Going Stupid with $EcoLab$

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Abstract

In 2005, Railsback et al. proposed a very simple model (Stupid Model) that could be implemented within a couple of hours, and later extended to demonstrate the use of common ABM platform functionality. They provided implementations of the model in several agent based modelling platforms, and compared the platforms for ease of implementation of this simple model, and performance.

In this paper, I implement Railsback et al’s Stupid Model in the $EcoLab$ simulation platform, a C++ based modelling platform, demonstrating that it is a feasible platform for these sorts of models, and compare the performance of the implementation with Repast, Mason and Swarm versions.

1 Introduction

Newcomers to agent based modelling (ABM) will be confused by the variety of different software platforms available to assist in implementing the models. Very few comparative studies between the different platforms have been done, as it is a time consuming task implementing all but the most trivial of models. Furthermore, familiarity with one platform and programming language will lend an automatic advantage in any metrics to that platform over other platforms that the model implementer is less familiar with.

In 2005, Railsback et al.\textsuperscript{14} proposed a very simple model that could be implemented within a couple of hours, and later extended to demonstrate the use of common ABM platform functionality. They gave it the name “Stupid Model”, partly for fun, but also to reiterate the recommendation of Grimm and Railsback\textsuperscript{5} that modelling projects should start with a “ridiculously simplified model”. Railsback et al. implemented their model across a range of ABM platforms: Objective-C and Java Swarm\textsuperscript{12}, Repast\textsuperscript{13} and Mason\textsuperscript{9} (both pure Java implementations) and Netlogo. This range of platforms reflects the authors’ collective programming expertise in Objective-C and Java, and with Netlogo having low barrier of entry (Logo was a popular language for teaching school children in the 1980s).
EcoLab grew out of a simulation platform supporting a particular class of model, into a general purpose simulation environment using C++\cite{17}. Other C++ agent-based modelling environments exist, eg SymBioSys\cite{11}, but none are as general purpose as EcoLab. Other general purpose agent based platforms can be used with C++ models. For instance, with Swarm, C++ code can be linked to Swarm’s objective C library through the shared C language interface, and C++ code can be linked to Repast’s Java library through the Java Native Interface. However, maintaining the interface code quickly becomes prohibitive in the face of evolving models, negating much of the benefits in using a simulation platform in the first place.

With EcoLab, it is possible to have a similar level of functionality as provided by Swarm or Repast for models implemented in C++, without the interface maintenance overhead. Additionally, EcoLab provides features for distributing the computation over multiple processors in a way that is easier to program than the raw Message Passing Interface (MPI)\cite{16}. With Railsback et al.’s Stupid Model specification, the possibility exists for directly comparing an EcoLab implemented agent based model with other platforms for both ease of implementation, and execution performance. Furthermore, the exercise illuminates those parts of EcoLab requiring improvement.

1.1 Why C++

C++\cite{19} is a mature object oriented programming language of more than 20 years standing. It has been widely adopted in industry, consequently open source reference compilers, as well as vendor-tuned optimising compilers exist for most contemporary computer architectures. Because of this popularity, and the availability of compilers, C++ has been extensively deployed for scientific computing since the mid-1990s. In High Performance Computing (HPC), the extreme end of scientific computing, the predominant computing language used for applications is Fortran, with code written in Fortran 77, or increasingly written using the newer Fortran 90 features. However C/C++ applications also make up a substantial fraction of the deployed applications, perhaps as high as 30%, with C++ standing to C in the same relationship as Fortran 90 does to Fortran 77, i.e. typically used as a “better C”\footnote{These numbers come from a decade of personal experience at managing the resource allocation process at a High Performance Computing Centre. These general numbers are backed up by anecdotal reports from a number of other people I have corresponded with.}. By contrast, Java\cite{4} has made negligible impact in HPC\footnote{Over the ten years of my personal experience, only one project used Java, out of several hundred that were mostly C/C++ or Fortran.}. There are several possible reasons for the lack of Java adoption in high performance computing. Firstly, most implementations compile to a virtual machine, and early Java Virtual Machines (JVMs) had performance problems. However, more recent JVMs deploy just in time compilation, which closes the performance gap between JVM executed code and natively compiled code. Secondly, certain language features missing in Java (notably operator overloading, and to a lesser extent generic programming) of
C++ (and Fortran 90 for that matter) assist in writing scientific codes that are closer to the mathematical specification. However, probably the most significant factor is time and innate conservatism of scientific programmers. C++ did not appear significantly in HPC applications until around 15 years after the language was first developed. With only a decade under its belt, Java’s time as an HPC application language might just be beginning[6].

