

## Founding Editors

Gerhard Goos

*Karlsruhe Institute of Technology, Karlsruhe, Germany*

Juris Hartmanis

*Cornell University, Ithaca, NY, USA*

## Editorial Board Members

Elisa Bertino

*Purdue University, West Lafayette, IN, USA*

Wen Gao

*Peking University, Beijing, China*

Bernhard Steffen 

*TU Dortmund University, Dortmund, Germany*

Gerhard Woeginger 

*RWTH Aachen, Aachen, Germany*

Moti Yung

*Columbia University, New York, NY, USA*

More information about this subseries at <http://www.springer.com/series/7408>

Simon McIntosh-Smith ·  
Bronis R. de Supinski · Jannis Klinkenberg (Eds.)


# OpenMP: Enabling Massive Node-Level Parallelism

17th International Workshop on OpenMP, IWOMP 2021  
Bristol, UK, September 14–16, 2021  
Proceedings

*Editors*

Simon McIntosh-Smith   
University of Bristol  
Bristol, UK

Bronis R. de Supinski   
Lawrence Livermore National Laboratory  
Livermore, CA, USA

Jannis Klinkenberg   
RWTH Aachen University  
Aachen, Germany

ISSN 0302-9743                      ISSN 1611-3349 (electronic)  
Lecture Notes in Computer Science  
ISBN 978-3-030-85261-0              ISBN 978-3-030-85262-7 (eBook)  
<https://doi.org/10.1007/978-3-030-85262-7>

LNCS Sublibrary: SL2 – Programming and Software Engineering

© Springer Nature Switzerland AG 2021

Chapter “FOTV: A Generic Device Offloading Framework for OpenMP” is licensed under the terms of the Creative Commons Attribution 4.0 International License (<http://creativecommons.org/licenses/by/4.0/>). For further details see license information in the chapter.

This work is subject to copyright. All rights are reserved by the Publisher, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed.

The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.

The publisher, the authors and the editors are safe to assume that the advice and information in this book are believed to be true and accurate at the date of publication. Neither the publisher nor the authors or the editors give a warranty, expressed or implied, with respect to the material contained herein or for any errors or omissions that may have been made. The publisher remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

This Springer imprint is published by the registered company Springer Nature Switzerland AG  
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

## Preface

OpenMP is a widely used application programming interface (API) for high-level parallel programming in Fortran, C, and C++. OpenMP has been supported in most high-performance compilers and by hardware vendors since it was introduced in 1997. Under the guidance of the OpenMP Architecture Review Board (ARB) and the diligent work of the OpenMP Language Committee, the OpenMP specification has evolved up to version 5.1, with version 5.2 soon to be released. OpenMP has become the most widely used HPC language as a result of its continuing evolution.

The latest proposed specification, which is documented in OpenMP Technical Report 10 (TR10), will be the basis of OpenMP 5.2 when the ARB releases it later this year. This version primarily reorganizes and refactors the specification of the directives and clauses that the language provides. These changes necessarily identified inconsistencies in the specification, particularly for the directive and clause syntax and the restrictions that apply to it. Thus, it will replace syntax inconsistencies with the form used more generally throughout the specification in addition to ensuring that common restrictions are consistently and clearly specified.

While these changes are small advancements, work has also begun on the next version of the specification: OpenMP 6.0. Larger changes that we anticipate for that version include the ability for a thread to create a task to be executed by a thread in a different parallel team and to enable free-agent threads to execute tasks in addition to the threads explicitly created for that team. While the details of the latter functionality are still under discussion, this volume includes a paper that explores a proposed mechanism for it. The papers that appear at IWOMP are one avenue through which the OpenMP Language Committee carefully evaluates and incorporates community needs into the OpenMP specification.

OpenMP is important both as a stand-alone parallel programming model and as part of a hybrid programming model for massively parallel, distributed memory systems consisting of homogeneous manycore nodes and heterogeneous node architectures, as found in leading supercomputers. As much of the increased parallelism in the exascale systems will be within a node, OpenMP has become widely used in top-end systems. Importantly, the features in OpenMP 6.0 will further support applications on such systems in addition to facilitating portable exploitation of specific system attributes.

