multiplied with different feature detector with a stride of 1 and also with rectilinear activation function to get the best feature from the transformed image and as a result we get her two different feature maps. Max pooling has been done and added with each of the convolution layer [6]. This approach helps to take the number row by row from pooled feature map and put them into one long column to get a one huge vector of inputs for an artificial neural network. two fully connected layer has been prepared and the categorical cross entropy has been used to calculate the loss. Finally, from the fully connected layer the output image has been obtained and it determines the detection of COVID-19 infections.

In Fig. 3, COVID-19 infected sample chest X-ray images have been shown after transforming with the proposed CA based image segmentation technique. Here, it can be observed that using this proposed segmentation technique some unwanted portion of the images has been removed. So, the infected areas are clearer which may help to identify the detection easily. Classification of medical images is a significant problem in the area of image recognition with the objective of classifying medical images into different categories for helping medical practitioners in disease diagnosing or in further research. In this work medical image classification will be done by categorizing and labeling groups of pixels or vectors within an image based on specific rules. In Medical Science, image classification enhances the grouping of these images into categories of diseases and optimizes the next step of a computer-aided diagnosis system.

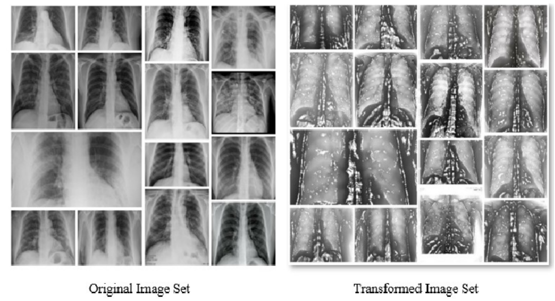

Fig. 3. COVID-19 Positive Chest X-ray.

An increasing image repository is required to diagnose different kind of diseases efficiently. CBIR based medical image analysis using CA can extract different features from medical images with which an effective repository can be created and that can be used for diagnosing any pre-recorded diseases. In medical applications, dividing an image into areas based on a specified description, such as segmenting body organs boundary detection, tumor detection and mass detection, the features can be extracted and will be stored in image database. As required the data can be retrieved and similarity functions will be mapped with the query image for diagnosing the disease.

In medical science, Bio-Medical images have a great impact for detecting several diseases. In this work, cellular automata-based image segmentation has been implemented and has been applied on different image dataset for detecting COVID-19 infection as well as to detect cancer in different organs.

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Rules.$L_{p,q}$

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We define the cellular automata $L_{p,q}$ that represent the multiplication by p in base q as follow :

$$\begin{aligned} L_{p,q} &: q^{\mathbb{Z}} \to q^{\mathbb{Z}} \\ L_{p,q}(x)_i &= (px_i + \left\lfloor \frac{x_{i+1}}{q/p} \right\rfloor) \bmod q \end{aligned}$$

Proposition 1: The cellular automata $L_{p,q}$ can be obtained from the dynamical systems $px \bmod 1$ defined on the unite interval $[0,1[$.

Proof : Let x be a point from $[0,1[$ written in base q as follow:

$$\begin{aligned} x &= x_1x_1x_3x_4......|_{B_q}, x_i \in \{0,...,q\} = \sum_{i=1}^{+\infty} \frac{x_i}{q^i}, x_i \in \{0,...,q\} \\ px &= \sum_{i=1}^{+\infty} \frac{px_i}{q^i} = \frac{px_1}{q} + \frac{px_2}{q^2} + ... + \frac{px_n}{q^n} + ... \end{aligned}$$

We have $\forall i \in \mathbb{N}$, the term $\frac{px_i}{q^i} = \frac{q\times t_i + r_i}{q^i}$ where $t_i = \left\lfloor \frac{x_i}{q/p} \right\rfloor$ and $r_i = px_i \bmod q$. Then:

$$\begin{aligned} px &= \sum_{i=1}^{+\infty} \frac{q\times t_i + r_i}{q^i} = \frac{qt_1+r_1}{q} + \frac{qt_2+r_2}{q^2} + \frac{qt_3+r_3}{q^3} + \frac{qt_4+r_4}{q^4}... \\ px &= t_1 + \frac{r_1+t_2}{q} + \frac{r_2+t_3}{q^2} + \frac{r_3+t_4}{q^3} + ... \\ px \bmod 1 &= \frac{(px_1 + \left\lfloor \frac{x_2}{q/p} \right\rfloor) \bmod q}{q} + \frac{(px_2 + \left\lfloor \frac{x_3}{q/p} \right\rfloor) \bmod q}{q^2} \\ &+ \frac{(px_3 + \left\lfloor \frac{x_4}{q/p} \right\rfloor) \bmod q}{q^4} + ... \\ px \bmod 1 &= \sum_{i=1}^{+\infty} \frac{(L_{p,q}(x))_i}{q^i}. \end{aligned}$$

□

The next proposition gives a general characterization of the k^{th} iterate of $L_{p,q}$ when q is a pure power of p.

