# FFTX: Release, Updates and Next Steps

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# FFTX Released

spiral.net/software/fftx.html

Spiral
Software/Hardware Generation for Performance

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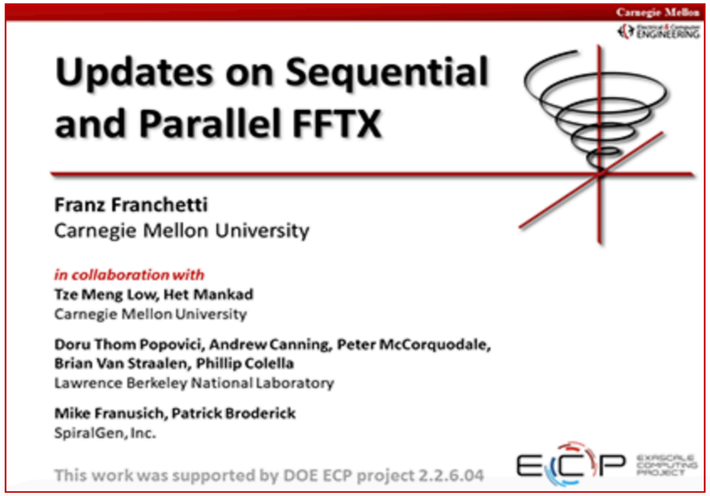
## FFTX and SPIRAL

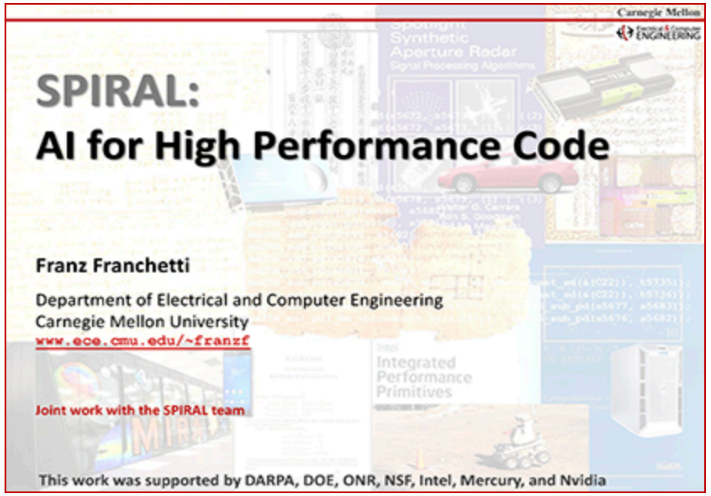
**(DE-AC02-05CH11231 — DOE FFTX)**

FFTX is the exascale follow-on to the FFTW open source discrete FFT package for executing the Fast Fourier Transform as well as higher-level operations composed of linear operations combined with DFT transforms. Though backwards compatible with FFTW, this is an entirely new work developed as a cooperative effort between Lawrence Berkeley National Laboratory, Carnegie Mellon University, and SpiralGen, Inc.

From casual look at its API, FFTX appears to be a pre-built library, but the heart of FFTX is a build-time code generator, SPIRAL, that produces very high performance kernels targeted to their specific uses and platform environments. Coupled to the platform-aware code generator is a sophisticated front end that interprets the details of the algorithms from the FFTX API, which it treats as a DSL for algorithm specification.

### Development



# Have You Ever Wondered About This?

## Numerical Linear Algebra

**LAPACK**
**ScaLAPACK**
LU factorization
Eigensolves
SVD

**BLAS, BLACS**
BLAS-1
BLAS-2
BLAS-3

## Spectral Algorithms

Convolution
Correlation
Upsampling
Poisson solver
…
?

**FFTW**
DFT, RDFT
1D, 2D, 3D,…
batch

## No LAPACK equivalent for spectral methods

- **Medium size 1D FFT (1k—10k data points) is most common library call**
  applications break down 3D problems themselves and then call the 1D FFT library
- **Higher level FFT calls rarely used**
  FFTW *guru* interface is powerful but hard to used, leading to performance loss
- **Low arithmetic intensity and variation of FFT use make library approach hard**
  Algorithm specific decompositions and FFT calls intertwined with non-FFT code

# FFTX and SpectralPACK

| Numerical Linear Algebra | | Spectral Algorithms |
| --- | --- | --- |
| **LAPACK**<br>LU factorization<br>Eigensolves<br>SVD<br>… | ≈ | **SpectralPACK**<br>Convolution<br>Correlation<br>Upsampling<br>Poisson solver<br>… |
| **BLAS**<br>BLAS-1<br>BLAS-2<br>BLAS-3 | | **FFTX**<br>DFT, RDFT<br>1D, 2D, 3D,…<br>batch |

**Define the LAPACK equivalent for spectral algorithms**

- **Define FFTX as the BLAS equivalent**
  provide user FFT functionality as well as algorithm building blocks
- **Define class of numerical algorithms to be supported by SpectralPACK**
  PDE solver classes (Green's function, sparse in normal/k space,…), signal processing,…
- **Library front-end, code generation and vendor library back-end**
  mirror concepts from FFTX layer

***FFTX and SpectralPACK solve the "spectral motif" long term***

# Example: Free Space Convolution in C++

## Numerical algorithm view

**Partial differential equation (PDE)**

$$\Delta(\Phi) = \rho$$

$$\rho : \mathbb{R}^3 \to \mathbb{R}$$

$$D = \mathrm{supp}(\rho) \subset \mathbb{R}^3$$

Poisson's equation. Δ is the Laplace operator

**Solution characterization**

$$\Phi : \mathbb{R}^3 \to \mathbb{R}$$

$$\Phi(\vec{x}) = \frac{Q}{4\pi||\vec{x}||} + o\left(\frac{1}{||\vec{x}||}\right) \text{ as } ||\vec{x}|| \to \infty$$

$$Q = \int_D \rho d\vec{x}$$

**Approach: Green's function**

$$\Phi(\vec{x}) = \int_D G(\vec{x} - \vec{y})\rho(\vec{y})d\vec{y} \equiv (G * \rho)(\vec{x}), \quad G(\vec{x}) = \frac{1}{4\pi||\vec{x}||_2}$$