However, for agent based simulation, C++ is not a popular choice, primarily due to its lack of reflection. Reflection is the ability to query an object’s type information at runtime, and in ABM systems like Swarm, reflection is used to implement probes, or the ability to observe all parts of a running simulation from within a graphical user interface[12]. However, with Classdesc, an effective reflection mechanism for C++ is possible[10, 18]. EcoLab uses Classdesc to implement probing, along with automatic checkpointing, the ability to script the model’s initialisation and ongoing computation, and for distributing agents to exploit any parallel computing capability.

2 Method

In line with Railsback et al.’s[14] methodology, I implemented Stupid Model using the current EcoLab release, version 4.D21. This is important to give a sense of the maturity of the platform. Otherwise, I might have been tempted to fix up any weaknesses encountered.

I followed the the explicit model specification[15] step by step, referring to the Repast Java implementation on the rare occasions the specification was ambiguous. Stupid Model consists of agents called “Stupid Bugs” moving around a Cartesian lattice. No two agents can occupy the same location, so movement involves selecting a cell within a 9 x 9 Moore neighbourhood, testing whether the cell is occupied and moving into the cell if empty. The search procedure is repeated until an empty cell is found. Since different frameworks potentially use different random number algorithms, initialised with a different seed, this introduces indeterminism into model runtimes. In order to reduce the impact of this indeterminism, the density of agents was chosen to be 0.1 (4000 agents in a 200 x 200 world) so that the standard deviation of runtimes was less than 10% of the mean.

For measuring application performance, I did both GUI runs, and batch mode runs. In EcoLab, a non-GUI batch run simply involves replacing the “GUI” command from the experiment script, with a call to “simulate”, and commenting out any graphical calls (plot, histogram and draw). In Repast, Swarm and Mason, a separate “BatchSwarm” needs to be provided by the programmer, but only the GUI versions of each model were published by Railsback et al. For batch measurements, I commented out the call to addAction that added the display actions. For the Repast implementation, I changed the batch parameter of SimInit::loadModel to true, and timed the run from the command line. With the Mason implementation, I again commented out the display action, and recorded the CPU time so as to discount the delays introduced by hav-
ing to click the button. In fact for all platforms, the reported values are the CPU time. For the Objective C Swarm version, I modified the code so that the StupidModelSwarm was directly called from main() rather than indirectly through StupidModelObserverSwarm.

I chose to measure the versions 10 and 11 of the Stupid Model. However, the stopping criteria is specified as when the maximum bug size reaches 100. Since bug growth depends on the availability of food, which itself is a function of a random number generator call, and also of the grazing history, this stopping criterion is indeterministic. For the purposes of inter-framework performance comparisons, I changed the stopping criterion to be a fixed number of bug updates (500).

In version 10 of Stupid Model, bugs will randomly select a cell within their neighbourhood, and moving to it if the cell is empty, otherwise repeating the selection process. In version 11, all cells in the neighbourhood are iterated over, and the bug moves to the empty cell with the most food.

