Ginkgo

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Contents

Chapter 1

Main Page

This is the main page for the Ginkgo library pdf documentation. The repository is hosted on `github`. Documentation on aspects such as the build system, can be found at the Installation Instructions page. The Example programs can help you get started with using Ginkgo.

Modules

The Ginkgo library can be grouped into `modules` and these modules form the basic building blocks of Ginkgo. The modules can be summarized as follows:

- Executors : Where do you want your code to be executed ?
- Linear Operators : What kind of operation do you want Ginkgo to perform ?
  - Solvers : Solve a linear system for a given matrix.
  - Preconditioners : Precondition a system for a solve.
  - SpMV employing different Matrix formats : Perform a sparse matrix vector multiplication with a particular matrix format.
- Logging : Monitor your code execution.
- Stopping criteria : Manage your iteration stopping criteria.

Chapter 2

Installation Instructions

Building

Use the standard cmake build procedure:

```
mkdir build; cd build
cmake -G "Unix Makefiles" [OPTIONS] .. && make
```

Replace `[OPTIONS]` with desired cmake options for your build. Ginkgo adds the following additional switches to control what is being built:

- `-DGINKGO_DEVEL_TOOLS={ON, OFF}` sets up the build system for development (requires clang-format, will also download git-cmake-format), default is `ON`
- `-DGINKGO_BUILD_TESTS={ON, OFF}` builds Ginkgo's tests (will download googletest), default is `ON`
- `-DGINKGO_BUILD_BENCHMARKS={ON, OFF}` builds Ginkgo's benchmarks (will download gflags and rapidjson), default is `ON`
- `-DGINKGO_BUILD_EXAMPLES={ON, OFF}` builds Ginkgo's examples, default is `ON`
- `-DGINKGO_BUILD_EXTLIB_EXAMPLE={ON, OFF}` builds the interfacing example with deal.II, default is `OFF`
- `-DGINKGO_BUILD_REFERENCE={ON, OFF}` build reference implementations of the kernels, useful for testing, default is `ON`
- `-DGINKGO_BUILD_OMP={ON, OFF}` builds optimized OpenMP versions of the kernels, default is `OFF`
- `-DGINKGO_BUILD_CUDA={ON, OFF}` builds optimized cuda versions of the kernels (requires CUDA), default is `OFF`
- `-DGINKGO_BUILD_DOC={ON, OFF}` creates an HTML version of Ginkgo's documentation from inline comments in the code. The default is `OFF`.
- `-DGINKGO_DOC_GENERATE_EXAMPLES={ON, OFF}` generates the documentation of examples in Ginkgo. The default is `ON`.
- `-DGINKGO_DOC_GENERATE_PDF={ON, OFF}` generates a PDF version of Ginkgo's documentation from inline comments in the code. The default is `OFF`.
- `-DGINKGO_DOC_GENERATE_DEV={ON, OFF}` generates the developer version of Ginkgo's documentation. The default is `OFF`.

- -DGINKGO_EXPORT_BUILD_DIR={ON, OFF} adds the Ginkgo build directory to the CMake package registry. The default is OFF.
- -DGINKGO_WITH_CLANG_TIDY={ON, OFF} makes Ginkgo call clang-tidy to find programming issues. The path can be manually controlled with the CMake variable -DGINKGO_CLANG_TIDY_PATH=<path>.
- -DGINKGO_WITH_IWYU={ON, OFF} makes Ginkgo call iwyu to find include issues. The path can be manually controlled with the CMake variable -DGINKGO_IWYU_PATH=<path>.
- -DGINKGO_VERBOSE_LEVEL=integer sets the verbosity of Ginkgo.
  - 0 disables all output in the main libraries,
  - 1 enables a few important messages related to unexpected behavior (default).
- -DCMAKE_INSTALL_PREFIX=path sets the installation path for make install. The default value is usually something like /usr/local
- -DCMAKE_BUILD_TYPE=type specifies which configuration will be used for this build of Ginkgo. The default is RELEASE. Supported values are CMake's standard build types such as DEBUG and RELEASE and the Ginkgo specific COVERAGE, ASAN (AddressSanitizer) and TSAN (ThreadSanitizer) types.
- -DBUILD_SHARED_LIBS={ON, OFF} builds ginkgo as shared libraries (OFF) or as dynamic libraries (ON), default is ON
- -DGINKGO_JACOBI_FULL_OPTIMIZATIONS={ON, OFF} use all the optimizations for the CUDA Jacobi algorithm. OFF by default. Setting this option to ON may lead to very slow compile time (>20 minutes) for the jacobi_generate_kernels.cu file and high memory usage.
- -DCMAKE_CUDA_HOST_COMPILER=path instructs the build system to explicitly set CUDA's host compiler to the path given as argument. By default, CUDA uses its toolchain's host compiler. Setting this option may help if you're experiencing linking errors due to ABI incompatibilities. This option is supported since CMake 3.8 but documented starting from 3.10.
- -DGINKGO_CUDA_ARCHITECTURES=<list> where <list> is a semicolon (;) separated list of architectures. Supported values are:
  - Auto
  - Kepler, Maxwell, Pascal, Volta
  - CODE, CODE(COMPUTE), (COMPUTE)

  Auto will automatically detect the present CUDA-enabled GPU architectures in the system. Kepler, Maxwell, Pascal and Volta will add flags for all architectures of that particular NVIDIA GPU generation. COMPUTE and CODE are placeholders that should be replaced with compute and code numbers (e.g. for compute_70 and sm_70 COMPUTE and CODE should be replaced with 70. Default is Auto. For a more detailed explanation of this option see the ARCHITECTURES specification list section in the documentation of the CudaArchitectureSelector CMake module.

For example, to build everything (in debug mode), use:

```
cmake  -G "Unix Makefiles" -H. -BDebug -DCMAKE_BUILD_TYPE=Debug -DGINKGO_DEVEL_TOOLS=ON \
              -DGINKGO_BUILD_TESTS=ON -DGINKGO_BUILD_REFERENCE=ON -DGINKGO_BUILD_OMP=ON \
              -DGINKGO_BUILD_CUDA=ON
cmake --build Debug
```

NOTE: Ginkgo is known to work with the Unix Makefiles and Ninja based generators. Other CMake generators are untested.

Third party libraries and packages

Ginkgo relies on third party packages in different cases. These third party packages can be turned off by disabling the relevant options.

- GINKGO_BUILD_CUDA=ON: `CudaArchitectureSelector` (CAS) is a CMake helper to manage C↩ UDA architecture settings;
- GINKGO_BUILD_TESTS=ON: Our tests are implemented with `Google Test`;
- GINKGO_BUILD_BENCHMARKS=ON: For argument management we use `gflags` and for JSON parsing we use `RapidJSON`;
- GINKGO_DEVEL_TOOLS=ON: `git-cmake-format` is our CMake helper for code formatting.

By default, Ginkgo uses the internal version of each package. For each of the packages `GTEST`, `GFLAGS`, `R↩ APIDJSON` and `CAS`, it is possible to force Ginkgo to try to use an external version of a package. For this, Ginkgo provides two ways to find packages. To rely on the CMake `find_package` command, use the CMake option `-DGINKGO_USE_EXTERNAL_<package>=ON`. Note that, if the external packages were not installed to the default location, the CMake option `-DCMAKE_PREFIX_PATH=<path-list>` needs to be set to the semicolon (`;`) separated list of install paths of these external packages. For more Information, see the `CMake documentation for CMAKE_PREFIX_PATH` for details.

To manually configure the paths Ginkgo relies on the `standard xSDK Installation policies` for all packages except `CAS` (as it is neither a library nor a header, it cannot be expressed through the `TPL` format):

- `-DTPL_ENABLE_<package>=ON`
- `-DTPL_<package>_LIBRARIES=/path/to/libraries.{so|a}`
- `-DTPL_<package>_INCLUDE_DIRS=/path/to/header/directory`

When applicable (e.g. for `GTest` libraries), a `;` separated list can be given to the `TPL_<package>_{LIBR↩ ARIES|INCLUDE_DIRS}` variables.

Installing Ginkgo

To install Ginkgo into the specified folder, execute the following command in the build folder

```
make install
```

If the installation prefix (see `CMAKE_INSTALL_PREFIX`) is not writable for your user, e.g. when installing Ginkgo system-wide, it might be necessary to prefix the call with `sudo`.

After the installation, CMake can find ginkgo with `find_package(Ginkgo)`. An example can be found in the `test_install`.

Chapter 3

Testing Instructions

Running the unit tests

You need to compile ginkgo with `-DGINKGO_BUILD_TESTS=ON` option to be able to run the tests.

Using make test

After configuring Ginkgo, use the following command inside the build folder to run all tests:

```
make test
```

The output should contain several lines of the form:

```
    Start  1: path/to/test
1/13 Test  #1: path/to/test .............................   Passed    0.01 sec
```

To run only a specific test and see more details results (e.g. if a test failed) run the following from the build folder:

```
./path/to/test
```

where `path/to/test` is the path returned by `make test`.

Using CTest

The tests can also be ran through CTest from the command line, for example when in a configured build directory:

```
ctest -T start -T build -T test -T submit
```

Will start a new test campaign (usually in `Experimental` mode), build Ginkgo with the set configuration, run the tests and submit the results to our CDash dashboard.

Another option is to use Ginkgo's CTest script which is configured to build Ginkgo with default settings, runs the tests and submits the test to our CDash dashboard automatically.

To run the script, use the following command:

```
ctest -S cmake/CTestScript.cmake
```

The default settings are for our own CI system. Feel free to configure the script before launching it through variables or by directly changing its values. A documentation can be found in the script itself.

Chapter 4

Running the benchmarks

In addition to the unit tests designed to verify correctness, Ginkgo also includes a benchmark suite for checking its performance on the system. To compile the benchmarks, the flag `-DGINKGO_BUILD_BENCHMARKS=ON` has to be set during the `cmake` step. In addition, the `ssget command-line utility` has to be installed on the system.

The benchmark suite tests Ginkgo's performance using the `SuiteSparse matrix collection` and artificially generated matrices. The suite sparse collection will be downloaded automatically when the benchmarks are run. Please note that the entire collection requires roughly 100GB of disk storage in its compressed format, and roughly 25GB of additional disk space for intermediate data (such us uncompressing the archive). Additionally, the benchmark runs usually take a long time (SpMV benchmarks on the complete collection take roughly 24h using the K20 GPU), and will stress the system.

The benchmark suite is invoked using the `make benchmark` command in the build directory. The behavior of the suite can be modified using environment variables. Assuming the `bash` shell is used, these can either be specified via the `export` command to persist between multiple runs:

```
export VARIABLE="value"
...
make benchmark
```

or specified on the fly, on the same line as the `make benchmark` command:

```
env VARIABLE="value" ... make benchmark
```

Since `make` sets any variables passed to it as temporary environment variables, the following shorthand can also be used:

```
make benchmark VARIABLE="value" ...
```

A combination of the above approaches is also possible (e.g. it may be useful to `export` the `SYSTEM_NAME` variable, and specify the others at every benchmark run).

Supported environment variables are described in the following list:

- `BENCHMARK={spmv, solver, preconditioner}` - The benchmark set to run. Default is `spmv`.
  - `spmv` - Runs the sparse matrix-vector product benchmarks on the SuiteSparse collection.

  - `solver` - Runs the solver benchmarks on the SuiteSparse collection. The matrix format is determined by running the `spmv` benchmarks first, and using the fastest format determined by that benchmark. The maximum number of iterations for the iterative solvers is set to 10,000 and the requested residual reduction factor to 1e-6.
  - `preconditioner` - Runs the preconditioner benchmarks on artificially generated block-diagonal matrices.

- `DRY_RUN={true, false}` - If set to `true`, prepares the system for the benchmark runs (downloads the collections, creates the result structure, etc.) and outputs the list of commands that would normally be run, but does not run the benchmarks themselves. Default is `false`.
- `EXECUTOR={reference,cuda,omp}` - The executor used for running the benchmarks. Default is `cuda`.
- `SEGMENTS=<N>` - Splits the benchmark suite into <N> segments. This option is useful for running the benchmarks on an HPC system with a batch scheduler, as it enables partitioning of the benchmark suite and running it concurrently on multiple nodes of the system. If specified, `SEGMENT_ID` also has to be set. Default is `1`.
- `SEGMENT_ID=<I>` - used in combination with the `SEGMENTS` variable. <I> should be an integer between 1 and <N>. If specified, only the <I>-th segment of the benchmark suite will be run. Default is `1`.
- `SYSTEM_NAME=<name>` - the name of the system where the benchmarks are being run. This option only changes the directory where the benchmark results are stored. It can be used to avoid overwriting the benchmarks if multiple systems share the same filesystem, or when copying the results between systems. Default is `unknown`.

Once `make benchmark` completes, the results can be found in `<Ginkgo build directory>/benchmark/results/<`
`YSTEM_NAME>/`. The files are written in the JSON format, and can be analyzed using any of the data analysis tools that support JSON. Alternatively, they can be uploaded to an online repository, and analyzed using Ginkgo's free web tool `Ginkgo Performance Explorer (GPE)`. (Make sure to change the "Performance data URL" to your repository if using GPE.)

Chapter 5

Example programs

Here you can find example programs that demonstrate the usage of Ginkgo.

Some examples are built on one another and some are stand-alone and demonstrate a concept of Ginkgo, which can be used in your own code.

You can browse the available example programs

1. as a graph that shows how example programs build upon each other.
2. as a list that provides a short synopsis of each program.
3. or grouped by topic.

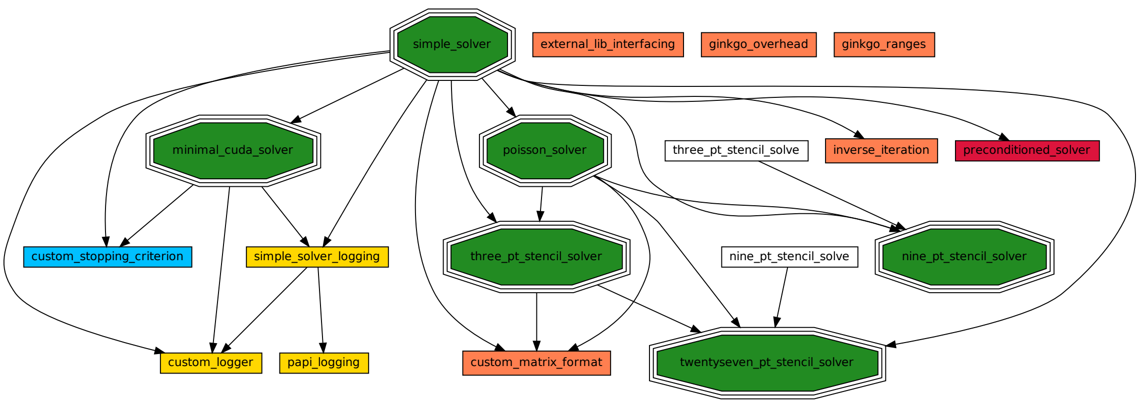
By default, all Ginkgo examples are built using CMake.

