Chapter 1

Introduction

1.1 Problem Formulation

Multi-scale phenomena are abundant in many application fields like material science, fluid dynamics, geophysics, meteorology and astrophysics. Representing and numerically simulating such processes is a challenging task since quite different scales have to be resolved, which often requires enormous amounts of storage and computational power. An important strategy in this context is adaptivity, i. e. local adjustment of the spatio-temporal resolution to the details to be resolved. A standard representation therefore are hierarchical, locally refined grids.

A specific adaptive approach for solving partial differential equations, usually called *AMR* (Adaptive Mesh Refinement), was introduced by Berger et al. in 1984 [10]. The basic idea is to combine the simplicity of structured grids and the advantages of local refinement. In this numerical scheme the computations are started on a set of coarse, potentially overlapping structured grids, that cover the computational domain. Local error criteria are applied to detect regions that require higher resolution. These are covered by subgrids with decreasing mesh spacing, which do not replace, but rather overlap the refined regions of the coarser patches. The equations are advanced on the finer subgrids and the refinement procedure recursively continues until all cells fulfill the considered error criteria, giving rise to a hierarchy of nested levels of refinement.

An advantage of this approach is that each subgrid is treated as a separate grid with its own storage space. This allows to process them almost independently during integration and hence AMR is well suited for parallel processing. Since the computations are carried out on structured grids, AMR further allows the reuse of many existing finite difference codes with only minor modifications.

In 1989 Berger et al. [9] proposed a variant of this scheme, called *Structured Adaptive Mesh Refinement (SAMR)*, which reduces some of the complexity of the original approach. While the separate subgrids in the AMR scheme could be rotated against each other, in SAMR they are aligned with the major axes of the coordinate system, which for example simplifies the computation of fluxes of (conserved) quantities through the cell faces. SAMR has become more and more popular in the last decade, and nowadays it is applied in many domains like hydrodynamics, meteorology and in particular in cosmology and relativistic astrophysics.

Due to this growing popularity, an increasing number of scientists is in need of appropriate interactive visualization techniques to interpret and analyze AMR simulation data. Tools for both, 2D analysis to quantitatively convey the information within single slices and 3D representations to apprehend the overall structure are required.

In this thesis we develop direct and indirect volume visualization algorithms for scalar fields that are defined on SAMR grids. Additionally we investigate the applicability of SAMR data structures for visualizing large datasets. The developed algorithms were designed to meet the following goals:

- *Accuracy*: Artifact-free visualization is a prerequisite for a faithful representation of scientific data. For AMR data problems typically arise at the interfaces between different levels of resolution. The existence of dangling nodes in these regions necessitates special attention to ensure globally continuous spatial interpolation. Also the special temporal refinement scheme of AMR can cause problems if dense output is required in the visualization phase.

- *Performance*: The visualization methods should allow interactive exploration even for large datasets. In order to achieve this, we designed algorithms that operate directly on the given SAMR grid, exploiting both, the inherent hierarchical structure of the data and the fact that the grid itself is composed of blocks with regular topology. An important design aspect thereby was that the resulting algorithms should allow the utilization of dedicated graphics hardware.

- *Usability*: The algorithms had to be provided to several research groups in the fields of cosmology and numerical relativity. Therefore the integration into an existing visualization system was another important design criterion. In particular the visualization routines had to allow an intuitive usage and the amount of user interaction had to be kept small.

1.2 Outline

This thesis is divided into three chapters; the next two cover basic concepts in the field of scientific visualization, while the last two focus on the new contribution of this thesis.

Chapter 2 starts with an overview about commonly used computational grids and data structures (Section 2.1). In particular the spatial and temporal refinement scheme of the AMR approach is discussed and notations that are used throughout this work are introduced in Section 2.2. The chapter ends with two sections on interpolation of discrete grid functions and spatial access methods (Section 2.4 and 2.3).

Chapter 3 addresses the most popular visualization methods for scalar data. While indirect methods usually involve some form of dimensionality reduction and/or conversion of the data to auxiliary graphics primitives, the underlying idea of direct volume rendering is to map the data field to physical quantities like absorption and emission coefficients and to compute the intensity distribution of light traveling through this semi-transparent medium in the image plane. Starting with a brief discussion of the rendering pipeline in Section 3.1, we review the most important indirect and direct volume rendering algorithms in Section 3.3 and 3.4.

Chapter 4 first gives an overview on related work in the field of accelerated volume rendering. Next we discuss a raycasting approach that is based on the utilization of an adaptive integration scheme (Section 4.3). In Section 4.4 we investigate approaches that accelerate texture-based volume rendering for the frequently occurring case of large, sparse data, i.e. highly resolved data where only a small fraction of the voxels contains relevant information.

In Chapter 5 our work on visualization of structured adaptive mesh refinement data is presented, starting with an overview about related work in this field in Section 5.1. We propose a domain decomposition scheme for SAMR hierarchies in Section 5.2 and discuss interpolation issues for discrete SAMR data in Section 5.3. In Section 5.4 we present indirect volume rendering methods; in particular an algorithm for the extraction of C^0-continuous isosurfaces is suggested. Software-, and hardware-based direct volume rendering approaches are presented in Section 5.5. In Section 5.6 we propose an approach for temporal interpolation of AMR data.

Key ideas described in this work have been presented at international conferences and in scientific journals over the last three years. The hardware-accelerated volume rendering approach for large, sparse datasets was published in [39]. The direct volume rendering algorithm for SAMR data appeared in [38]. An application of this approach in a cooperation with several scientists at the NATIONAL CENTER FOR SUPERCOMPUTING APPLICATIONS (NCSA) and the UNIVERSITY OF PENNSYLVANIA, for rendering one of the most complex AMR simulation ever carried out in numerical astrophysics, was presented at the IEEE VISUALIZATION 2002 conference [37].

All algorithms have been implemented in the framework of an extension to the 3D-visualization system AMIRA [82, 1], developed at the ZUSE-INSTITUTE BERLIN.