From version 12, bugs can reproduce and die according to random dynamics, so the amount of work per update step will depend on the number of living bugs. Even though these higher version models are more computationally intensive, run times cannot be compared between different platforms due to differences in the order that random numbers are generated. Hence the Stupid 16 measurements reported in table 2 should be taken with a certain amount of salt. Nevertheless, I verified that all models executed for 1000 steps, and that the number of Stupid Bugs was roughly the same for each platform (approximately 8-900 after the initial population explosion).

Railsback et al. did not do any performance analysis or tuning. For C++ code, performance tuning can deliver big performance improvements. EcoTab can be built with performance counters enabled for the individual TCL commands, and a single run indicated that the initial approach used for evaluating the stopping criterion (evaluating the maximum of the vector of bug sizes in TCL) was very expensive. By implementing a specialised max_bugsize() (all of 4 lines of C++ code) improved performance by about a factor of four. However, for the inter-platform performance comparison, the stopping condition was changed to a fixed number of bug update steps, so this optimisation makes no difference to the performance benchmarks.

A more detailed performance profile using the standard GNU/Linux profiling tool gprof, indicated that updating the food availability was a bottleneck, and that cache utilisation could be improved by laying the data contiguously in memory, which is not the case when the data is stored as members of a cell object. This optimisation, which needed some substantial recoding of the model, improved overall performance by a factor of two for model version 16, although it only made about a 10% improvement for version 11. It should be noted that this optimisation technique should also be available for the Java and Objective-C platforms, and presumably may deliver a similar performance boost.

All performance benchmarks were run on a 2GHz Intel Pentium M processor with 1GB memory running Slackware Linux 10.0. The Java version used for Repast and Mason was SDK 1.4.2 standard edition. The compiler used for
Swarm and EcoLab was GCC 3.4.3. I also did a comparison EcoLab run using the Intel C++ compiler 9.0, but this was more than 50% slower than the GCC compiled code. This somewhat surprising result indicates that icc’s strength lies in vectorising loops that access data contiguously to exploit the inbuilt SSE instructions, but that for more general purpose ABM code, GCC performs better (at least on Linux!).

The sourcecode for EcoLab Stupid Model is available from the EcoLab website.[3]

3 Results

Similar to all the platforms reviewed by Railsback et al., EcoLab proved capable of implementing all functionality for all versions of Stupid Model. Implementing the first version took longer than any of the remaining versions, as EcoLab does not provide a ready-to-use spatial library. Instead it provides a more general library called Graphcode[18]. Graphcode’s abstraction is a network, or graph of objects, with the links between objects representing data flow. Graphcode can distribute the objects across multiple processors using the Classdesc serialisation library. A cellular space such as found in Swarm or Repast will be a set of objects, each one wired to its neighbours. In such a way, Graphcode can easily represent Cartesian and hexagonal topologies by the way the neighbourhoods are wired. However, the only example using Graphcode provided in the EcoLab was a continuous space example, each cell holding objects located within a certain region of space. Examples of models using different sorts of spatial topologies, as well as a few common cases being supplied as a library would improve the beginner’s experience of EcoLab.

In retrospect, it may have been simpler to implement the spatial class on top of a standard vector of cells. This would have gotten the initial model up and running quicker, but limited the model to sequential usage only. By using Graphcode, we enable parallel processing capability.

One thing that became clear in this exercise is the need for a smart reference type. Objects like bugs need a reference to the cell in which they inhabit, scheduling lists need references to the bugs that they schedule and so on. Because bugs move from cell to cell, it is better for the cells to have a reference to the bug it contains (if any) rather than for the cell to store the bug itself. In C, the only possibility for references are pointers, which are difficult to serialise properly due to the fact that C makes no guarantees about whether a pointer is valid or not. Substantial care is required to ensure that references remain valid in the event of an object such as a bug being deleted from the system. Classdesc accepts a pragma that asserts that a pointer is either valid or NULL, and whether the pointer chains form cycles or not to allow serialisation, but it’s up to the programmer to ensure software bugs do not invalidate this assertion.