An example for building the examples and using Ginkgo as an external library without CMake can be found in the script provided for each example, which should be called with the form: `./build.sh PATH_TO_GINKGO_BUILD_DIR`

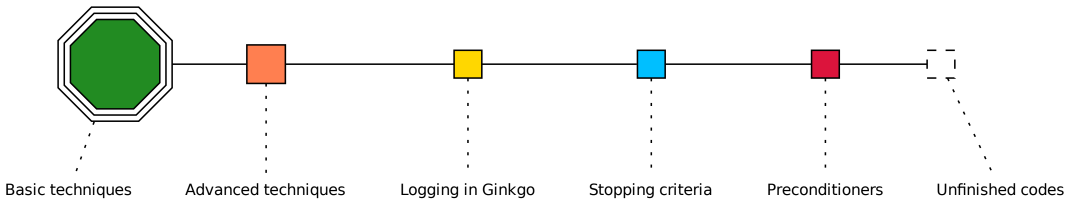
By default, Ginkgo is compiled with at least `-DGINKGO_BUILD_REFERENCE=ON`. To execute on a GPU, you need to have a GPU on the system and must have compiled Ginkgo with the `-DGINKGO_BUILD_CUDA=ON` option.

Connections between example programs

The following graph shows the connections between example programs and how they build on each other. Click on any of the boxes to go to one of the programs. If you hover your mouse pointer over a box, a brief description of the program should appear.



Legend:



Example programs

The simple-solver program	A minimal CG solver in Ginkgo, which reads a matrix from a file.
The minimal-cuda-solver program	A minimal solver on the CUDA executor than can be run on NVI←DIA GPU's.
The poisson-solver program	Solve an actual physically relevant problem, the poisson problem. The matrix is generated within Ginkgo.
The preconditioned-solver program	Using a Jacobi preconditioner to solve a linear system.
The three-pt-stencil-solver program	Using a three point stencil to solve the poisson equation with array views.
The nine-pt-stencil-solver program	Using a nine point 2D stencil to solve the poisson equation with array views.
The twentyseven-pt-stencil-solver program	Using a twentyseven point 3D stencil to solve the poisson equation with array views.
The external-lib-interfacing program	Using Ginkgo's solver with the external library deal.II.
The custom-logger program	Creating a custom logger specifically for comparing the recurrent and the real residual norms.
The custom-matrix-format program	Creating a matrix-free stencil solver by using Ginkgo's advanced methods to build your own custom matrix format.
The inverse-iteration program	Using Ginkgo to compute eigenvalues of a matrix with the inverse iteration method.
The simple-solver-logging program	Using the logging functionality in Ginkgo to get solver and other information to diagnose and debug your code.
The papi-logging program	Using the PAPI logging library in Ginkgo to get advanced information about your code and its behaviour.
The ginkgo-overhead program	Measuring the overhead of the Ginkgo library.
The custom-stopping-criterion program	Creating a custom stopping criterion for the iterative solution process.
The ginkgo-ranges program	Using the ranges concept to factorize a matrix with the LU factorization.

Example programs grouped by topics

Basic techniques

Solving a simple linear system with choice of executors.	The simple-solver program
Using the CUDA executor	The minimal-cuda-solver program
Using preconditioners	The preconditioned-solver program
Solving a physically relevant problem	The poisson-solver program, The three-pt-stencil-solver program, The nine-pt-stencil-solver program, The twentyseven-pt-stencil-solver program, The custom-matrix-format program
Reading in a matrix and right hand side from a file.	The simple-solver program, The minimal-cuda-solver program, The preconditioned-solver program, The inverse-iteration program, The simple-solver-logging program, The papi-logging program, The custom-stopping-criterion program, The custom-logger program

Advanced techniques

Using Ginkgo with external libraries.	The external-lib-interfacing program
Customizing Ginkgo	The custom-logger program, The custom-stopping-criterion program, The custom-matrix-format program
Writing your own matrix format	The custom-matrix-format program
Using Ginkgo to construct more complex linear algebra routines.	The inverse-iteration program
Logging within Ginkgo.	The simple-solver-logging program, The papi-logging program, The custom-logger program
Constructing your own stopping criterion.	The custom-stopping-criterion program
Using ranges in Ginkgo.	The ginkgo-ranges program

Chapter 6

The custom-logger program

The simple solver with a custom logger example.

This example depends on simple-solver, simple-solver-logging, minimal-cuda-solver.

Introduction

The custom-logger example shows how Ginkgo's API can be leveraged to implement application-specific callbacks for Ginkgo's events. This is the most basic way of extending Ginkgo and a good first step for any application developer who wants to adapt Ginkgo to his specific needs.

Ginkgo's gko::log::Logger abstraction provides hooks to the events that happen during the library execution. These hooks concern any low-level event such as memory allocations, deallocations, copies and kernel launches up to high-level events such as linear operator applications and completion of solver iterations.

In this example, a simple logger is implemented to track the solver's recurrent residual norm and compute the true residual norm. At the end of the solver execution, a comparison table is shown on-screen.

About the example

Each example has the following sections:

1. **Introduction:**This gives an overview of the example and mentions any interesting aspects in the example that might help the reader.
2. **The commented program:** This section is intended for you to understand the details of the example so that you can play with it and understand Ginkgo and its features better.
3. **Results:** This section shows the results of the code when run. Though the results may not be completely the same, you can expect the behaviour to be similar.
4. **The plain program:** This is the complete code without any comments to have an complete overview of the code.

The commented program

Include files

This is the main ginkgo header file.

```
#include <ginkgo/ginkgo.hpp>
```

Add the fstream header to read from data from files.

```
#include <fstream>
```

Add the C++ iomanip header to prettify the output.

```
#include <iomanip>
```

Add formatting flag modification capabilities.

```
#include <ios>
```

Add the C++ iostream header to output information to the console.

```
#include <iostream>
```

Add the string manipulation header to handle strings.

```
#include <string>
```

Add the vector header for storing the logger's data

```
#include <vector>
```

Utility function which gets the scalar value of a Ginkgo gko::matrix::Dense matrix representing the norm of a vector.

```
template <typename ValueType>
double get_norm(const gko::matrix::Dense<ValueType> *norm)
{
```

Put the value on CPU thanks to the master executor

```
auto cpu_norm = clone(norm->get_executor()->get_master(), norm);
```

Return the scalar value contained at position (0, 0)

```
    return cpu_norm->at(0, 0);
}
```

Utility function which computes the norm of a Ginkgo gko::matrix::Dense vector.

```
template <typename ValueType>
double compute_norm(const gko::matrix::Dense<ValueType> *b)
{
```

Get the executor of the vector

```
auto exec = b->get_executor();
```

Initialize a result scalar containing the value 0.0.

```
auto b_norm = gko::initialize<gko::matrix::Dense<ValueType>>({0.0}, exec);
```

Use the dense `compute_norm2` function to compute the norm.

```
b->compute_norm2(lend(b_norm));
```

Use the other utility function to return the norm contained in `b_norm`‘

```
    return get_norm(lend(b_norm));
}
```

Custom logger class which intercepts the residual norm scalar and solution vector in order to print a table of real vs recurrent (internal to the solvers) residual norms.

```
template <typename ValueType>
struct ResidualLogger : gko::log::Logger {
```

Output the logger's data in a table format

```
void write() const
{
```

Print a header for the table

```
std::cout << "Recurrent vs real residual norm:" << std::endl;
std::cout << '|' << std::setw(10) << "Iteration" << '|' << std::setw(25)
          << "Recurrent Residual Norm" << '|' << std::setw(25)
          << "Real Residual Norm" << '|' << std::endl;
```

Print a separation line. Note that for creating `10` characters `std::setw()` should be set to `11`.

```
std::cout << '|' << std::setfill('-') << std::setw(11) << '|'
          << std::setw(26) << '|' << std::setw(26) << '|'
          << std::setfill(' ') << std::endl;
```

Print the data one by one in the form

```
std::cout << std::scientific;
for (std::size_t i = 0; i < iterations.size(); i++) {
    std::cout << '|' << std::setw(10) << iterations[i] << '|'
              << std::setw(25) << recurrent_norms[i] << '|'
              << std::setw(25) << real_norms[i] << '|' << std::endl;
}
```

std::defaultfloat could be used here but some compilers do not support it properly, e.g. the Intel compiler

```
std::cout.unsetf(std::ios_base::floatfield);
```

Print a separation line

```
    std::cout << '|' << std::setfill('-') << std::setw(11) << '|'
              << std::setw(26) << '|' << std::setw(26) << '|'
              << std::setfill(' ') << std::endl;
}

using gko_dense = gko::matrix::Dense<ValueType>;
```

Customize the logging hook which is called everytime an iteration is completed

```
void on_iteration_complete(const gko::LinOp *,
                           const gko::size_type &iteration,
                           const gko::LinOp *residual,
                           const gko::LinOp *solution,
                           const gko::LinOp *residual_norm) const override
{
```

If the solver shares a residual norm, log its value

```
if (residual_norm) {
    auto dense_norm = gko::as<gko_dense>(residual_norm);
```

Add the norm to the `recurrent_norms` vector

```
recurrent_norms.push_back(get_norm(dense_norm));
```

Otherwise, use the recurrent residual vector

```
} else {
    auto dense_residual = gko::as<gko_dense>(residual);
```

Compute the residual vector's norm

```
auto norm = compute_norm(gko::lend(dense_residual));
```

Add the computed norm to the `recurrent_norms` vector

```
    recurrent_norms.push_back(norm);
}
```

If the solver shares the current solution vector

```
if (solution) {
```

Store the matrix's executor

```
auto exec = matrix->get_executor();
```

Create a scalar containing the value 1.0

```
auto one = gko::initialize<gko_dense>({1.0}, exec);
```

Create a scalar containing the value -1.0

```
auto neg_one = gko::initialize<gko_dense>({-1.0}, exec);
```

Instantiate a temporary result variable

```
auto res = gko::clone(b);
```

Compute the real residual vector by calling apply on the system matrix

```
matrix->apply(gko::lend(one), gko::lend(solution),
              gko::lend(neg_one), gko::lend(res));
```

Compute the norm of the residual vector and add it to the `real_norms` vector

```
    real_norms.push_back(compute_norm(gko::lend(res)));
} else {
```

Add to the `real_norms` vector the value -1.0 if it could not be computed

```
    real_norms.push_back(-1.0);
}
```

Add the current iteration number to the `iterations` vector

```
    iterations.push_back(iteration);
}
```

Construct the logger and store the system matrix and b vectors

```
    ResidualLogger(std::shared_ptr<const gko::Executor> exec,
                   const gko::LinOp *matrix, const gko_dense *b)
        : gko::log::Logger(exec, gko::log::Logger::iteration_complete_mask),
          matrix{matrix},
          b{b}
    {}

private:
```

Pointer to the system matrix

```
const gko::LinOp *matrix;
```

Pointer to the right hand sides

```
const gko_dense *b;
```

Vector which stores all the recurrent residual norms

```
mutable std::vector<ValueType> recurrent_norms{};
```

Vector which stores all the real residual norms

```
mutable std::vector<ValueType> real_norms{};
```

Vector which stores all the iteration numbers

```
    mutable std::vector<std::size_t> iterations{};
};

int main(int argc, char *argv[])
{
```

Use some shortcuts. In Ginkgo, vectors are seen as a gko::matrix::Dense with one column/one row. The advantage of this concept is that using multiple vectors is a now a natural extension of adding columns/rows are necessary.

```
using vec = gko::matrix::Dense<>;
```

The gko::matrix::Csr class is used here, but any other matrix class such as gko::matrix::Coo, gko::matrix::Hybrid, gko::matrix::Ell or gko::matrix::Sellp could also be used.

```
using mtx = gko::matrix::Csr<>;
```

The gko::solver::Cg is used here, but any other solver class can also be used.

```
using cg = gko::solver::Cg<>;
```

Print the ginkgo version information.

```
std::cout << gko::version_info::get() << std::endl;
```

Where do you want to run your solver ?

The gko::Executor class is one of the cornerstones of Ginkgo. Currently, we have support for an gko::OmpExecutor, which uses OpenMP multi-threading in most of its kernels, a gko::ReferenceExecutor, a single threaded specialization of the OpenMP executor and a gko::CudaExecutor which runs the code on a NVIDIA GPU if available.

Note

With the help of C++, you see that you only ever need to change the executor and all the other functions/ routines within Ginkgo should automatically work and run on the executor with any other changes.

```
std::shared_ptr<gko::Executor> exec;
if (argc == 1 || std::string(argv[1]) == "reference") {
    exec = gko::ReferenceExecutor::create();
} else if (argc == 2 && std::string(argv[1]) == "omp") {
    exec = gko::OmpExecutor::create();
} else if (argc == 2 && std::string(argv[1]) == "cuda" &&
           gko::CudaExecutor::get_num_devices() > 0) {
    exec = gko::CudaExecutor::create(0,
      gko::OmpExecutor::create());
} else {
    std::cerr << "Usage: " << argv[0] << " [executor]" << std::endl;
    std::exit(-1);
}
```

Reading your data and transfer to the proper device.

Read the matrix, right hand side and the initial solution using the read function.

