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A Cooperative Compiler and Runtime Checkpoint/Restart Approach for Kokkos

SIAM-PP'22, MS-38

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MOTIVATION

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Performance Portability

- Write one implementation that
  - can run on multiple platforms
  - can enable suitable memory access patterns for different platforms
  - can exploit platform-specific features
- Examples:
  - Kokkos
  - RAJA
  - DPC++

Kokkos

- What's Kokkos?
  - Kokkos enables single performance portable codes
    - ✓ CPUs, NVIDIA GPUs, …
  - Kokkos provides data abstractions critical for performance portability not available in OpenMP or OpenACC (Kokkos::View)
  - Essential parallel constructs
    - ✓ Kokkos::parallel_for();
    - ✓ Kokkos::parallel_reduce();
    - ✓ Kokkos::parallel_scan();

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Kokkos Example

```
1  View<int*> x("x", N);                              // Constuct a View (length: N)
2  // Parallel For
3  parallel_for(RangePolicy<>(0, N),                  // 1D Range (0 to N)
4               [=] (int i) {                         // C++11 lambda
5                 x(i) = i;                           // Computational Body
6               });
7
8  int result = 0;
9  // Parallel Reduce
10 parallel_reduce(RangePolicy<>(0, N),               // 1D Range (0 to N)
11                 [=] (int i, int &update) {         // C++11 lambda
12                   update += x(i);                  // Computational Body
13                 }, result);                        // Value to update
14 std::cout << result << std::endl;
```

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Enabling Resiliency in Performance Portable Programs

- Why important?
  - Increasing the number of nodes from 10,000 to 22,000 increases the probability of failures by a factor of 20x on the Blue Waters System [1]
- Typical approach: Manual checkpointing
  - e.g., for Kokkos [2]
- Research question: Any way to automate it?

[1] Martino et al. “Measuring and Understanding Extreme-Scale Application Resilience: A Field Study of 5,000,000 HPC Application Runs” (DSN’15)

[2] Morales et al. “Towards High Performance Resilience Using Performance Portable Abstractions” (Euro-Par’21)

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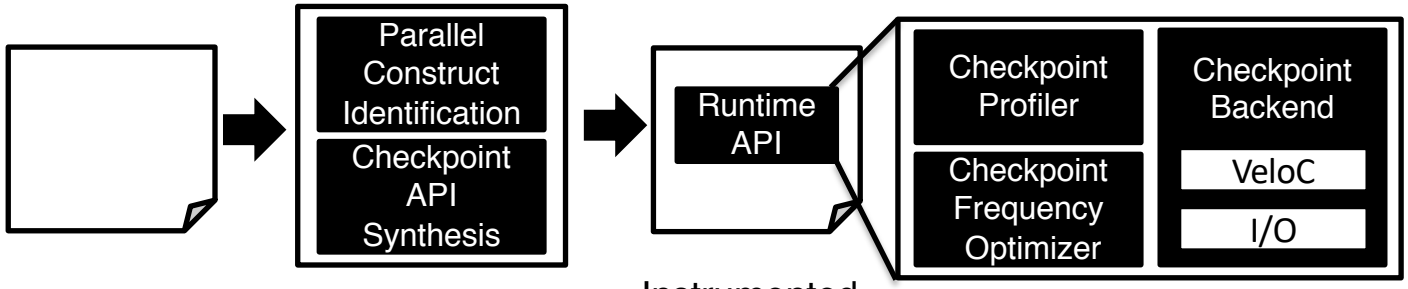
Big picture



- We propose:
  - a source-to-source compiler that analyzes Kokkos programs and automatically generates Checkpoint/restart API
  - a runtime provides
    - ✓ 1) platform-independent Checkpoint/restart API routines
    - ✓ 2) optimizes the frequency of checkpointing when possible

