A new implementation of Holland's Complex Adaptive Systems model with the aim of seeking answers to some fundamental open questions.

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Project Background and Motivation

• In the early 1990’s John Holland of the University of Michigan and the Santa Fe Institute (SFI), began work on a set of models with the objective of capturing the key mechanisms and properties of what he called Complex Adaptive Systems (CAS).

• Holland pointed out that CAS are all around us and make up the bulk of real world systems that we are exposed to.

• Examples of CAS given by Holland are Ecologies, Economies, Immune Systems, Developing Embryos, the functioning of complex cities such as New York and the human brain.

• Holland published his mature ideas on CAS in his 1995 book *Hidden Order*.

• Several attempts have been made over the years to implement the ECHO model, though they have tended to be incomplete implementations of Holland’s earlier ideas, most notably the code implemented by SFI which is still available on the Web.
Project Background and Motivation (cont.)

• The SFI ECHO code publicly available on the Web is in poor condition and is no longer supported. It has structural problems and does not lend itself to extension required to support further research.
• Papers published on ECHO have been largely inconclusive on the efficacy of the model and how well it describes the mechanisms and properties of a CAS.
• This project grew out of my interest in complex systems, my familiarity with ECHO through Holland’s book *Hidden Order*, and my concern about the need to make progress in understanding and developing this important model.

**CAS Definition:** A CAS is a system composed of many interacting semi-autonomous agents, where each agent has a few simple individual behaviors, which when aggregated with other agents can produce systems with emergent behaviors of high complexity (See Dissertation for reference).
Project Objectives

• The main objective of the project was to implement a new version of ECHO (to be called jECHO) using object oriented techniques and a well documented software development process.

• The implementation would specifically focus on Holland’s mature ideas described in *Hidden Order* (1995).

• The implementation would include the adhesion mechanism which enables the formation of multi-agent aggregates, and which has received very little attention in previous implementations.

• The project would include an investigation of the behavior of ECHO using ideas from previously published tests. Also, some tests of my own devising would focus on understanding the range of evolutionary dynamics possible from ECHO, and whether aggregates could form as a result of the adhesion mechanism.

• The software and documentation created during the project are to be made available on an Internet web site for the CAS research community to explore and extend.
Research Questions

The following research questions were instrumental in guiding my thinking while planning and designing this project:

– Do the agent interactions and resource transformations described by Holland in *Hidden Order* actually produce CAS behavior?
– Will the seven basic elements (four properties and three mechanisms) of a CAS proposed by Holland in *Hidden Order* be displayed in the behavior of jECHO?
– Will the adhesion mechanism described in *Hidden Order* lead to the formation of multi-agent aggregates?
– What tests would provide a thorough exploration of the behavior of jECHO?
– Should the jECHO implementation not exhibit CAS behavior then what modifications might be made to the model that could lead to CAS behavior?
– What are potentially fruitful avenues for future work on the ECHO CAS model?
A version of ECHO was produced at SFI in the early 1990’s and subjected to several tests over a number of years. Investigators reported that the model displayed species abundance similar to that seen in natural systems [Forest and Jones (1994)*].

Variants of ECHO were developed to study food webs and relative species abundance. Schmitz and Booth (1997), Hraber and Milne (1996)*.

Smith and Bedau (1999) came to the conclusion that ECHO does not exemplify the features of CAS as described in Holland (1995). Their main reason for this assertion is “there is no evidence of the emergence of a diversity of hierarchically organized adaptive aggregates”.

It was not too surprising that Smith and Bedau came to this conclusion as the SFI version they used did not contain Holland’s adhesion mechanism for the creation of multi-agent aggregates.

My view of the previous work is that it is inconclusive on the mature version of Holland’s ideas expressed in *Hidden Order* and has left more questions than answers. A better version of ECHO is needed for additional experimentation to be able to move forward. Hence the need for jECHO.

* See Dissertation for full references
Project Methodology

• The project methodology was based on the Unified Process described by Larman (2001) and used diagrams from the Unified Modeling Language (UML) to document the Inception and Elaboration phases.

• A Use Case diagram and Use Case scenario descriptions were created to describe user interaction with jECHO. A Domain model was created to understand ECHO entities and their relationships.

• The specific mechanisms defined by Holland for each of his first 5 ECHO models were described and analyzed.

• The Java based RePast multi-agent simulation framework was selected and analyzed as a foundation for implementing jECHO.

• Detailed class and sequence diagrams were created to describe the design of jECHO.

• Tests from the literature were selected in addition to some tests of my own devising.
Project Phases, Activities and Artifacts

The following diagram shows the phases of the project and the major activities and artifacts created during each phase.

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**PHASE**
- Inception
- Elaboration
- Construction
- Transition

**ACTIVITY**
- Analysis Model
- Design Model
- Coding
- Tests

**ARTIFACTS**
- Use Cases
- Domain Diagram
- Sequence Diagram
- Class Diagram
- Sequence Diagrams
- Eco Triangle
- Smith & Bedau
- My Own Tests
A use case analysis of the jECHO simulation environment was created. Based on this analysis, a sequence diagram showing the interaction between a researcher and jECHO was then developed.
A Domain model of ECHO described in *Hidden Order* was created to understand entities in the ECHO world. The diagram on the right shows the relationship between the ECHO World, Sites within the World and Agents that inhabit the Sites.
Central to an understanding of ECHO is that each agent possesses a Chromosome consisting of Tags and Conditions made up of resources (e.g., a, b, c, d), which determines the agents capabilities and behavior when it interacts with other agents.