Note

Ginkgo uses C++ smart pointers to automatically manage memory. To this end, we use our own object ownership transfer functions that under the hood call the required smart pointer functions to manage object ownership. The gko::share , gko::give and gko::lend are the functions that you would need to use.

```
auto A = share(gko::read<mtx>(std::ifstream("data/A.mtx"), exec));
auto b = gko::read<vec>(std::ifstream("data/b.mtx"), exec);
auto x = gko::read<vec>(std::ifstream("data/x0.mtx"), exec);
```

Creating the solver

Generate the gko::solver factory. Ginkgo uses the concept of Factories to build solvers with certain properties. Observe the Fluent interface used here. Here a cg solver is generated with a stopping criteria of maximum iterations of 20 and a residual norm reduction of 1e-15. You also observe that the stopping criteria(gko::stop) are also generated from factories using their build methods. You need to specify the executors which each of the object needs to be built on.

```
auto solver_gen =
    cg::build()
        .with_criteria(
            gko::stop::Iteration::build().with_max_iters(20u).on(exec),
            gko::stop::ResidualNormReduction<>::build()
                .with_reduction_factor(1e-15)
                .on(exec))
        .on(exec);
```

Instantiate a ResidualLogger logger.

```
auto logger = std::make_shared<ResidualLogger<double>>(exec, gko::lend(A),
                                                      gko::lend(b));
```

Add the previously created logger to the solver factory. The logger will be automatically propagated to all solvers created from this factory.

```
solver_gen->add_logger(logger);
```

Generate the solver from the matrix. The solver factory built in the previous step takes a "matrix"(a gko::LinOp to be more general) as an input. In this case we provide it with a full matrix that we previously read, but as the solver only effectively uses the apply() method within the provided "matrix" object, you can effectively create a gko::LinOp class with your own apply implementation to accomplish more tasks. We will see an example of how this can be done in the custom-matrix-format example

```
auto solver = solver_gen->generate(A);
```

Finally, solve the system. The solver, being a gko::LinOp, can be applied to a right hand side, b to obtain the solution, x.

```
solver->apply(lend(b), lend(x));
```

Print the solution to the command line.

```
std::cout << "Solution (x): \n";
write(std::cout, lend(x));
```

Print the table of the residuals obtained from the logger

```
logger->write();
```

To measure if your solution has actually converged, you can measure the error of the solution. one, neg_one are objects that represent the numbers which allow for a uniform interface when computing on any device. To compute the residual, all you need to do is call the apply method, which in this case is an spmv and equivalent to the LAPACK z_spmv routine. Finally, you compute the euclidean 2-norm with the compute_norm2 function.

```
    auto one = gko::initialize<vec>({1.0}, exec);
    auto neg_one = gko::initialize<vec>({-1.0}, exec);
    auto res = gko::initialize<vec>({0.0}, exec);
    A->apply(lend(one), lend(x), lend(neg_one), lend(b));
    b->compute_norm2(lend(res));

    std::cout << "Residual norm sqrt(r^T r): \n";
    write(std::cout, lend(res));
}
```

Results

The following is the expected result:

```
Solution (x):
%%MatrixMarket matrix array real general
19 1
0.252218
0.108645
0.0662811
0.0630433
0.0384088
0.0396536
0.0402648
0.0338935
0.0193098
0.0234653
0.0211499
0.0196413
0.0199151
0.0181674
0.0162722
0.0150714
0.0107016
0.0121141
0.0123025
Recurrent vs real residual norm:
| Iteration|  Recurrent Residual Norm|       Real Residual Norm|
|----------|-------------------------|-------------------------|
|         0|             4.358899e+00|             4.358899e+00|
|         1|             2.304548e+00|             2.304548e+00|
|         2|             1.467706e+00|             1.467706e+00|
|         3|             9.848751e-01|             9.848751e-01|
|         4|             7.418330e-01|             7.418330e-01|
|         5|             5.136231e-01|             5.136231e-01|
|         6|             3.841650e-01|             3.841650e-01|
|         7|             3.164394e-01|             3.164394e-01|
|         8|             2.277088e-01|             2.277088e-01|
|         9|             1.703121e-01|             1.703121e-01|
|        10|             9.737220e-02|             9.737220e-02|
|        11|             6.168306e-02|             6.168306e-02|
|        12|             4.541231e-02|             4.541231e-02|
|        13|             3.195304e-02|             3.195304e-02|
|        14|             1.616058e-02|             1.616058e-02|
|        15|             6.570152e-03|             6.570152e-03|
|        16|             2.643669e-03|             2.643669e-03|
|        17|             8.588089e-04|             8.588089e-04|
|        18|             2.864613e-04|             2.864613e-04|
|        19|             1.641952e-15|             2.107881e-15|
|----------|-------------------------|-------------------------|
Residual norm sqrt(r^T r):
%%MatrixMarket matrix array real general
1 1
2.10788e-15
```

Comments about programming and debugging

The plain program

```
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#include <ginkgo/ginkgo.hpp>

#include <fstream>
#include <iomanip>
#include <ios>
#include <iostream>
#include <string>
#include <vector>

template <typename ValueType>
double get_norm(const gko::matrix::Dense<ValueType> *norm)
{
    auto cpu_norm = clone(norm->get_executor()->get_master(), norm);
    return cpu_norm->at(0, 0);
}

template <typename ValueType>
double compute_norm(const gko::matrix::Dense<ValueType> *b)
{
    auto exec = b->get_executor();
    auto b_norm = gko::initialize<gko::matrix::Dense<ValueType>>({0.0}, exec);
    b->compute_norm2(lend(b_norm));
    return get_norm(lend(b_norm));
}

template <typename ValueType>
struct ResidualLogger : gko::log::Logger {
    void write() const
    {
        std::cout << "Recurrent vs real residual norm:" << std::endl;
        std::cout << '|' << std::setw(10) << "Iteration" << '|' << std::setw(25)
                  << "Recurrent Residual Norm" << '|' << std::setw(25)
                  << "Real Residual Norm" << '|' << std::endl;
        std::cout << '|' << std::setfill('-') << std::setw(11) << '|'
                  << std::setw(26) << '|' << std::setw(26) << '|'
                  << std::setfill(' ') << std::endl;
        std::cout << std::scientific;
        for (std::size_t i = 0; i < iterations.size(); i++) {
            std::cout << '|' << std::setw(10) << iterations[i] << '|'
                      << std::setw(25) << recurrent_norms[i] << '|'
                      << std::setw(25) << real_norms[i] << '|' << std::endl;
        }
        std::cout.unsetf(std::ios_base::floatfield);
        std::cout << '|' << std::setfill('-') << std::setw(11) << '|'
                  << std::setw(26) << '|' << std::setw(26) << '|'
                  << std::setfill(' ') << std::endl;
    }

    using gko_dense = gko::matrix::Dense<ValueType>;

    void on_iteration_complete(const gko::LinOp *,
                               const gko::size_type &iteration,
                               const gko::LinOp *residual,
                               const gko::LinOp *solution,
                               const gko::LinOp *residual_norm) const override
    {
        if (residual_norm) {
            auto dense_norm = gko::as<gko_dense>(residual_norm);
            recurrent_norms.push_back(get_norm(dense_norm));
        } else {
            auto dense_residual = gko::as<gko_dense>(residual);
            auto norm = compute_norm(gko::lend(dense_residual));
            recurrent_norms.push_back(norm);
        }

        if (solution) {
            auto exec = matrix->get_executor();
            auto one = gko::initialize<gko_dense>({1.0}, exec);
            auto neg_one = gko::initialize<gko_dense>({-1.0}, exec);
            auto res = gko::clone(b);
            matrix->apply(gko::lend(one), gko::lend(solution),
                          gko::lend(neg_one), gko::lend(res));
```

```
            real_norms.push_back(compute_norm(gko::lend(res)));
        } else {
            real_norms.push_back(-1.0);
        }

        iterations.push_back(iteration);
    }

    ResidualLogger(std::shared_ptr<const gko::Executor> exec,
                   const gko::LinOp *matrix, const gko_dense *b)
        : gko::log::Logger(exec, gko::log::Logger::iteration_complete_mask),
          matrix{matrix},
          b{b}
    {}

private:
    const gko::LinOp *matrix;
    const gko_dense *b;
    mutable std::vector<ValueType> recurrent_norms{};
    mutable std::vector<ValueType> real_norms{};
    mutable std::vector<std::size_t> iterations{};
};


int main(int argc, char *argv[])
{
    using vec = gko::matrix::Dense<>;
    using mtx = gko::matrix::Csr<>;
    using cg = gko::solver::Cg<>;

    std::cout << gko::version_info::get() << std::endl;

    std::shared_ptr<gko::Executor> exec;
    if (argc == 1 || std::string(argv[1]) == "reference") {
        exec = gko::ReferenceExecutor::create();
    } else if (argc == 2 && std::string(argv[1]) == "omp") {
        exec = gko::OmpExecutor::create();
    } else if (argc == 2 && std::string(argv[1]) == "cuda" &&
               gko::CudaExecutor::get_num_devices() > 0) {
        exec = gko::CudaExecutor::create(0,
      gko::OmpExecutor::create());
    } else {
        std::cerr << "Usage: " << argv[0] << " [executor]" << std::endl;
        std::exit(-1);
    }

    auto A = share(gko::read<mtx>(std::ifstream("data/A.mtx"), exec));
    auto b = gko::read<vec>(std::ifstream("data/b.mtx"), exec);
    auto x = gko::read<vec>(std::ifstream("data/x0.mtx"), exec);

    auto solver_gen =
        cg::build()
            .with_criteria(
                gko::stop::Iteration::build().with_max_iters(20u).on(exec),
                gko::stop::ResidualNormReduction<>::build()
                    .with_reduction_factor(1e-15)
                    .on(exec))
            .on(exec);

    auto logger = std::make_shared<ResidualLogger<double>>(exec, gko::lend(A),
                                                           gko::lend(b));

    solver_gen->add_logger(logger);

    auto solver = solver_gen->generate(A);


    solver->apply(lend(b), lend(x));

    std::cout << "Solution (x): \n";
    write(std::cout, lend(x));

    logger->write();

    auto one = gko::initialize<vec>({1.0}, exec);
    auto neg_one = gko::initialize<vec>({-1.0}, exec);
    auto res = gko::initialize<vec>({0.0}, exec);
    A->apply(lend(one), lend(x), lend(neg_one), lend(b));
    b->compute_norm2(lend(res));

    std::cout << "Residual norm sqrt(r^T r): \n";
    write(std::cout, lend(res));
}
```

Chapter 7

The custom-matrix-format program

The custom matrix format example.

This example depends on simple-solver, poisson-solver, three-pt-stencil-solver, .

Introduction

This example solves a 1D Poisson equation:

$u : [0, 1] \rightarrow R$
$u'' = f$
$u(0) = u0$
$u(1) = u1$

using a finite difference method on an equidistant grid with `K` discretization points (`K` can be controlled with a command line parameter). The discretization is done via the second order Taylor polynomial:

$u(x + h) = u(x) - u'(x)h + 1/2u''(x)h^2 + O(h^3)$
$u(x - h) = u(x) + u'(x)h + 1/2u''(x)h^2 + O(h^3)/+$
$- -$
$-u(x - h) + 2u(x) + -u(x + h) = -f(x)h^2 + O(h^3)$

For an equidistant grid with K "inner" discretization points $x1, ..., xk$,and step size $h = 1/(K + 1)$, the formula produces a system of linear equations

$2u_1 - u_2 = -f_1h^2 + u0$
$-u_(k - 1) + 2u_k - u_(k + 1) = -f_kh^2, k = 2, ..., K - 1$
$-u_(K - 1) + 2u_K = -f_Kh^2 + u1$

which is then solved using Ginkgo's implementation of the CG method preconditioned with block-Jacobi. It is also possible to specify on which executor Ginkgo will solve the system via the command line. The function 'f'is set to '$f(x) = 6x$' (making the solution '$u(x) = x^3$'), but that can be changed in the `main` function.

The intention of this example is to show how a custom linear operator can be created and integrated into Ginkgo to achieve performance benefits.

About the example

The commented program

```
#include <iostream>
#include <map>
#include <string>


#include <omp.h>
#include <ginkgo/ginkgo.hpp>
```

A CUDA kernel implementing the stencil, which will be used if running on the CUDA executor. Unfortunately, NVCC has serious problems interpreting some parts of Ginkgo's code, so the kernel has to be compiled separately.

```
extern void stencil_kernel(std::size_t size, const double *coefs,
                           const double *b, double *x);
```

A stencil matrix class representing the 3pt stencil linear operator. We include the gko::EnableLinOp mixin which implements the entire LinOp interface, except the two apply_impl methods, which get called inside the default implementation of apply (after argument verification) to perform the actual application of the linear operator. In addition, it includes the implementation of the entire PolymorphicObject interface.

It also includes the gko::EnableCreateMethod mixin which provides a default implementation of the static create method. This method will forward all its arguments to the constructor to create the object, and return an std::unique_ptr to the created object.

```
class StencilMatrix : public gko::EnableLinOp<StencilMatrix>,
                      public gko::EnableCreateMethod<StencilMatrix> {
public:
```

This constructor will be called by the create method. Here we initialize the coefficients of the stencil.

```
    StencilMatrix(std::shared_ptr<const gko::Executor> exec,
                  gko::size_type size = 0, double left = -1.0,
                  double center = 2.0, double right = -1.0)
        : gko::EnableLinOp<StencilMatrix>(exec, gko::dim<2>{size}),
          coefficients(exec, {left, center, right})
    {}

protected:
    using vec = gko::matrix::Dense<>;
    using coef_type = gko::Array<double>;
```

Here we implement the application of the linear operator, x = A $*$ b. apply_impl will be called by the apply method, after the arguments have been moved to the correct executor and the operators checked for conforming sizes.