Proposition 2: $\forall x \in q^{\mathbb{Z}}$, if $\exists k \in \mathbb{N}$ such that $q = p^k$ then:

$$L^k_{p,q}(x)_i = (p^{k-1} \left\lfloor \frac{px_{i+1}}{q} \right\rfloor + (\left\lfloor \frac{p^k x_{i+1}}{q} \right\rfloor) \bmod p^{k-1}) \bmod q = x_{i+1}$$

Proof : Let x be an element from $q^{\mathbb{Z}}$.We have:

$$\frac{L_{p,q}(x)_{i+1}}{q/p} = \frac{(px_{i+1} + \left\lfloor \frac{x_{i+2}}{q/p} \right\rfloor) \bmod q}{q/p} \tag{1}$$

$$\begin{aligned} \left\lfloor \frac{L_{p,q}(x)_{i+1}}{q/p} \right\rfloor &= \left\lfloor \frac{px_{i+1}}{q/p} + \frac{\left\lfloor \frac{x_{i+2}}{q/p} \right\rfloor}{q/p} \bmod p \right\rfloor \\ &= \left\lfloor \frac{px_{i+1}}{q/p} \right\rfloor \bmod p \end{aligned}$$

Then for any integer k :

$$\left\lfloor \frac{L^k_{p,q}(x)_{i+1}}{q/p} \right\rfloor = \left\lfloor \frac{pL^{k-1}_{p,q}(x)_{i+1}}{q/p} \right\rfloor \bmod p \tag{2}$$

Let calculate $L^k_{p,q}(x)$:

$$\begin{aligned} L^k_{p,q}(x)_i &= (pL^{k-1}(x)_i + \left\lfloor \frac{L^{k-1}(x)_{i+1}}{q/p} \right\rfloor) \bmod q \\ &= (p(pL^{k-2}(x)_i + \left\lfloor \frac{L^{k-2}(x)_{i+1}}{q/p} \right\rfloor) + \left\lfloor \frac{L^{k-1}(x)_{i+1}}{q/p} \right\rfloor) \bmod q \\ &= (p^2L^{k-2}(x)_i + p\left\lfloor \frac{L^{k-2}(x)_{i+1}}{q/p} \right\rfloor + \left\lfloor \frac{L^{k-1}(x)_{i+1}}{q/p} \right\rfloor) \bmod q \\ &= (p^2(pL^{k-3}(x)_i + \left\lfloor \frac{L^{k-3}(x)_{i+1}}{q/p} \right\rfloor) + p\left\lfloor \frac{L^{k-2}(x)_{i+1}}{q/p} \right\rfloor \\ &+ \left\lfloor \frac{L^{k-1}(x)_{i+1}}{q/p} \right\rfloor) \bmod q \\ &= (p^3L^{k-3}(x)_i + p^2\left\lfloor \frac{L^{k-3}(x)_{i+1}}{q/p} \right\rfloor + p\left\lfloor \frac{L^{k-2}(x)_{i+1}}{q/p} \right\rfloor \\ &+ \left\lfloor \frac{L^{k-1}(x)_{i+1}}{q/p} \right\rfloor) \bmod q \\ &= .... \\ &= (p^kL^{k-k}(x)_i + p^{k-1}\left\lfloor \frac{L^{k-k}(x)_{i+1}}{q/p} \right\rfloor + ... + p\left\lfloor \frac{L^{k-2}_{p,q}(x)_{i+1}}{q/p} \right\rfloor \\ &+ \left\lfloor \frac{L^{k-1}_{p,q}(x)_{i+1}}{q/p} \right\rfloor) \bmod q \\ &= (p^kx_i + p^{k-1}\left\lfloor \frac{x_{i+1}}{q/p} \right\rfloor + ... + p\left\lfloor \frac{L^{k-2}_{p,q}(x)_{i+1}}{q/p} \right\rfloor \\ &+ \left\lfloor \frac{L^{k-1}_{p,q}(x)_{i+1}}{q/p} \right\rfloor) \bmod q \\ &= (p^kx_i + p^{k-1}\left\lfloor \frac{x_{i+1}}{q/p} \right\rfloor + \left\lfloor \frac{L^{k-1}_{p,q}(x)_{i+1}}{q/p} \right\rfloor \\ &\underbrace{+p^{k-2}\left\lfloor \frac{L_{p,q}(x)_{i+1}}{q/p} \right\rfloor + ... + p\left\lfloor \frac{L^{k-2}_{p,q}(x)_{i+1}}{q/p} \right\rfloor}_{=0 \text{ by } (2)}) \bmod q \\ &= (p^kx_i + p^{k-1}\left\lfloor \frac{x_{i+1}}{q/p} \right\rfloor + \left\lfloor \frac{L^{k-1}_{p,q}(x)_{i+1}}{q/p} \right\rfloor) \bmod q \end{aligned}$$

It remains just to simplify the expression of $\left\lfloor \frac{L^{k-1}_{p,q}(x)_{i+1}}{q/p} \right\rfloor$.

