ProtoX: A First Look

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Problem

Stencil Operations: A key component in numerical solutions to partial differential equations (PDEs).

Proto: It is a domain specific library written in C++ that provides a high level of abstraction for solving PDEs using various numerical methods.

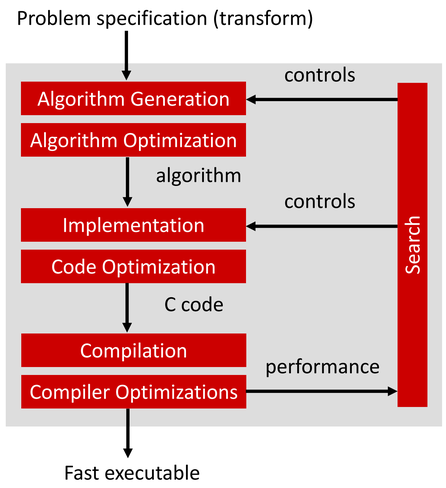
- **Shortcoming:** Abstraction fusion is something no compiler can easily perform.
- **Our Goal:** To interpret Proto as a Domain Specific Language with the help of SPIRAL [1],[2] and obtain better performance.

SPIRAL

Spiral:
Complete automation of the implementation and optimization task

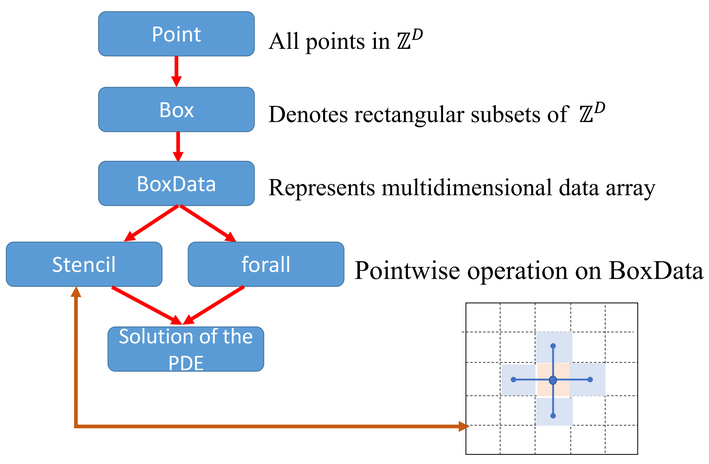
Basic idea:
Declarative representation of algorithms using the Operator Language (OL)

Rewriting systems to generate and optimize algorithms



Proto

Design layout and class structure in Proto



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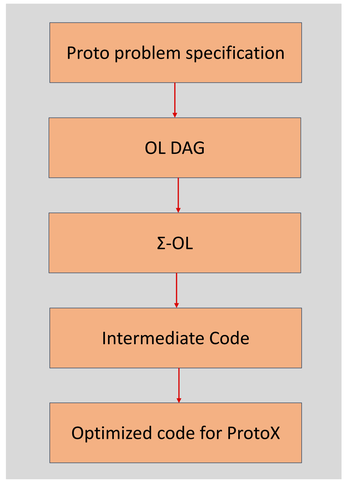
ProtoX

Proto Frontend:
Proto source library interpreted as an embedded DSL

SPIRAL Backend:
Proto dataflow fed into SPIRAL as OL. It is then broken down into loop based Σ-OL that is translated into optimized C++ source code.

ProtoX:
Optimized code linked into Proto code to be executed in place of original specification.



ProtoX: Example

2D Euler equations for Gas Dynamics

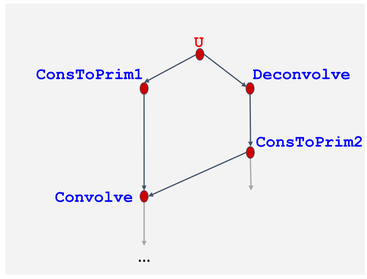
The 2D Euler equation used in gas dynamics takes the form of a conservation equation [3], $\frac{\partial U}{\partial t} + \nabla \cdot \vec{F}(U) = 0$, where

$$U_t = \begin{bmatrix} \rho \\ \rho u_x \\ \rho u_y \\ E \end{bmatrix}_t , \quad F(U)_x = \begin{bmatrix} \rho u_x \\ \rho u_x^2 + p \\ \rho u_x u_y \\ (E+p)u_x \end{bmatrix}_x , \quad F(U)_y = \begin{bmatrix} \rho u_y \\ \rho u_x u_y \\ \rho u_y^2 + p \\ (E+p)u_y \end{bmatrix}_y$$

and the total energy is $E = \frac{p}{\gamma - 1} + \frac{1}{2}\rho(u_x^2 + u_y^2)$.