For simplicity, we assume that there is always only one right hand side and the stride of consecutive elements in the vectors is 1 (both of these are always true in this example).

```
void apply_impl(const gko::LinOp *b, gko::LinOp *x) const override
{
```

we only implement the operator for dense RHS. gko::as will throw an exception if its argument is not Dense.

```
auto dense_b = gko::as<vec>(b);
auto dense_x = gko::as<vec>(x);
```

we need separate implementations depending on the executor, so we create an operation which maps the call to the correct implementation

```
struct stencil_operation : gko::Operation {
    stencil_operation(const coef_type &coefficients, const vec *b,
                      vec *x)
        : coefficients{coefficients}, b{b}, x{x}
    {}
```

OpenMP implementation

```
            void run(std::shared_ptr<const gko::OmpExecutor>) const override
            {
                auto b_values = b->get_const_values();
                auto x_values = x->get_values();
#pragma omp parallel for
                for (std::size_t i = 0; i < x->get_size()[0]; ++i) {
                    auto coefs = coefficients.get_const_data();
                    auto result = coefs[1] * b_values[i];
                    if (i > 0) {
                        result += coefs[0] * b_values[i - 1];
                    }
                    if (i < x->get_size()[0] - 1) {
                        result += coefs[2] * b_values[i + 1];
                    }
                    x_values[i] = result;
                }
            }
```

CUDA implementation

```
void run(std::shared_ptr<const gko::CudaExecutor>) const override
{
    stencil_kernel(x->get_size()[0], coefficients.get_const_data(),
                   b->get_const_values(), x->get_values());
}
```

We do not provide an implementation for reference executor. If not provided, Ginkgo will use the implementation for the OpenMP executor when calling it in the reference executor.

```
        const coef_type &coefficients;
        const vec *b;
        vec *x;
    };
    this->get_executor()->run(
        stencil_operation(coefficients, dense_b, dense_x));
}
```

There is also a version of the apply function which does the operation x = alpha ∗ A ∗ b + beta ∗ x. This function is commonly used and can often be better optimized than implementing it using x = A ∗ b. However, for simplicity, we will implement it exactly like that in this example.

```
    void apply_impl(const gko::LinOp *alpha, const gko::LinOp *b,
                    const gko::LinOp *beta, gko::LinOp *x) const override
    {
        auto dense_b = gko::as<vec>(b);
        auto dense_x = gko::as<vec>(x);
        auto tmp_x = dense_x->clone();
        this->apply_impl(b, lend(tmp_x));
        dense_x->scale(beta);
        dense_x->add_scaled(alpha, lend(tmp_x));
    }

private:
    coef_type coefficients;
};
```

Creates a stencil matrix in CSR format for the given number of discretization points.

```
void generate_stencil_matrix(gko::matrix::Csr<> *matrix)
{
    const auto discretization_points = matrix->get_size()[0];
    auto row_ptrs = matrix->get_row_ptrs();
    auto col_idxs = matrix->get_col_idxs();
    auto values = matrix->get_values();
    int pos = 0;
    const double coefs[] = {-1, 2, -1};
    row_ptrs[0] = pos;
    for (int i = 0; i < discretization_points; ++i) {
        for (auto ofs : {-1, 0, 1}) {
            if (0 <= i + ofs && i + ofs < discretization_points) {
                values[pos] = coefs[ofs + 1];
                col_idxs[pos] = i + ofs;
                ++pos;
            }
        }
        row_ptrs[i + 1] = pos;
    }
}
```

Generates the RHS vector given `f` and the boundary conditions.

```
template <typename Closure>
void generate_rhs(Closure f, double u0, double u1, gko::matrix::Dense<> *rhs)
{
    const auto discretization_points = rhs->get_size()[0];
    auto values = rhs->get_values();
    const auto h = 1.0 / (discretization_points + 1);
    for (int i = 0; i < discretization_points; ++i) {
        const auto xi = (i + 1) * h;
        values[i] = -f(xi) * h * h;
    }
    values[0] += u0;
    values[discretization_points - 1] += u1;
}
```

Prints the solution `u`.

```
void print_solution(double u0, double u1, const gko::matrix::Dense<> *u)
{
    std::cout << u0 << '\n';
    for (int i = 0; i < u->get_size()[0]; ++i) {
        std::cout << u->get_const_values()[i] << '\n';
    }
    std::cout << u1 << std::endl;
}
```

Computes the 1-norm of the error given the computed `u` and the correct solution function `correct_u`.

```
template <typename Closure>
double calculate_error(int discretization_points, const gko::matrix::Dense<> *u,
                       Closure correct_u)
{
    const auto h = 1.0 / (discretization_points + 1);
    auto error = 0.0;
    for (int i = 0; i < discretization_points; ++i) {
        using std::abs;
        const auto xi = (i + 1) * h;
        error +=
            abs(u->get_const_values()[i] - correct_u(xi)) /
      abs(correct_u(xi));
    }
    return error;
}
```

```
int main(int argc, char *argv[])
{
```

Some shortcuts

```
using vec = gko::matrix::Dense<double>;
using mtx = gko::matrix::Csr<double, int>;
using cg = gko::solver::Cg<double>;

if (argc < 2) {
    std::cerr << "Usage: " << argv[0] << " DISCRETIZATION_POINTS [executor]"
              << std::endl;
    std::exit(-1);
}
```

Get number of discretization points

```
const unsigned int discretization_points =
    argc >= 2 ? std::atoi(argv[1]) : 100u;
const auto executor_string = argc >= 3 ? argv[2] : "reference";
```

Figure out where to run the code

```
const auto omp = gko::OmpExecutor::create();
std::map<std::string, std::shared_ptr<gko::Executor>> exec_map{
    {"omp", omp},
    {"cuda", gko::CudaExecutor::create(0, omp)},
    {"reference", gko::ReferenceExecutor::create()}};
```

executor where Ginkgo will perform the computation

```
const auto exec = exec_map.at(executor_string);  // throws if not valid
```

executor used by the application

```
const auto app_exec = exec_map["omp"];
```

problem:

```
auto correct_u = [](double x) { return x * x * x; };
auto f = [](double x) { return 6 * x; };
auto u0 = correct_u(0);
auto u1 = correct_u(1);
```

initialize vectors

```
auto rhs = vec::create(app_exec, gko::dim<2>(discretization_points, 1));
generate_rhs(f, u0, u1, lend(rhs));
auto u = vec::create(app_exec, gko::dim<2>(discretization_points, 1));
for (int i = 0; i < u->get_size()[0]; ++i) {
    u->get_values()[i] = 0.0;
}
```

Generate solver and solve the system

```
cg::build()
    .with_criteria(gko::stop::Iteration::build()
                       .with_max_iters(discretization_points)
                       .on(exec),
                   gko::stop::ResidualNormReduction<>::build()
                       .with_reduction_factor(1e-6)
                       .on(exec))
    .on(exec)
```

notice how our custom StencilMatrix can be used in the same way as any built-in type

```
        ->generate(
            StencilMatrix::create(exec, discretization_points, -1, 2, -1))
        ->apply(lend(rhs), lend(u));

    print_solution(u0, u1, lend(u));
    std::cout << "The average relative error is "
              << calculate_error(discretization_points, lend(u), correct_u) /
                     discretization_points
              << std::endl;
}
```

Results

Comments about programming and debugging

The plain program

```
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#include <iostream>
#include <map>
#include <string>


#include <omp.h>
#include <ginkgo/ginkgo.hpp>


extern void stencil_kernel(std::size_t size, const double *coefs,
                           const double *b, double *x);


class StencilMatrix : public gko::EnableLinOp<StencilMatrix>,
                      public gko::EnableCreateMethod<StencilMatrix> {
public:
    StencilMatrix(std::shared_ptr<const gko::Executor> exec,
                  gko::size_type size = 0, double left = -1.0,
                  double center = 2.0, double right = -1.0)
        : gko::EnableLinOp<StencilMatrix>(exec, gko::dim<2>{size}),
          coefficients(exec, {left, center, right})
    {}

protected:
    using vec = gko::matrix::Dense<>;
    using coef_type = gko::Array<double>;

    void apply_impl(const gko::LinOp *b, gko::LinOp *x) const override
    {
        auto dense_b = gko::as<vec>(b);
        auto dense_x = gko::as<vec>(x);

        struct stencil_operation : gko::Operation {
            stencil_operation(const coef_type &coefficients, const vec *b,
                              vec *x)
                : coefficients{coefficients}, b{b}, x{x}
            {}

            void run(std::shared_ptr<const gko::OmpExecutor>) const override
            {
                auto b_values = b->get_const_values();
                auto x_values = x->get_values();
#pragma omp parallel for
```

```
                for (std::size_t i = 0; i < x->get_size()[0]; ++i) {
                    auto coefs = coefficients.get_const_data();
                    auto result = coefs[1] * b_values[i];
                    if (i > 0) {
                        result += coefs[0] * b_values[i - 1];
                    }
                    if (i < x->get_size()[0] - 1) {
                        result += coefs[2] * b_values[i + 1];
                    }
                    x_values[i] = result;
                }
            }

            void run(std::shared_ptr<const gko::CudaExecutor>) const override
            {
                stencil_kernel(x->get_size()[0], coefficients.get_const_data(),
                               b->get_const_values(), x->get_values());
            }


            const coef_type &coefficients;
            const vec *b;
            vec *x;
        };
        this->get_executor()->run(
            stencil_operation(coefficients, dense_b, dense_x));
    }

    void apply_impl(const gko::LinOp *alpha, const gko::LinOp *b,
                    const gko::LinOp *beta, gko::LinOp *x) const override
    {
        auto dense_b = gko::as<vec>(b);
        auto dense_x = gko::as<vec>(x);
        auto tmp_x = dense_x->clone();
        this->apply_impl(b, lend(tmp_x));
        dense_x->scale(beta);
        dense_x->add_scaled(alpha, lend(tmp_x));
    }

private:
    coef_type coefficients;
};


void generate_stencil_matrix(gko::matrix::Csr<> *matrix)
{
    const auto discretization_points = matrix->get_size()[0];
    auto row_ptrs = matrix->get_row_ptrs();
    auto col_idxs = matrix->get_col_idxs();
    auto values = matrix->get_values();
    int pos = 0;
    const double coefs[] = {-1, 2, -1};
    row_ptrs[0] = pos;
    for (int i = 0; i < discretization_points; ++i) {
        for (auto ofs : {-1, 0, 1}) {
            if (0 <= i + ofs && i + ofs < discretization_points) {
                values[pos] = coefs[ofs + 1];
                col_idxs[pos] = i + ofs;
                ++pos;
            }
        }
        row_ptrs[i + 1] = pos;
    }
}


template <typename Closure>
void generate_rhs(Closure f, double u0, double u1, gko::matrix::Dense<> *rhs)
{
    const auto discretization_points = rhs->get_size()[0];
    auto values = rhs->get_values();
    const auto h = 1.0 / (discretization_points + 1);
    for (int i = 0; i < discretization_points; ++i) {
        const auto xi = (i + 1) * h;
        values[i] = -f(xi) * h * h;
    }
    values[0] += u0;
    values[discretization_points - 1] += u1;
}


void print_solution(double u0, double u1, const gko::matrix::Dense<> *u)
{
    std::cout << u0 << '\n';
    for (int i = 0; i < u->get_size()[0]; ++i) {
        std::cout << u->get_const_values()[i] << '\n';
    }
```

```
    std::cout << u1 << std::endl;
}


template <typename Closure>
double calculate_error(int discretization_points, const gko::matrix::Dense<> *u,
                       Closure correct_u)
{
    const auto h = 1.0 / (discretization_points + 1);
    auto error = 0.0;
    for (int i = 0; i < discretization_points; ++i) {
        using std::abs;
        const auto xi = (i + 1) * h;
        error +=
            abs(u->get_const_values()[i] - correct_u(xi)) /
      abs(correct_u(xi));
    }
    return error;
}


int main(int argc, char *argv[])
{
    using vec = gko::matrix::Dense<double>;
    using mtx = gko::matrix::Csr<double, int>;
    using cg = gko::solver::Cg<double>;

    if (argc < 2) {
        std::cerr << "Usage: " << argv[0] << " DISCRETIZATION_POINTS [executor]"
                  << std::endl;
        std::exit(-1);
    }

    const unsigned int discretization_points =
        argc >= 2 ? std::atoi(argv[1]) : 100u;
    const auto executor_string = argc >= 3 ? argv[2] : "reference";

    const auto omp = gko::OmpExecutor::create();
    std::map<std::string, std::shared_ptr<gko::Executor>> exec_map{
        {"omp", omp},
        {"cuda", gko::CudaExecutor::create(0, omp)},
        {"reference", gko::ReferenceExecutor::create()}};

    const auto exec = exec_map.at(executor_string);  // throws if not valid
    const auto app_exec = exec_map["omp"];

    auto correct_u = [](double x) { return x * x * x; };
    auto f = [](double x) { return 6 * x; };
    auto u0 = correct_u(0);
    auto u1 = correct_u(1);

    auto rhs = vec::create(app_exec, gko::dim<2>(discretization_points, 1));
    generate_rhs(f, u0, u1, lend(rhs));
    auto u = vec::create(app_exec, gko::dim<2>(discretization_points, 1));
    for (int i = 0; i < u->get_size()[0]; ++i) {
        u->get_values()[i] = 0.0;
    }

    cg::build()
        .with_criteria(gko::stop::Iteration::build()
                           .with_max_iters(discretization_points)
                           .on(exec),
                       gko::stop::ResidualNormReduction<>::build()
                           .with_reduction_factor(1e-6)
                           .on(exec))
        .on(exec)
        ->generate(
            StencilMatrix::create(exec, discretization_points, -1, 2, -1))
        ->apply(lend(rhs), lend(u));

    print_solution(u0, u1, lend(u));
    std::cout << "The average relative error is "
              << calculate_error(discretization_points, lend(u), correct_u) /
                     discretization_points
              << std::endl;
}
```

Chapter 8

The custom-stopping-criterion program

The custom stopping criterion creation example.

This example depends on simple-solver, minimal-cuda-solver.

Introduction

About the example

The commented program

```
#include <ginkgo/ginkgo.hpp>


#include <fstream>
#include <iostream>
#include <string>
#include <thread>


/ **
 * The ByInteraction class is a criterion which asks for user input to stop
 * the iteration process. Using this criterion is slightly more complex than the
 * other ones, because it is asynchronous therefore requires the use of threads.
 * /
class ByInteraction
    : public gko::EnablePolymorphicObject<ByInteraction, gko::stop::Criterion>
       {
    friend class gko::EnablePolymorphicObject<ByInteraction,
                                              gko::stop::Criterion>;
    using Criterion = gko::stop::Criterion;

public:
    GKO_CREATE_FACTORY_PARAMETERS(parameters, Factory)
    {
        / **
         * Boolean set by the user to stop the iteration process
         * /
        std::add_pointer<volatile bool>::type GKO_FACTORY_PARAMETER(
            stop_iteration_process, nullptr);
    };
    GKO_ENABLE_CRITERION_FACTORY(ByInteraction, parameters, Factory);
    GKO_ENABLE_BUILD_METHOD(Factory);

protected:
    bool check_impl(gko::uint8 stoppingId, bool setFinalized,
                    gko::Array<gko::stopping_status> *stop_status,
                    bool *one_changed, const Criterion::Updater &) override
    {
        bool result = *(parameters_.stop_iteration_process);
```

```
        if (result) {
            this->set_all_statuses(stoppingId, setFinalized, stop_status);
            *one_changed = true;
        }
        return result;
    }

    explicit ByInteraction(std::shared_ptr<const gko::Executor> exec)
        : EnablePolymorphicObject<ByInteraction, Criterion>(std::move(exec))
    {}

    explicit ByInteraction(const Factory *factory,
                           const gko::stop::CriterionArgs &args)

        : EnablePolymorphicObject<ByInteraction, Criterion>(
              factory->get_executor()),
          parameters_{factory->get_parameters()}
    {}
};


void run_solver(volatile bool *stop_iteration_process,
                std::shared_ptr<gko::Executor> exec)
{
```

Some shortcuts

```
using mtx = gko::matrix::Csr<>;
using vec = gko::matrix::Dense<>;
using bicg = gko::solver::Bicgstab<>;
```

Read Data

```
auto A = share(gko::read<mtx>(std::ifstream("data/A.mtx"), exec));
auto b = gko::read<vec>(std::ifstream("data/b.mtx"), exec);
auto x = gko::read<vec>(std::ifstream("data/x0.mtx"), exec);
```

