

# Towards Frabjous: A Two-Level System for Functional Reactive Agent-Based Epidemic Simulation

Author names removed for  
anonymous review

## ABSTRACT

Computational epidemic models, such as the simulation of a disease moving through a population, are being employed more frequently by health policy-makers. However, these models present several obstacles to widespread adoption. They are complex entities and have a high cost of development and maintenance. Current tools can be opaque, requiring multidisciplinary collaboration between a modeler and an expert programmer. In this paper, we describe the use of functional reactive programming (FRP), a programming paradigm created by imbuing a functional programming language with an intrinsic sense of time, to represent agent-based models in a concise and transparent way. We document the conversion of several agent-based models developed in the popular hybrid modeling tool AnyLogic [21] to a representation in FRP. We also introduce Frabjous, a programming framework and domain-specific language (DSL) for computational modeling. Frabjous is a unique system that generates human-readable and modifiable FRP code from a model specification, allowing modelers to have two transparent representations which to program: a high-level model specification, and a full programming language with an agent-based modeling framework.

## Categories and Subject Descriptors

I.6.5 [Simulation and Modeling]: Model Development; Modeling Methodologies; J.3 [Life and Medical Sciences]: Health

## General Terms

Languages, Experimentation

## Keywords

Functional reactive, simulation, dynamic model, domain-specific language, agent-based simulation, agent-based modeling

## 1. INTRODUCTION

While computational health models have proven valuable lenses for understanding public health issues, such models are only now

beginning to be applied to many pressing public health issues [17, 16]. This reflects limits in the software support for modeling; the development of these models can be cumbersome and slow.

The application of dynamic models to public health is further limited because such models are frequently challenging to build, difficult to understand and evaluate, computationally expensive, and difficult to share and collaboratively explore in policy decision team.

A key aspect of this problem lies in how the models are specified and developed. Many are represented by imperative programming languages such as Java and Objective-C [17]. Despite the use of frameworks and problem solving environments (PSEs) to handle the complexity of the code, these representations are fundamentally opaque and verbose. Developers must understand the programming language, the framework, and the model, which frequently demands considerable skills in software engineering.

Functional programming (FP), on the other hand, is well-documented for being concise and transparent [2, 8]. As well, declarative languages are frequently easier to parallelize [3, 20]. For an agent-based model with hundreds or thousands of agents working in parallel, parallel computing can lead to great gains in turnaround, facilitating experimentation and domain insight.

Though functional programming appears well-suited to representing simulation models, FP presents specific difficulties for representing a time-varying system, since a declarative style avoids a direct, mutable representation of the system state. As an alternative, we adopt functional reactive programming (FRP), originally developed by Elliot and Hudak [7], to represent time as an intrinsic part of the paradigm.

In this work, we provide two main contributions. First, we explore a promising method for specifying agent-based epidemiological models with functional reactive programming by translating several models into Haskell/Yampa, an FRP framework. Second, we specify a domain-specific language, Frabjous, that generates readable and concise Haskell/Yampa code. Model specifications can be written, modified, or extended in either the Frabjous language or directly in Haskell/Yampa, leading to a flexible system that is always transparent for model structure and parameters.

We begin with a description of agent-based epidemiological simulation, and an overview of FRP. We then show how a simple model can be represented in FRP. We next give an overview for the Frabjous language and system. We conclude with our overall findings and future directions for this work.

## 2. COMPUTATIONAL HEALTH MODELS

In this section, we provide a brief overview of computational health models, current tools, and challenges encountered by modelers.

Permission to make digital or hard copies of all or part of this work for personal or classroom use is granted without fee provided that copies are not made or distributed for profit or commercial advantage and that copies bear this notice and the full citation on the first page. To copy otherwise, to republish, to post on servers or to redistribute to lists, requires prior specific permission and/or a fee.

WOODSTOCK '97 El Paso, Texas USA

Copyright 20XX ACM X-XXXXX-XX-X/XX/XX ...\$10.00.