C++ also supports static references (eg int&), which are established at the time of the reference’s creation, and then immutable until the reference is destroyed. These references are always valid, however the lack of dynamic control makes them unsuitable for agent based simulations where agents may
be dropped or moved, and appropriate references updated. Furthermore static reference cycles cannot be handled with serialisation at all, since the serialisation descriptors cannot distinguish an object from its reference.

Whilst it is possible to use EcoLab with a nonserialisable model, one gives up substantial functionality doing so, including the ability to checkpoint/restart the model.

What is needed actually is something like Java’s reference type, where objects are created on the heap, and the programmer simply manipulates references. Once all references to an object have been destroyed, Java’s garbage collector takes care of destroying the object, reclaiming the memory used.

It is possible to implement something like this in C++, using operator overloading to give the resulting type the “look and feel” of a pointer. Such types are usually called smart pointers. The well known Boost library[2] provides a few different versions, some of which are being considered for inclusion in the C++ standard library. EcoLab provides the template ref, which is parameterised by the target type of the reference. Unlike the Boost versions (in which you pass the smart pointer a pointer for it to control), ref has control over the entire lifecycle of the object it points to. The first time a ref object is dereferenced, the target object is created on the heap, and it keeps track of the number of references to the target object, so that once all references to are destroyed, so is the target object.

The version of ref supplied in the current EcoLab has a number of deficiencies, however, most notable of which is that it doesn’t provide any way of testing whether the target object exists or not. For the purposes of this exercise, I copied the ref.h header file, and added the necessary functionality. This improved ref.h will be incorporated in future releases of EcoLab.

Agents usually need to refer to the environment, or world in which they live. In languages like Java or Objective C, this is simply managed by having the agent store a reference to the world, and/or cell. However, this will set up a reference cycle which will play havoc with model serialisation if the serialisation algorithm doesn’t explicitly account for cycles. EcoLab provides a routine that serialises arbitrary graphs constructed with pointer references. However, it does not currently support the presence of cycles with the ref<> data type. With C++, however, there is a simple workaround. The model is a global variable, and agents can refer to their cell by holding an index into a container of cells stored within this global model. This is the approach I have taken with Stupid Model, and indeed this technique is used in other EcoLab models. However, if the ref<> data type were extended to support serialisation of cyclic graphs, the method deployed in Java and Objective C models can be supported as well.

Line counts are often considered a proxy for the amount of effort a programmer must expend to implement a problem. Table 1 shows the line counts for the 16 different Stupid Model cases for each of the Railsback implementations, as well as the EcoLab implementation. The EcoLab implementation also includes two additional cases, which build upon version 16. The model is parallelised using EcoLab’s MPI-based parallel processing features, and finally, the “field” optimisation whereby the food data is stored in contiguous memory.
Table 1: Source code line-counts (as reported by the unix command ‘wc’) for the different Stupid Model versions. Makefiles are not included (Swarm & EcoLab), since these are fairly boiler plate code, and fairly negligible. EcoLab counts include the TCL scripts.

| Version | Repast | Mason | Obj-C Swarm | £ab |
|---------|--------|-------|-------------|-----|
| 1       | 158    | 169   | 578         | 253 |
| 2       | 158    | 214   | 622         | 259 |
| 3       | 250    | 263   | 865         | 281 |
| 4       | 256    |       | 896         | 310 |
| 5       | 312    | 296   | 968         | 322 |
| 6       | 306    | 362   | 1005        | 338 |
| 7       | 359    | 316   | 1070        | 337 |
| 8       | 258    | 365   | 1144        | 320 |
| 9       | 368    | 369   | 1152        | 336 |
| 10      | 381    | 383   | 1191        | 352 |
| 11      | 391    | 409   | 1253        | 358 |
| 12      | 497    | 494   | 1614        | 416 |
| 13      | 484    |       | 1636        | 419 |
| 14      | 501    |       | 1360        | 432 |
| 15      | 646    | 670   | 1761        | 515 |
| 16      | 753    | 816   | 2174        | 662 |
| parallel|        |       |             | 753 |
| field   |        |       |             | 894 |

the two Java platforms seems to need a similar number of lines of code, yet the Swarm implementation needed up to three times the number. Whilst a factor of two or three in source line count is not particularly significant, it does indicate that it takes a bit more effort to implement Swarm models.

