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TUTORIAL VII

Introduction to Reversible Computing

Kalyan S. Perumalla

Oak Ridge National Laboratory, Tennessee, USA

perumallaks@ornl.gov

TUTORIAL DESCRIPTION

This tutorial provides an introduction to the concept of reversible computing, adopting an expanded view: in addition to a quick overview of the traditional energy-motivated hardware viewpoint, it provides an in-depth coverage of an emerging application-motivated software approach to reversible computing. It is useful for understanding different novel ways in which reversible computing offers potential in large-scale computing (such as the envisioned exa-scale developments) complementing current approaches. The significance of generalized reversible computing to future parallel processing is illustrated in the context of fault tolerance, debugging, and synchronization in future very large-scale supercomputing. The tutorial covers theory, hardware and software aspects, salient fundamental limits, complexity analyses, algorithms, and automation approaches for reversible computing. Paradigms to relax conventional forward-only programming to reversible programming will be presented, including “compute-copy-uncompute” and “compute-rollback-commit” paradigms for low-power computing and optimistic parallel synchronization respectively. Practical algorithms will be presented for reversibility of common operations such as dynamic memory allocation and random number generation from complex distributions. Recent results will be presented indicating the possibility of overcoming the memory wall in some applications via reliance on software-level reversible computing instead of on checkpointing. Concepts underlying the design of new reversible programming languages will be articulated, and current compilation approaches for reversible execution of existing programs will be described with an initial case study on the C language. Outstanding challenges will be identified in a wider adoption of reversible computing in parallel processing, including reversible computer arithmetic and input/output interfaces, for which a few novel directions will be presented.

TUTORIAL OUTLINE

The following is the general outline of the topics covered in the tutorial.

- Background - Concepts, Related concepts, History, Terminology
- Motivation
 - Low-power/adiabatic Computing, Quantum Computing
 - Processor Architectures, Speculative Computing, VLIW, Super-Criticality
 - Exascale Computing: Fault Tolerance, Debugging, Synchronization

- Theory
 - Energy usage, Thermodynamic Views, Adiabatic Computing Principles, Heat Generation in Computing, Clean and Dirty bits
 - Fundamental results - Bit erasure, Landauer limit, “Bennett’s Trick”
 - Reversible Turing Machines (TM), Reversible simulation of irreversible TM
 - Time vs. Space Complexity Analyses; Pebble games
- Reversible Hardware
 - Basic concepts – Gates, Reversibility, Universality, Toffoli gate, Fredkin gate
 - Reversible Instruction Set Architectures - Pendulum, Rollback chip
 - Spectrum - Circuits, Processors, Instruction Sets, Compilers, Languages, Models
- Reversible Software
 - Relaxation of Computational Paradigms for Reversibility
 - Reversible Programming Languages Overview
 - Salient Janus Language Constructs and Examples
 - Unified Approach Combining Reversible Computation and Checkpointing
 - Compilation Approach and Case Study of Reverse C Compiler
 - Reversible Random Number Generation
 - Reversible Dynamic Memory Allocation
 - Reversible Numerical Computation Challenges and Solution Approaches
 - Benchmark Results – Reversible Computing for Rollback-based Recovery in Fault Tolerance

SELECTED REFERENCES

1. Bennett, C. H., “Logical Reversibility of Computation,” IBM Journal of Res. and Dev., Vol. 17(6), pp. 525-532, 1973.
2. Levine, R. and A. Sherman, “A Note on Bennett’s Time-Space Tradeoff for Reversible Computation,” SIAM Journal on Computing, Vol. 19(4), pp. 673-677, 1990.
3. Bennett, C. H., “Notes on Landauer’s Principle, Reversible Computation, and Maxwell’s Demon,” Studies In History and Philosophy of Science Part B: Studies In History and Philosophy of Modern Physics, Vol. 34(3), pp. 501-510, 2003.
4. Akgul, T. and V. Mooney, “Assembly Instruction Level Reverse Execution for Debugging,” ACM Transactions on Software Engineering Methodology, Vol. 13(2), 149-198, 2004.
5. Frank, M., “Introduction to Reversible Computing: Motivation, Progress, and Challenges,” ACM Computing Frontiers, pp. 385-390, 2005.
6. De Vos, A., “Reversible Computing: Fundamentals, Quantum Computing, and Applications,” John Wiley & Sons, ISBN 978-3-527- 40992-1, 2010
7. Bahl, M. and C. Eisenbeis, “Impact of Reverse Computing on Information Locality in Register Allocation for High Performance Computing,” Intl. Journal of Parallel Programming, pp. 1-28, 2012.
8. Perumalla, K. S., “Introduction to Reversible Computing,” Chapman Hall/CRC Press, 1st Edition, ISBN 978-1439873403, 2013.
9. Perumalla, K.S. and A. J. Park, “Reverse Computation for Rollback-based Fault Tolerance in Large Parallel Systems,” Cluster Computing: Journal of Networks, Software Tools and Applications, 2013 [DOI: 10.1007/s10586-013-0277-4, Special Issue on Unconventional Cluster Architectures and Applications]
10. Perumalla, K.S., and V. Protopopescu, “Reversible Simulations of Elastic Collisions,” ACM Transactions on Modeling and Computer Simulation (TOMACS), Volume 23, Number 2, 2013.

REQUIREMENTS AND TARGET AUDIENCE

Although the topic of reversible computing is relevant across many disciplines, this particular offering will be primarily customized for an audience of computer scientists. Further, some familiarity with parallel or distributed computing (at senior undergraduate or higher level) will be assumed.

The tutorial is suitable for computer scientists interested in gaining exposure to the relatively unconventional concept of reversible computing. The audience can gain an appreciation of the distinction between hardware versus software aspects of reversible computing and their respective applicability in the short-term and longer-term. The audience will gain a quick snapshot of classical results, recent developments, and future outlook with respect to reversible computing-based algorithms, runtime systems, libraries, and hardware implementations.

TUTORIAL DURATION

The tutorial material will be presented in a 2.5-hour session.

A/V AND EQUIPEMNT

A standard projector and screen is sufficient for this tutorial.

INSTRUCTOR BIOGRAPHY



Kalyan Perumalla, Ph.D., is a senior R&D staff member and manager at the Oak Ridge National Laboratory. He is the founding Group Leader of the Discrete Computing Systems Group in the Computational Sciences and Engineering Division. He also serves as an adjunct professor in the School of Computational Sciences and Engineering at the Georgia Institute of Technology.

Dr. Perumalla is a winner of the US Department of Energy Early Career Award in Advanced Scientific Computing Research, 2010-2015, providing \$2.5 million for research dedicated to reversible software at Exascale. His primary research contributions are in the application of reversible computation to high performance computing and in advancing the vision of a new class of supercomputing applications using parallel discrete event simulations. He has published articles and delivered distinguished lectures and invited tutorials on these topics. His recent book *Introduction to Reversible Computing* is among the first few in its area. He co-authored another book, three book chapters, and over 100 articles in peer-reviewed conferences and journals. Four of his co-authored papers received the best paper awards, in 1999, 2002, 2005 and 2008, and two were finalists in 2010. His research prototype tools in parallel and distributed computing have been disseminated to research institutions worldwide. He earned his Ph.D. in computer science from the Georgia Institute of Technology in 1999. Dr. Perumalla serves as program committee member, editorial board member, and reviewer for multiple international conferences and journals in computing.