## 2.1 The SIR Model

One example of an agent-based health model is the Susceptible, Infectious, Recovered (SIR) model (see Figure 1). A class-stylized abstraction of the dynamics of infectious diseases such as measles, chickenpox, pertussis [1]. Every agent in this system has one of three states - Susceptible, where the agent is not protected from the disease and may be infected; Infectious, where the agent is infected with the disease and may pass it on to Susceptible agents; and Recovered, where the agent no longer has the disease (and is temporarily or permanently protected from being infected). A simple version of this model has agents positioned on a two-dimensional grid, where each Susceptible neighbour of an Infectious agent has a defined probability of being infected. We will use this model as an example to illustrate our process and findings.

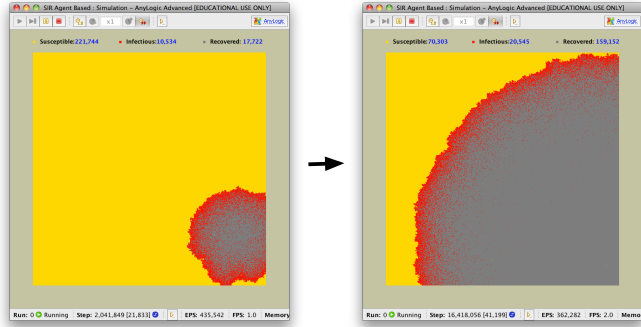


Figure 1: SIR Model. Yellow squares are Susceptible agents, Red are Infectious, and Grey are Recovered.

## 2.2 Current Tools

The past two decades have seen a rapid rise in the number of modeling packages supporting agent-based modeling. These include REPASt/Simbuilder, SWARM, SDML, NETLOGO, and, most recently, AnyLogic [14, 15, 11, 22, 12, 21].

Most of these systems require custom programming to fine-tune simulation behaviour and analyze model operation. Traditionally, agent-based models have been created in imperative programming languages such as Java and Objective-C [17, 16, 21, 22]. Many researchers interested in agent-based modeling find themselves dissuaded by the need to learn general-purpose programming languages and principles and practices of software engineering in order to apply the necessary tools.

These programming environments also offer poor support for important domain-specific logic and metadata, such as are required for dimensional analysis or maintaining information on the quality of data used. In an unfortunately high fraction of cases [17], the modeler must serve as a software developer as well, a task for which they typically lack training. Taken together, these factors result in longer development times, lack of model transparency and a higher risk of human error in models.

By contrast, functional languages and closely related declarative techniques have recently been demonstrated to offer admirable expressiveness, transparency of reasoning, and economy of effort in specifying dynamic systems [17, 16].

## 2.3 SIR Model Implementation in AnyLogic

AnyLogic is a Java-based modeling problem solving environment (PSE). It provides a graphical user interface (GUI) for graphical manipulation of models, but much of the functionality to build

a model consists of Java code. Furthermore, because this code is hidden behind the GUI, a modeler must both understand Java and the AnyLogic object-oriented framework before they can build anything beyond a basic model. Even a programmer experienced with this tool must sometimes scan across properties associated with multiple components of the model to find salient features from the model. See Figure 2 for a screenshot of AnyLogic in use.

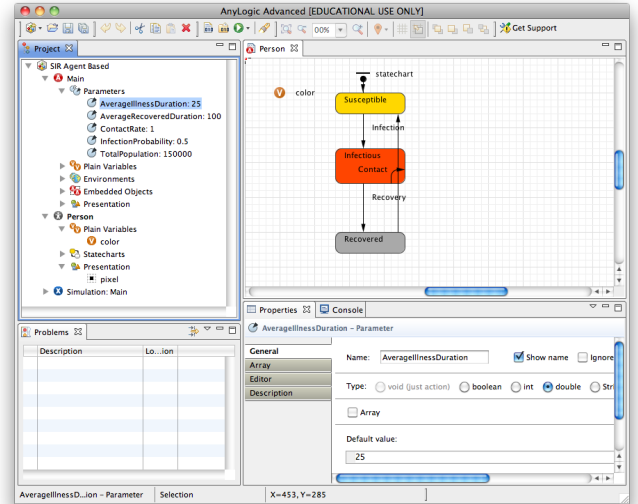


Figure 2: SIR Model implemented in AnyLogic. Note how, through hiding of information, the user must hunt to find details. On the other hand, if AnyLogic were to show all of the Java code, the result would not be much better.