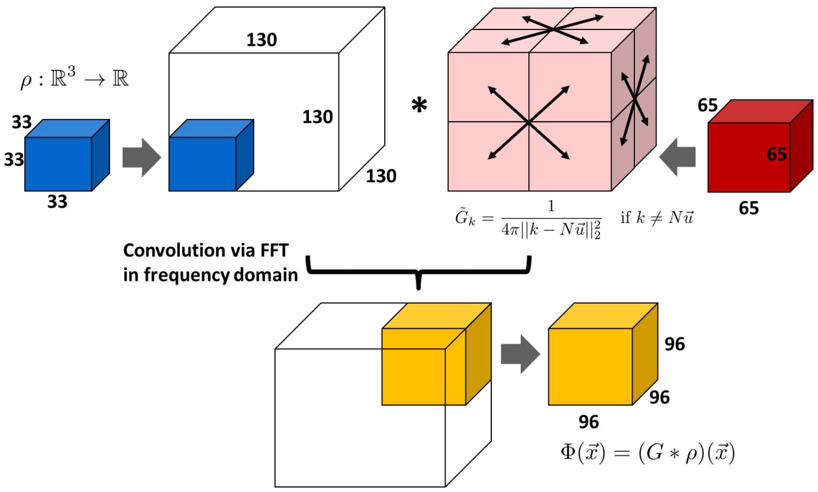
Solution: ϕ(.) = convolution of RHS ρ(.) with Green's function *G*(.). Efficient through FFTs (frequency domain)

**Method of Local Corrections (MLC)**

$$\tilde{G}_k = \frac{1}{4\pi||k - N\vec{u}||_2^2} \quad \text{if } k \neq N\vec{u}$$

Green's function kernel in frequency domain

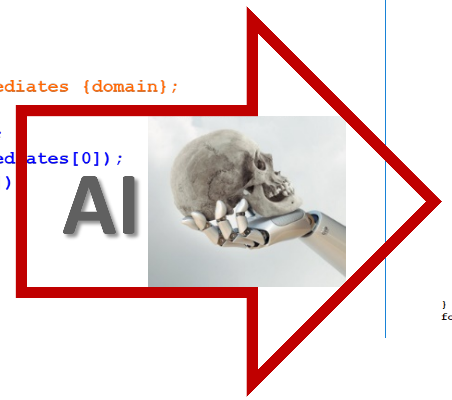
## Whiteboard view




## User program view

```
#include "fftx3.hpp"
...
int main(int argc, char* argv[])
{
  tracing=true;
  int nx, ny, nz;
  box_t<3> domain(point_t<3>({{1,1,1}}), point_t<3>({{nx,ny,nz}}));

  array_t<3,std::complex<double>> inputs(domain);
  array_t<3,std::complex<double>> outputs(domain);
  std::array<array_t<3,std::complex<double>>,2> intermediates {domain};

  MDDFT(domain.extents(), 1, intermediates[0], inputs);
  RCDiag(domain.extents(), 1, intermediates[1], intermediates[0]);
  IMDDFT(domain.extents(), 1, outputs, intermediates[1]);
}
```

"classical compiler"




## Backend program view

hockney_130_33_96.c - Notepad

File Edit Format View Help

```
                a2370 = D43[(b416 + 2)];
                a2371 = D43[(b416 + 3)];
                T113[(b415 + 26)] = ((a2368*t2146) - (a2369*t2147));
                T113[(b415 + 27)] = ((a2369*t2146) + (a2368*t2147));
                T113[(b415 + 104)] = ((a2370*t2148) - (a2371*t2149));
                T113[(b415 + 105)] = ((a2371*t2148) + (a2370*t2149));
                t2150 = (s1076 - s1080);
                t2151 = (s1077 + s1081);
                t2152 = (s1076 + s1080);
                t2153 = (s1077 - s1081);
                a2372 = D43[(b416 + 4)];
                a2373 = D43[(b416 + 5)];
                a2374 = D43[(b416 + 6)];
                a2375 = D43[(b416 + 7)];
                T113[(b415 + 52)] = ((a2372*t2150) - (a2373*t2151));
                T113[(b415 + 53)] = ((a2373*t2150) + (a2372*t2151));
                T113[(b415 + 78)] = ((a2374*t2152) - (a2375*t2153));
                T113[(b415 + 79)] = ((a2375*t2152) + (a2374*t2153));
            }
        }
        for(int i68 = 0; i68 <= 64; i68++) {
            double s1094, s1095, s1096, s1097;
            int a2406, a2407;
            a2406 = (2*i68);
            s1094 = T113[a2406];
            s1095 = T113[(a2406 + 1)];
            s1096 = T113[(a2406 + 130)];
            s1097 = T113[(a2406 + 131)];
            a2407 = ((260*i18) + a2406);
            T112[a2407] = (s1094 + s1096);
            T112[(a2407 + 1)] = (s1095 + s1097);
            T112[(a2407 + 130)] = (s1094 - s1096);
            T112[(a2407 + 131)] = (s1095 - s1097);
        }
    }
    for(int i17 = 0; i17 <= 129; i17++) {
        static double T179[260];
```