The community of OpenMP researchers and developers is united under the cOMPunity organization. This organization has held workshops on OpenMP around the world since 1999: the European Workshop on OpenMP (EWOMP), the North American Workshop on OpenMP Applications and Tools (WOMPAT), and the Asian Workshop on OpenMP Experiences and Implementation (WOMPEI) attracted annual audiences from academia and industry. The International Workshop on OpenMP (IWOMP) consolidated these three workshop series into a single annual international event that rotates across Europe, Asia-Pacific, and the Americas. The first IWOMP workshop was organized under the auspices of cOMPunity. Since that workshop, the

IWOMP Steering Committee has organized these events and guided development of the series. The first IWOMP meeting was held in 2005, in Eugene, Oregon, USA. Since then, meetings have been held each year, in Reims, France; Beijing, China; West Lafayette, USA; Dresden, Germany; Tsukuba, Japan; Chicago, USA; Rome, Italy; Canberra, Australia; Salvador, Brazil; Aachen, Germany; Nara, Japan; Stony Brook, USA; Barcelona, Spain, and Auckland, New Zealand. Each workshop draws participants from research, program developer groups, and industry throughout the world. In 2020, IWOMP continued the series with technical papers and tutorials presented through a virtual conference, due to the COVID-19 pandemic. We thank the generous support of sponsors that help make these meetings successful, they are cited on the conference pages (present and archived) at the [iwomp.org](http://iwomp.org) website.

The evolution of the specification would be impossible without active research in OpenMP compilers, runtime systems, tools, and environments. The OpenMP research community is vibrant and dedicated to continuing to improve OpenMP. As we move beyond the present needs, and adapt and evolve OpenMP to the expanding parallelism in new architectures, the OpenMP research community will continue to play a vital role. The papers in this volume demonstrate the adaption of new features found in OpenMP 5.0 and 5.1 and show how the OpenMP feature set can significantly enhance user experiences on a wide range of systems. These papers also demonstrate the forward thinking of the research community, and potential OpenMP directions and further improvements for systems on the horizon.

The IWOMP website ([www.iwomp.org](http://www.iwomp.org)) has the latest workshop information, as well as links to archived events. This publication contains proceedings of the 17th International Workshop on OpenMP, IWOMP 2021. The workshop program included 15 technical papers and tutorials on OpenMP. All technical papers were peer reviewed by at least four different members of the Program Committee. The work evidenced by these authors and the committee demonstrates that OpenMP will remain a key technology well into the future.

September 2021

Simon McIntosh-Smith  
Bronis R. de Supinski  
Jannis Klinkenberg

# Organization

## General Chair

Simon McIntosh-Smith      University of Bristol, UK

## Program Committee Chair

Bronis R. de Supinski      Lawrence Livermore National Laboratory, USA

## Publication Chair

Jannis Klinkenberg      RWTH Aachen University, Germany

## Tutorial Chairs

Yun (Helen) He      National Energy Research Scientific Computing Center  
(NERSC), USA

Tom Deakin      University of Bristol, UK

## Local Organiser Chair

Tim Lewis      Croftedge Marketing, UK

## Program Committee

|                       |   |
|-----------------------|---|
| Patrick Atkinson      | NVIDIA, UK                                  |
| Eduard Ayguade        | Universitat Politècnica de Catalunya, Spain |
| Mark Bull             | University of Edinburgh, UK                 |
| Sunita Chandrasekaran | University of Delaware, USA                 |
| Florina M. Ciorba     | University of Basel, Switzerland            |
| Bronis R. de Supinski | Lawrence Livermore National Laboratory, USA |
| Tom Deakin            | University of Bristol, UK                   |
| Johannes Doerfert     | Argonne National Laboratory, USA            |
| Alex Duran            | Intel Iberia, Spain                         |
| Deepak Eachempati     | HPE, USA                                    |
| Jini George           | AMD, USA                                    |
| Oscar Hernandez       | Oak Ridge National Laboratory, USA          |
| Paul Kelly            | Imperial, UK                                |
| Jannis Klinkenberg    | RWTH Aachen University, Germany             |
| Michael Kruse         | Argonne National Laboratory, USA            |
| Kelvin Li             | IBM, USA                                    |
| Chunhua Liao          | Lawrence Livermore National Laboratory, USA |