In table 1 execution times for various stupid model versions is reported. As described in §2, versions 10 & 11 were run in batch mode with as much graphical output turned off as possible. The Java versions performed slightly better for version 10, and the C++ version did better on version 11. However, given the possible range of implementation strategies, one should not read too much into this, except that the myth of Java being slow relative to C++ should be now be firmly laid to rest. The result is broadly in line with other observations that Java implementations tend to be within a factor of 2 of natively compiled applications[1,7]. The results for Swarm though confirm Railsback et al’s the observation that Objective C performance lags that of the Java (and also now C++) versions. Unfortunately, my knowledge of Objective-C and Swarm internals is not up to the task of explaining this result.

In version 16, the full graphical version of the model was run. This included a display of the space, a plot of the number of bugs and a histogram of bug sizes. It should be noted that the Mason implementation lacked the plot and histogram, apparently because this functionality is absent within the Mason
Table 2: Execution CPU times (in seconds) for several Stupid Model versions for different platforms. Versions 10 and 11 were performed in batch mode (no graphical output, no GUI control, Mason excepted), version 16 in GUI mode with a plot and histogram. EcoLab’s field version uses raster rather than canvas for display, and omits the expensive histogram widget. All these figures need considerable qualification (see text).

| Version | Repast | Mason | Obj-C Swarm | EcoLab |
|---------|--------|-------|-------------|--------|
| 10      | 3.5    | 3.4   | 71          | 3.9    |
| 11      | 32.7   | 21.3  | 165         | 14.9   |
| 16      | 44     | 40.5  | 402         | 1014   |
| field   |        |       |             | 67     |

toolkit itself, but provided by 3rd party add-ons. One thing that stands out is the slowness of EcoLab. The TCL-based plotting widgets used in EcoLab (also used in Swarm) are slow relative to the equivalent Java offerings. Furthermore, this benchmark displays the space environment using a canvas, which is a high level drawing tool with roughly the same sort of functionality as a standard drawing application (eg. the drawing application in OpenOffice or Xfig). The bugs, predators and empty cells are rendered as coloured squares. The other platforms provide dedicated raster objects for rendering spatial displays. In the “field” version of Stupid Model, instead of representing the model’s objects as squares, a single pixmap object is created on the canvas and manipulated through low level Tk library calls. This amounts to about 40 lines of code, and improves the display performance dramatically. The result listed under the row “field” also omits the expensive histogram functionality (but still displayed the plot of bug numbers).

4 Parallel implementation

Having put the extra work into building the space class on top of Graphcode rather than using a simple vector, it raises the question of whether Stupid Model can be effectively parallelised.

The first thing that becomes apparent is that Stupid Model as specified is inherently sequential. Two bugs are not allowed to occupy the same spatial location, and movement into a location is performed on a first come first served basis. Since the order in which bugs perform their update move is randomised, the obvious parallel generalisation in a shared memory context is to use locks to prevent two bugs on different processors simultaneously moving to the same location. However, EcoLab is designed for use with distributed parallel systems, and obtaining the state of a cell located on a remote processor is expensive. In fact, in the MPI transport layer used by EcoLab, such functionality is only supported by “one-sided” communications of MPI 2, a relatively new feature that is not well supported and typically poorly implemented. Instead, the recommended
approach in EcoLab is to have separate communication and computation phases, with a snapshot of neighbouring data at the previous timestep supplied to each processor during the communication phase.

