FortranX: Harnessing Code Generation, Portability, and Heterogeneity in Fortran

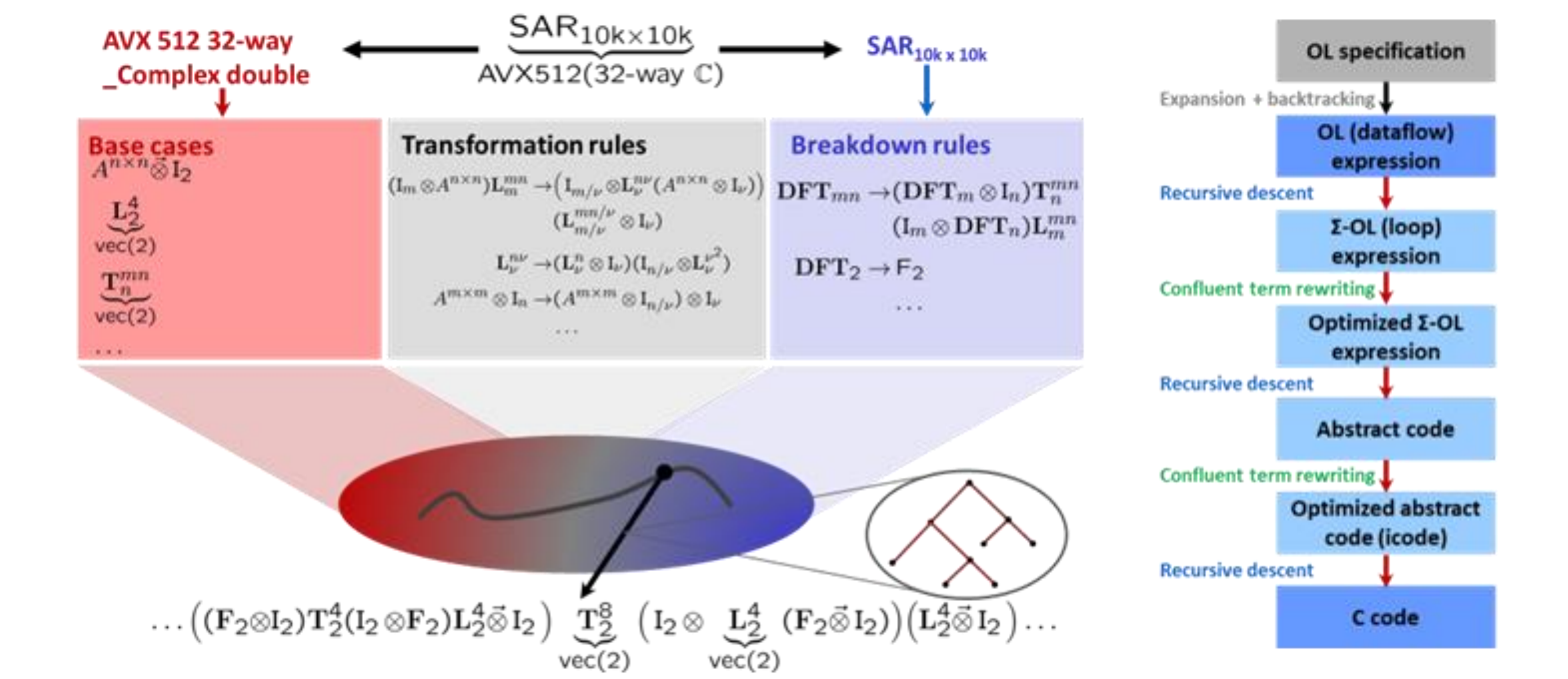
Sanil Rao*, Mike Franusich+, Mohammad Alaul Haque Monil†, Het Mankad†, Jeffery S. Vetter†, Franz Franchetti*