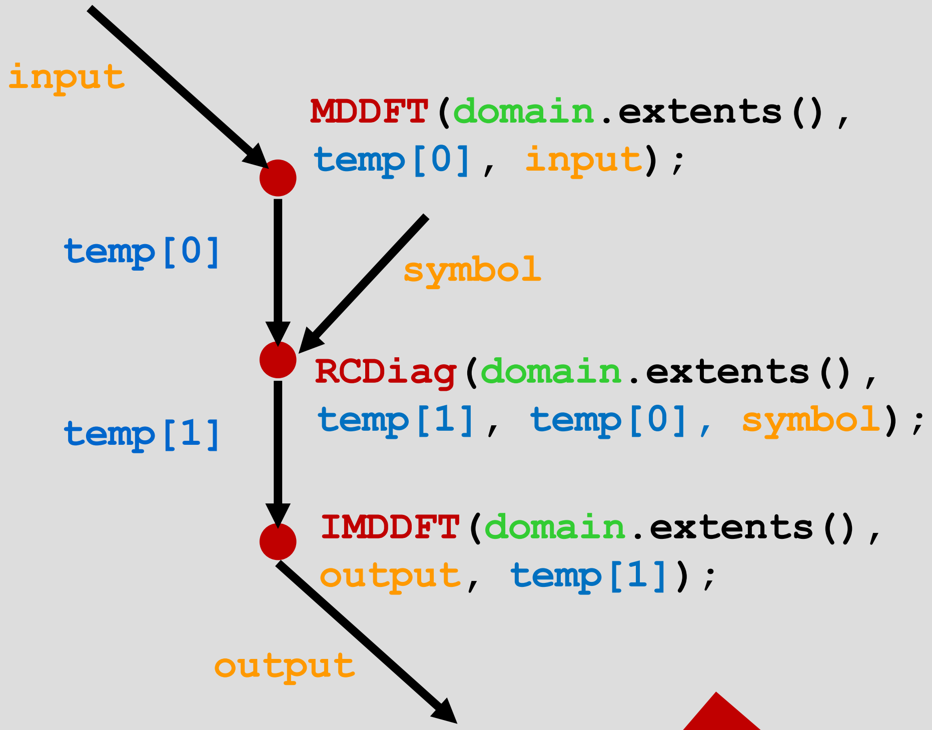
# Method 1: Delayed Execution in FFTX C++ Code

```
#include "fftx3.hpp"
...
int main(int argc, char* argv[])
{
  int nx, ny, nz;
  box_t<3> domain(point_t<3>({{1,1,1}}), point_t<3>({{nx,ny,nz}}));

  array_t<3,std::complex<double>> input(domain);
  array_t<3,std::complex<double>> symbol(domain);
  array_t<3,std::complex<double>> output(domain);

  // will not be materialized
  fftx::tmp_array<array_t<3,std::complex<double>>,2> temp {domain};
  // no-op, just collect calling parameters, delayed execution
  MDDFT(domain.extents(), temp[0], input);
  // no-op, just collect calling parameters, delayed execution
  RCDiag(domain.extents(), temp[1], temp[0], symbol);
  // passing in the output triggers RTC and execution of the entire delayed sequence
  MDDFT(domain.extents(), output, temp[1]);
  // output now contains the correct result, but temp[] was never materialized
}
```

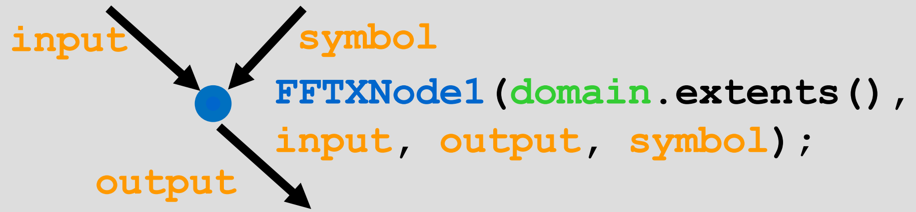
**Captures library semantics and replaces with generated high-performance kernel through runtime compilation**

# Method 2: 3D Convolution FFTX DAG Transformation

## MLIR DAG



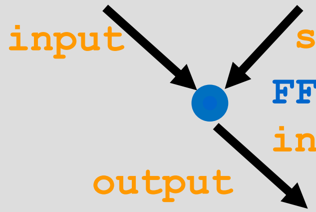

## MLIR DAG + FFTXNode Supernodes



# Method 2: FFTXNode Inserted in FFTX C++ Code/MLIR

```
#include "fftx3.hpp"
...
int main(int argc, char* argv[])
{
  int nx, ny, nz;
  box_t<3> domain(point_t<3>({{1,1,1}}), point_t<3>({{nx,ny,nz}}));

  array_t<3,std::complex<double>> input(domain);
  array_t<3,std::complex<double>> symbol(domain);
  array_t<3,std::complex<double>> output(domain);

  // original FFTX code
  // captured as FFTXNode1 by high level MLIR transformation
  // std::array<array_t<3,std::complex<double>>,2> temp {domain};
  // MDDFT(domain.extents(), temp[0], input);
  // RCDiag(domain.extents(), temp[1], temp[0], symbol);
  // IMDDFT(domain.extents(), output, temp[1]);
  // compiler generated FFTXNode replacement code
  // injected at LLVM/MLIR level
  FFTXNode1.execEnv(DEFAULT).run(domain.extents(), input, output, symbol);
}
```

## FFTXNode Supernode




```
FFTXNode1(domain.extents(),
input, output, symbol);
```

# FFTXNode Runtime Compilation

```
// kernels as strings for the CUDA JIT
kernels[2] = { "__global__ void ker_mdprdft3d_4x4x42(double  *Y) {\n"
"    double s100, s101, s102, s97, s98, s99; \n"
"    int a191, a192; \n"
"    a191 = ((24*blockIdx.y) + (6*blockIdx.x)); \n"
"    s97 = P2[a191]; \n"
"    s98 = P2[(a191 + 4)]; \n"
"    s99 = (s97 + s98); \n"
"    s100 = (s97 - s98); \n"
"    s101 = (2.0*P2[(a191 + 2)]); \n"
"    s102 = (2.0*P2[(a191 + 3)]); \n"
"    a192 = ((16*blockIdx.y) + (4*blockIdx.x)); \n"
"    Y[a192] = (s99 + s101); \n"
"    Y[(a192 + 2)] = (s99 - s101); \n"
"    Y[(a192 + 1)] = (s100 + s102); \n"
"    Y[(a192 + 3)] = (s100 - s102); \n"
"} \n", 1, DOUBLE_PY};
```