Or, by (2) we have for any $k \in \mathbb{N}$:

$$\begin{aligned} \left\lfloor \frac{L^{k-1}_{p,q}(x)_{i+1}}{q/p} \right\rfloor &= \left\lfloor \frac{p^2L^{k-2}_{p,q}(x)_{i+1}}{q} \right\rfloor \bmod p \\ \text{by induction} &= \left\lfloor \frac{p^3L^{k-3}_{p,q}(x)_{i+1}}{q} \right\rfloor \bmod p^2 \\ &= ... \\ &= \left\lfloor \frac{p^kL^{k-k}_{p,q}(x)_{i+1}}{q} \right\rfloor \bmod p^{k-1} \\ &= \left\lfloor \frac{p^kx_{i+1}}{q} \right\rfloor \bmod p^{k-1} \end{aligned}$$

By replacing $\left\lfloor \frac{L^{k-1}_{p,q}(x)_{i+1}}{q/p} \right\rfloor$ in $L^k_{p,q}(x)$ we get :

$$\begin{aligned} L^k_{p,q}(x)_i &= (p^{k-1}\left\lfloor \frac{x_{i+1}}{q/p} \right\rfloor + \left\lfloor \frac{p^kx_{i+1}}{q} \right\rfloor \bmod p^{k-1}) \bmod q \\ &= x_{i+1}. \end{aligned}$$

$\square$

Remark 1: If we assume that p is juste a divisor of q then (3)still true. In this case we have:

$$L^k_{p,q}(x)_i = (p^k x_i + p^{k-1}\left\lfloor \frac{x_{i+1}}{q/p}\right\rfloor + \left\lfloor \frac{L^{k-1}_{p,q}(x)_{i+1}}{q/p}\right\rfloor) \bmod q$$

Proposition 3: If $\forall k \in \mathbb{N}$, $p^k \bmod q \neq 0$ then $L_{p,q}$ cannot be a square root of the shift.

In particular, if $p \wedge q = 1$ or p is just a divisor of q then the multiplication rules $L_{p,q}$ associated cannot be a square roots of the shift.

Proof : Let $k \in \mathbb{N}$ an integer. Consider a point $x \in \{0,..,q-1\}^{\mathbb{Z}}$ that contains just one 1 at the position $i_0 \in \mathbb{Z}$ and 0 otherwise. i.e:

$$x_{i_0} = 1 \text{ and } \forall i \neq i_0, x_i = 0$$

Then we get :

$$\begin{aligned} L^k_{p,q}(x)_{i_0} &= (p^k x_{i_0} + p^{k-1}\left\lfloor \frac{p x_{i_0+1}}{q}\right\rfloor + \left\lfloor \frac{L^{k-1}_{p,q}(x)_{i_0+1}}{q/p}\right\rfloor) \bmod q \\ &= p^k \bmod q \\ &\neq 0 \text{ by hypothesis..} \end{aligned}$$

$\square$

I. First case : q is a pure power of p

In this section we give some properties of the rules $L_{p,q}$ in the case where they are a square roots of the shift.

Proposition 4: The multiplication rules $L_{p,q}$ are positively expansive.

Proof : Since the shift is expansive $\Rightarrow \exists\varepsilon > 0, \forall x \neq y \in X, \exists n \in \mathbb{N} : d(F^n(x), F^n(y)) \geq \varepsilon$.

By consequence, $\exists\varepsilon > 0, \forall x \neq y \in x, \exists n_1 = kn \in \mathbb{N} : d(G^{n_1}(x), G^{n_1}(y)) \geq \varepsilon$. $\square$

Consequence : The rules $L_{p,q}$ are mixing. (Blanchard and Maas).

Proposition 5: The rules $L_{p,q}$ are open but not permutive.

Proof :

1) Let start by proving the non permutivity. Let take the words $u = 0$ and $b = 0$ we have

$$\begin{aligned} L_{p,q}(00) &= 0 \text{ and } L_{p,q}(01) = 0. \\ L_{p,q}(00) &= 0 \text{ and } L_{p,q}(p^{k-1}0) = 0. \end{aligned}$$

Then, $L_{p,q}$ is neither left permutive nor right permutive.

2) $\Rightarrow$ Let prove that $L_{p,q}$ are right closing.

Let x, y be two elements from $q^{\mathbb{Z}}$ which are left asymptotic.

i.e, $x_{(-\infty,n)} = y_{(-\infty,n)}$. We suppose that $x_n \neq y_n$ and $L_{p,q}(x) = L_{p,q}(y)$.