*Carnegie Mellon University, +SpiralGen Inc., †Oak Ridge National Laboratory

Problem

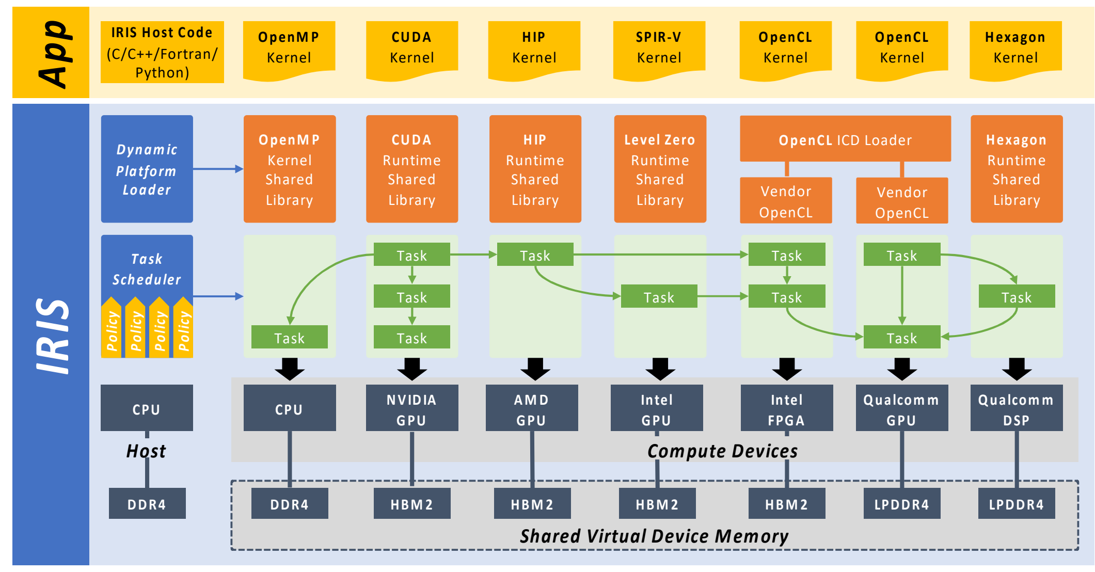
- Many scientific applications are written and maintained in Fortran.
- New systems leverage novel programming models and hardware architectures which are not easily accessible in Fortran.
- FortranX is an automated approach to recognize and optimize Fortran applications, generating optimized kernels that can execute on various hardware platforms without source code modification.

IRISX[3]: SPIRAL + IRIS


AVX 512 32-way _Complex double
$\underbrace{\mathrm{SAR}_{10k\times 10k}}_{\mathrm{AVX512(32\text{-}way}\ \mathbb{C})}$
$\mathrm{SAR}_{10k\times 10k}$
Base cases
$A^{n\times n}\vec{\otimes}\mathrm{I}_2$
$\underbrace{\mathrm{L}_2^4}_{\mathrm{vec}(2)}$
$\underbrace{\mathrm{T}_n^{mn}}_{\mathrm{vec}(2)}$
Transformation rules
$(\mathrm{I}_m\otimes A^{n\times n})\mathrm{L}_m^{mn}\to(\mathrm{I}_{m/\nu}\otimes\mathrm{L}_\nu^{n\nu}(A^{n\times n}\otimes\mathrm{I}_\nu))(\mathrm{L}_{m/\nu}^{mn/\nu}\otimes\mathrm{I}_\nu)$
$\mathrm{L}_\nu^{n\nu}\to(\mathrm{L}_\nu^n\otimes\mathrm{I}_\nu)(\mathrm{I}_{n/\nu}\otimes\mathrm{L}_\nu^{\nu^2})$
$A^{m\times m}\otimes\mathrm{I}_n\to(A^{m\times m}\otimes\mathrm{I}_{n/\nu})\otimes\mathrm{I}_\nu$
Breakdown rules
$\mathrm{DFT}_{mn}\to(\mathrm{DFT}_m\otimes\mathrm{I}_n)\mathrm{T}_n^{mn}(\mathrm{I}_m\otimes\mathrm{DFT}_n)\mathrm{L}_m^{mn}$
$\mathrm{DFT}_2\to\mathrm{F}_2$
$\dots\big((\mathrm{F}_2\otimes\mathrm{I}_2)\mathrm{T}_2^4(\mathrm{I}_2\otimes\mathrm{F}_2)\mathrm{L}_2^4\vec{\otimes}\mathrm{I}_2\big)\underbrace{\mathrm{T}_2^8}_{\mathrm{vec}(2)}\big(\mathrm{I}_2\otimes\underbrace{\mathrm{L}_2^4}_{\mathrm{vec}(2)}(\mathrm{F}_2\vec{\otimes}\mathrm{I}_2)\big)\big(\mathrm{L}_2^4\vec{\otimes}\mathrm{I}_2\big)\dots$
OL specification
Expansion + backtracking
OL (dataflow) expression
Recursive descent
Σ-OL (loop) expression
Confluent term rewriting
Optimized Σ-OL expression
Recursive descent
Abstract code
Confluent term rewriting
Optimized abstract code (icode)
Recursive descent
C code