Cooperate

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Related Work

	Language	IR	Note
Elkhouly et al.	Sequential C + directive on data access	LLVM IR	Sequential
Bronevetsky et al.	OpenMP C	ROSE	OpenMP
Lehr et al.	MPI + C	LLVM IR	Type Safe Checking Only
Shahneous et al.	OpenSHMEM	LLVM IR	Suggestion Only
Our Approach	Kokkos (C++)	Clang AST	Full translation

Note: compilers are typically used to perform selective instruction duplication (SID) e.g., Swift

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Related work (Cont'd)

- clang-tidy for Kokkos (not for resilience)

```
$ clang-tidy kokkos-implicit-this-capture.cpp -checks=-\*,kokkos\* -- -
I$PWD/Inputs/kokkos
…
warning: Lambda passed to parallel_for implicitly captures this. [kokkos-
implicit-this-capture]
        10, KOKKOS_LAMBDA(int x) { my_int = x; });
```

https://github.com/kokkos/llvm-project/tree/master/
https://github.com/kokkos/llvm-project/tree/master/clang-tools-extra/clang-tidy/kokkos

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DESIGN

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High-level Overview (lambda)

Original Code

```
1  Kokkos::View<int*> A(“A”, N);
2  Kokkos::View<int*> B(“B”, N);
3  for (int t = 0; t < T; t++) {
4    Kokkos::parallel_for(”modA”,
5    N, KOKKOS_LAMBDA (int i) {
6      A(i) = B(i);
7    });
8    …
9  }
```

Translated

```
1  Kokkos::View<int*> A(“A”, N);
2  Kokkos::View<int*> B(“B”, N);
3  loop_enter();
4  for (int t = 0; t < T; t++) {
5    loop_start(t);
6    Kokkos::parallel_for(”modA”,
7    N, KOKKOS_LAMBDA (int i) {
8      A(i) = B(i);
9    });
10   checkpoint(A);
11   …
12   loop_end(t);
13 }
14 loop_exit();
```

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High-level Overview (functor)

Original Code

```
1  Kokkos::View<int*> A("A", N);
2  Kokkos::View<int*> B("B", N);
3  for (int t = 0; t < T; t++) {
4    Functor functor(A, B);
5    Kokkos::parallel_for("modA",
6    N, functor);
7  …
8  }
```

```
struct Functor {
 void operator ()(const size_t i)
 const {
      A(idx) = B(idx);
 }
 // synthesized by translator
 void checkpoint() { checkpoint(A); }
};
```

Translated

```
1  Kokkos::View<int*> A("A", N);
2  Kokkos::View<int*> B("B", N);
3  loop_enter();
4  for (int t = 0; t < T; t++) {
5    loop_start(t);
6    Functor functor(A, B);
7    Kokkos::parallel_for("modA",
8    N, functor);
9    functor.checkpoint(A);
10   …
11   loop_end(t);
12 }
13 loop_exit();
```

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Compiler

- Open question: How to analyze C++ program?
  - LLVM IR-based
    - ✓ Pros: Lots of analyzer and optimizer passes
    - ✓ Cons: It's very hard to locate the start/end of a specific function
  - Clang AST-based (Our approach)
    - ✓ Pros: it's relatively easy to locate the start/end of a specific function
    - ✓ Cons: its analyzers/optimizers would not be as powerful as LLVM's ones

```
// ClangAST
LambdaExpr … '(lambda at test.cpp:55:40)'
| …
| - CompoundStmt …
      BinaryOperator … int' lvalue '='
      | -CXXoperatorCallExpr … 'int' lvalue '()'
      | | …
      | | -DeclRefExpr … 'const Kokkos::View<int *>' … 'A'
…
```

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Compiler (Cont'd)

- Checkpoint API insertion
  1. Identify Kokkos constructs in user's program
     - ✓ Kokkos::parallel_for, reduce, scan
  2. Analyze the body of a lambda expression/the parenthesis operator and identify which View is used
  3. Insert checkpoint API immediately after Kokkos::parallel_for
     - ✓ Optimization: do not checkpoint a View that is read-only
- Loop API Insertion
  - Insert loop_enter(), loop_start(), loop_end(), loop_exit() to all for-loops

Note: the current implementation performs the above actions for each lambda and it does not do any data flow analyses to analyze the lifetime of Views.