In order to have $L_{p,q}(x)_{n-1} = L_{p,q}(y)_{n-1}$ the components x_n, y_n have to belong to one of the following sets:

$$\{0, ..., \frac{q}{p} - 1\}$$
$$\{\frac{q}{p}, ..., 2\frac{q}{p} - 1\}$$
$$...$$
$$\{(p-1)\frac{q}{p}, ..., q - 1\}$$

In each set, we will have $L_{p,q}(x)_n \neq L_{p,q}(y)_n$.

$\Rightarrow$Let prove that the rules $L_{p,q}$ are left closing.

Let x, y be two elements from $q^{\mathbb{Z}}$ which are right closing.

i.e, $x_{(n,\infty)} = y_{(n,\infty)}$. We suppose that $x_n \neq y_n$ and $L_{p,q}(x) = L_{p,q}(y)$.

In order to have $L_{p,q}(x)_n = L_{p,q}(y)_n$ then x_n, y_n have to belong to one of the following sets :

$$\begin{aligned} \{kp \text{ with } k &\in \mathbb{N} \text{ and} kp < q\} \\ \{(k+1)p \text{ with } k &\in \mathbb{N} \text{ and } (k+1)p < q\} \\ &... \\ \{(k + \frac{q}{p} - 1)p \text{ with } k &\in \mathbb{N} \text{ and } (k + \frac{q}{p} - 1)p < q\} \end{aligned}$$

But in all sets we will have $L_{p,q}(x)_{n-1} \neq L_{p,q}(y)_{n-1}$.

$\square$

Remark 2: The precedent proof still correct if p is just a divisor of q.

II. Second Case where the rules $L_{p,q}$ are not a square roots of the shift

A. If $p \wedge q = 1$

In the case where we have p and q are mutually prime, the rules $L_{p,q}$ are left closing but not right closing and they are not injective. So, by Kurka and Nasu theorem the rules are not expansive but still sensitive.

Proposition 6: If $p \wedge q = 1$, the rules $L_{p,q}$ are left closing but not right closing.

Proof : Let x, y be two elements from $q^{\mathbb{Z}}$ and left asymptotic. i.e: $x_{(-\infty,n)} = y_{(-\infty,n)}$ and $x_n \neq y_n$. As $p \wedge q = 1$ then there exist $x_{n+1} \neq y_{n+1}$

such that

$$L_{p,q}(x_n x_{n+1}) = L_{p,q}(y_n y_{n+1})$$

By consequence, we can construct x and y which are left asymptotic and distinct with the same image by $L_{p,q}$.

Then, $L_{p,q}$ are not right closing for any $p \wedge q = 1$. But they are left closing. Indeed,

Let x and y two right asymptotic points.. i.e: $x_{(n,+\infty)} = y_{(n,+\infty)}$ and $x_n \neq y_n$ then for any x_{n-1} and $y_{n-1} \in \{0, ..., q\}$ we will have :

$$L_{p,q}(x_{n-1}x_n) \neq L_{p,q}(y_{n-1}y_n). \qquad (\clubsuit)$$

Then $L_{p,q}(x) \neq L_{p,q}(y)$. $\square$

Consequence: In the previous proof we constructed two distinct points x and y having the same image by $L_{p,q}$. Then the rules $L_{p,q}$ cannot be injective if $p \wedge q = 1$.

Example 1: **multiplication by 3 in base 7**

The two following points have the same image by $L_{3,7}$.

$$\begin{aligned} x &= ...005252(52)^{\infty} \\ y &= ...0023252(52)^{\infty} \\ L_{3,7}(x) &= L_{3,7}(y) = ..00021111(1)^{\infty} \end{aligned}$$

Proposition 7: If $p \wedge q = 1$, the rules $L_{p,q}$ are sensitive.

Proof : For $\varepsilon = \frac{1}{2}; \forall x \in q^{\mathbb{Z}}, \forall\ m > 0$. Let choose a point y as follow :

$$y_{[0,m]} = x_{[0,m]} \text{ and } y_{-1} \neq x_{-1}$$

Then by $(\clubsuit)$ we will have $L_{p,q}(x)_{-1} \neq L_{p,q}(y)_{-1} \Rightarrow d(L_{p,q}(x), L_{p,q}(y)) \geq \frac{1}{2}$. $\square$

Strictly periodic points of cellular automata with almost equicontinuous points

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Cellular automata are computational objects used and studied as models in many applied domains.

They are used to model complex systems, for example in statistical physics as microscale models of hydrodynamics, to model social choices or tumor growth.

This interest is due to the enormous potential they hold in modeling complex systems.

A cellular automaton is made of an infinite lattice of finite identical automata. The lattice is usually $\mathbb{Z}^n$ with n called the dimension of the cellular automaton. Each automaton updates its state synchronously according to a local rule on the basis of its actual state and of the one of a fixed finite set of neighboring automata. The set of possible states of an automaton is called the alphabet and each element of the alphabet is referred to as a letter. A configuration is a snapshot of the state of all automata in the lattice.