FFTX generated output sent to target runtime compilation system

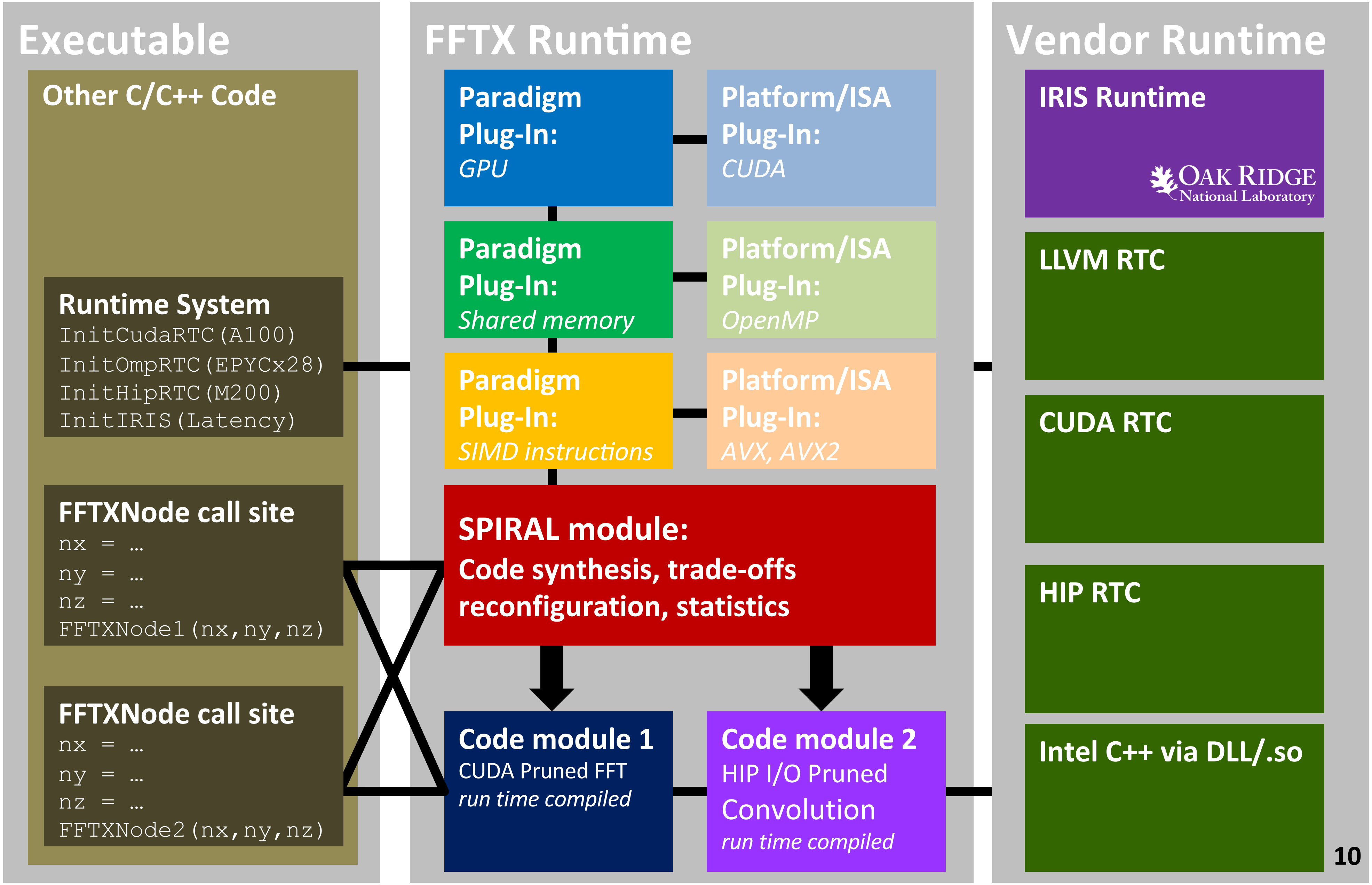
```
// main transform function encoded as integer table
transform = {Conv3D, 3, {4, 4, 4}, 3,
    { kernels[0], dim3(4, 3, 1), dim3(1, 1, 1), 1, DOUBLE_PX },
    { kernels[1], dim3(4, 3, 1), dim3(1, 1, 1), 0 },
    { kernels[2], dim3(4, 4, 1), dim3(1, 1, 1), 1, DOUBLE_PY }};
```

FFTX output for small SPIRAL interpreter

```
FFTXNode1.run(double  *Y, double  *X, double *sym) {
    // one-time JITs kernel, interprets and executes integer table
    compileAndExecute(transform, MODE_JIT_CACHE);
}
```

FFTXNode run() method invokes SPIRAL and RTC

# FFTX Runtime



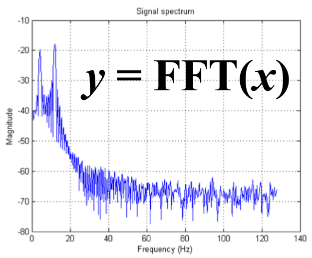
# SPIRAL: Go from Mathematics to Software

## Given:

- **Mathematical problem specification**
  *core mathematics does not change*
- **Target computer platform**
  *varies greatly, new platforms introduced often*