How robust is the compiler?

- Our compiler is able to translate 9 Kokkos applications including 3 real-world applications

Benchmark Suite	Benchmark
N/A	Heat-Dist, NimbleSM
Polybench MPI (stencil)	Jacobi-1D/2D, Heat-3D, Fdtd-2D, Seidel-2D
Mantevo	miniAero/miniFE

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CAC Runtime

- Provides a generic checkpoint/restart API independent of datatype and checkpoint runtime
  - Uses Kokkos::ViewHolderBase for de-templating Views but keeping memory information
    - ✓ Kokkos::View<int*>, Kokkos::View<double*>, …
  - Keeps format of Resilient Kokkos [1] configuration file to enable changing checkpoint backends without application code changes
    - ✓ VeloC, StdFile, …

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[1] Morales et al. “Towards High Performance Resilience Using Performance Portable Abstractions” (Euro-Par’21)

CAC Runtime (Cont'd)

- Gathers checkpoint regions within loops for write aggregations
- Automatically updates loop iteration variables after recovery
- Dynamically optimizes checkpoint frequency
  - User provides estimated MTBF
  - Calculates time-weighted average checkpoint cost

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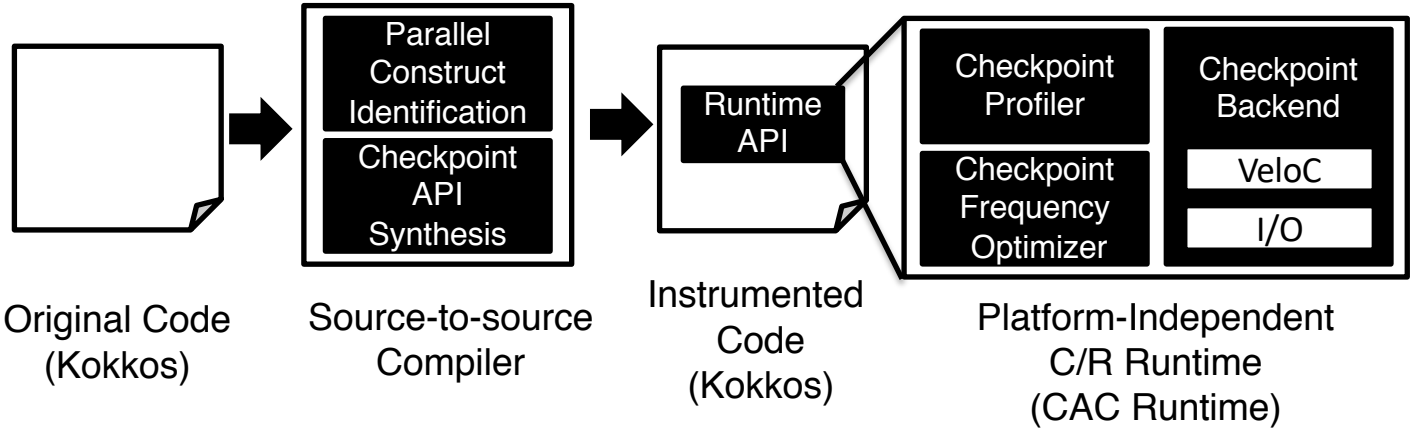
IMPLEMENTATION

Implementation



- Compiler: implemented as a Clang's tool (executable)
- Runtime: a standalone library which depends on
  - Kokkos-Resilience (Proprietary)
  - VeloC: https://veloc.readthedocs.io/en/latest/