|                 |  |
|-----------------|--|
| Will Lovett     | Arm, UK  |
| Larry Meadows   | Intel, USA   |
| Kent Milfeld    | TACC, USA  |
| Stephen Olivier | Sandia National Laboratories, USA                        |
| Joachim Protze  | RWTH Aachen University, Germany                          |
| Mitsuhsa Sato   | RIKEN Center for Computational<br>Science (R-CCS), Japan |
| Thomas Scogland | Lawrence Livermore National Laboratory, USA              |
| Adrian Tate     | NAG, UK  |
| Terry Wilmarth  | Intel, USA   |
| Justs Zarins    | EPCC, UK   |

## Website

|           |                         |
|-----------|-------------------------|
| Tim Lewis | Croftedge Marketing, UK |
|-----------|-------------------------|

## IWOMP Steering Committee

### Steering Committee Chair

|                    |                                 |
|--------------------|---------------------------------|
| Matthias S. Müller | RWTH Aachen University, Germany |
|--------------------|---------------------------------|

### Steering Committee

|                               |  |
|-------------------------------|--|
| Dieter an Mey                 | RWTH Aachen University, Germany                          |
| Eduard Ayguadé                | BSC, Universitat Politècnica de Catalunya, Spain         |
| Mark Bull                     | EPCC, University of Edinburgh, UK                        |
| Barbara Chapman               | Stony Brook University, USA                              |
| Bronis R. de Supinski         | Lawrence Livermore National Laboratory, USA              |
| Rudolf Eigenmann              | University of Delaware, USA                              |
| William Gropp                 | University of Illinois, USA                              |
| Michael Klemm                 | AMD, Germany   |
| Kalyan Kumaran                | Argonne National Laboratory, USA                         |
| Lawrence Meadows              | Intel, USA   |
| Stephen L. Olivier            | Sandia National Laboratories, USA                        |
| Ruud van der Pas              | University of Delaware, USA                              |
| Alistair Rendell              | Flinders University, Australia                           |
| Mitsuhsa Sato                 | RIKEN Center for Computational Science (R-CCS),<br>Japan |
| Sanjiv Shah                   | Intel, USA   |
| Oliver Sinnen                 | University of Auckland, New Zealand                      |
| Josemar Rodrigues de<br>Souza | SENAI Unidade CIMATEC, Brazil                            |
| Christian Terboven            | RWTH Aachen University, Germany                          |
| Matthijs van Waveren          | OpenMP ARB & CS Group, France                            |



# Contents

## Synchronization and Data

|   |    |
|---|----|
| Improving Speculative taskloop in Hardware Transactional Memory . . . . . | 3  |
| <i>Juan Salamanca and Alexandro Baldassin</i>                             |    |
| Vectorized Barrier and Reduction in LLVM OpenMP Runtime . . . . .         | 18 |
| <i>Muhammad Nufail Farooqi and Miquel Pericàs</i>                         |    |

## Tasking Extensions I

|   |    |
|---|----|
| Enhancing OpenMP Tasking Model: Performance and Portability . . . . . | 35 |
| <i>Chenle Yu, Sara Royuela, and Eduardo Quiñones</i>                  |    |
| OpenMP Taskloop Dependences . . . . .                                 | 50 |
| <i>Marcos Maroñas, Xavier Teruel, and Vicenç Beltran</i>              |    |