In addition to its chromosome, each agent possesses a reservoir where it stores resources gained from interactions with the site it lives on, and with other agents.
As a result of the requirements modeling and analysis of the problem domain a detailed design consisting of class and sequence diagrams was created.
jECHO: Results and Analysis

Once the implementation of jECHO was completed, the first test was to create an agent ecology mentioned by Holland in *Hidden Order* called the ‘Caterpillar-Ant-Fly Ecological Triangle. The diagram on the left shows the Offense and Defense tags of the initial agent population. The graph on the right shows the agent population against number of generations for a high rate of mutation. The main purpose of this particular test was to prove the operation of jECHO.
The second test was based on work published by Smith and Bedau (1999). They subjected the SFI version of ECHO to a series of tests where they varied the mutation rate from very high to very low values and observed the effect on population dynamics. The results obtained from jECHO are not directly comparable with those from SFI as the earlier version of ECHO implemented different interaction mechanisms. However, the tests do show the dramatic impact that mutation rate has on evolutionary dynamics.
The final tests were intended to exercise the multi-site capabilities of jECHO and also to explore the adhesion mechanism by determining whether multi-agent aggregates could be created.

The 16 site test shown on the left above displays almost chaotic behavior with wide swings in agent population. The two tests shown in the middle and on the right each had 9 sites and the same mutation rates, however, changes were made to the agent tags and conditions to experiment with various factors including adhesion into multi-agent aggregates. The blue line at the bottom of each graph shows the number of aggregates formed against generation number. By experimenting with tags it was possible to bring about the formation of multi-agent aggregates.
In Hidden Order, Holland proposed 7 basic elements that he thought were common to all CAS. One aim of the testing was to seek evidence for these elements in jECHO. Taking each in turn:

• **Aggregation (Property):** A number of jECHO simulations showed the creation of multi-agent aggregates formed by the adhesion mechanism. jECHO certainly has this element as a design feature.

• **Tagging (Mechanism):** Tagging is designed into the ECHO model and has a major impact on the type of behavior displayed by in a simulation. A minor change in a starting tag can significantly alter the observed behavior.

• **NonLinearity (Property):** Some of the simulations show either exponential growth, or almost chaotic behavior that is suggestive nonlinear behavior.

• **Flows (Property):** Flow patterns occur within jECHO due to agent death and the freeing of resources for accumulation by other agents. They also come about through agent resource transformations. Improved analytical displays giving additional information on resource flows are needed to see this property more clearly within jECHO.
jECHO: Results and Analysis (Cont.)

- **Diversity (Property):** Over the range of generations simulated with jECHO genetic novelty seems to be introduced into the simulation by on-going crossover and mutation of agent chromosomes. Whether perpetual novelty is possible with a simulator such as jECHO is still an open question in my mind.

- **Internal Models (Mechanism):** My contention is that agents which are the most successful in that they spread their genetic material the furthest through a population have the ‘best’ internal model (chromosome) for dealing with the environment at that point in time. However, conditions can change quickly, which might invalidate a successful agent’s ‘internal model’ (such as the arising of a better adapted chromosome due to a mutation).

- **Building Blocks (Mechanism):** Holland sees building blocks as the components that come together to generate the internal models of a CAS. The successful building blocks (well proven pieces of Tags and Conditions) will rapidly spread throughout a population. ECHO has this feature by design.
Conclusions

• This project has successfully delivered a new implementation (jECHO) of Holland’s ECHO model of a Complex Adaptive System.
• jECHO implements the first 5 ECHO models described in Hidden Order including the rarely studied adhesion mechanism.
• The adhesion mechanism has shown that it is possible for multi-agent aggregates to form within ECHO.
• jECHO shows evidence for all seven of the basic elements of a CAS described by Holland in Hidden Order. What is not clear is whether this is a complete list of CAS elements. Nor is the relative importance of each CAS element yet understood.
• Better analytical tools are required within jECHO before a determination can be made as to whether ECHO is indeed a CAS.
• A subset of configurations (agent tags, conditions, sites, etc) within jECHO appear to have the potential for perpetual novelty (open ended evolution), though more work is needed to investigate this.
Further Work

The following are areas in which future effort on jECHO should be focused:

- **Improve performance:** To be able to set up simulation runs of sufficient complexity and to be able to run them for hundreds of thousands of generations will require significant improvements to be made to the performance of jECHO.

- **Implement Model 6:** The final model described by Holland in *Hidden Order* will bring about full implementation of multi-agent features which should allow deeper questions about CAS to be investigated.

- **Create tools for observing and analyzing complex behavior:** An immense number of interactions and events are occurring in parallel within jECHO. New tools and new ways of observing complexity are needed if much headway is to be made toward a theory of CAS.

- **Devise classifications that enable predictions about CAS behavior:** Developing a classification metric for long term evolutionary dynamics may allow greater insight into where the interesting behavior can be found within ECHO and possibly give insight into how the model can be developed further.
jECHO on the Web

• jECHO is available for download at the following url: http://www.brianmcindoe.com
• Be sure to follow the instructions as jECHO has dependencies on Java and also the RePast simulation framework.