Create solver factory and solve system

```
auto solver = bicg::build()
                  .with_criteria(ByInteraction::build()
                                     .with_stop_iteration_process(
                                         stop_iteration_process)
                                     .on(exec))
                  .on(exec)
                  ->generate(A);
solver->add_logger(gko::log::Stream<>::create(
    exec, gko::log::Logger::iteration_complete_mask, std::cout, true));
solver->apply(lend(b), lend(x));

std::cout << "Solver stopped" << std::endl;
```

Print solution

```
std::cout << "Solution (x): \n";
write(std::cout, lend(x));
```

Calculate residual

```
    auto one = gko::initialize<vec>({1.0}, exec);
    auto neg_one = gko::initialize<vec>({-1.0}, exec);
    auto res = gko::initialize<vec>({0.0}, exec);
    A->apply(lend(one), lend(x), lend(neg_one), lend(b));
    b->compute_norm2(lend(res));

    std::cout << "Residual norm sqrt(r^T r): \n";
    write(std::cout, lend(res));
}


int main(int argc, char *argv[])
{
```

Print version information

```
std::cout << gko::version_info::get() << std::endl;
```

Figure out where to run the code

```
std::shared_ptr<gko::Executor> exec;
if (argc == 1 || std::string(argv[1]) == "reference") {
    exec = gko::ReferenceExecutor::create();
} else if (argc == 2 && std::string(argv[1]) == "omp") {
    exec = gko::OmpExecutor::create();
} else if (argc == 2 && std::string(argv[1]) == "cuda" &&
           gko::CudaExecutor::get_num_devices() > 0) {
    exec = gko::CudaExecutor::create(0,
      gko::OmpExecutor::create());
} else {
    std::cerr << "Usage: " << argv[0] << " [executor]" << std::endl;
    std::exit(-1);
}
```

Declare a user controled boolean for the iteration process

```
volatile bool stop_iteration_process{};
```

Create a new a thread to launch the solver

```
std::thread t(run_solver, &stop_iteration_process, exec);
```

Look for an input command "stop" in the console, which sets the boolean to true

```
    std::cout << "Type 'stop' to stop the iteration process" << std::endl;
    std::string command;
    while (std::cin >> command) {
        if (command == "stop") {
            break;
        } else {
            std::cout << "Unknown command" << std::endl;
        }
    }
    std::cout << "User input command 'stop' - The solver will stop!"
              << std::endl;
    stop_iteration_process = true;
    t.join();
}
```

Results

This is the expected output:

```
.
.
.
.
.
[LOG] >>> iteration 15331 completed with solver LinOp[gko::solver::Bicgstab<double>,0x7f2f38003c10] with
      residual LinOp[gko::matrix::Dense<double>,0x7f2f380048e0], solution LinOp[gko::LinOp const*,0] and
      residual_norm LinOp[gko::LinOp const*,0]
LinOp[gko::matrix::Dense<double>,0x7f2f380048e0][
        6.21705e-164
        -1.18919e-164
        7.89129e-165
        -6.78013e-165
```

```
        -2.42405e-164
        -4.29503e-165
        6.16567e-166
        -3.34064e-164
        6.38335e-165
        7.86768e-165
        -1.80969e-165
        -4.17609e-166
        2.5395e-165
        -5.34283e-166
        -4.10476e-166
        -1.50132e-166
        -1.25732e-165
        -1.82819e-166
        -2.0927e-165
]

// Typing 'stop' stops the solver.

User input command 'stop' - The solver will stop

LinOp[gko::matrix::Dense<double>,0x7f2f38004730][
        0.252218
        0.108645
        0.0662811
        0.0630433
        0.0384088
        0.0396536
        0.0402648
        0.0338935
        0.0193098
        0.0234653
        0.0211499
        0.0196413
        0.0199151
        0.0181674
        0.0162722
        0.0150714
        0.0107016
        0.0121141
        0.0123025
]

Solver stopped
Solution (x):
%%MatrixMarket matrix array real general
19 1
0.252218
0.108645
0.0662811
0.0630433
0.0384088
0.0396536
0.0402648
0.0338935
0.0193098
0.0234653
0.0211499
0.0196413
0.0199151
0.0181674
0.0162722
0.0150714
0.0107016
0.0121141
0.0123025
Residual norm sqrt(r^T r):
%%MatrixMarket matrix array real general
1 1
1.06135e-15
```

Comments about programming and debugging

The plain program

```
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```

```
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#include <ginkgo/ginkgo.hpp>


#include <fstream>
#include <iostream>
#include <string>
#include <thread>


class ByInteraction
    : public gko::EnablePolymorphicObject<ByInteraction, gko::stop::Criterion>
       {
    friend class gko::EnablePolymorphicObject<ByInteraction,
                                              gko::stop::Criterion>;
    using Criterion = gko::stop::Criterion;

public:
    GKO_CREATE_FACTORY_PARAMETERS(parameters, Factory)
    {
        std::add_pointer<volatile bool>::type GKO_FACTORY_PARAMETER(
            stop_iteration_process, nullptr);
    };
    GKO_ENABLE_CRITERION_FACTORY(ByInteraction, parameters, Factory);
    GKO_ENABLE_BUILD_METHOD(Factory);

protected:
    bool check_impl(gko::uint8 stoppingId, bool setFinalized,
                    gko::Array<gko::stopping_status> *stop_status,
                    bool *one_changed, const Criterion::Updater &) override
    {
        bool result = *(parameters_.stop_iteration_process);
        if (result) {
            this->set_all_statuses(stoppingId, setFinalized, stop_status);
            *one_changed = true;
        }
        return result;
    }

    explicit ByInteraction(std::shared_ptr<const gko::Executor> exec)
        : EnablePolymorphicObject<ByInteraction, Criterion>(std::move(exec))
    {}

    explicit ByInteraction(const Factory *factory,
                           const gko::stop::CriterionArgs &args)

        : EnablePolymorphicObject<ByInteraction, Criterion>(
              factory->get_executor()),
          parameters_{factory->get_parameters()}
    {}
};


void run_solver(volatile bool *stop_iteration_process,
                std::shared_ptr<gko::Executor> exec)
{
    using mtx = gko::matrix::Csr<>;
    using vec = gko::matrix::Dense<>;
    using bicg = gko::solver::Bicgstab<>;

    auto A = share(gko::read<mtx>(std::ifstream("data/A.mtx"), exec));
```

```
    auto b = gko::read<vec>(std::ifstream("data/b.mtx"), exec);
    auto x = gko::read<vec>(std::ifstream("data/x0.mtx"), exec);

    auto solver = bicg::build()
                      .with_criteria(ByInteraction::build()
                                         .with_stop_iteration_process(
                                             stop_iteration_process)
                                         .on(exec))
                      .on(exec)
                      ->generate(A);
    solver->add_logger(gko::log::Stream<>::create(
        exec, gko::log::Logger::iteration_complete_mask, std::cout, true));
    solver->apply(lend(b), lend(x));

    std::cout << "Solver stopped" << std::endl;

    std::cout << "Solution (x): \n";
    write(std::cout, lend(x));

    auto one = gko::initialize<vec>({1.0}, exec);
    auto neg_one = gko::initialize<vec>({-1.0}, exec);
    auto res = gko::initialize<vec>({0.0}, exec);
    A->apply(lend(one), lend(x), lend(neg_one), lend(b));
    b->compute_norm2(lend(res));

    std::cout << "Residual norm sqrt(r^T r): \n";
    write(std::cout, lend(res));
}


int main(int argc, char *argv[])
{
    std::cout << gko::version_info::get() << std::endl;

    std::shared_ptr<gko::Executor> exec;
    if (argc == 1 || std::string(argv[1]) == "reference") {
        exec = gko::ReferenceExecutor::create();
    } else if (argc == 2 && std::string(argv[1]) == "omp") {
        exec = gko::OmpExecutor::create();
    } else if (argc == 2 && std::string(argv[1]) == "cuda" &&
               gko::CudaExecutor::get_num_devices() > 0) {
        exec = gko::CudaExecutor::create(0,
      gko::OmpExecutor::create());
    } else {
        std::cerr << "Usage: " << argv[0] << " [executor]" << std::endl;
        std::exit(-1);
    }

    volatile bool stop_iteration_process{};

    std::thread t(run_solver, &stop_iteration_process, exec);

    std::cout << "Type 'stop' to stop the iteration process" << std::endl;
    std::string command;
    while (std::cin >> command) {
        if (command == "stop") {
            break;
        } else {
            std::cout << "Unknown command" << std::endl;
        }
    }
    std::cout << "User input command 'stop' - The solver will stop!"
              << std::endl;
    stop_iteration_process = true;
    t.join();
}
```

Chapter 9

The external-lib-interfacing program

The external library(deal.II) interfacing example.

Introduction

About the example

The commented program

```
#include <deal.II/base/function.h>
#include <deal.II/base/logstream.h>
#include <deal.II/base/quadrature_lib.h>
#include <deal.II/dofs/dof_accessor.h>
#include <deal.II/dofs/dof_handler.h>
#include <deal.II/dofs/dof_tools.h>
#include <deal.II/fe/fe_q.h>
#include <deal.II/fe/fe_values.h>
#include <deal.II/grid/grid_generator.h>
#include <deal.II/grid/grid_out.h>
#include <deal.II/grid/grid_refinement.h>
#include <deal.II/grid/tria.h>
#include <deal.II/grid/tria_accessor.h>
#include <deal.II/grid/tria_iterator.h>
#include <deal.II/lac/constraint_matrix.h>
#include <deal.II/lac/dynamic_sparsity_pattern.h>
#include <deal.II/lac/full_matrix.h>
#include <deal.II/lac/precondition.h>
#include <deal.II/lac/solver_bicgstab.h>
#include <deal.II/lac/sparse_matrix.h>
#include <deal.II/lac/vector.h>
#include <deal.II/numerics/data_out.h>
#include <deal.II/numerics/matrix_tools.h>
#include <deal.II/numerics/vector_tools.h>
```

The following two files provide classes and information for multithreaded programs. In the first one, the classes and functions are declared which we need to do assembly in parallel (i.e. the `WorkStream` namespace). The second file has a class MultithreadInfo which can be used to query the number of processors in your system, which is often useful when deciding how many threads to start in parallel.

```
#include <deal.II/base/multithread_info.h>
#include <deal.II/base/work_stream.h>
```

The next new include file declares a base class `TensorFunction` not unlike the `Function` class, but with the difference that the return value is tensor-valued rather than scalar of vector-valued.

```
#include <deal.II/base/tensor_function.h>

#include <deal.II/numerics/error_estimator.h>
```

Ginkgo's header file

```
#include <ginkgo/ginkgo.hpp>
```

This is C++, as we want to write some output to disk:

```
#include <fstream>
#include <iostream>
```

The last step is as in previous programs:

```
namespace Step9 {
using namespace dealii;
```

AdvectionProblem class declaration

Following we declare the main class of this program. It is very much like the main classes of previous examples, so we again only comment on the differences.

```
template <int dim>
class AdvectionProblem {
public:
    AdvectionProblem();
    ~AdvectionProblem();
    void run();

private:
    void setup_system();
```

The next set of functions will be used to assemble the matrix. However, unlike in the previous examples, the `assemble_system()` function will not do the work itself, but rather will delegate the actual assembly to helper functions `assemble_local_system()` and `copy_local_to_global()`. The rationale is that matrix assembly can be parallelized quite well, as the computation of the local contributions on each cell is entirely independent of other cells, and we only have to synchronize when we add the contribution of a cell to the global matrix.

The strategy for parallelization we choose here is one of the possibilities mentioned in detail in the threads module in the documentation. Specifically, we will use the WorkStream approach discussed there. Since there is so much documentation in this module, we will not repeat the rationale for the design choices here (for example, if you read through the module mentioned above, you will understand what the purpose of the `AssemblyScratchData` and `AssemblyCopyData` structures is). Rather, we will only discuss the specific implementation.

If you read the page mentioned above, you will find that in order to parallelize assembly, we need two data structures – one that corresponds to data that we need during local integration ("scratch data", i.e., things we only need as temporary storage), and one that carries information from the local integration to the function that then adds the local contributions to the corresponding elements of the global matrix. The former of these typically contains the FEValues and FEFaceValues objects, whereas the latter has the local matrix, local right hand side, and information about which degrees of freedom live on the cell for which we are assembling a local contribution. With this information, the following should be relatively self-explanatory:

```
struct AssemblyScratchData {
    AssemblyScratchData(const FiniteElement<dim> &fe);
    AssemblyScratchData(const AssemblyScratchData &scratch_data);

    FEValues<dim> fe_values;
    FEFaceValues<dim> fe_face_values;
};

struct AssemblyCopyData {
    FullMatrix<double> cell_matrix;
    Vector<double> cell_rhs;
    std::vector<types::global_dof_index> local_dof_indices;
};

void assemble_system();
void local_assemble_system(
    const typename DoFHandler<dim>::active_cell_iterator &cell,
    AssemblyScratchData &scratch, AssemblyCopyData &copy_data);
void copy_local_to_global(const AssemblyCopyData &copy_data);
```

The following functions again are as in previous examples, as are the subsequent variables.

```
    void solve();
    void refine_grid();
    void output_results(const unsigned int cycle) const;

    Triangulation<dim> triangulation;
    DoFHandler<dim> dof_handler;

    FE_Q<dim> fe;

    ConstraintMatrix hanging_node_constraints;

    SparsityPattern sparsity_pattern;
    SparseMatrix<double> system_matrix;

    Vector<double> solution;
    Vector<double> system_rhs;
};
```

Equation data declaration

Next we declare a class that describes the advection field. This, of course, is a vector field with as many components as there are space dimensions. One could now use a class derived from the `Function` base class, as we have done for boundary values and coefficients in previous examples, but there is another possibility in the library, namely a base class that describes tensor valued functions. In contrast to the usual `Function` objects, we provide the compiler with knowledge on the size of the objects of the return type. This enables the compiler to generate efficient code, which is not so simple for usual vector-valued functions where memory has to be allocated on the heap (thus, the `Function::vector_value` function has to be given the address of an object into which the result is to be written, in order to avoid copying and memory allocation and deallocation on the heap). In addition to the known size, it is possible not only to return vectors, but also tensors of higher rank; however, this is not very often requested by applications, to be honest...

The interface of the `TensorFunction` class is relatively close to that of the `Function` class, so there is probably no need to comment in detail the following declaration:

```
template <int dim>
class AdvectionField : public TensorFunction<1, dim> {
public:
    AdvectionField() : TensorFunction<1, dim>() {}

    virtual Tensor<1, dim> value(const Point<dim> &p) const;

    virtual void value_list(const std::vector<Point<dim>> &points,
                            std::vector<Tensor<1, dim>> &values) const;
```

In previous examples, we have used assertions that throw exceptions in several places. However, we have never seen how such exceptions are declared. This can be done as follows:

```
DeclException2(ExcDimensionMismatch, unsigned int, unsigned int,
               << "The vector has size " << arg1 << " but should have "
               << arg2 << " elements.");
```

The syntax may look a little strange, but is reasonable. The format is basically as follows: use the name of one of the macros `DeclExceptionN`, where `N` denotes the number of additional parameters which the exception object shall take. In this case, as we want to throw the exception when the sizes of two vectors differ, we need two arguments, so we use `DeclException2`. The first parameter then describes the name of the exception, while the following declare the data types of the parameters. The last argument is a sequence of output directives that will be piped into the `std::cerr` object, thus the strange format with the leading $<<$ operator and the like. Note that we can access the parameters which are passed to the exception upon construction (i.e. within the `Assert` call) by using the names `arg1` through `argN`, where `N` is the number of arguments as defined by the use of the respective macro `DeclExceptionN`.

To learn how the preprocessor expands this macro into actual code, please refer to the documentation of the exception classes in the base library. Suffice it to say that by this macro call, the respective exception class is declared, which also has error output functions already implemented.