## 3. FUNCTIONAL REACTIVE PROGRAMMING

In this section, we summarize the technique of functional reactive programming (FRP) and describe its use to represent agent-based computational health models.

### 3.1 Functional Programming

Functional programming is a programming paradigm in which the computer languages define pure functions, without mutable state or other computational effects tying them together. Hence, sequencing of program execution, which is mandated by these effects, is only provided by function calls. These languages are often called declarative languages. Examples of functional programming languages include Scheme, ML, and Haskell.<sup>1</sup>

Functional programming provides concise and expressive code, often orders of magnitude shorter than imperative languages, and with a structure that often exposes the fundamental algorithm more clearly. This means that functional programs can be transparent, enabling a computational modeler to debug by inspection. Essentially, reasoning about functional programs is simpler, involving less of the global execution state, because of the reduced and explicitly constructed side effects.

However, by avoiding explicit manipulation of the global execution state, it can be difficult to represent a time-varying system in a functional paradigm. In purely-functional programming languages

<sup>1</sup>In fairness, Scheme and ML provide some imperative features, but use of these is discouraged.

Model	AnyLogic	Haskell/Yampa
Game of Life	839	70
SIR	1282	70
ESRD/TB	2222	166

**Figure 3: Source lines of code for model implementations comparing Java code generated by AnyLogic for an executable file and our hand-programmed Haskell/Yampa implementations.**

like Haskell, system state is represented as a hidden parameter using *monads* [23]. In a non-purely-functional programming language like ML, code must take on an imperative style, reducing the elegance and transparency of functional programming language. This makes traditional functional programming poorly suited to agent-based modeling.

### 3.2 Functional Reactive Programming

Functional reactive programming (FRP) endeavors accommodate sequencing in functional programs by imbuing a language to have an intrinsic notion of time [13, 4]. This allows us to overcome the problem of representing a time-varying system in a functional language. In addition, FRP provides an effective mechanism for visualization of output - indeed, its original purpose was to produce animation [7].

To improve FRP code, Hughes developed the concept of the *arrow* [9]. Arrows are a generalization of *monads* that are used in functional programming for sequencing. Monads encapsulate computation, forming a list or pipeline of computation that can make a programmer's job easier. An example from Haskell is IO monad, which is used to transmit the external state of the world as a hidden parameter.

While monads form a pipeline, *arrows* form a graph. One can have multiple arrows converge and split. This leads to a natural representation of circuits and dynamic systems. In the case of FRP, arrows are used to implicitly interpret time. Paterson made this approach more transparent with his excellent syntactic sugar - arrows essentially make graphical diagrams in the code, improving readability [19].

### 3.3 SIR model written with FRP

We implemented the SIR model in the functional programming language Haskell, using Yale's Yampa [4] environment for FRP (see Figure 4). For visualization, we used wxFruit, an implementation of Fruit (Functional Reactive User Interface Toolkit) using wxWidget bindings [6, 5]. We used the Glasgow Haskell Compiler (GHC) version 6.12.3.

Computational models written in Haskell/Yampa were orders of magnitude shorter than their Java counterparts produced by AnyLogic (see Figure 3 for a comparison of source lines of code). Note that while the SIR model used as a continuous example, additional models were implemented in Haskell/Yampa and Frabjous but cannot be reported in similar detail due to space limitations. These include Conway's Game of Life, an early example of cellular automata, and ESRD/TB, a model examining comorbidities of chronic kidney disease and tuberculosis.

Many of the models fit on one page of code. However, this conciseness comes at a cost. Though transparent to a programmer familiar with functional reactive programming, much of the syntax is difficult to understand by the layperson. Higher order functions and FRP syntax made the language complicated to those unfamiliar with this programming paradigm (see Figure 4 for an example). To overcome this obstacle, we chose to develop an agent-based mod-

```

— states of agents
susceptible :: StateSF
susceptible = dSwitch (constant Sus &&&
    (arr (/=[]) >>> edge))
    (\_ -> infected)

```

**Figure 4: Excerpt from the Haskell/Yampa implementation of the SIR model.**

```

— state definitions for diagram flu
diagram_flu = state_flu_susceptible

state_flu_susceptible = state output
    transitions

where
    output = State_flu_susceptible
    transitions = transition1
    transition1 = receive "infect"
        state_flu_susceptible

```

**Figure 5: Excerpt of the Haskell/Yampa code generated by the Frabjous system prototype for the SIR model.**

eling framework and domain-specific language (DSL) in Haskell.