The study of CA as symbolic dynamical systems began with Hedlund. Dynamical behavior of cellular automata is studied mainly in the context of discrete dynamical systems by equipping the space of configurations with the product topology which make it homeomorphic to the Cantor space.

Gilman introduced a classification of cellular automata using Bernoulli measures which are not necessarily invariant. He also introduced the concepts of measurable equicontinuous point and of measurable expansivity.

Cellular automata can then be divided into three classes : cellular automata with equicontinuous points, with almost equicontinuous points but without equicontinuous points and almost expansive cellular automata.

Cellular automata with almost equicontinuous points are characterized by the existence of a class $B_{[-n,n]}$ with measure $\mu(B_{[-n,n]}) > 0$ for all integer $n \geq 0$. For $x \in A^{\mathbb{Z}}$ $B_{[-n,n]}(x)$ is defined by:
$B_{[-n,n]}(x) = \{y \in A^{\mathbb{Z}} : (F^j(x))_{[-n,n]} = (F^j(y))_{[-n,n]} \quad \forall\, j \in \mathbb{N}^*\}$

For any interval $[i1, i2]$ the relation $\mathfrak{R}$ defined by $x\mathfrak{R}y$ if and only if $\forall\, j \in \mathbb{N}^*$: $F^j_{[i1,i2]}(x) = F^j_{[i1,i2]}(y)$ is an equivalence relation and the sets $B_{[i1,i2]}(x)$ are the equivalence classes.

If we visualize the behavior of x as an array $(a_{i,j})$ with entry $a_{i,j} = (F^i(x))_j$ then $B_{[i1,i2]}(x)$ is the set of all y whose behavior agrees with that of x on the infinite vertical strip under the interval $[i1, i2]$.

The following proposition and its proof is a result due to Gilman. The technique is used in the proof of our main result.

Proposition 0.1: If there exist a point x and an integer $m \neq 0$ such that
$B_{[-n,n]}(x) \cup \sigma^{-m}(B_{[-n,n]}(x)) \neq \emptyset$ with $n > r$ $(the\ radius\ of\ the\ automaton\ F)$ then the common sequence $(F^i(y)_{[-n,n]})_{i\in\mathbb{N}}$ of all points $y \in B_{[-n,n]}(x)$ is ultimately periodic.

Proof 0.1: First remark that for each shift periodic point $\overline{w}$of period P, the cardinal of the set $\{F^i(\overline{w}); i \in \mathbb{N}\}$ is finite and less or equal to $(\sharp A)^p$ (for all integer $k \geq 0$ one has $\sigma^p \circ F^k(\overline{w}) = F^k \circ \sigma^p(\overline{w}) = F^k(\overline{w})$). This implies that the sequence $(F^i(\overline{w}))_{i\in\mathbb{N}}$ is ultimately periodic. Since all the elements of $B_n(x)$ share the same ultimately periodic sequence $(F^i(x)_{]-n,n[})_{i\in\mathbb{N}}$, we only need to show that $B_n(x)$ contains a shift periodic element $\overline{w}$ to finish the proof.
Now suppose without loosing generalities that $m > 0$, pick a point $y_1 \in B_n(x) \cap \sigma^{-m}(B_n(x))$ and put $w = y_1]-n, -n+m-1[$.
We claim that for all point x, integers $n \geq r$ and $y \in B_n(x)$, all points $z, z^{'}$ that verify $z_{]-\infty,-n[} = y_{]-\infty,-n[}$, $z_{]-n+1,+\infty[} = x_{]-n+1,+\infty[}$, $z^{'}_{]-\infty,-n[} = x_{]-\infty,-n[}$ and $z^{'}_{]-n+1,+\infty[} = y_{]-n+1,+\infty[}$ belong to $B_n(x)$.
We prove the claim only for z using a recurrence proof. To simplify, we indifferently denote by f, the local rule of F which is a block maps from A^{2r+1} to A and also all the finite extensions of f which are block maps from A^{2r+1+k} to A^{k+1} with $k \in \mathbb{N}$.
Since $y \in B_n(x)$ we have $z]-n, n[= y]-n, n[= x]-n, n[$.
Suppose that for $i > 0$ one has
$F^t(z)]-n, n[= F^t(x)]-n, n[$ for $0 \leq t \leq i$. In this case we have $F^t(z)]-\infty, -n[= F^t(y)]-\infty, -n[$ for $0 \leq t \leq i$ and $F^{i+1}(z)]-n, 0[= f(F^i(z)]-n-r, r[) = f(F^i(z)]-n-r, -n-1[F^i(x)]-n, r[) = f(F^i(y)]-n-r, -n-1[F^i(x)]-n, r[) = F^{i+1}(x)]-n, 0[$.
Since $F^{i+1}(z)]1, n[= f(F^i(x)]-r+1, n+r[) = F^{i+1}(x)]1, n[$ it follows that $F^{i+1}(z)]-n, n[= F^{i+1}(x)]-n, n[$. We can conclude saying that $(F^k(z)]-n, n[)_{k\in\mathbb{N}} = (F^k(z)]-n, n[)_{k\in\mathbb{N}}$ which implies that $z \in B_n(x)$.
Now we apply the claim to a point $\sigma^m(y_1) \in B_n(x) \cap B_n(x)$. The points y_1 and $\sigma^m(y_1)$ belong to $B_n(x)$, so the point y_2 such that $y_2]-\infty, -n[= \sigma^m(y_1)]-\infty, -n[$ and $y_2]-n+1, +\infty[= y_1]-n+1, +\infty[$ belongs to $B_n(x)$.
We can see that $y_2]-n-m, -n+m-1[= ww$ and $y_2 \in \sigma^m B_n(x) \cap B_n(x) \cap \sigma^{-m} B_n(x)$. Next we construct

