UPIR: Toward the Design of Unified Parallel Intermediate Representation for Parallel Programming Models

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ABSTRACT

The complexity of heterogeneous computing architectures, as well as the demand for productive and portable parallel application development, have driven the evolution of parallel programming models to become more comprehensive and complex than before. Enhancing the conventional compilation technologies and software infrastructure to be parallelism-aware has become one of the main goals of recent compiler development. In this work, we propose the design of unified parallel intermediate representation (UPIR) for multiple parallel programming models and for enabling unified compiler transformation for the models. UPIR specifies three commonly used parallelism patterns (SPMD, data and task parallelism), data attributes and explicit data movement and memory management, and synchronization operations used in parallel programming. We demonstrate UPIR via a prototype implementation in the ROSE compiler for unifying IR for both OpenMP and OpenACC and in both C/C++ and Fortran, for unifying the transformation that lowers both OpenMP and OpenACC code to LLVM runtime, and for exporting UPIR to LLVM MLIR dialect. The fully extended paper of this abstract can be found from https://arxiv.org/abs/2209.10643.

CCS CONCEPTS

• **Software and its engineering → Compilers**.

KEYWORDS

Compiler transformation, Parallel intermediate representation, OpenMP, OpenACC, MLIR

ACM Reference Format:
Anjia Wang, Xinyao Yi, and Yonghong Yan. 2022. UPIR: Toward the Design of Unified Parallel Intermediate Representation for Parallel Programming Models. In *International Conference on Parallel Architectures and Compilation Techniques (PACT '22), October 8–12, 2022, Chicago, IL,USA.* ACM, New York, NY, USA, 2 pages. https://doi.org/10.1145/3559009.3569646

1 INTRODUCTION

The past two decades have seen dramatically increased complexity of computer systems, including the significant increase of parallelism from 10s to 100s and 1000s computing units and cores, the wide adoption of heterogeneous architecture such as CPU, GPUs and vector units in a computer system, and the significant enhancement to the conventional memory hierarchy using new memory technologies such as 3D-stacked memory and NVRAM. Demands from users and applications for computing have also become high and diverse, ranging from computational science, large-scale data analysis, and artificial intelligence that adopts the computation-intensive deep neural network methods. Together they have driven the evolution of parallel programming models to become more comprehensive and complex with multifaceted goals including delivering portable performance across diverse architectures, being highly expressible for the wide ranges of users and applications, and allowing for high performance implementation and tools support.

It is observed that existing parallel programming models share common parallelism functionality and use similar interfaces of essential capability for programming parallelism [2]. However, supporting these parallel models in one compiler often has to create language-dependent compiler passes of the same functionality for different models. We believe one of the barriers is the lack of language-independent abstraction of the fundamental entities and constructs for parallelism. This has hindered the research and development of parallelism-aware analysis and transformation across multiple programming models.

In this work, we propose the notion and specification of *unified parallel intermediate representation (UPIR)* to enable language-neutral parallelism-aware compilation. We create a prototype implementation in ROSE compiler, and demonstrate UPIR for unifying IR for offloading code in both OpenMP and OpenACC and in both C/C++ and Fortran. The demonstration includes a unified transformation that lowers OpenMP and OpenACC offloading code to LLVM OpenMP runtime. UPIR is also implemented as LLVM MLIR dialect, thus the ROSE-based UPIR compiler is able to export the UPIR of a program to its MLIR dialect.

2 UNIFIED PARALLEL INTERMEDIATE REPRESENTATION (UPIR)

As existing parallel programming models share common parallelism functionality and similar interfaces of essential capability for programming parallelism [2], a language-independent abstraction of the fundamental entities and constructs for parallelism and their connections can be constructed in a unified intermediate representation serving as the backbone to enable unified and common parallelism-aware analysis and transformation. The UPIR design and specification include 1) the three commonly used parallelism patterns, namely single program multiple data (SPMD), data parallelism, and task parallelism including offloading tasks; 2) data

PACT '22, October 8–12,2022, Chicago, IL, USA

ACM ISBN 978-1-4503-9868-8/22/10.
https://doi.org/10.1145/3559009.3569646

attributes and explicit data movement and memory management for assisting data-aware optimization for parallel programs; and 3) synchronization operations used in parallel programming for optimizing synchronization cost by the compiler. Table 1 shows the UPIR's support and mapping for the language constructs of OpenMP and OpenACC.