## 4. FRABJOUS

We present an initial specification of Frabjous, our domain-specific language and framework for developing functional reactive agent-based simulation ("FRABjous"). Frabjous provides a high-level natural language to generate Haskell/Yampa code, which can then be further fine-tuned. Although our system is still a prototype, initial results show promise. The Haskell/Yampa code is co and human-readable, a rarity for generated code. See Figures 6 and 5 for examples of a Frabjous specification and generated code.

### 4.1 Language Specification

Here we detail the Frabjous DSL specification. Frabjous describes a labelled transition system. Programmers define a *model*, with an *environment*, a set of *agents*, and a set of *networks* of agents.

A *model* is the top-level system abstraction described by Frabjous. It has a defined name, and encapsulates everything required to run an agent-based simulation.

An *agent* is the bottom-level system abstraction. Several agents exist in the model. Each has a unique identifier, as well as a list of associated networks, confounders, diagrams, and populations (described later).

A *diagram* is shorthand for a state-transition diagram. A diagram has a unique identifier, a starting state, and a list of associated states. A *state* is part of a diagram. Each state describes a state of an agent with respect to the distinctions captured in this diagram; for example, in the SIR model, there are three states: Susceptible, Infectious, and Recovered. Every state has unique identifier, a list of messages, a list of variables, a list of transitions to other states in the same diagram, and display information for visualization when the model is in execution. A *transition* is the means by which an agent switches between states. Each transition has a trigger (de-

```

discrete model sir

on startup send "infect" to anyone

network connections of people
  by vonneumann

diagram flu starting with susceptible

state susceptible displays yellow
  on receive "infect" switch to
    infectious

state infectious displays red
  on timeout 10 switch to recovered
  on rate 1 send "infect" to
    neighbour connections

state recovered displays blue

agent people with
  flu
  population 100

```

Figure 6: SIR model written in Frabjous.

scribed below) and a target state.

A *message* is the means by which agents communicate to each other. Each message has a *trigger*, an event that will initiate the sending of a message or the transition from one state in a diagram to another. A trigger can be: “startup”, where the event will trigger when the simulation starts running; “rate”, a probabilistic method representing a poisson process where a mean of  $n$  triggers will occur per unit of time; “timeout”, where a trigger will occur after  $n$  time units; “expression”, where a trigger will occur when a boolean expression evaluates to true; “enter”, where a trigger will occur when an agent transitions to the specified state; and “leave”, where a trigger will occur when an agent transitions from the specified state. For example, in [a SIR model](#), an Infectious agent might send a message to another agent to represent contact. If the receiving agent is in the Susceptible state, it will have a probability to switch states to Infectious. An example of a trigger in the SIR model is the infection of patient 0 on startup.

A *target* is a set of agents to receive a message. At this point in time, we limit it to: “Anyone”, where one agent at random is selected to receive the message; “Everyone”, where every agent receives the message; “Neighbour”, where an agent’s neighbor is selected at random from a specified network; and “Neighbours”, where an agent’s entire neighbourhood from a specified network receives the message. For example, each Infected agent sends a message to `Neighbour connections`, where `connections` is the only network defined in the model. See Figure 7 for neighbourhood information.

A *confounder* is a way of combining diagrams, the internal state abstraction for each agent. Each confounder has a list of diagrams to combine, and a list of messages that provide greater control over ways these diagrams interact. In this way, health modelers can study the interaction between different diseases. See Section 4.4 for more details.

A *network* is an arrangement of agents, determining how they are

connected to each other. Each network has a unique identifier, the identifier of a type of agent, and a *structure*, a defined method for creating *neighbourhoods* in a network. Network structure is dependent upon the model’s *environment*, which can be either discrete or continuous. See Figure 7 for more details about network structure and environment.