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PRELIMINARY EVALUATIONS

Applications

- Platform:
  - Sandia Machine: Kahuna
    - ✓ a dual socket intel E5-2683v3 2.00GHz CPU (28 cores)
    - ✓ High memory data-analytics machine (256GB)
    - ✓ 56GB/s FDR Infiniband network
    - ✓ CephFS distributed filesystem
- Application: Heat-distribution (MPI+Kokkos)
  - 4-points iterative stencil kernel
  - Variants:
    - ✓ Raw VeloC
    - ✓ Auto-translated by the compiler + CACRuntime

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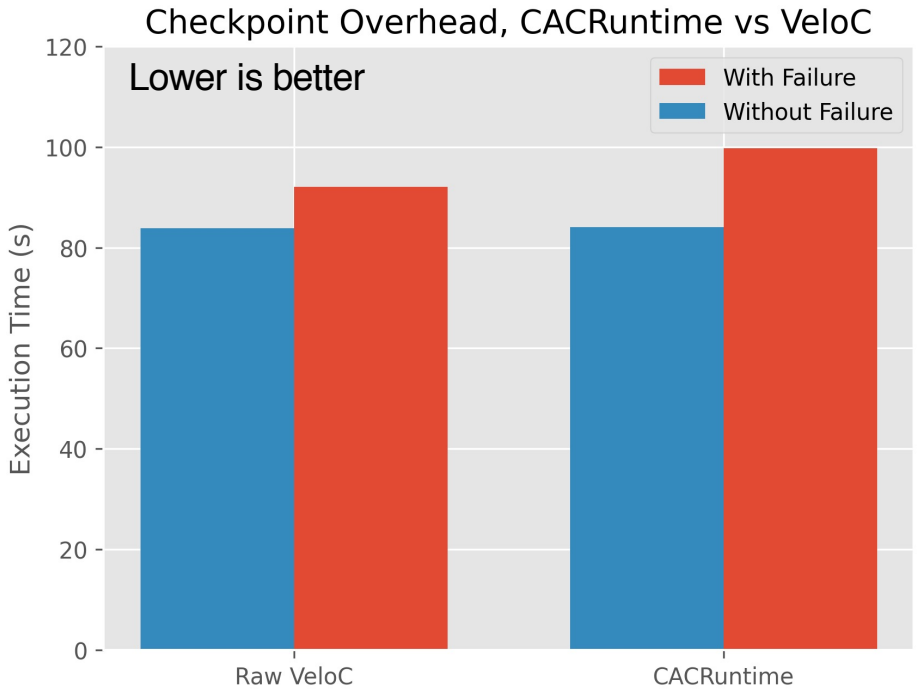
Heat-distribution

- Parameters
  - 8 nodes
    - ✓256MB checkpoint per node
  - 6 Checkpoints per (non-failing) run
- Contrived MTTF
  - On the order of seconds

Heat-distribution Results



- CACRuntime
  - Very similar to the baseline without failures
  - Some more overhead in recovery
    - ✓ Doesn't know to skip restoring initialization views
    - ✓ Checkpoints an additional time after recovery
  - Our version checkpoints as frequently as the raw version after frequency optimization
  - Our version does not require any manual checkpointing

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CONCLUSIONS

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Conclusions

- Introduced A Cooperative Compiler and Runtime Checkpoint/Restart Approach for Kokkos
  - Compiler automatically generates checkpoint/restart API
    - ✓ robust enough to translate 9 Kokkos+MPI applications
  - Runtime automatically
    - ✓ performs write aggregation
    - ✓ optimizes the frequency of checkpointing
    - ✓ updates loop iteration variables after recovery

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Future Work

- Evaluate other applications
  - An MPI version of Polybench
  - Mantevo
  - NimbleSM
- Compare our approach with Kokkos-Resilience [1]
- Enhance the CACRuntime
  - Asynchronous Checkpointing
  - Runtime Alias Checking
- Use GPUs

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[1] Morales et al. “Towards High Performance Resilience Using Performance Portable Abstractions” (Euro-Par’21)