```
};
```

The following two functions implement the interface described above. The first simply implements the function as described in the introduction, while the second uses the same trick to avoid calling a virtual function as has already been introduced in the previous example program. Note the check for the right sizes of the arguments in the second function, which should always be present in such functions; it is our experience that many if not most programming errors result from incorrectly initialized arrays, incompatible parameters to functions and the like; using assertion as in this case can eliminate many of these problems.

```
template <int dim>
Tensor<1, dim> AdvectionField<dim>::value(const Point<dim> &p) const
{
    Point<dim> value;
    value[0] = 2;
    for (unsigned int i = 1; i < dim; ++i)
        value[i] = 1 + 0.8 * std::sin(8 * numbers::PI * p[0]);

    return value;
}


template <int dim>
void AdvectionField<dim>::value_list(const std::vector<Point<dim>> &points,
                                     std::vector<Tensor<1, dim>> &values) const
{
    Assert(values.size() == points.size(),
           ExcDimensionMismatch(values.size(), points.size()));

    for (unsigned int i = 0; i < points.size(); ++i)
        values[i] = AdvectionField<dim>::value(points[i]);
}
```

Besides the advection field, we need two functions describing the source terms (`right hand side`) and the boundary values. First for the right hand side, which follows the same pattern as in previous examples. As described in the introduction, the source is a constant function in the vicinity of a source point, which we denote by the constant static variable `center_point`. We set the values of this center using the same template tricks as we have shown in the step-7 example program. The rest is simple and has been shown previously, including the way to avoid virtual function calls in the `value_list` function.

```
template <int dim>
class RightHandSide : public Function<dim> {
public:
    RightHandSide() : Function<dim>() {}

    virtual double value(const Point<dim> &p,
                         const unsigned int component = 0) const;
```

```
    virtual void value_list(const std::vector<Point<dim>> &points,
                            std::vector<double> &values,
                            const unsigned int component = 0) const;

private:
    static const Point<dim> center_point;
};


template <>
const Point<1> RightHandSide<1>::center_point = Point<1>(-0.75);

template <>
const Point<2> RightHandSide<2>::center_point = Point<2>(-0.75, -0.75);

template <>
const Point<3> RightHandSide<3>::center_point = Point<3>(-0.75, -0.75, -0.75);
```

The only new thing here is that we check for the value of the `component` parameter. As this is a scalar function, it is obvious that it only makes sense if the desired component has the index zero, so we assert that this is indeed the case. `ExcIndexRange` is a global predefined exception (probably the one most often used, we therefore made it global instead of local to some class), that takes three parameters: the index that is outside the allowed range, the first element of the valid range and the one past the last (i.e. again the half-open interval so often used in the C++ standard library):

```
template <int dim>
double RightHandSide<dim>::value(const Point<dim> &p,
                                 const unsigned int component) const
{
    (void)component;
    Assert(component == 0, ExcIndexRange(component, 0, 1));
    const double diameter = 0.1;
    return ((p - center_point).norm_square() < diameter * diameter
                ? .1 / std::pow(diameter, dim)
                : 0);
}


template <int dim>
void RightHandSide<dim>::value_list(const std::vector<Point<dim>> &points,
                                    std::vector<double> &values,
                                    const unsigned int component) const
{
    Assert(values.size() == points.size(),
           ExcDimensionMismatch(values.size(), points.size()));

    for (unsigned int i = 0; i < points.size(); ++i)
        values[i] = RightHandSide<dim>::value(points[i], component);
}
```

Finally for the boundary values, which is just another class derived from the `Function` base class:

```
template <int dim>
class BoundaryValues : public Function<dim> {
public:
    BoundaryValues() : Function<dim>() {}

    virtual double value(const Point<dim> &p,
                         const unsigned int component = 0) const;

    virtual void value_list(const std::vector<Point<dim>> &points,
                            std::vector<double> &values,
                            const unsigned int component = 0) const;
};


template <int dim>
double BoundaryValues<dim>::value(const Point<dim> &p,
                                  const unsigned int component) const
{
    (void)component;
    Assert(component == 0, ExcIndexRange(component, 0, 1));

    const double sine_term =
        std::sin(16 * numbers::PI * std::sqrt(p.norm_square()));
    const double weight = std::exp(-5 * p.norm_square()) / std::exp(-5.);
    return sine_term * weight;
```

```
}


template <int dim>
void BoundaryValues<dim>::value_list(const std::vector<Point<dim>> &points,
                                     std::vector<double> &values,
                                     const unsigned int component) const
{
    Assert(values.size() == points.size(),
           ExcDimensionMismatch(values.size(), points.size()));

    for (unsigned int i = 0; i < points.size(); ++i)
        values[i] = BoundaryValues<dim>::value(points[i], component);
}
```

GradientEstimation class declaration

Now, finally, here comes the class that will compute the difference approximation of the gradient on each cell and weighs that with a power of the mesh size, as described in the introduction. This class is a simple version of the `DerivativeApproximation` class in the library, that uses similar techniques to obtain finite difference approximations of the gradient of a finite element field, or of higher derivatives.

The class has one public static function `estimate` that is called to compute a vector of error indicators, and a few private functions that do the actual work on all active cells. As in other parts of the library, we follow an informal convention to use vectors of floats for error indicators rather than the common vectors of doubles, as the additional accuracy is not necessary for estimated values.

In addition to these two functions, the class declares two exceptions which are raised when a cell has no neighbors in each of the space directions (in which case the matrix described in the introduction would be singular and can't be inverted), while the other one is used in the more common case of invalid parameters to a function, namely a vector of wrong size.

Two other comments: first, the class has no non-static member functions or variables, so this is not really a class, but rather serves the purpose of a `namespace` in C++. The reason that we chose a class over a namespace is that this way we can declare functions that are private. This can be done with namespaces as well, if one declares some functions in header files in the namespace and implements these and other functions in the implementation file. The functions not declared in the header file are still in the namespace but are not callable from outside. However, as we have only one file here, it is not possible to hide functions in the present case.

The second comment is that the dimension template parameter is attached to the function rather than to the class itself. This way, you don't have to specify the template parameter yourself as in most other cases, but the compiler can figure its value out itself from the dimension of the DoF handler object that one passes as first argument.

Before jumping into the fray with the implementation, let us also comment on the parallelization strategy. We have already introduced the necessary framework for using the WorkStream concept in the declaration of the main class of this program above. We will use it again here. In the current context, this means that we have to define (i) classes for scratch and copy objects, (ii) a function that does the local computation on one cell, and (iii) a function that copies the local result into a global object. Given this general framework, we will, however, deviate from it a bit. In particular, WorkStream was generally invented for cases where each local computation on a cell *adds* to a global object – for example, when assembling linear systems where we add local contributions into a global matrix and right hand side. WorkStream is designed to handle the potential conflict of multiple threads trying to do this addition at the same time, and consequently has to provide for some way to ensure that only thread gets to do this at a time. Here, however, the situation is slightly different: we compute contributions from every cell individually, but then all we need to do is put them into an element of an output vector that is unique to each cell. Consequently, there is no risk that the write operations from two cells might conflict, and the elaborate machinery of WorkStream to avoid conflicting writes is not necessary. Consequently, what we will do is this: We still need a scratch object that holds, for example, the FEValues object. However, we only create a fake, empty copy data structure. Likewise, we do need the function that computes local contributions, but since it can already put the result into its final location, we do not need a copy-local-to-global function and will instead give the WorkStream::run() function an empty function object – the equivalent to a NULL function pointer.

```
class GradientEstimation {
public:
    template <int dim>
    static void estimate(const DoFHandler<dim> &dof,
                         const Vector<double> &solution,
                         Vector<float> &error_per_cell);

    DeclException2(ExcInvalidVectorLength, int, int,
                   << "Vector has length " << arg1 << ", but should have "
                   << arg2);
    DeclException0(ExcInsufficientDirections);

private:
    template <int dim>
    struct EstimateScratchData {
        EstimateScratchData(const FiniteElement<dim> &fe,
                            const Vector<double> &solution,
                            Vector<float> &error_per_cell);
        EstimateScratchData(const EstimateScratchData &data);

        FEValues<dim> fe_midpoint_value;
        const Vector<double> &solution;
        Vector<float> &error_per_cell;
    };

    struct EstimateCopyData {};

    template <int dim>
    static void estimate_cell(
        const typename DoFHandler<dim>::active_cell_iterator &cell,
        EstimateScratchData<dim> &scratch_data,
        const EstimateCopyData &copy_data);
};
```

AdvectionProblem class implementation

Now for the implementation of the main class. Constructor, destructor and the function `setup_system` follow the same pattern that was used previously, so we need not comment on these three function:

```
template <int dim>
AdvectionProblem<dim>::AdvectionProblem() : dof_handler(triangulation), fe(1)
{}


template <int dim>
AdvectionProblem<dim>::~AdvectionProblem()
{
    dof_handler.clear();
}


template <int dim>
void AdvectionProblem<dim>::setup_system()
{
    dof_handler.distribute_dofs(fe);
    hanging_node_constraints.clear();
    DoFTools::make_hanging_node_constraints(dof_handler,
                                            hanging_node_constraints);
    hanging_node_constraints.close();

    DynamicSparsityPattern dsp(dof_handler.n_dofs(), dof_handler.n_dofs());
    DoFTools::make_sparsity_pattern(dof_handler, dsp, hanging_node_constraints,
                                    / *keep_constrained_dofs = * / true);
    sparsity_pattern.copy_from(dsp);

    system_matrix.reinit(sparsity_pattern);

    solution.reinit(dof_handler.n_dofs());
    system_rhs.reinit(dof_handler.n_dofs());
}
```

In the following function, the matrix and right hand side are assembled. As stated in the documentation of the main class above, it does not do this itself, but rather delegates to the function following next, utilizing the WorkStream concept discussed in threads .

If you have looked through the threads module, you will have seen that assembling in parallel does not take an incredible amount of extra code as long as you diligently describe what the scratch and copy data objects are, and if you define suitable functions for the local assembly and the copy operation from local contributions to global objects. This done, the following will do all the heavy lifting to get these operations done on multiple threads on as many cores as you have in your system:

```
template <int dim>
void AdvectionProblem<dim>::assemble_system()
{
    WorkStream::run(dof_handler.begin_active(), dof_handler.end(), *this,
                    &AdvectionProblem::local_assemble_system,
                    &AdvectionProblem::copy_local_to_global,
                    AssemblyScratchData(fe), AssemblyCopyData());
```

After the matrix has been assembled in parallel, we still have to eliminate hanging node constraints. This is something that can't be done on each of the threads separately, so we have to do it now. Note also, that unlike in previous examples, there are no boundary conditions to be applied to the system of equations. This, of course, is due to the fact that we have included them into the weak formulation of the problem.

```
    hanging_node_constraints.condense(system_matrix);
    hanging_node_constraints.condense(system_rhs);
}
```

As already mentioned above, we need to have scratch objects for the parallel computation of local contributions. These objects contain FEValues and FEFaceValues objects, and so we will need to have constructors and copy constructors that allow us to create them. In initializing them, note first that we use bilinear elements, soGauss formulae with two points in each space direction are sufficient. For the cell terms we need the values and gradients of the shape functions, the quadrature points in order to determine the source density and the advection field at a given point, and the weights of the quadrature points times the determinant of the Jacobian at these points. In contrast, for the boundary integrals, we don't need the gradients, but rather the normal vectors to the cells. This determines which update flags we will have to pass to the constructors of the members of the class:

```
template <int dim>
AdvectionProblem<dim>::AssemblyScratchData::AssemblyScratchData(
    const FiniteElement<dim> &fe)
    : fe_values(fe, QGauss<dim>(2),
                update_values | update_gradients | update_quadrature_points |
                    update_JxW_values),
      fe_face_values(fe, QGauss<dim - 1>(2),
                     update_values | update_quadrature_points |
                         update_JxW_values | update_normal_vectors)
{}

template <int dim>
AdvectionProblem<dim>::AssemblyScratchData::AssemblyScratchData(
    const AssemblyScratchData &scratch_data)
    : fe_values(scratch_data.fe_values.get_fe(),
                scratch_data.fe_values.get_quadrature(),
                update_values | update_gradients | update_quadrature_points |
                    update_JxW_values),
      fe_face_values(scratch_data.fe_face_values.get_fe(),
                     scratch_data.fe_face_values.get_quadrature(),
                     update_values | update_quadrature_points |
                         update_JxW_values | update_normal_vectors)
{}
```

Now, this is the function that does the actual work. It is not very different from the `assemble_system` functions of previous example programs, so we will again only comment on the differences. The mathematical stuff follows closely what we have said in the introduction.

There are a number of points worth mentioning here, though. The first one is that we have moved the FEValues and FEFaceValues objects into the ScratchData object. We have done so because the alternative would have been to simply create one every time we get into this function – i.e., on every cell. It now turns out that the FEValues classes were written with the explicit goal of moving everything that remains the same from cell to cell into the construction of the object, and only do as little work as possible in FEValues::reinit() whenever we move to a new cell. What this means is that it would be very expensive to create a new object of this kind in this function as we would have to do it for every cell – exactly the thing we wanted to avoid with the FEValues class. Instead, what we do is create it only once (or a small number of times) in the scratch objects and then re-use it as often as we can.

This begs the question of whether there are other objects we create in this function whose creation is expensive compared to its use. Indeed, at the top of the function, we declare all sorts of objects. The `AdvectionField`, `RightHandSide` and `BoundaryValues` do not cost much to create, so there is no harm here. However, allocating memory in creating the `rhs_values` and similar variables below typically costs a significant amount of time, compared to just accessing the (temporary) values we store in them. Consequently, these would be candidates for moving into the `AssemblyScratchData` class. We will leave this as an exercise.