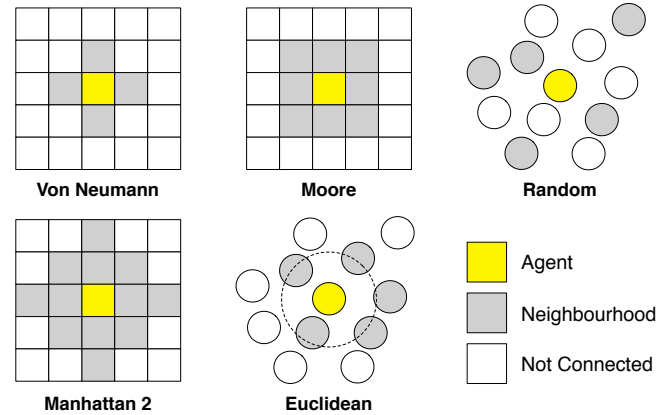


Figure 7: Examples of different types of neighbourhoods. Moore, Von Neumann, and Manhattan neighbourhoods are only available in a discrete environment where agents form a grid. Euclidean and Random neighbourhoods are only available in a continuous environment, where agents are distributed randomly in 2D space.

## 4.2 System Description

The Frabjous system has two components: a compiler, which generates Haskell/Yampa code from a Frabjous model specification, and a Haskell/Yampa library intended to make generated code more readable. We hope to use the Frabjous specification as a way to rapidly develop initial models, and then provide the full programming environment of Haskell/Yampa to tweak or further improve more sophisticated models. Our goal is to have modelers develop at both levels, and be able to see the entire model at a glance from either representation.

The Frabjous compiler was developed in Haskell/Yampa using the Parsec library [10]. The system is partially implemented; the parsing module is complete along with rudimentary type-checking, and the code generator is partially implemented. The Frabjous library is still under development. The Glasgow Haskell Compiler (GHC) will be used to compile generated code into a binary executable.

## 4.3 Language Features

Our partial implementation shows promising results in human-readable generated code. In addition, both representations are extremely concise (see Figure 3). Hand-crafted Haskell/Yampa code is approximately four times shorter than the Java code generated by AnyLogic. Frabjous-generated Haskell/Yampa code length is expected to be similar to that of our hand-crafted examples.

The higher-level character of the specification helps in maintaining modeler reasoning at the domain level, which is important in creating, extending, debugging, and seeking to understand a model. Through Frabjous, modelers can think in terms of the domain rather than at the level of a programming language.

## 4.4 The Confound Statement





One particularly exciting feature of Frabjous is the *confound* statement. This statement allows two different models to be combined and interact in a defined way. We hope to provide modelers with the ability to confound agent-based models in a similar fashion that functional programmers compose functions. The combinatorial explosion of combining different simulations (for example, simulating two or more diseases interacting within a single agent) is not well handled in aggregate simulation models [18]. While agent-based tools avoid this combinatorial explosion, modular specification of comorbidities is not supported in a modular fashion in existing agent-based simulation tools. Through this we hope to provide increased manageability of large model sets and better support collaboration between modelers.

## 5. SUMMARY

We have demonstrated a need for more transparent and efficient tools (in terms of both computational resources as well as human skills) in the domain of agent-based simulation. We have provided a case for using functional reactive programming to meet this need. Initial exploration has demonstrated that this approach yields concise and transparent code for expert programmers, but a language barrier for less experienced programmers. The development of a domain-specific language and domain library (Frabjous) has compensated for these problems and presents a step towards a viable solution.

## 6. FUTURE WORK

We plan to complete the implementation of the Frabjous system by finishing the code generation and base library modules. Iterative design and evaluation with additional computational health modelers will provide a deeper understanding of how we can effectively develop a tool that is transparent, effective, and easy to use by computational modelers.

To address this need, there are planned improvements to evaluate the computational efficiency by parallelization. We plan to use CUDA to compute each agents' actions and interactions in parallel at each time step. Preliminary investigation suggests that this will be a simple conversion [3], but one that could offer important incentives for using the Frabjous framework.