SPIRAL[1]:

- Complete automation of the implementation and optimization task.
- Rewriting systems to perform algorithmic selection and optimization for various hardware backends.



IRIS[2]:

- Portable runtime system supporting various hardware backends.
- Heterogenous execution by utilizing multiple devices for concurrent tasks.

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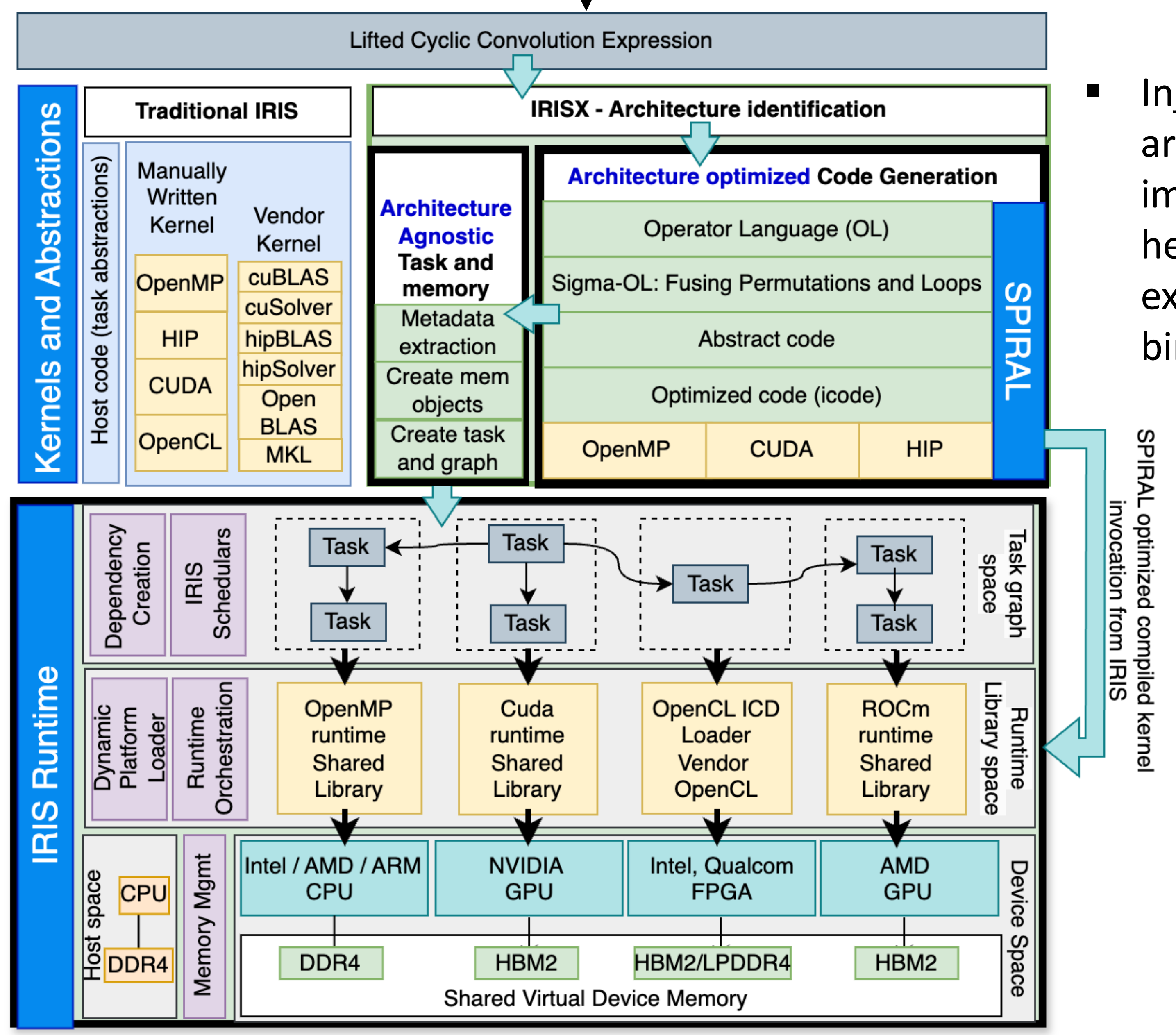
Cyclic Convolution Example

```
program cyclic_convolution
  allocate(out_arr, in_arr, sym_arr, tmp_box)

  planf = fftw_plan_dft_r2c_3d(dims(3),dims(2),
          dims(1),in_arr, tmp_box, FFTW_ESTIMATE)
  planb = fftw_plan_dft_c2r_3d(dims(3),dims(2),
          dims(1),tmp_box, out_arr, FFTW_ESTIMATE)

  ! forward FFT
  call fftw_execute_dft_r2c(planf, in_arr, tmp_box)

  ! pointwise multiply
  tmp_box = tmp_box * sym_arr

  ! inverse FFT
  call fftw_execute_dft_c2r(planb, tmp_box, out_arr)

  call fftw_destroy_plan(planf)
  call fftw_destroy_plan(planb)
end program cyclic_convolution
```

