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FRANCE 2030
PROGRAMME DE RECHERCHE
NUMÉRIQUE POUR L'EXASCALE

Polyhedral Model for Kokkos Code Optimization

ExaSoft General Assembly 2024

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INRIA

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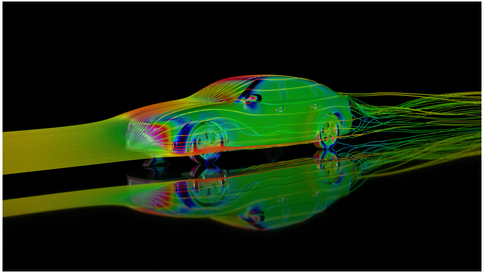
Context

Thèse

Thesis Topic: (starting 01/10/2023)
Disambiguation of C++ Complexity for Advanced Program Optimization and Parallelization.

- **Programme de recherche exploratoire (PEPR) Numérique pour l'exascale (NumPEx)**
  - **Work Package 1**
    Efficient and composable programming models.
  - **Work Package 2**
    Just-in-Time code optimization with continuous feedback loop.

Simulation code



- Complex code with multiple computational kernels and numerous nested loops
- Supercomputer with millions of multi-architecture cores

Changing Simulation Programming Language

With the evolution of programming paradigms and architectures, the **CEA** needs to modernize the language used to write simulation code.

- Transition from Fortran to C++.
- Need to replace old Fortran technologies.
- Need to provide developers with tools to easily program simulation codes in C++.

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A choice has been made to use the **Kokkos** library to provide a high-level abstraction of parallelism.

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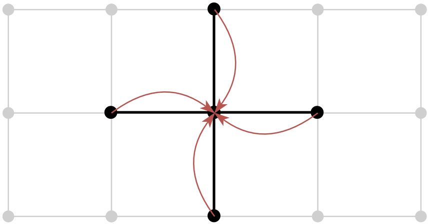
Kokkos

What is Kokkos ?

- Modern C++ template library
- Developed by the United States Department of Energy
- Abstraction of parallelism
- Performance portability across different architectures (CPU, GPU)

Kokkos: Stencil example C++ code



```
void stencil(float *A, float *B, long m, long n)
{
  for (int i = 1; i < m - 1; i++)
    for (int j = 1; j < n - 1; j++)
      B[i * n + j] = A[i * n + j] + A[i * n + (j - 1)] + A[i * n + (j + 1)] +
                     A[(i - 1) * n + j] + A[(i + 1) * n + j];
}
```

Listing 1: Native C++ code of stencil

Kokkos: Stencil example code

```
void stencil(Kokkos::View<float**> &A, Kokkos::View<float**> &B, long m, long n)
{
  const auto policy = Kokkos::MDRangePolicy<
                                    Kokkos::Serial,
                                    Kokkos::Rank<2>
                                            >({1, 1}, {m - 1, n - 1});

  Kokkos::parallel_for(policy, KOKKOS_LAMBDA(long i, long j) {
      B(i, j) = A(i, j) + A(i, j - 1) + A(i, j + 1) + A(i - 1, j) + A(i + 1, j);
    });
}
```

Listing 2: Kokkos code of stencil

Kokkos optimizations

- **Performance optimization**:
  - Manual structure of code optimizations (linear array, tilling).
  - Preprocessor macros can be used to enable optimizations.
- **Performance portability**:
  - Kokkos provides a high-level abstraction of parallelism.
  - Code written with Kokkos can be executed on different architectures.

Objectives

The main objective is:

- Understand the structure of Kokkos codes.
- Propose a transparent solution to the user to optimize the code.
- Evaluate the performance of the proposed solution.

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- Natural loops with constant lower/upper bounds and a regular iteration space.

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To do this, we will use the **Polyhedral Model** to optimize the code.

Polyhedral Model

What is the Polyhedral Model?

- A mathematical representation of loop nests in a program using polyhedra within a multidimensional space.
- Enables linear transformations of loops to optimize memory access, reduce dependencies, reorganize instructions, cache locality, vectorization, loop tilling and identify parallelism opportunities.

Constraints for Applying the Polyhedral Model

- **Static Control Parts (SCoPs)**:
  - Code must be composed of regions where control flow is statically predictable.

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  - Avoid irregular control flow constructs like `goto` statements or early exits.

