

A Framework for Large Scale Complex Adaptive Systems Modeling, Simulation, and Analysis

(Doctoral Consortium)

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ABSTRACT

Complex adaptive systems (CAS) exhibit properties beyond complex systems such as self-organization, adaptability and modularity. Designing models of CAS is typically a non-trivial task as many components are made up of sub-components and rely on a large number of complex interactions. Studying features of these models also requires specific work for each system. Moreover, running these models as simulations with a large number of entities requires a large amount of processing power. We propose a framework that consists of a modeling language, analysis tools, and simulation engine, called CASTLE. We propose a language, Complex Adaptive Systems Language (CASL), which is designed for simple creation of CAS models while remaining domain agnostic. In particular, an extension to CASL, called CASL-SG, that introduces the concept of ‘semantic grouping’ allows for large scale simulations to execute on relatively modest hardware. A component of our framework, the observation module, aims to provide an extensible and expandable set of metrics to study key features of CAS such as aggregation, adaptability, and modularity, compatibility with existing analysis tools, while also allowing for more domain-specific techniques.

Keywords

Complex Adaptive Systems; Self-Organization; Emergence

1. INTRODUCTION

Complex adaptive systems are a type of complex system where entities and the environment are encouraged to adapt and interact with each other in order to achieve desired properties and provide a more realistic abstraction of real-life scenarios. Complex adaptive systems have become ubiquitous in domains such as social networks, supply chains, healthcare networks, smart-cities and smart-grids, the “Internet of Things”, and the Internet itself [2, 6]. Complex adaptive systems must support the concepts of adaptation, modularity, and diversity and contain interactive environments [4, 5, 7]. Environments contain other entities and can act as commu-

nication mediums that allow for stigmergical interactions, system wide events, and self-organization.

Designing CAS models has been achieved using a variety of languages and frameworks, however, these have been either too domain-specific, or too domain-agnostic. Domain-agnostic attempts have resulted in models that do not adhere to CAS rules, while domain-specific attempts have resulted in developing techniques that are not adaptable to other domains.

Analysis of CAS suffers from a shortage of specific metrics and tools. Existing metrics to identify properties such as self-organization and adaptability are application or domain specific and thus are difficult to generalize, or only work for simple and small-scale models such as Flocks of Birds, Game of Life, or ant colonies [3, 8]. The primary of goals of my work are:

1. Provide a standard for agent-based CAS modeling and simulation that utilize the above definition of CAS
2. Provide a flexible modeling approach that is domain agnostic and can be used for complex, realistic models
3. Provide a set of tools and metrics to study these models and their myriad properties. Few CAS specific metrics exist, despite CAS exhibiting many properties
4. Allow for large, complex, and modular simulations to be executed on relatively modest hardware. This will allow for researchers to construct and study very large CAS models without the need for specialized hardware

2. CURRENT WORK

Our prototype framework, called CASTLE, consists of the CASL or CASL-SG modeler, the code generator, a simulator, an observation tool, and a visualizer as shown in Figure 2. Our language, CASL, provides constructs for design-

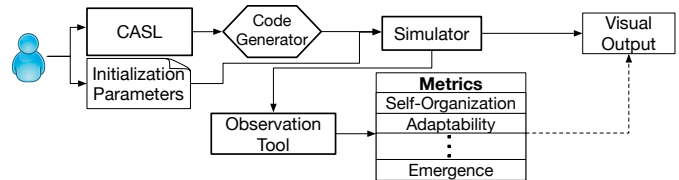


Figure 1: CASTLE Framework Overview
ing models to capture the salient features of a CAS such as

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adaptation and modularity, along with other complex systems features such as interactions and behaviors [2]. CASL also requires entities to be defined as either agents or environments. We propose an extension to the language and framework, called CASL-SG, which requires the model designer to restructure their initial model slightly, by considering the collective relationship between entities. Each collective, or group, consists of agents that have a semantic relationship. As such, we refer to these collectives as ‘semantic groups’. This relationship is also dependent on how particular agents are represented and in many cases, how agents are represented can form the basis for their relationship. For example, in an emergency department, a patient has a much stronger relationship with a doctor than a nurse or a pathology technician. As collective behaviors and aggregation is a key feature of CAS, defining which entities comprise ‘semantic groups’ is relatively intuitive. This has previously been achieved for models where the environment is represented by two or three dimensional space such as a flock of birds model or a traffic model, and has relied on forming groups based solely on the agent’s position in space.

Once a model is constructed in the CASL modeler, code is generated only if all the required constraints have been adhered to. The generated code is then executed in the simulator, which may require initialization parameters which can be provided by a configuration file. The observation tool is comprised of several modules that analyze various features of a CAS such as emergence, self-organization, adaptability, runtimes, interactions, and domain-specific features. The observation tool is designed to be extensible to allow for new metrics to be added, that may either be designed specifically for the current simulation or for a more domain-agnostic purpose. To aid the observation module, CASL allows for certain model features to be flagged so that these are utilized by a particular metric. For example, an agent may make multiple types of interactions, but only one type is considered useful for study. CASL allows the model designer to flag that particular interaction type for use in an interaction metric.

We have designed and implemented a range of metrics for our observation tool to study key CAS features such as criticality, self-organization, emergence, and adaptability. We have performed extensive experiments using these metrics by analyzing two distinct CAS models, namely an emergency department and a Game of Life model.

3. RESULTS

We have implemented several models in CASL using semantic groups such as Game of Life, Flock of Birds, an Emergency Department, and a social network. Our prototype simulator relies on Repast Symphony [1] for simulation scheduling and our distribution is achieved using parallel processing. For very large models, CASL with semantic groups provides a significant runtime decrease when compared to CASL without semantic groups. A Game of Life simulation with 4 million cells took 28 minutes using a single group, which was reduced to 8 minutes when using 100 semantic groups. A Flock of Birds simulation with 5,000 agents was roughly 18.5 times faster than the non-semantic group equivalent. Furthermore, semantic grouping allowed for executions with more than 10,000 agents to finish, which was not possible using the non-semantic group equivalent. Our significantly more complex emergency department sim-

ulation had a speed up of roughly 50% when using 30 semantic groups, compared to one semantic group. We have attained similar speed-ups across our other simulations.

Our metrics were able to detect criticality, self-organization, emergence, and adaptability in several cases of our emergency department and Game of Life models. Further work, including refining existing metrics, and creation of new ones is ongoing. In addition, the observation module of CASTLE allows for external analysis tools to utilize the data generated by a simulation.

4. CONCLUSION AND FUTURE WORK

We propose a framework, CASTLE, for modeling, simulating, and analyzing complex adaptive systems. Our language, CASL, is capable of creating CAS models, while the extension, CASL-SG, is capable of designing models that can be simulated with very large numbers of agents. We are currently using CASTLE to perform an in-depth study of smart cities focusing on transportation networks. We aim to use our observation tool, existing metrics, and other analysis tool-kits to study smart cities from a complex adaptive systems perspective. We focus our analysis on examining emergent behaviors, self-organization, and adaptability. Our future work includes designing new metrics to study more complex properties such as self-similarity and feedback loops, improving the performance benefits gained with CASL-SG by enabling the simulation to utilize GPU acceleration, as well as allowing metrics to be defined using CASL. In addition, we aim to showcase to flexibility and power of CASL-SG by creating models of realistic systems.

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