DAG for the spatial discretization of 2D Euler equations

```
inline void operator()(
   BoxData<T, NUMCOMPS>&a_Rhs,
   std::array<BoxData<T,NUMCOMPS>, DIM>&
   a_fluxes,const BoxData<T, NUMCOMPS>&
   a_U, T a_scale = 1.0) const
   {  …
     Vector W_bar = forallOp<double,
       NUMCOMPS>(ctoprmnum, "consToPrim",
       f_consToPrim, a_U, gamma);
     Vector U = Operator::deconvolve(a_U);
     Vector W = forallOp<double,
       NUMCOMPS>(ctoprmnum, "consToPrim",
       f_consToPrim, U, gamma);
     Vector W_ave = Operator::_convolve(W,
       W_bar);
       …
   }
```



OL DAG in SPIRAL

$$\text{BoxOPEuler}_{n,\gamma} \rightarrow \cdots (\text{Convolve}_n) \circ (\text{I}_{4n^2} \oplus \text{ConsToPrim2}_{n,\gamma}) \circ \begin{bmatrix} \text{ConsToPrim1}_{n,\gamma} \\ \text{Deconvolve}_n \end{bmatrix} \circ \text{X}_{i \times n \times n}^{i=1,\cdots,4}$$

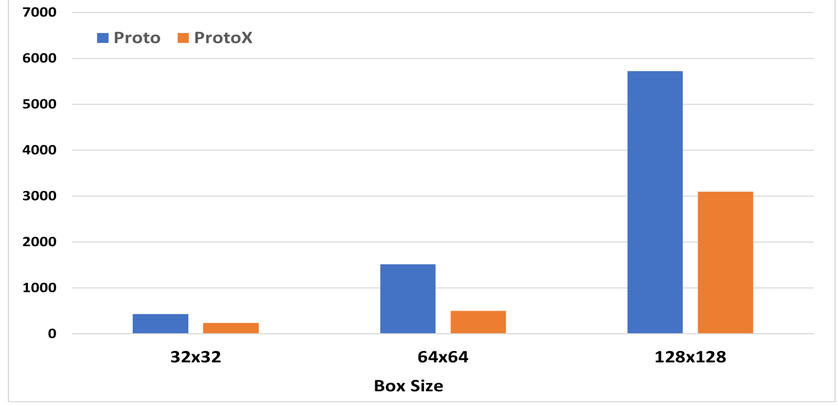
Σ − OL in SPIRAL

$$\left(\sum_{j=0}^{N-1} \text{S}_{r_j} \cdot \text{Convolve}_j \cdot \text{G}_{s_j}\right)\left(\left(\sum_{j=0}^{N-1} \text{S}_{p_j} \cdot \text{ConsToPrim1}_j \cdot \text{G}_{f \circ g}\right) \times \left(\sum_{j=0}^{N-1} \text{S}_{u_j} \text{ConsToPrim2}_j \cdot \text{Deconvolve}_j \text{G}_{g \circ f}\right)\right)$$