## Wanted:

- **Very good implementation of specification on platform**
- **Proof of correctness**




on


**automatic**

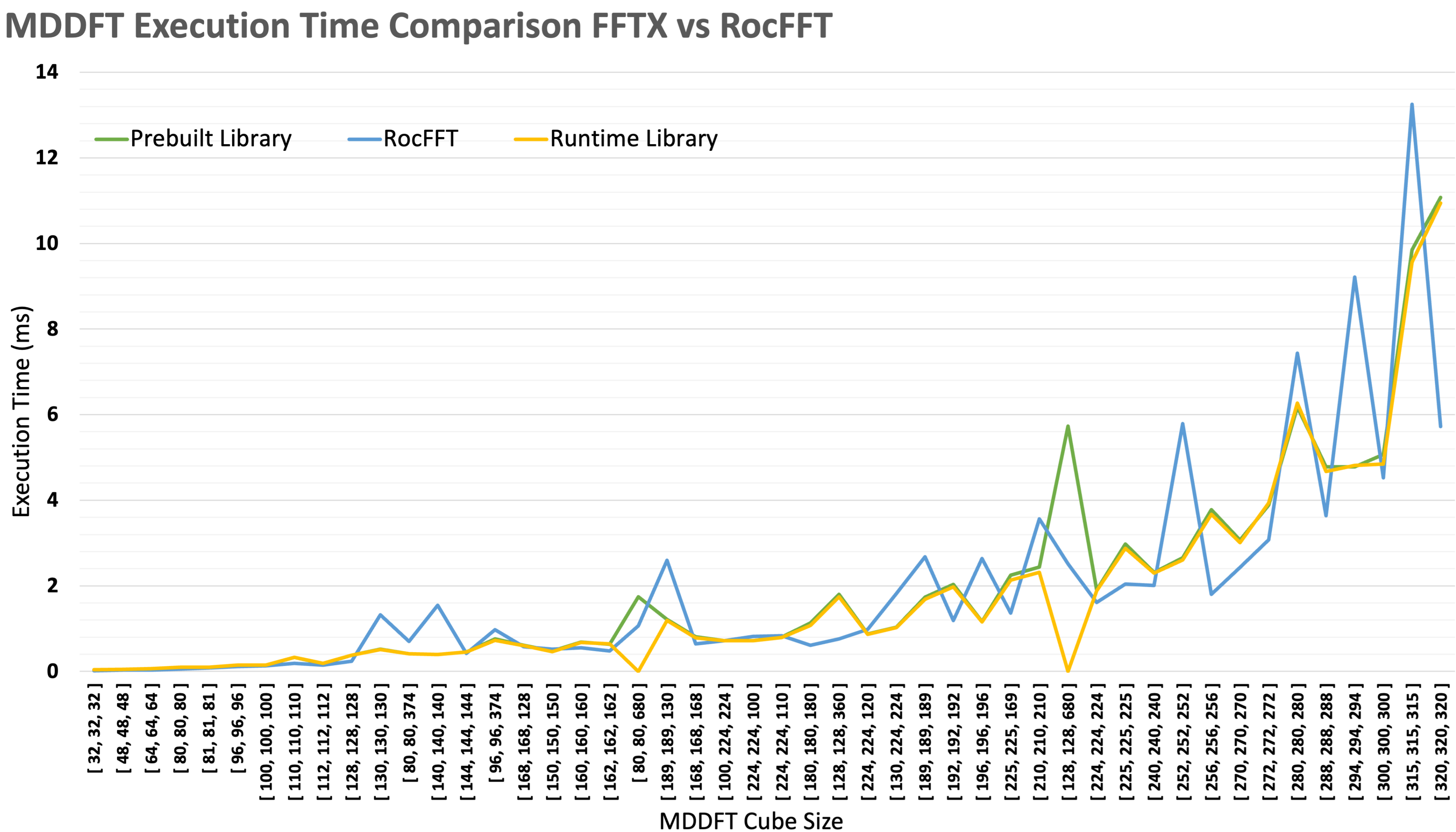
```
void fft64(double  *Y, double  *X) {
    ...
    s5674 = _mm256_permute2f128_pd(s5672, s5673, (0) | ((2) << 4));
    s5675 = _mm256_permute2f128_pd(s5672, s5673, (1) | ((3) << 4));
    s5676 = _mm256_unpacklo_pd(s5674, s5675);
    s5677 = _mm256_unpackhi_pd(s5674, s5675);
    s5678 = *((a3738 + 16));
    s5679 = *((a3738 + 17));
    s5680 = _mm256_permute2f128_pd(s5678, s5679, (0) | ((2) << 4));
    s5681 = _mm256_permute2f128_pd(s5678, s5679, (1) | ((3) << 4));
    s5682 = _mm256_unpacklo_pd(s5680, s5681);
    s5683 = _mm256_unpackhi_pd(s5680, s5681);
    t5735 = _mm256_add_pd(s5676, s5682);
    t5736 = _mm256_add_pd(s5677, s5683);
    t5737 = _mm256_add_pd(s5670, t5735);
    t5738 = _mm256_add_pd(s5671, t5736);
    t5739 = _mm256_sub_pd(s5670, _mm256_mul_pd(_mm_vbroadcast_sd(&(C22)), t5735));
    t5740 = _mm256_sub_pd(s5671, _mm256_mul_pd(_mm_vbroadcast_sd(&(C22)), t5736));
    t5741 = _mm256_mul_pd(_mm_vbroadcast_sd(&(C23)), _mm256_sub_pd(s5677, s5683));
    t5742 = _mm256_mul_pd(_mm_vbroadcast_sd(&(C23)), _mm256_sub_pd(s5676, s5682));
    ...
}
```


