

2008

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Recommended Citation

Felder, Gary, "CLUSTEREASY: A Program for Simulating Scalar Field Evolution on Parallel Computers" (2008). *Faculty Publications*. Paper 3.

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CLUSTEREASY

A Program for Simulating Scalar Field Evolution on Parallel Computers

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(Dated: November 18, 2013)

We describe a new, parallel programming version of the scalar field simulation program LATTICEEASY. The new C++ program, CLUSTEREASY, can simulate arbitrary scalar field models on distributed-memory clusters. The speed and memory requirements scale well with the number of processors. As with the serial version of LATTICEEASY, CLUSTEREASY can run simulations in one, two, or three dimensions, with or without expansion of the universe, with customizable parameters and output. The program and its full documentation are available on the LATTICEEASY website at <http://www.science.smith.edu/departments/Physics/fstaff/gfelder/latticeeasy/>. In this paper we provide a brief overview of what CLUSTEREASY does and the ways in which it does and doesn't differ from the serial version of LATTICEEASY.

I. INTRODUCTION

Studying the early universe requires describing the evolution of interacting fields in a dense, high-energy environment. The study of reheating after inflation and the subsequent thermalization of the fields produced in this process typically involves non-perturbative interactions of fields with exponentially large occupation numbers in states far from thermal equilibrium. Various approximation methods have been applied to these calculations, including linearized analysis and the Hartree approximation. These methods fail, however, as soon as the field fluctuations become large enough that they can no longer be considered small perturbations. In such a situation linear analysis no longer makes sense and the Hartree approximation neglects important rescattering terms. In many models of inflation preheating can amplify fluctuations to these large scales within a few oscillations of the inflaton field. Moreover, such large amplification appears to be a generic feature, arising via parametric resonance in single-field inflationary models and tachyonic instabilities in hybrid models.

The only way to fully treat the nonlinear dynamics of these systems is through lattice simulations. These simulations directly solve the classical equations of motion for the fields. Although this approach involves the approximation of neglecting quantum effects, these effects are exponentially small once preheating begins. So in any inflationary model in which preheating can occur lattice simulations provide the most accurate means of studying post-inflationary dynamics.

In 2000 G.F. and Igor Tkachev released LATTICEEASY [1], a C++ program for simulating scalar field evolution in an expanding universe. In the ensuing years LATTICEEASY has been used by us and other groups to study such topics as preheating, baryogenesis, gravity wave production, and more. These simulations have been extremely useful, but they have for the most part been confined to relatively simple toy models, primarily due to computational limitations. To study cosmology in more complex models such as the MSSM or GUT theories will require the use of large, parallel clusters. CLUSTEREASY is a version of LATTICEEASY that can be run in parallel on multiple processors.

Section II of this paper gives a brief overview of what LATTICEEASY does and how to use it, and notes the modifications that must be made in the LATTICEEASY files to run them in CLUSTEREASY. Section III describes the algorithms used to parallelize the simulations. For more detailed documentation the reader is referred to the LATTICEEASY website

<http://www.science.smith.edu/departments/Physics/fstaff/gfelder/latticeeasy/>

II. OVERVIEW

LATTICEEASY consists of several C++ files, but only two are designed to be modified by most users. Each particular scalar field potential that the program solves is encoded in a *model file* called `model.h`, in which the user enters equations for the potential and its various derivatives. The parameters that control individual runs are stored in a file called `parameters.h`. These parameters include physical quantities such as masses and couplings, numerical quantities such as the number of gridpoints and the size of the time step, and parameters to control what types of output are generated by the simulation.

at $i_{totalgrid} = 0$ and $i_{totalgrid} = 3$ to processor 1, which would send the values at $i_{totalgrid} = 4$ and $i_{totalgrid} = 7$ to processor 0.

The actual arrays allocated by the program are even larger than this, however, because of the extra storage required by the Fourier Transform routines. In two and three dimensions CLUSTEREASY uses FFTW. When you Fourier Transform the fields the Nyquist modes are stored in extra positions in the last dimension, so the last dimension is $N+2$ instead of N . The total size per field of the array at each processor is thus typically $n+2$ in 1D, $(n+2) \times (N+2)$ in 2D and $(n+2) \times N \times (N+2)$ in 3D. In 2D FFTW sometimes requires extra storage for intermediate calculations as well, in which case the array may be somewhat larger than this, but usually not much. This does not occur in 3D.

IV. CONCLUSIONS

We have found that the speed of the simulation scales roughly as the number of processors, provided that number is significantly smaller than N , the number of gridpoints along each edge of the lattice. A good rule of thumb is that you probably won't get much benefit from using more processors than $N/4$. Also, you will get slightly better performance per processor if the number of processors is a factor of N so that the processors can divide the lattice up evenly.

CLUSTEREASY offers the opportunity to do simulations of much larger, more complex, and more realistic early universe theories than was possible with serial simulations. We offer it in the hope that it will be useful to the research community.

Acknowledgements

The usual thanks offered in a paper are inadequate for the impressive contributions made by students and other collaborators on this project. Significant work on the project was done in particular by Sirein Awadalla, Douglas Swanson, and Hal Finkel. Others who contributed include Jing Li, Dessislava Michaylova, and Olga Navros. I would also like to thank Richard Easther for valuable discussions and the Canadian Institute for Theoretical Astrophysics for hosting me during part of this work. Finally, I would like to thank Igor Tkachev, my collaborator on LATTICEASY, without whom none of this would have been possible. G.F. was supported by NSF grant PHY-0456631.

[1] G. N. Felder and I. Tkachev, [hep-ph/0011159].