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- **Single Entry and Exit Points**
- **No Irregular Control Flow**
  - Avoid irregular control flow constructs like `goto` statements or early exits.
- **Data Dependence Analysis**:
  - Code should allow for clear determination of read and write accesses to memory locations.

Polyhedral Model Example

Visual representation of a polyhedral transformation:

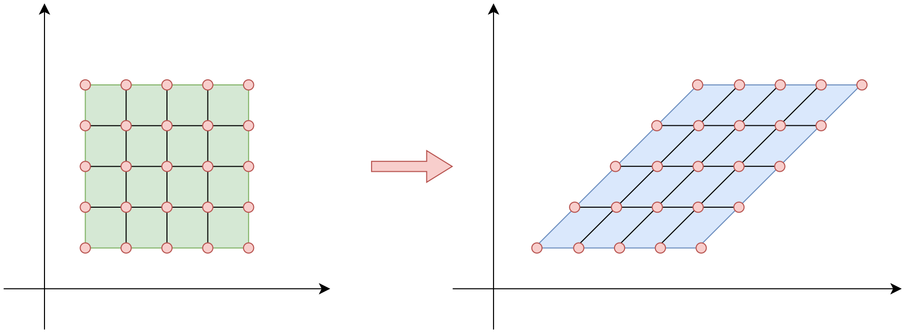

Figure 1: Polyhedral representation of a skewing transformation

Polyhedral Model Example

```c
for (int i = 1; i < n - 1; i++)
  for (int j = 1; j < m - 1; j++)
    A[i][j] = A[i][j] + A[i + 1][j] + A[i][j + 1];
```

Listing 3: Stencil before transformation

Polyhedral Model Example

```c
for (int i = 1; i < n - 1; i++)
  for (int j = 1; j < m - 1; j++)
    A[i][j] = A[i][j] + A[i + 1][j] + A[i][j + 1];
```

Listing 5: Stencil before transformation

```c
for (int i = 0; i <= n + m - 2; i++) {
  int lbj = max(0, i - n + 1);
  int ubj = min(i, m - 1);
  #pragma omp parallel for
  for (int j = lbj; j <= ubj; j++)
    A[(i - j)][j] = A[(i - j)][j] + A[(i - j)][j + 1] + A[(i - j) + 1][j];
}
```

Listing 6: Stencil after transformation

Several Polyhedral Tools

- **Polly**:
  - An LLVM project that provides a polyhedral optimizer for LLVM.
  - Transforms loop nests in LLVM intermediate representation (IR) to optimize performance.

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- **Pluto**:
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  - Transforms loop nests in C code to optimize performance.
- **Apollo**:
  - A runtime polyhedral optimizer.
  - Transforms loop nests based on runtime behavior.

Constraints of Kokkos Codes

Application of the Polyhedral Model on Kokkos Codes:

- Regular "perfect" loops for the application of the polyhedral model.
- Code already parallelized.
- C++ too complex for the source code to be analyzed.
- Complexity of the analysis due to the complexity of the generated code.
- Targets different architectures.

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Currently no tools are able to apply the polyhedral model to Kokkos codes.

Why polly ?

- Analyzes and optimizes loop nests directly in LLVM intermediate representation.
- Disambiguation of the C++ complexity.
- Simple to use, directly integrated in LLVM.
- Provides a set of optimization options to transform loop nests.

Current work

Polly modifications

- Manual search of SCoPs
- Interprocedural analysis to extend and inline functions in order to maximize the size of SCoPs.

Kokkos modifications

Polly's modifications is not enough we need to modify Kokkos:

- Modification of the user API to allow the addition of an option to give the user the choice to use instrumentation for Polly.
- Rewriting of the Serial backend to have clean loops (remove tiles).

Kokkos modifications

```
void stencil(Kokkos::View<float**> &A, Kokkos::View<float**> &B, long m, long n)
{
  const auto policy = Kokkos::MDRangePolicy<
                                           Kokkos::Serial,
                                           Kokkos::Rank<2>
                                                   >({1, 1}, {m - 1, n - 1});

  Kokkos::parallel_for<Kokkos::usePolyOpt>(policy, KOKKOS_LAMBDA(long i, long j) {
      B(i, j) = A(i, j) + A(i, j - 1) + A(i, j + 1) + A(i - 1, j) + A(i + 1, j);
    });
}
```

Listing 7: Kokkos code of stencil with modification

Current work

- Currently no results.
- Only applicable on Serial Kokkos backend.
- The SCoPs search still depends on code generation.

Questions?