performance

+

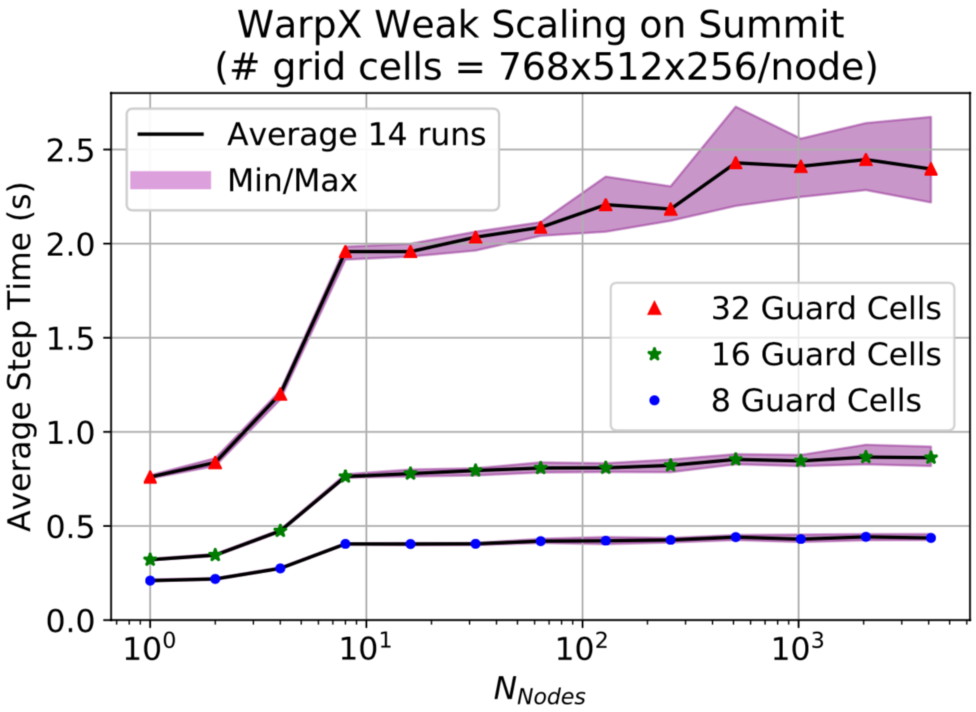

QED.