As Stupid Model is a pedagogical model, there is no one right answer as to respecifying the model for parallelisation. Perhaps the most obvious approach would be to allow multiple bugs to share a single location within the space. This would certainly simplify the code, as additional logic was required to enforce the one-bug-per-location requirement. However, in the spirit of adventure, I propose the following protocol for allowing bugs to migrate from one processor to the next, whilst maintaining the one-bug-per-location property. As in the sequential algorithm, bugs examine their neighbourhood, and choose the cell with the highest food resource as a destination. If the destination lies on the current processor, and the cell is empty, the bug is free to move. If the destination is remote, however, the bug’s desire to move to a remote cell is lodged with an emigration register. Then after all bugs have performed their move, the emigration register is passed to the remote processor, which approves or denies the request depending on whether the destination is already occupied, or an immigration request has already been allowed. The immigration approval list is passed back to the requesting processor, and approved bugs are migrated between processors. The remaining bugs do not move.

I coded this solution into the stupid-parallel version, and also the field optimised version stupid-field. None of the other versions are parallel aware code — building them and running them in parallel will only result in the model running on processor 0, with the remaining processors idle.

With the stupid-parallel version, it became immediately clear that the Prepare_Neighbours() step dominated the calculation. This highlighted a hitherto unsuspected source of inefficiency in Graphcode’s Prepare_Neighbours() method. To build the list of neighbours to transmit, Graphcode loops over the neighbours of local cells, adding to the list any remote neighbour found. However, this leads to many duplicates, as one cell may be the neighbour of many other cells — for the Stupid Model case, each cell in the transfer list will be duplicated 36 times. In a more common von Neumann neighbourhood of radius 1 there is no duplication, and in the Moore neighbourhood of radius 1 the duplication is only 3 times. In choosing a Moore neighbourhood of radius 4 for their Stupid Model, Railsback et al. unwittingly made this inefficiency blatant.

However, even with this inefficiency corrected, Prepare_Neighbours() is still an expensive overhead. The example problem I tested was the same 200 × 200 spatial grid, and so 2 × 200 × 4 × N_p cells need to be transferred each time step (N_p > 1 being the number of processors). This overhead can be amortised by increasing the problem size.

In the stupid-field case, the food_available data is not stored in the cell, but in the additional field data structure, so is not transferred with the cell data during the Prepare_Neighbours() step. In fact, only the food data has any affect on bug movement, so Prepare_Neighbours() is eliminated altogether. In the stupid-field version of the model, we do not transfer the food data, but duplicate the update calculation on the overlap area between two processors. A
Figure 1: Speedup curves for stupid-parallel and stupid-field for a 200 × 200 grid with 4000 stupid bugs moving and growing. Bug reproduction and mortality as well as predation have been turned off. At no stage does stupid-parallel run as fast in parallel as it does sequentially, due to the overheads of the Prepare Neighbours() step.

The single Prepare Neighbours() step is done at the beginning of the model run to ensure access to the food data.

Figure 1 shows the speedup curve for both the stupid-parallel and stupid-field model, for the same input script used for the stupid10 and stupid11 benchmarks reported in table 2.

The parallel computing experiments were performed on Linux cluster (Beowulf style) with dual 3GHz Pentium 4 Xeon nodes connected via Gigabit Ethernet. Each node has 2GB of memory.

5 Conclusion

The aim of this study was to answer the following questions:

• is EcoLab suitable for the sorts of agent based models that other more well known platforms are used for

• what performance advantages, if any, does the use of C++ provide

• what deficiencies are present in EcoLab
Stupid Model is a nontrivial, yet fairly simple agent based model that could be implemented without an excessive amount of programming. *EcoLab* has shown itself to be capable of implementing Stupid Model with about the same sort of effort reported by developers of Repast and Mason versions of the model, and was implemented in around the same number of lines of code. Furthermore, performance was on a par with these Java-based platforms.

The main deficiencies encountered were:

- A lack of specialised space library, or library of examples in the use of Graphcode for implementing spaces.
- A lack of a simple raster object for displaying spaces. The provided canvas functionality is very slow.
- GUI functionality is slow compared with the Java-based functionality.
- The smart pointer template ref needs to be improved.