y_3 by applying the claim to $\sigma^m(y^2)$ and $\sigma^{-m}(y^2)$ (remark that $\sigma^m(y^2) \in B_n(\sigma^{-m}(y^2) = B_n(x)))$. The point y_3 is such that $y_3]-\infty,-n[= \sigma^m(y_2)]-\infty,-n[$ and $y_3]-n+1,+\infty[= \sigma^{-m}(y_2)]-n+1,+\infty[$. Since we have $y_3]-n-2m,2m-1[= wwww$, we can repeat the same process to $\sigma^{2m}(y_3)$ and $\sigma^{-2m}(y_3$ to construct a point y_4 such that $y_3]-n-4m,4m-1[= w^8$. Finally, the sequence $(y_n)_{n\in\mathbb{N}}$ of points of $B_n(x)$ that we construct by this algorithm converges to the shift periodic point $\overline{w} =^\infty w^\infty = ...wwww....$Since $B_n(x)$ is closed and compact,$\overline{w}$is in $B_n(x)$.

Another significant information about the dynamical behavior of cellular automata is given by temporally periodic configurations. If the set of the temporally periodic configurations of a cellular automaton is dense, then the cellular automaton has dense periodic points which are a fundamental property of the popular Devaney's definition of chaos for discrete dynamical systems.

We can classify two distinct types of temporally periodic configurations in cellular automata: the temporally periodic configurations that are also spatially periodic (jointly periodic points) and the ones that are not (strictly temporally periodic points). Among all temporally periodic configurations, the strictly periodic configurations are the ones that provide more information about the cellular automata dynamical behavior. Indeed any cellular automata has at least one jointly periodic configuration and it is well known that both surjective equicontinuous cellular automata which are the most stable and expansive cellular automata which are the most chaotic exhibit a dense set of jointly periodic orbits.

In this work we extend a result of Pietro Di Lena, Luciano Margara and Alberto Dennunzio about the density of the set of strictly temporally periodic to cellular automata with almost equicontinuous points.

Let $(A^{\mathbb{Z}};F)$ be a cellular automaton and μ an F-invariant and shift ergodic measure. We show that:

Proposition 0.2: If F has almost equicontinuous points then the set of strictly temporally periodic points of F is dense in the topological support of μ.

Proof 0.2:

Let r be the radius of the cellular automaton and z an almost equicontinuous point,
so $\mu(B_{[-r,r]}(z)) > 0$. Since μ is a shift ergodic measure $\exists p > 2r+1$ such that
$\mu(S = B_{[-r,r]}(z) \cap \sigma^{-p}(B_{[-r,r]}(z))) > 0$.

From the Poincare recurrence theorem, there exists $m \in \mathbb{N}^*$ and $x \in S$ such that
$F^m(x)_{[-r,r+p]} = x_{[-r,r+p]}$. Set $w = z_{[-r,r]} = x_{[-r,r]} = x_{[-r+p,r+p]}$ and $u = x_{[r,-r+p]}$.
Since $p-2r \geq 2$ $\exists v \neq u$ such that $|wv| = |wu|$.
From the proof of proposition 0.1 the shift periodic points $a = (wv)^\infty$, $b = (wu)^\infty$ and the point y such that
$y_{]-\infty,-r[} = (wv)^\infty$ $y_{[-r,+\infty[} = (wu)^\infty$ belong to S. Let us define the sequence $(y^{(i)})_{i\in\mathbb{N}}$ by:

$$\begin{cases} y^{(0)} = y_{[-r,r+p]} = wuw \\ y^{(i)} = y_{[-r-ip,r+(i+1)p]} = (wv)^i \; wuw \; (uw)^i \end{cases}$$