# FFTX Single Device Results on Frontier

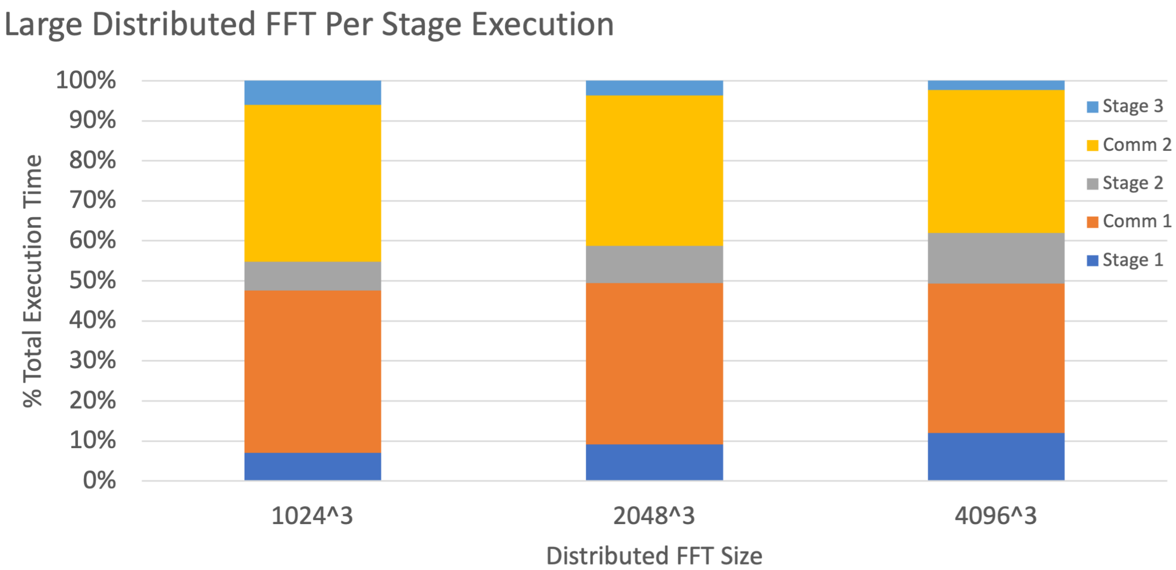



**FFTX is competitive with vendor libraries while having options of prebuilding or runtime compiling kernels**

# FFTX Distributed Results



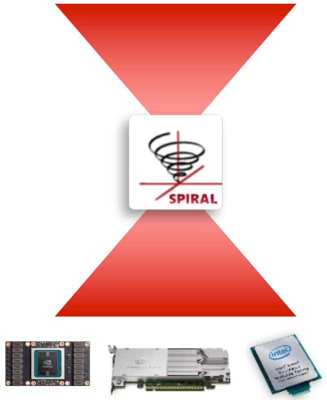

**FFTX integrated with WarpX running at scale**

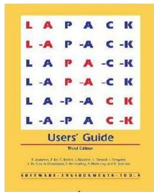


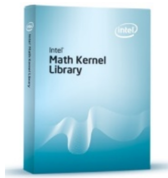

**Communication dominates local computation for large distributed FFTs**

# Proof of Concept: SnowWhite and LibraryX

## Multi-language, Multi target

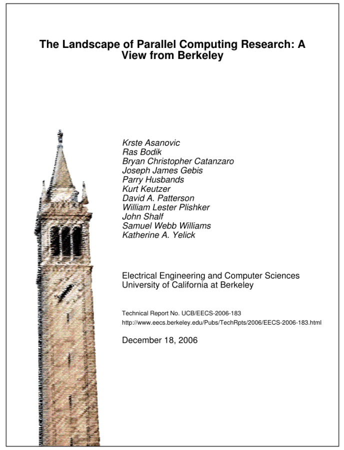



*Powered by SPIRAL*
*code generation/synthesis*

## Cross-"Dwarf" optimization


The Landscape of Parallel Computing Research: A View from Berkeley

Krste Asanovic
Ras Bodik
Bryan Christopher Catanzaro
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Parry Husbands
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William Lester Plishker
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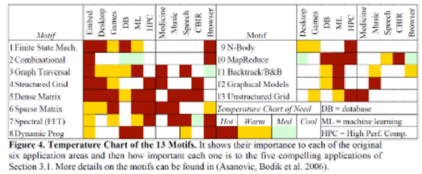
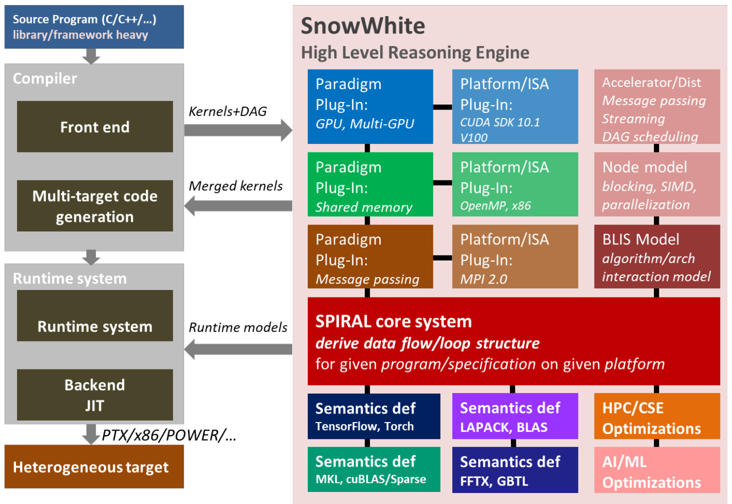
Technical Report No. UCB/EECS-2006-183
http://www.eecs.berkeley.edu/Pubs/TechRpts/2006/EECS-2006-183.html

December 18, 2006



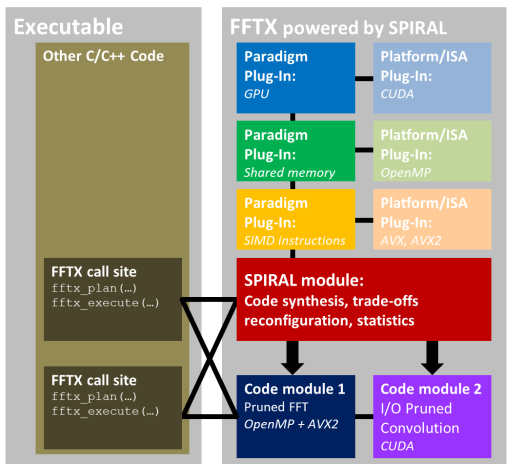
*Cross-call, cross-library, cross-motif*