- Optimization by fusing operations (merging multiplication into FFT stages) and removing unneeded temporaries.

Idiomatic Translation Compiler Pass

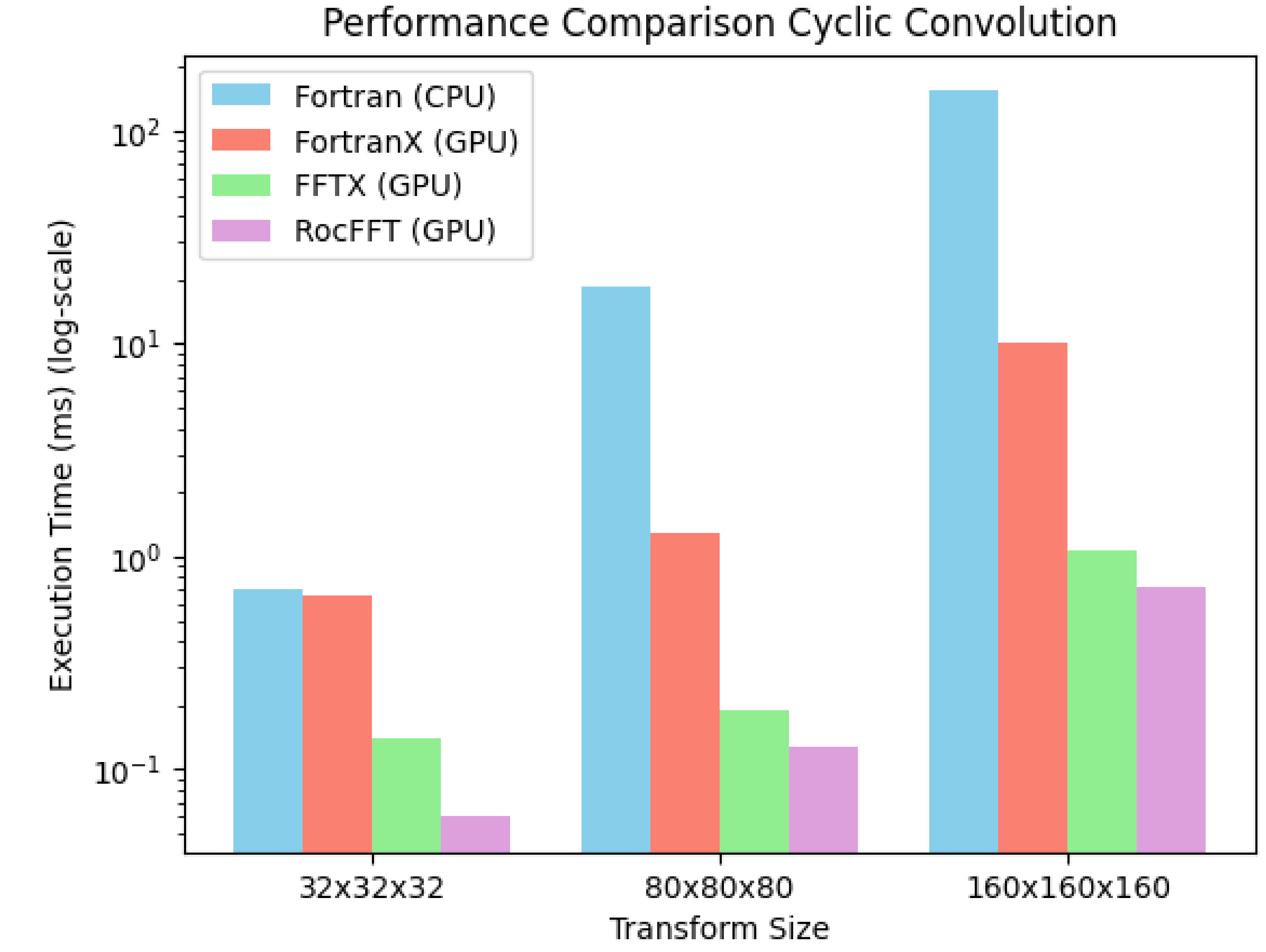
- Compiler pass that recognizes the idiom of cyclic convolution.



- Injection of IRISX for architecture-specific implementations and heterogenous task execution in a portable binary.

a.out

Performance



- Without source code modification, FortranX achieves up to **15x** performance improvement over the sequential CPU baseline and can be further optimized for specific hardware and overhead reduction.

Conclusion & Future Work

- FortranX enables the compiler to recognize key algorithms and leverages IRISX for optimized kernel generation and task execution.
- We are continuing development of FortranX for large cross-motif applications including sparse linear algebra and structured grids.

References

[1] F. Franchetti, T.-M. Low, T. Popovici, R. Veras, D. G. Spampinato, J. Johnson, M. Puschel, J. C. Hoe, and J. M. F. Moura, “SPIRAL: Extreme performance portability,” Proceedings of the IEEE, special issue on “From High Level Specification to High Performance Code”, vol. 106, no. 11, 2018.

[2] J. Kim, S. Lee, B. Johnston, and J. S. Vetter, “IRIS: A portable runtime system exploiting multiple heterogeneous programming systems,” in 2021 IEEE High Performance Extreme Computing Conference, HPEC 2021, Waltham, MA, USA, September 20-24, 2021, pp. 1–8, IEEE, 2021.

[3] Sanil Rao, Mohammad Alaul Haque Monil, Het Mankad, Jeffrey Vetter, and Franz Franchetti. 2023. FFTX-IRIS: Towards Performance Portability and Heterogeneity for SPIRAL Generated Code. In Proceedings of the SC '23 Workshops of The International Conference on High Performance Computing, Network, Storage, and Analysis (SC-W '23). Association for Computing Machinery, New York, NY, USA, 1635–1641. https://doi.org/10.1145/3624062.3624242