ProtoX Sample Fused Code

```
void full_eulerv3(double  *Y, const double  *X, double gamma1, double a_scale1, double dx1, double  *wavespeed, double  *retval1) {
  static double T1[12176];
  // ConsToPrim 1
  for(int i1 = 0; i1 <= 1599; i1++) {
    T1[i1] = X[i1];  T1[(i1 + 1600)]  = (X[(i1 + 1600)] / X[i1]);  T1[(i1 + 3200)]  = (X[(i1 + 3200)] / X[i1]); double a233 = (gamma1 - 1.0);
    double a234 = (0.5*a233);
    T1[(i1 + 4800)] = ((a233*X[(i1 + 4800)]) - (((0.5*a233)*((T1[(i1 + 1600)]*T1[(i1 + 1600)])*X[i1])) + ((0.5*a233)*((T1[(i1 + 3200)] *T1[(i1 +
     3200)])*X[i1])));
  }
  // Deconvolve +  ConsToPrim 2
  for(int i2 = 0; i2 <= 1443; i2++) {
    double a371, a372, s93, s94, s95, s96, s97, s98, t112;  nt b47 = ((40*(i2 / 38)) + (i2 % 38));
    s93 = X[(b47 + 41)]; s94 = X[(b47 + 1641)]; s95 = X[(b47 + 3241)]; s96 = X[(b47 + 4841)];
    t112 = (s93 - (0.041666666666666664*((X[(b47 + 1)] - (4.0*s93)) + X[(b47 + 40)] + X[(b47 + 42)] + X[(b47 + 81)])));
    T1[(i2 + 6400)] = t112;
    s97 = ((s94 - (0.041666666666666664*((X[(b47 + 1601)] - (4.0*s94)) + X[(b47 + 1640)] + X[(b47 + 1642)] + X[(b47 + 1681)]))) / t112);
    T1[(i2 + 7844)] = s97;
    s98 = ((s95 - (0.041666666666666664*((X[(b47 + 3201)] - (4.0*s95)) + X[(b47 + 3240)] + X[(b47 + 3242)] + X[(b47 + 3281)]))) / t112);
    T1[(i2 + 9288)] = s98;
    T1[(i2 + 10732)] = (((gamma1 - 1.0)*(s96 - (0.041666666666666664*((X[(b47 + 4801)] - (4.0*s96)) + X[(b47 + 4840)] + X[(b47 + 4842)] +
     X[(b47 + 4881)])))) - (((0.5*(gamma1 -  1.0))*((s97*s97)*t112)) + (a372*((s98*s98)*t112))));
  }
  // Convolve
  for(int i4 = 0; i4 <= 1443; i4++) {
    int b94 = ((40*(i4 / 38)) + (i4 % 38));
    T83[i4] = ((0.041666666666666664*((T1[(b94 + 1)] - (4.0*T1[(b94 + 41)])) + T1[(b94 + 40)] + T1[(b94 + 42)] + T1[(b94 + 81)])) + T1[(i4 +
     6400)]);
    T83[(i4 + 1444)] = ((0.041666666666666664*((T1[(b94 + 1601)] - (4.0*T1[(b94 + 1641)])) + T1[(b94 + 1640)] + T1[(b94 + 1642)] + T1[(b94
     + 1681)])) +  T1[(i4 + 7844)]);
    T83[(i4 + 2888)] = ((0.041666666666666664*((T1[(b94 + 3201)] - (4.0*T1[(b94 + 3241)])) + T1[(b94 + 3240)] + T1[(b94 + 3242)] + T1[(b94
     + 3281)])) +  T1[(i4 + 9288)]);
    T83[(i4 + 4332)] = ((0.041666666666666664*((T1[(b94 + 4801)] - (4.0*T1[(b94 + 4841)])) + T1[(b94 + 4840)] + T1[(b94 + 4842)] + T1[(b94
     + 4881)])) +  T1[(i4 + 10732)]);
    }
}
```

ProtoX optimized 2D Euler achieves up to **4x** performance improvement over the reference implementation



Conclusion & Future Work

- We demonstrate ProtoX, a system that interprets Proto as a Domain Specific Language using the 2D Euler equations as an example.
- Up to 4X improvement can be seen in the initial results. Efforts are being made for further optimization.
- The future goal is to add more targets and make ProtoX interoperable with FFTX [4] to do cross library optimization.

References

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[3]P. McCorquodale et. al., "A high order finite volume method for conservationlaws on locally refined grid" , Communications in Applied Mathematics and Computational Science, vol. 6, No.1, 2011
[4] F. Franchetti *et al.*, "FFTX and SpectralPack: A First Look," 2018 IEEE 25th International Conference on High Performance Computing Workshops, 2018, pp. 18-27