## SnowWhite: SPIRAL inside compilers



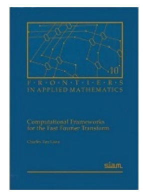

*DARPA PAPPA, X-Stack Bluestone*

## LibraryX, powered by SPIRAL





*GBTLX NTTX*



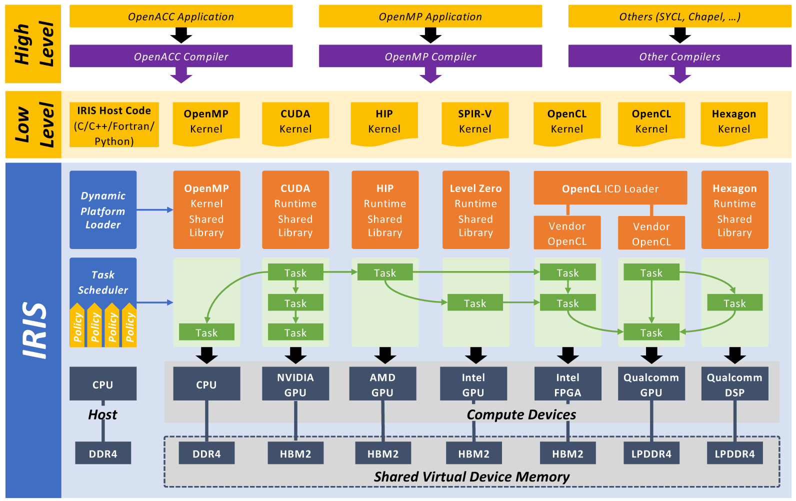
*FFTX (ECP)*

*Multiple active libraries, one infrastructure*

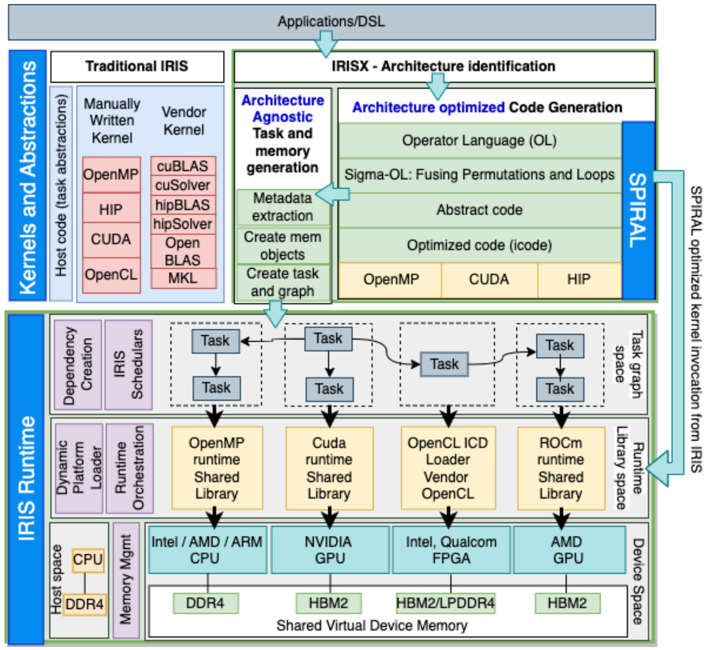
# Preview: IRISX

## Heterogenous Landscape

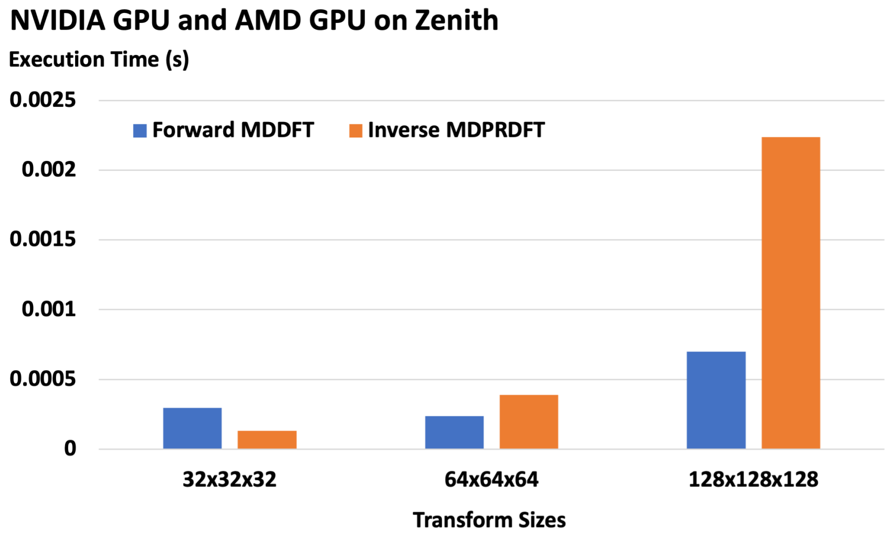
## IRIS: Intelligent Task Scheduling




## IRISX: LibraryX + IRIS




## Automatic Portability and Heterogeneity

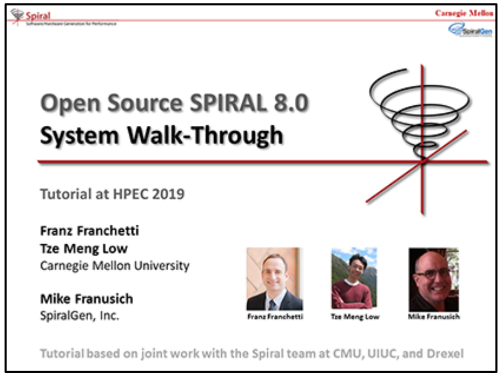


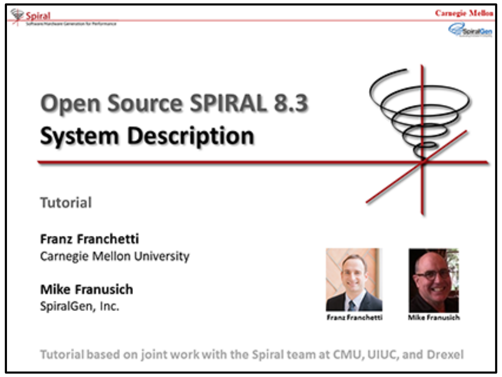

Sanil Rao, Mohammad Alaul Haque Monil, Het Mankad, Jeffrey Vetter, and Franz Franchetti. 2023. FFTX-IRIS: Towards Performance Portability and Heterogeneity for SPIRAL Generated Code. In Proceedings of the SC '23 Workshops of The International Conference on High Performance Computing, Network, Storage, and Analysis (SC-W '23).

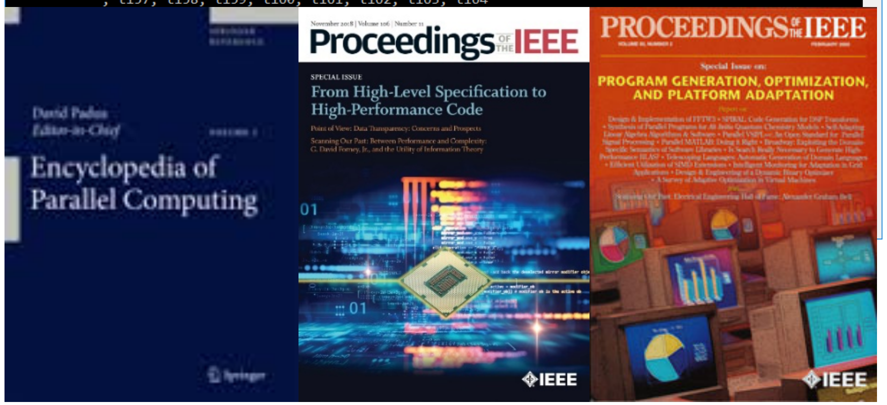
# SPIRAL 8.5.0: Available Under Open Source

- **Release of FFTX 1.0.0**
- **Open-Source SPIRAL available**
  - non-viral license (BSD)
  - Initial version, effort ongoing to open-source whole system
  - Commercial support via SpiralGen, Inc.


- **Tutorial material available online**




- **FFTX and SPIRAL available via GitHub**

| | | |
|---|---|---|
| spiral-software | 8.5.0-release | https://github.com/spiral-software/spiral-software |
| spiral-package-fftx | 1.1.0-release | https://github.com/spiral-software/spiral-package-fftx |
| spiral-package-simt | 1.1.0-release | https://github.com/spiral-software/spiral-package-simt |
| spiral-package-jit | 1.0.0-release | https://github.com/spiral-software/spiral-package-jit |
| FFTX | 1.0.0-release | https://github.com/spiral-software/fftx |