	UPIR	OpenMP	OpenACC
SPMD parallelism	spmd	teams, parallel	parallel
Data parallelism	loop loop-parallel	distribute, for, simd	loop, gang worker, vector
Async task parallelism	task	task, taskwait	async, wait
Data attributes	data	map(to/from) shared, private firstprivate	data(copyin/out) shared, private firstprivate
Synchronization	sync	barrier, atomic, critical	wait, atomic

Table 1: Mapping of parallel programming model constructs with UPIR design

3 EVALUATION

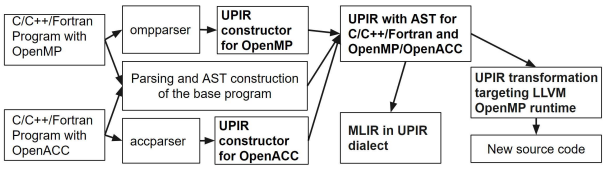


Figure 1: UPIR implementation in ROSE compiler to support C/C++/Fortran and OpenMP and OpenACC

Our prototype is implemented in ROSE source-to-source compiler [1]. Figure 1 shows how UPIR is generated from OpenMP and OpenACC source code, in both C and Fortran, and followed by a unified transformation. The UPIR is also implemented with LLVM TableGen to produce the UPIR dialects in MLIR, allowing the ROSE implementation of the UPIR to be exported to MLIR (Figure 2).

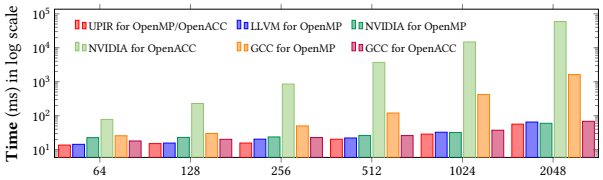
UPIR helps compilers conduct a unified transformation for multiple parallel programming models. We pick two offloading kernels for evaluation: AXPY and 2D stencil. The evaluation compared our ROSE-based UPIR compiler, NVIDIA HPC SDK, and GCC compiler, all for both OpenMP and OpenACC, and Clang/LLVM for OpenMP only. For the OpenMP version, our implementation can achieve up to 1.28x speedup over LLVM and 25.89x speed up over GCC in average for all the problem sizes we selected. For the OpenACC version, UPIR shows up to 235.1x speedup over NVIDIA compiler and 1.15x speedup over GCC in average for all the evaluated problem sizes. The performance results for 2D stencil are shown in Figure 3.

4 CONCLUSION

In this work, we present UPIR, a unified parallel intermediate representation used for representing parallelism of parallel programming models to assist parallelism-aware compiler analysis, transformation and optimization. It is designed to support a wide-variety of

```
1  func @axpy(%arg0: memref<*xi32, 8>, %arg1: memref<*xi32, 8>, %
       arg2: i32, %arg3: i32) {
2    ... // %2, %3, %4, %5 are the data used in the parallel region
3    %2 = upir.parallel_data_info(x, shared, implicit, tofrom,
         implicit, read-only)
4    %3, %4, %5 = ...
5    %c6_i32 = constant 1024 : i32
6    upir.task target(nvptx) data(%2, %3, %4, %5) {
7      upir.spmd num_units(%c6_i32 : i32) data(%2, %3, %4, %5)
         target(gpu) {
8        %c0 = constant 0 : index
9        %c1 = constant 1 : index
10       upir.loop induction-var(%arg4) lowerBound(%c0) upperBound
           (%arg3) step(%c1) {
11         upir.loop-parallel worksharing {
12           ...
13   } } } } }
```

Figure 2: AXPY in UPIR MLIR dialect, for OpenMP and OpenACC GPU Offloading



Problem size: filter size = 7, array size = N*N, where N = 64, 128, ...

Figure 3: 2D stencil performance of UPIR compiler, LLVM, NVIDIA, and GCC compilers

parallel programming models and the prototype implementation in ROSE compiler support C/C++/Fortran, OpenMP, and OpenACC. UPIR enables a unified compiler transformation for multiple parallel programming models.

Our experiments show that the UPIR compiler utilizes the unified transformation to compile both OpenMP and OpenACC programs. It achieves promising performance and saves much development effort for supporting new programming models by leveraging the UPIR and the unified transformation. We believe that UPIR provides a comprehensive, flexible and extensible compiler IR designed for compiler development targeting modern heterogeneous parallel systems. Furthermore, having the unified IR would enable lots of interesting research and accelerate the implementation of supporting new programming models in a compiler.

ACKNOWLEDGMENTS

This material is based upon work supported by the National Science Foundation under Grant No. 1833332 and 2015254.

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