```
template <int dim>
void AdvectionProblem<dim>::local_assemble_system(
    const typename DoFHandler<dim>::active_cell_iterator &cell,
    AssemblyScratchData &scratch_data, AssemblyCopyData &copy_data)
{
```

First of all, we will need some objects that describe boundary values, right hand side function and the advection field. As we will only perform actions on these objects that do not change them, we declare them as constant, which can enable the compiler in some cases to perform additional optimizations.

```
const AdvectionField<dim> advection_field;
const RightHandSide<dim> right_hand_side;
const BoundaryValues<dim> boundary_values;
```

Then we define some abbreviations to avoid unnecessarily long lines:

```
const unsigned int dofs_per_cell = fe.dofs_per_cell;
const unsigned int n_q_points =
    scratch_data.fe_values.get_quadrature().size();
const unsigned int n_face_q_points =
    scratch_data.fe_face_values.get_quadrature().size();
```

We declare cell matrix and cell right hand side...

```
copy_data.cell_matrix.reinit(dofs_per_cell, dofs_per_cell);
copy_data.cell_rhs.reinit(dofs_per_cell);
```

... an array to hold the global indices of the degrees of freedom of the cell on which we are presently working...

```
copy_data.local_dof_indices.resize(dofs_per_cell);
```

... and array in which the values of right hand side, advection direction, and boundary values will be stored, for cell and face integrals respectively:

```
std::vector<double> rhs_values(n_q_points);
std::vector<Tensor<1, dim>> advection_directions(n_q_points);
std::vector<double> face_boundary_values(n_face_q_points);
std::vector<Tensor<1, dim>> face_advection_directions(n_face_q_points);
```

... then initialize the `FEValues` object...

```
scratch_data.fe_values.reinit(cell);
```

... obtain the values of right hand side and advection directions at the quadrature points...

```
advection_field.value_list(scratch_data.fe_values.get_quadrature_points(),
                           advection_directions);
right_hand_side.value_list(scratch_data.fe_values.get_quadrature_points(),
                           rhs_values);
```

... set the value of the streamline diffusion parameter as described in the introduction...

```
const double delta = 0.1 * cell->diameter();
```

... and assemble the local contributions to the system matrix and right hand side as also discussed above:

```
for (unsigned int q_point = 0; q_point < n_q_points; ++q_point)
    for (unsigned int i = 0; i < dofs_per_cell; ++i) {
        for (unsigned int j = 0; j < dofs_per_cell; ++j)
            copy_data.cell_matrix(i, j) +=
                ((advection_directions[q_point] *
                  scratch_data.fe_values.shape_grad(j, q_point) *
                  (scratch_data.fe_values.shape_value(i, q_point) +
                   delta *
                       (advection_directions[q_point] *
                        scratch_data.fe_values.shape_grad(i, q_point)))) *
                 scratch_data.fe_values.JxW(q_point));

        copy_data.cell_rhs(i) +=
            ((scratch_data.fe_values.shape_value(i, q_point) +
              delta * (advection_directions[q_point] *
                       scratch_data.fe_values.shape_grad(i, q_point))) *
             rhs_values[q_point] * scratch_data.fe_values.JxW(q_point));
    }
```

Besides the cell terms which we have built up now, the bilinear form of the present problem also contains terms on the boundary of the domain. Therefore, we have to check whether any of the faces of this cell are on the boundary of the domain, and if so assemble the contributions of this face as well. Of course, the bilinear form only contains contributions from the `inflow` part of the boundary, but to find out whether a certain part of a face of the present cell is part of the inflow boundary, we have to have information on the exact location of the quadrature points and on the direction of flow at this point; we obtain this information using the FEFaceValues object and only decide within the main loop whether a quadrature point is on the inflow boundary.

```
for (unsigned int face = 0; face < GeometryInfo<dim>::faces_per_cell;
     ++face)
    if (cell->face(face)->at_boundary()) {
```

Ok, this face of the present cell is on the boundary of the domain. Just as for the usual FEValues object which we have used in previous examples and also above, we have to reinitialize the FEFaceValues object for the present face:

```
scratch_data.fe_face_values.reinit(cell, face);
```

For the quadrature points at hand, we ask for the values of the inflow function and for the direction of flow:

```
boundary_values.value_list(
    scratch_data.fe_face_values.get_quadrature_points(),
    face_boundary_values);
advection_field.value_list(
    scratch_data.fe_face_values.get_quadrature_points(),
    face_advection_directions);
```

Now loop over all quadrature points and see whether it is on the inflow or outflow part of the boundary. This is determined by a test whether the advection direction points inwards or outwards of the domain (note that the normal vector points outwards of the cell, and since the cell is at the boundary, the normal vector points outward of the domain, so if the advection direction points into the domain, its scalar product with the normal vector must be negative):

```
for (unsigned int q_point = 0; q_point < n_face_q_points; ++q_point)
    if (scratch_data.fe_face_values.normal_vector(q_point) *
            face_advection_directions[q_point] <
        0)
```

If the is part of the inflow boundary, then compute the contributions of this face to the global matrix and right hand side, using the values obtained from the FEFaceValues object and the formulae discussed in the introduction:

```
            for (unsigned int i = 0; i < dofs_per_cell; ++i) {
                for (unsigned int j = 0; j < dofs_per_cell; ++j)
                    copy_data.cell_matrix(i, j) -=
                        (face_advection_directions[q_point] *
                         scratch_data.fe_face_values.normal_vector(
                             q_point) *
                         scratch_data.fe_face_values.shape_value(
                             i, q_point) *
                         scratch_data.fe_face_values.shape_value(
                             j, q_point) *
                         scratch_data.fe_face_values.JxW(q_point));

                copy_data.cell_rhs(i) -=
                    (face_advection_directions[q_point] *
                     scratch_data.fe_face_values.normal_vector(
                         q_point) *
                     face_boundary_values[q_point] *
                     scratch_data.fe_face_values.shape_value(i,
                                                             q_point) *
                     scratch_data.fe_face_values.JxW(q_point));
            }
}
```

Now go on by transferring the local contributions to the system of equations into the global objects. The first step was to obtain the global indices of the degrees of freedom on this cell.

```
    cell->get_dof_indices(copy_data.local_dof_indices);
}
```

The second function we needed to write was the one that copies the local contributions the previous function has computed and put into the copy data object, into the global matrix and right hand side vector objects. This is essentially what we always had as the last block of code when assembling something on every cell. The following should therefore be pretty obvious:

```
template <int dim>
void AdvectionProblem<dim>::copy_local_to_global(
    const AssemblyCopyData &copy_data)
{
    for (unsigned int i = 0; i < copy_data.local_dof_indices.size(); ++i) {
        for (unsigned int j = 0; j < copy_data.local_dof_indices.size(); ++j)
            system_matrix.add(copy_data.local_dof_indices[i],
                              copy_data.local_dof_indices[j],
                              copy_data.cell_matrix(i, j));

        system_rhs(copy_data.local_dof_indices[i]) += copy_data.cell_rhs(i);
    }
}
```

Following is the function that solves the linear system of equations. As the system is no more symmetric positive definite as in all the previous examples, we can't use the Conjugate Gradients method anymore. Rather, we use a solver that is tailored to nonsymmetric systems like the one at hand, the BiCGStab method. As preconditioner, we use the Block Jacobi method.

```
template <int dim>
void AdvectionProblem<dim>::solve()
{
```

Assert that the system be symmetric.

```
Assert(system_matrix.m() == system_matrix.n(), ExcNotQuadratic());
auto num_rows = system_matrix.m();
```

Make a copy of the rhs to use with Ginkgo.

```
std::vector<double> rhs(num_rows);
std::copy(system_rhs.begin(), system_rhs.begin() + num_rows, rhs.begin());
```

Ginkgo setup Some shortcuts: A vector is a Dense matrix with co-dimension 1. The matrix is setup in CSR. But various formats can be used. Look at Ginkgo's documentation.

```
using vec = gko::matrix::Dense<>;
using mtx = gko::matrix::Csr<>;
using bicgstab = gko::solver::Bicgstab<>;
using bj = gko::preconditioner::Jacobi<>;
using val_array = gko::Array<double>;
```

Where the code is to be executed. Can be changed to `omp` or `cuda` to run on multiple threads or on gpu's

```
std::shared_ptr<gko::Executor> exec = gko::ReferenceExecutor::create();
```

Setup Ginkgo's data structures

```
auto b = vec::create(exec, gko::dim<2>(num_rows, 1),
                     val_array::view(exec, num_rows, rhs.data()), 1);
auto x = vec::create(exec, gko::dim<2>(num_rows, 1));
auto A = mtx::create(exec, gko::dim<2>(num_rows),
                     system_matrix.n_nonzero_elements());
mtx::value_type *values = A->get_values();
mtx::index_type *row_ptr = A->get_row_ptrs();
mtx::index_type *col_idx = A->get_col_idxs();
```

Convert to standard CSR format As deal.ii does not expose its system matrix pointers, we construct them individually.

```
row_ptr[0] = 0;
for (auto row = 1; row <= num_rows; ++row) {
    row_ptr[row] = row_ptr[row - 1] + system_matrix.get_row_length(row - 1);
}

std::vector<mtx::index_type> ptrs(num_rows + 1);
std::copy(A->get_row_ptrs(), A->get_row_ptrs() + num_rows + 1,
          ptrs.begin());
for (auto row = 0; row < system_matrix.m(); ++row) {
    for (auto p = system_matrix.begin(row); p != system_matrix.end(row);
         ++p) {
```

write entry into the first free one for this row

```
col_idx[ptrs[row]] = p->column();
values[ptrs[row]] = p->value();
```

then move pointer ahead

```
        ++ptrs[row];
    }
}
```

Ginkgo solve The stopping criteria is set at maximum iterations of 1000 and a reduction factor of 1e-12. For other options, refer to Ginkgo's documentation.

```
auto solver_gen =
    bicgstab::build()
        .with_criteria(
            gko::stop::Iteration::build().with_max_iters(1000).on(exec),
            gko::stop::ResidualNormReduction<>::build()
                .with_reduction_factor(1e-12)
                .on(exec))
        .with_preconditioner(bj::build().on(exec))
        .on(exec);
auto solver = solver_gen->generate(gko::give(A));
```

Solve system

```
solver->apply(gko::lend(b), gko::lend(x));
```

Copy the solution vector back to deal.ii's data structures.

```
std::copy(x->get_values(), x->get_values() + num_rows, solution.begin());

/ *******************************************************
 * deal.ii internal solver. Here for reference.
 SolverControl           solver_control (1000, 1e-12);
 SolverBicgstab<>        bicgstab (solver_control);

 PreconditionJacobi<> preconditioner;
 preconditioner.initialize(system_matrix, 1.0);

 bicgstab.solve (system_matrix, solution, system_rhs,
                 preconditioner);
******************************************************* /
```

Give the solution back to deall.ii

```
    hanging_node_constraints.distribute(solution);
}
```

The following function refines the grid according to the quantity described in the introduction. The respective computations are made in the class `GradientEstimation`. The only difference to previous examples is that we refine a little more aggressively (0.5 instead of 0.3 of the number of cells).

```
template <int dim>
void AdvectionProblem<dim>::refine_grid()
{
    Vector<float> estimated_error_per_cell(triangulation.n_active_cells());

    GradientEstimation::estimate(dof_handler, solution,
                                 estimated_error_per_cell);

    GridRefinement::refine_and_coarsen_fixed_number(
        triangulation, estimated_error_per_cell, 0.5, 0.03);

    triangulation.execute_coarsening_and_refinement();
}
```

Writing output to disk is done in the same way as in the previous examples. Indeed, the function is identical to the one in step-6.

```
template <int dim>
void AdvectionProblem<dim>::output_results(const unsigned int cycle) const
{
    {
        GridOut grid_out;
        std::ofstream output("grid-" + std::to_string(cycle) + ".eps");
        grid_out.write_eps(triangulation, output);
    }

    {
        DataOut<dim> data_out;
        data_out.attach_dof_handler(dof_handler);
        data_out.add_data_vector(solution, "solution");
        data_out.build_patches();

        std::ofstream output("solution-" + std::to_string(cycle) + ".vtk");
        data_out.write_vtk(output);
    }
}
```

... as is the main loop (setup – solve – refine)

```
template <int dim>
void AdvectionProblem<dim>::run()
{
    for (unsigned int cycle = 0; cycle < 6; ++cycle) {
        std::cout << "Cycle " << cycle << ':' << std::endl;

        if (cycle == 0) {
            GridGenerator::hyper_cube(triangulation, -1, 1);
            triangulation.refine_global(4);
        } else {
            refine_grid();
        }


        std::cout << "   Number of active cells:       "
                  << triangulation.n_active_cells() << std::endl;

        setup_system();

        std::cout << "   Number of degrees of freedom: " << dof_handler.n_dofs()
                  << std::endl;

        assemble_system();
        solve();
        output_results(cycle);
    }
}
```

GradientEstimation class implementation

Now for the implementation of the `GradientEstimation` class. Let us start by defining constructors for the `EstimateScratchData` class used by the `estimate_cell()` function:

```
template <int dim>
GradientEstimation::EstimateScratchData<dim>::EstimateScratchData(
    const FiniteElement<dim> &fe, const Vector<double> &solution,
    Vector<float> &error_per_cell)
    : fe_midpoint_value(fe, QMidpoint<dim>(),
                        update_values | update_quadrature_points),
      solution(solution),
      error_per_cell(error_per_cell)
{}

template <int dim>
GradientEstimation::EstimateScratchData<dim>::EstimateScratchData(
    const EstimateScratchData &scratch_data)
    : fe_midpoint_value(scratch_data.fe_midpoint_value.get_fe(),
                        scratch_data.fe_midpoint_value.get_quadrature(),
                        update_values | update_quadrature_points),
      solution(scratch_data.solution),
      error_per_cell(scratch_data.error_per_cell)
{}
```

Next for the implementation of the `GradientEstimation` class. The first function does not much except for delegating work to the other function, but there is a bit of setup at the top.

Before starting with the work, we check that the vector into which the results are written has the right size. Programming mistakes in which one forgets to size arguments correctly at the calling site are quite common. Because the resulting damage from not catching such errors is often subtle (e.g., corruption of data somewhere in memory, or non-reproducible results), it is well worth the effort to check for such things.