For addressing the space library issue, I will start with implementing a few well known ABM models to build up a library of practice. Where code appears in common, this can be refactored into a library.

To address the GUI performance, a possible future strategy is to develop a Classdesc C++/Java interface to enable C++ coded *EcoLab* models to run under a Java framework such as Repast. A similar strategy was investigated integrating C++ and Objective C using Classdesc to look at Swarm integration, however it never found practical use and is no longer being maintained[8]. The feasibility of doing this with a Java platform will be the subject of future work.

References

[1] RF Boisvert, J. Moreira, M. Philippsen, and R. Pozo. Java and numerical computing. *Computing in Science & Engineering* [see also IEEE Computational Science and Engineering], 3(2):18–24, 2001.

[2] Boost C++ Libraries. [http://www.boost.org/](http://www.boost.org/).

[3] *EcoLab* website. [http://ecolab.sourceforge.net](http://ecolab.sourceforge.net).

[4] James Gosling, Bill Joy, and Guy L. Steele, Jr. *The Java Language Specification*. Addison-Wesley, 3rd edition, 2005.

[5] V. Grimm and S. F. Railsback. *Individual-based Modeling and Ecology*. Princeton UP, 2005.

[6] Java Grande. [http://www.javagrande.org/](http://www.javagrande.org/).

[7] J.P.Lewis and Ulrich Neumann. Performance of Java versus C++. [http://www.idiom.com~zilla/Computer/javaCbenchmark.html](http://www.idiom.com~zilla/Computer/javaCbenchmark.html) 2003.
[8] Richard Leow and Russell K. Standish. Running C++ models under the Swarm environment. In Proceedings SwarmFest 2003, 2003. arXiv:cs.MA/0401025

[9] Sean Luke, Claudio Cioffi-Revilla, Liviu Panait, Keith Sullivan, and Gabriel Balan. MASON: A multiagent simulation environment. Simulation, 81:517–527, 2005.

[10] Duraid Madina and Russell K. Standish. A system for reflection in C++. In Proceedings of AUUG2001: Always on and Everywhere. Australian Unix Users Group, 2001.

[11] David McFadzean. SimBioSys: A class framework for biological simulations. Master’s thesis, Dept. of Computer Science, Calgary, Alberta, 1994. http://www.lucifer.com/~david/thesis/

[12] Nelson Minar, Roger Burkhart, Christopher G. Langton, and Manor Askenazi. The Swarm simulation system: A toolkit for building multi-agent simulations. Technical Report WP96-06-042, Santa Fe Institute, 1996. http://www.swarm.org.

[13] M.J. North, N.T. Collier, and J.R. Vos. Experiences creating three implementations of the Repast agent modeling toolkit. ACM Transactions on Modeling and Computer Simulation, 16:1–25, 2006.

[14] S. F. Railsback, S. L. Lytinen, and S. K. Jackson. Agent-based simulation platforms: Review and development recommendations. Simulation, 82:609–623, 2006.

[15] Steve Railsback, Steve Lytinen, and Volker Grimm. StupidModel and extensions: A template and teaching tool for agent-based modeling platforms. http://condor.depaul.edu/~slytinen/abm/StupidModel

[16] Marc Snir et al. MPI: the complete reference. MIT Press, Cambridge, MA, 1996.

[17] Russell K. Standish and Richard Leow. EcoLab: Agent based modeling for C++ programmers. In Proceedings SwarmFest 2003, 2003. arXiv:cs.MA/0401026

[18] Russell K. Standish and Duraid Madina. Classdesc and graphcode: support for scientific programming in C++. International Journal for High Performance Computing and Applications, 2006. submitted.

[19] Bjarne Stroustrup. The C++ Programming Language. Addison-Wesley, Reading, Mass., 3rd edition, 1997.