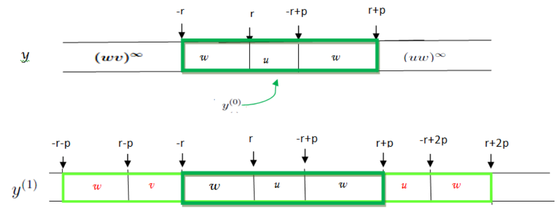


Fig. 1: Construction of the terms of the sequence $(y^{(i)})_{i\in\mathbb{N}}$

We need to prove by induction that $y^{(i)} \in B_{[-r-(i-1)p,r+ip]}(y)$ $\forall i \in \mathbb{N}^*$
For $i = 1$, Since $y^{(1)}_{[-r-p,r+2p]} = wv \; wuw \; uw$ so $y^{(1)}_{[-r,r+p]} = y_{[-r,r+p]} = wuw$. Suppose that for $j > 0$ one has $F^t(y^{(1)})_{[-r,r+p]} = F^t(y)_{[-r,r+p]}$ for $0 \leq t \leq j$. In this case

$$\begin{aligned} F^{j+1}(y^{(1)})_{[-r,r+p]} &= f(F^j(y^{(1)})_{[-2r,2r+p]}) \\ &= f(F^j(y^{(1)})_{[-2r,-r]} F^j(y)_{[-r,r+p]} F^j(y^{(1)})_{[r+p,r+2p]}) \\ &= F^{j+1}(y)_{[-r,r+p]} \end{aligned}$$

We can conclude that $(F^j(y^{(1)})_{[-r,r+p]})_{j\in\mathbb{N}} = (F^j(y)_{[-r,r+p]})_{j\in\mathbb{N}}$ which implies that
$y^{(1)} \in B_{[-r,r+p]}(y)$
Next, assuming that $y^{(i-1)} \in B_{[-r-(i-2)p,r+(i-1)p]}(y)$ and using the same arguments as in step $i = 1$ we prove that $(F^j(y^{(i)})_{[-r-(i-1)p,r+ip]})_{j\in\mathbb{N}} = (F^j(y)_{[-r-(i-1)p,r+ip]})_{j\in\mathbb{N}}$ which implies that $y^{(i)} \in B_{[-r-(i-1)p,r+ip]}(y)$.
Since for all $i \in \mathbb{N}$ $y^{(i)} \in B_{[-r-(i-1)p,r+ip]}(y)$ it follows that

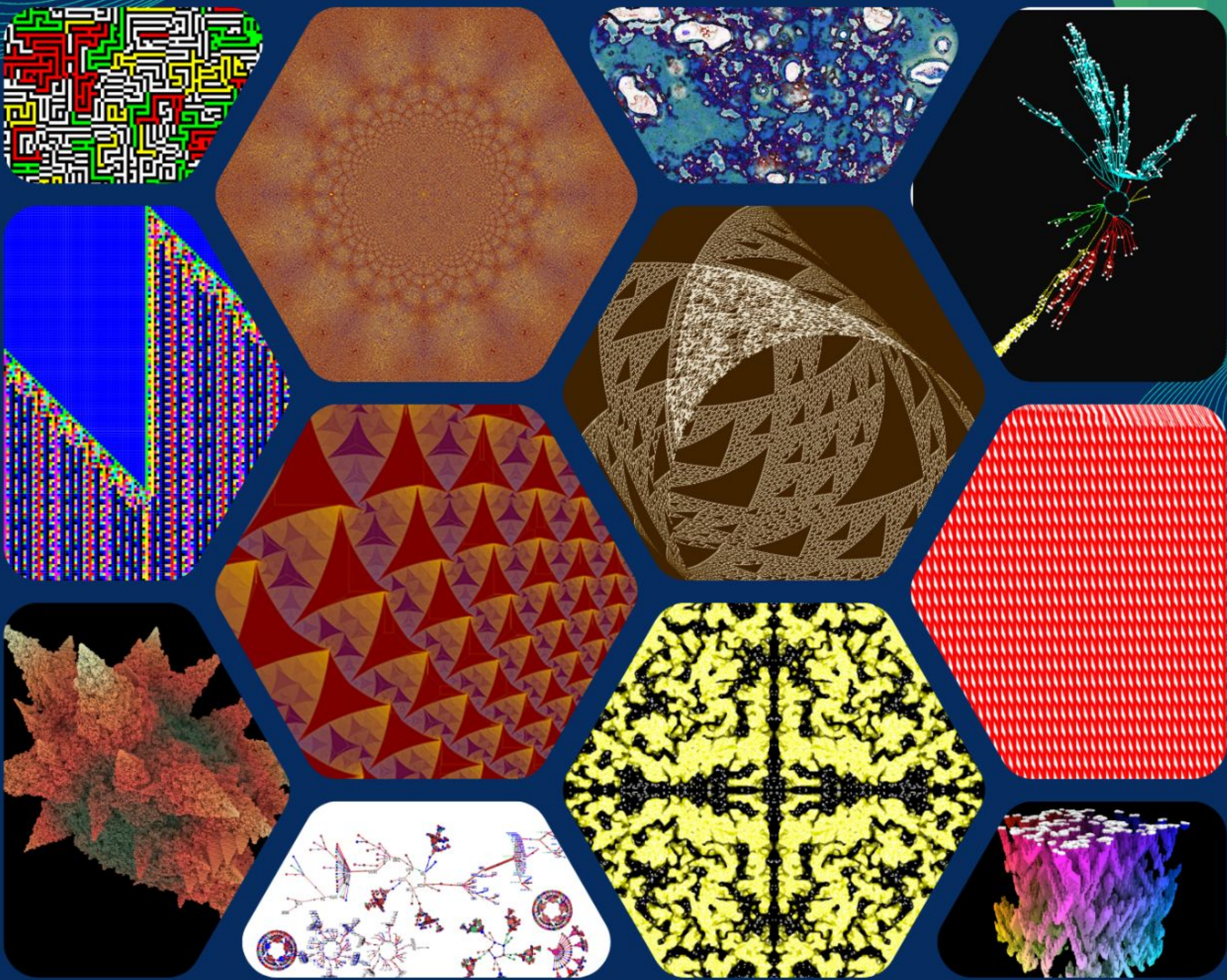
$$y^{(i)} \in B_{[-r,r+p]}(y) = B_{[-r,r]}(z) \cap \sigma^{-p}(B_{[-r,r]}(z)) = S$$