## Applications

|  |    |
|--|----|
| Outcomes of OpenMP Hackathon: OpenMP Application Experiences<br>with the Offloading Model (Part I) . . . . .   | 67 |
| <i>Barbara Chapman, Buu Pham, Charlene Yang, Christopher Daley,<br/>Colleen Bertoni, Dhruva Kulkarni, Dossay Oryspayev, Ed D'Azevedo,<br/>Johannes Doerfert, Keren Zhou, Kiran Ravikumar, Mark Gordon,<br/>Mauro Del Ben, Meifeng Lin, Melisa Alkan, Michael Kruse,<br/>Oscar Hernandez, P. K. Yeung, Paul Lin, Peng Xu, Swaroop Pophale,<br/>Tosaporn Sattasathuchana, Vivek Kale, William Huhn,<br/>and Yun (Helen) He</i> |    |
| Outcomes of OpenMP Hackathon: OpenMP Application Experiences<br>with the Offloading Model (Part II) . . . . .  | 81 |
| <i>Barbara Chapman, Buu Pham, Charlene Yang, Christopher Daley,<br/>Colleen Bertoni, Dhruva Kulkarni, Dossay Oryspayev, Ed D'Azevedo,<br/>Johannes Doerfert, Keren Zhou, Kiran Ravikumar, Mark Gordon,<br/>Mauro Del Ben, Meifeng Lin, Melisa Alkan, Michael Kruse,<br/>Oscar Hernandez, P. K. Yeung, Paul Lin, Peng Xu, Swaroop Pophale,<br/>Tosaporn Sattasathuchana, Vivek Kale, William Huhn,<br/>and Yun (Helen) He</i> |    |

|   |     |
|---|-----|
| An Empirical Investigation of OpenMP Based Implementation of Simplex Algorithm . . . . .                        | 96  |
| <i>Arkaprabha Banerjee, Pratvi Shah, Shivani Nandani, Shantanu Tyagi, Sidharth Kumar, and Bhaskar Chaudhury</i> |     |
| Task Inefficiency Patterns for a Wave Equation Solver . . . . .   | 111 |
| <i>Holger Schulz, Gonzalo Brito Gadeschi, Oleksandr Rudyy, and Tobias Weinzierl</i>                             |     |
| <b>Case Studies</b>   |     |
| Comparing OpenMP Implementations with Applications Across A64FX Platforms . . . . .                             | 127 |
| <i>Benjamin Michalowicz, Eric Raut, Yan Kang, Tony Curtis, Barbara Chapman, and Dossay Oryspayev</i>            |     |
| A Case Study of LLVM-Based Analysis for Optimizing SIMD Code Generation . . . . .                               | 142 |
| <i>Joseph Huber, Weile Wei, Giorgis Georgakoudis, Johannes Doerfert, and Oscar Hernandez</i>                    |     |
| <b>Heterogenous Computing and Memory</b>  |     |
| Experience Report: Writing a Portable GPU Runtime with OPENMP 5.1. . . . .                                      | 159 |
| <i>Shilei Tian, Jon Chesterfield, Johannes Doerfert, and Barbara Chapman</i>                                    |     |
| FOTV: A Generic Device Offloading Framework for OpenMP . . . . .  | 170 |
| <i>Jose Luis Vazquez and Pablo Sanchez</i>  |     |
| Beyond Explicit Transfers: Shared and Managed Memory in OpenMP. . . . .   | 183 |
| <i>Brandon Neth, Thomas R. W. Scogland, Alejandro Duran, and Bronis R. de Supinski</i>                          |     |
| <b>Tasking Extensions II</b>  |     |
| Communication-Aware Task Scheduling Strategy in Hybrid MPI+OpenMP Applications . . . . .                        | 197 |
| <i>Romain Pereira, Adrien Roussel, Patrick Carribault, and Thierry Gautier</i>                                  |     |
| An OpenMP Free Agent Threads Implementation . . . . .   | 211 |
| <i>Victor Lopez, Joel Criado, Raúl Peñacoba, Roger Ferrer, Xavier Teruel, and Marta Garcia-Gasulla</i>          |     |
| Author Index . . . . .  | 227 |