## 7. ACKNOWLEDGEMENTS

*Acknowledgements removed for anonymous review*

## References

- [1] R. M. Anderson and R. M. May. *Infectious Diseases of Humans Dynamics and Control*. Oxford University Press, 1992.
- [2] J. Backus. Can functional programming be liberated from the von Neumann style? *Comm. ACM*, 21(8):613–641, 1978.
- [3] M. M. Chakaravarty, R. Leshchinskiy, S. Peyton-Jones, G. Keller, and S. Marlow. Data parallel Haskell: a status report. In *Workshop on Declarative Aspects of Multicore Programming*, pages 10–18. ACM Press, January 2007.
- [4] A. Courtney, H. Nilsson, and J. Peterson. The yampa arcade. *Proceedings of the 2003 ACM SIGPLAN Workshop on Haskell*, pages 7–18, 2003.
- [5] A. Courtney, B. Robinson, and P. Hudak. wxfruit, March 2009. <http://www.haskell.org/haskellwiki/WxFruit>.
- [6] A. A. Courtney. *Modeling user interfaces in a functional language*. PhD thesis, Yale University, New Haven, CT, USA, 2004. AAI3125177.
- [7] C. Elliott and P. Hudak. Functional reactive animation. *International Conference on Functional Programming*, pages 263–273, 1997.
- [8] J. Hughes. Why functional programming matters. *the Computer Journal*, 32(8):98–107, 1989.
- [9] J. Hughes. Generalising monads to arrows. *Science of Computer Programming*, 37:67–111, 2000.
- [10] D. Leijen and E. Meijer. Parsec: Direct style monadic parser combinators for the real world. Technical Report UU-CS-2001-27, Department of Computer Science, Universiteit Utrecht, 2001.
- [11] N. Minar, R. Burkhart, C. Langton, and M. Askenazi. The swarm simulation system: A toolkit for building multi-agent simulations. Working Papers 96-06-042, Santa Fe Institute, June 1996.
- [12] S. Moss, H. Gaylard, S. Wallis, and B. Edmonds. Sdml: A multi-agent language for organizational modelling. *Computational and Mathematical Organization Theory*, 4:43–69, 1998. 10.1023/A:1009600530279.
- [13] H. Nilsson, A. Courtney, and J. Peterson. Functional reactive programming, continued. *Proceedings of the 2002 ACM SIGPLAN workshop on Haskell*, pages 51–64, 2002.
- [14] M. J. North, N. T. Collier, and J. R. Vos. Experiences creating three implementations of the repast agent modeling toolkit. *ACM Trans. Model. Comput. Simul.*, 16:1–25, January 2006.
- [15] M. J. North, T. R. Howe, N. T. Collier, and J. R. Vos. The repast symphony runtime system. In C. M. Macal, M. J. North, and D. Sallach, editors, *Proceedings of the Agent 2005 Conference on Generative Social Processes Models and Mechanisms*, number 1, pages 151–158, 2005.
- [16] N. Osgood. Systems dynamics and agent-based approaches: Clarifying the terminology and tradeoffs. *Proceedings of the First International Congress of Business Dynamics*, 2006.
- [17] N. Osgood. Using traditional and agent based toolsets for system dynamics: Present tradeoffs and future evolution. *Proceedings of the 2007 International Conference on System Dynamics*, 2007.
- [18] N. Osgood. Representing progression and interactions of comorbidities in aggregate and individual-based systems models. In *Proceedings, The 27th International Conference of the System Dynamics Society*, page 20, Albuquerque, July 2009.
- [19] R. Paterson. A new notation for arrows. In *International Conference on Functional Programming*, pages 229–240. ACM Press, Sept. 2001.
- [20] S. Peyton-Jones, R. Leshchinskiy, G. Keller, and M. M. Chakaravarty. Harnessing the multicores: Nested data parallelism in Haskell. In *Conference on Foundations of Software Technology and Theoretical Computer Science*, pages 1–32, 2008.
- [21] X. Technologies. *AnyLogic (Version 6)*. XJ Technologies, St. Petersburg, Russia, 2007.
- [22] S. Tisue. Netlogo: Design and implementation of a multi-agent modeling environment. In *Proceedings of Agent*, 2004.
- [23] P. Wadler. The essence of functional programming. In *Proceedings of the 19th ACM SIGPLAN-SIGACT symposium on Principles of programming languages*, POPL '92, pages 1–14, New York, NY, USA, 1992. ACM.