The sequence $(y^i)_{i\in\mathbb{N}}$ of points of S converge to $y' = (wv)^\infty wuw(uw)^\infty$. Since S is closed $y' \in S$ and since the F orbit of each point in S share the same central coordinates, it follows that $F^m(y')_{[-r,r+p]} = x_{[-r,r+p]} = y'_{[-r,r+p]} = wuw$ which implies that $F^m(y')_{[-r,+\infty[} = y'_{[-r,+\infty[}$.

Using the same arguments we prove that there exists a point $x' \in B_{[-r-p,r-p]} \cap \sigma^{-p}(B_{[-r-p,r-p]})$ such that $F^m(y')_{[-r-p,r]} = x'_{[-r-p,r]} = y'_{[-r-p,r]} = wvw$ which implies that
$F^m(y')_{]-\infty,-r]} = y'_{]-\infty,-r]}$.

It follows that $F^m(y') = y'$ and permit to conclude.

Exhibition on Art of Cellular Automata



PANEL DISCUSSION

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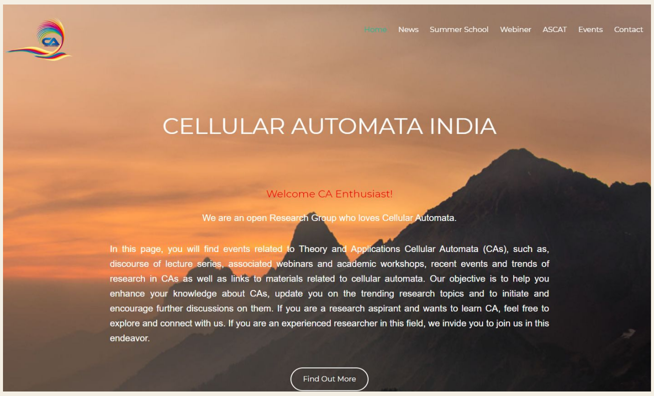
IIEST, Shibpur owes its origin to the erstwhile Bengal Engineering College, the history of which goes to the nineteenth century when industries in the sense we understand today, were practically absent. IIEST Shibpur was started by the name of Civil Engineering College on 24th November, 1856, in the premises of the Writers Building, Calcutta. In 1880, the campus was shifted to the Premises of Bishop's College. From 1920 to 2004, it was running as Bengal Engineering College (BEC), Shibpur. On October 2004, it was converted to full fledged State University and President of India renamed it as Bengal Engineering and Science University (BESU), Shibpur. Government of India awarded "Institution of National Importance" to promote research and higher education on March 2014 and renamed BESU as Indian Institute of Engineering Science and Technology (IIEST), Shibpur.

IIEST, Shibpur functions as an Institute of higher learning and advanced research. Prime activities include creation and dissemination of knowledge; producing engineers, scientists, and entrepreneurs of highest quality equipped with the latest technologies and developing innovation technology solutions for the cause of the society.

Kolkata, 'The City of Joy', formerly known as Calcutta, is one of India's largest cities. The city is housed on the east bank of the Hooghly River. Once, Kolkata served as the capital of India and even today, the city is dubbed as the cultural capital of India. Kolkata has aptly restored the heritage buildings, colonial walls and historical artefacts prevalent during the British rule. The city also exhibits typical Bengali culture that is especially favoured by those who love food, music, fine arts and literature.



Cellular Automata India (CAI) is an open Research Group for those who loves Cellular Automata. This group was initiated during the pandemic to act as a platform to listen, interact, exchange ideas and participate with the eminent scientists over the globe in the field of cellular automata. A discourse of lecture series, webinars series and academic workshops have been conducted through CAI. The Indian Summer School on Cellular Automata and ASCAT series are also offspring events of CAI.