```
template <int dim>
void GradientEstimation::estimate(const DoFHandler<dim> &dof_handler,
                                  const Vector<double> &solution,
                                  Vector<float> &error_per_cell)
{
    Assert(error_per_cell.size() ==
               dof_handler.get_triangulation().n_active_cells(),
           ExcInvalidVectorLength(
               error_per_cell.size(),
               dof_handler.get_triangulation().n_active_cells()));

    WorkStream::run(dof_handler.begin_active(), dof_handler.end(),
                    &GradientEstimation::template estimate_cell<dim>,
                    std::function<void(const EstimateCopyData &)>(),
                    EstimateScratchData<dim>(dof_handler.get_fe(), solution,
                                             error_per_cell),
                    EstimateCopyData());
}
```

Following now the function that actually computes the finite difference approximation to the gradient. The general outline of the function is to first compute the list of active neighbors of the present cell and then compute the quantities described in the introduction for each of the neighbors. The reason for this order is that it is not a one-liner to find a given neighbor with locally refined meshes. In principle, an optimized implementation would find neighbors and the quantities depending on them in one step, rather than first building a list of neighbors and in a second step their contributions but we will gladly leave this as an exercise. As discussed before, the worker function passed to WorkStream::run works on "scratch" objects that keep all temporary objects. This way, we do not need to create and initialize objects that are expensive to initialize within the function that does the work, every time it is called for a given cell. Such an argument is passed as the second argument. The third argument would be a "copy-data" object (see threads for more information) but we do not actually use any of these here. Because WorkStream::run() insists on passing three arguments, we declare this function with three arguments, but simply ignore the last one.

(This is unsatisfactory from an esthetic perspective. It can be avoided, at the cost of some other trickery. If you allow, let us here show how. First, assume that we had declared this function to only take two arguments by omitting the unused last one. Now, WorkStream::run still wants to call this function with three arguments, so we need to find a way to "forget" the third argument in the call. Simply passing WorkStream::run the pointer to the function as we do above will not do this – the compiler will complain that a function declared to have two arguments is called with three arguments. However, we can do this by passing the following as the third argument when calling WorkStream::run() above:

```
std::function<void (const typename DoFHandler<dim>::active_cell_iterator
&,
                    EstimateScratchData<dim>                  &,
                    EstimateCopyData                          &)>
  (std::bind (&GradientEstimation::template estimate_cell<dim>,
             std::placeholders::_1,
             std::placeholders::_2))
```

This creates a function object taking three arguments, but when it calls the underlying function object, it simply only uses the first and second argument – we simply "forget" to use the third argument :-) In the end, this isn't completely obvious either, and so we didn't implement it, but hey – it can be done!)

Now for the details:

```
template <int dim>
void GradientEstimation::estimate_cell(
    const typename DoFHandler<dim>::active_cell_iterator &cell,
    EstimateScratchData<dim> &scratch_data, const EstimateCopyData &)
{
```

We need space for the tensor `Y`, which is the sum of outer products of the y-vectors.

```
Tensor<2, dim> Y;
```

Then we allocate a vector to hold iterators to all active neighbors of a cell. We reserve the maximal number of active neighbors in order to avoid later reallocations. Note how this maximal number of active neighbors is computed here.

```
std::vector<typename DoFHandler<dim>::active_cell_iterator>
    active_neighbors;
active_neighbors.reserve(GeometryInfo<dim>::faces_per_cell *
                         GeometryInfo<dim>::max_children_per_face);
```

First initialize the `FEValues` object, as well as the `Y` tensor:

```
scratch_data.fe_midpoint_value.reinit(cell);
```

Then allocate the vector that will be the sum over the y-vectors times the approximate directional derivative:

```
Tensor<1, dim> projected_gradient;
```

Now before going on first compute a list of all active neighbors of the present cell. We do so by first looping over all faces and see whether the neighbor there is active, which would be the case if it is on the same level as the present cell or one level coarser (note that a neighbor can only be once coarser than the present cell, as we only allow a maximal difference of one refinement over a face in deal.II). Alternatively, the neighbor could be on the same level and be further refined; then we have to find which of its children are next to the present cell and select these (note that if a child of a neighbor of an active cell that is next to this active cell, needs necessarily be active itself, due to the one-refinement rule cited above).

Things are slightly different in one space dimension, as there the one-refinement rule does not exist: neighboring active cells may differ in as many refinement levels as they like. In this case, the computation becomes a little more difficult, but we will explain this below.

Before starting the loop over all neighbors of the present cell, we have to clear the array storing the iterators to the active neighbors, of course.

```
active_neighbors.clear();
for (unsigned int face_no = 0; face_no < GeometryInfo<dim>::faces_per_cell;
     ++face_no)
    if (!cell->at_boundary(face_no)) {
```

First define an abbreviation for the iterator to the face and the neighbor

```
const typename DoFHandler<dim>::face_iterator face =
    cell->face(face_no);
const typename DoFHandler<dim>::cell_iterator neighbor =
    cell->neighbor(face_no);
```

Then check whether the neighbor is active. If it is, then it is on the same level or one level coarser (if we are not in 1D), and we are interested in it in any case.

```
if (neighbor->active())
    active_neighbors.push_back(neighbor);
else {
```

If the neighbor is not active, then check its children.

```
if (dim == 1) {
```

To find the child of the neighbor which bounds to the present cell, successively go to its right child if we are left of the present cell (n==0), or go to the left child if we are on the right (n==1), until we find an active cell.

```
typename DoFHandler<dim>::cell_iterator neighbor_child =
    neighbor;
while (neighbor_child->has_children())
    neighbor_child =
        neighbor_child->child(face_no == 0 ? 1 : 0);
```

As this used some non-trivial geometrical intuition, we might want to check whether we did it right, i.e. check whether the neighbor of the cell we found is indeed the cell we are presently working on. Checks like this are often useful and have frequently uncovered errors both in algorithms like the line above (where it is simple to involuntarily exchange `n==1` for `n==0` or the like) and in the library (the assumptions underlying the algorithm above could either be wrong, wrongly documented, or are violated due to an error in the library). One could in principle remove such checks after the program works for some time, but it might be a good things to leave it in anyway to check for changes in the library or in the algorithm above.

Note that if this check fails, then this is certainly an error that is irrecoverable and probably qualifies as an internal error. We therefore use a predefined exception class to throw here.

```
Assert(
    neighbor_child->neighbor(face_no == 0 ? 1 : 0) == cell,
    ExcInternalError());
```

If the check succeeded, we push the active neighbor we just found to the stack we keep:

```
    active_neighbors.push_back(neighbor_child);
} else
```

If we are not in 1d, we collect all neighbor children ‘behind' the subfaces of the current face

```
            for (unsigned int subface_no = 0;
                 subface_no < face->n_children(); ++subface_no)
                active_neighbors.push_back(
                    cell->neighbor_child_on_subface(face_no,
                                                    subface_no));
    }
}
```

OK, now that we have all the neighbors, lets start the computation on each of them. First we do some preliminaries: find out about the center of the present cell and the solution at this point. The latter is obtained as a vector of function values at the quadrature points, of which there are only one, of course. Likewise, the position of the center is the position of the first (and only) quadrature point in real space.

```
const Point<dim> this_center =
    scratch_data.fe_midpoint_value.quadrature_point(0);

std::vector<double> this_midpoint_value(1);
scratch_data.fe_midpoint_value.get_function_values(scratch_data.solution,
                                                   this_midpoint_value);
```

Now loop over all active neighbors and collect the data we need. Allocate a vector just like this_midpoint_value which we will use to store the value of the solution in the midpoint of the neighbor cell. We allocate it here already, since that way we don't have to allocate memory repeatedly in each iteration of this inner loop (memory allocation is a rather expensive operation):

```
std::vector<double> neighbor_midpoint_value(1);
typename std::vector<typename DoFHandler<dim>::active_cell_iterator>::
    const_iterator neighbor_ptr = active_neighbors.begin();
for (; neighbor_ptr != active_neighbors.end(); ++neighbor_ptr) {
```

First define an abbreviation for the iterator to the active neighbor cell:

```
const typename DoFHandler<dim>::active_cell_iterator neighbor =
    *neighbor_ptr;
```

Then get the center of the neighbor cell and the value of the finite element function thereon. Note that for this information we have to reinitialize the FEValues object for the neighbor cell.

```
scratch_data.fe_midpoint_value.reinit(neighbor);
const Point<dim> neighbor_center =
    scratch_data.fe_midpoint_value.quadrature_point(0);

scratch_data.fe_midpoint_value.get_function_values(
    scratch_data.solution, neighbor_midpoint_value);
```

Compute the vector y connecting the centers of the two cells. Note that as opposed to the introduction, we denote by y the normalized difference vector, as this is the quantity used everywhere in the computations.

```
Tensor<1, dim> y = neighbor_center - this_center;
const double distance = y.norm();
y /= distance;
```

Then add up the contribution of this cell to the Y matrix...

```
for (unsigned int i = 0; i < dim; ++i)
    for (unsigned int j = 0; j < dim; ++j) Y[i][j] += y[i] * y[j];
```

... and update the sum of difference quotients:

```
    projected_gradient +=
        (neighbor_midpoint_value[0] - this_midpoint_value[0]) / distance *
        y;
}
```

If now, after collecting all the information from the neighbors, we can determine an approximation of the gradient for the present cell, then we need to have passed over vectors y which span the whole space, otherwise we would not have all components of the gradient. This is indicated by the invertibility of the matrix.

If the matrix should not be invertible, this means that the present cell had an insufficient number of active neighbors. In contrast to all previous cases, where we raised exceptions, this is, however, not a programming error: it is a runtime error that can happen in optimized mode even if it ran well in debug mode, so it is reasonable to try to catch this error also in optimized mode. For this case, there is the AssertThrow macro: it checks the condition like the Assert macro, but not only in debug mode; it then outputs an error message, but instead of terminating the program as in the case of the Assert macro, the exception is thrown using the throw command of C++. This way, one has the possibility to catch this error and take reasonable counter actions. One such measure would be to refine the grid globally, as the case of insufficient directions can not occur if every cell of the initial grid has been refined at least once.

```
AssertThrow(determinant(Y) != 0, ExcInsufficientDirections());
```

If, on the other hand the matrix is invertible, then invert it, multiply the other quantity with it and compute the estimated error using this quantity and the right powers of the mesh width:

```
const Tensor<2, dim> Y_inverse = invert(Y);

Tensor<1, dim> gradient = Y_inverse * projected_gradient;
```

The last part of this function is the one where we write into the element of the output vector what we have just computed. The address of this vector has been stored in the scratch data object, and all we have to do is know how to get at the correct element inside this vector – but we can ask the cell we're on the how-manyth active cell it is for this:

```
    scratch_data.error_per_cell(cell->active_cell_index()) =
        (std::pow(cell->diameter(), 1 + 1.0 * dim / 2) *
         std::sqrt(gradient.norm_square()));
}
}  // namespace Step9
```

Main function

The `main` function is similar to the previous examples. The main difference is that we use MultithreadInfo to set the maximum number of threads (see Parallel computing with multiple processors accessing shared memory" documentation module for more explanation). The number of threads used is the minimum of the environment variable DEAL_II_NUM_THREADS and the parameter of `set_thread_limit`. If no value is given to `set_thread_limit`, the default value from the Intel Threading Building Blocks (TBB) library is used. If the call to `set_thread_limit` is omitted, the number of threads will be chosen by TBB indepently of DEAL_II_NUM_THREADS.

```
int main()
{
    try {
        dealii::MultithreadInfo::set_thread_limit();

        Step9::AdvectionProblem<2> advection_problem_2d;
        advection_problem_2d.run();
    } catch (std::exception &exc) {
        std::cerr << std::endl
                  << std::endl
                  << "----------------------------------------------------"
                  << std::endl;
        std::cerr << "Exception on processing: " << std::endl
                  << exc.what() << std::endl
                  << "Aborting!" << std::endl
                  << "----------------------------------------------------"
                  << std::endl;
        return 1;
    } catch (...) {
        std::cerr << std::endl
                  << std::endl
                  << "----------------------------------------------------"
                  << std::endl;
        std::cerr << "Unknown exception!" << std::endl
                  << "Aborting!" << std::endl
                  << "----------------------------------------------------"
                  << std::endl;
        return 1;
    }

    return 0;
}
```

Results

Comments about programming and debugging

The plain program

```
/* ---------------------------------------------------------------------
 *
 * Copyright (C) 2000 - 2018 by the deal.II authors
 *
 * This file is part of the deal.II library.
 *
 * The deal.II library is free software; you can use it, redistribute
 * it, and/or modify it under the terms of the GNU Lesser General
 * Public License as published by the Free Software Foundation; either
 * version 2.1 of the License, or (at your option) any later version.
 * The full text of the license can be found in the file LICENSE at
 * the top level of the deal.II distribution.
 *
 * ---------------------------------------------------------------------

 *
 * Author: Wolfgang Bangerth, University of Heidelberg, 2000
 */

/* ---------------------------------------------------------------------
 *
 * This file has been taken verbatim from the deal.ii (version 9.0)
 * examples directory and modified.
 *
 * This example aims to demonstrate the ease with which Ginkgo can
 * be interfaced with other libraries. The only modification/ addition
 * has been to the AdvectionProblem::solve () function.
 *
 */

#include <deal.II/base/function.h>
#include <deal.II/base/logstream.h>
#include <deal.II/base/quadrature_lib.h>
#include <deal.II/dofs/dof_accessor.h>
#include <deal.II/dofs/dof_handler.h>
#include <deal.II/dofs/dof_tools.h>
#include <deal.II/fe/fe_q.h>
#include <deal.II/fe/fe_values.h>
#include <deal.II/grid/grid_generator.h>
#include <deal.II/grid/grid_out.h>
#include <deal.II/grid/grid_refinement.h>
#include <deal.II/grid/tria.h>
#include <deal.II/grid/tria_accessor.h>
#include <deal.II/grid/tria_iterator.h>
#include <deal.II/lac/constraint_matrix.h>
#include <deal.II/lac/dynamic_sparsity_pattern.h>
#include <deal.II/lac/full_matrix.h>
#include <deal.II/lac/precondition.h>
#include <deal.II/lac/solver_bicgstab.h>
#include <deal.II/lac/sparse_matrix.h>
#include <deal.II/lac/vector.h>
#include <deal.II/numerics/data_out.h>
#include <deal.II/numerics/matrix_tools.h>
#include <deal.II/numerics/vector_tools.h>

#include <deal.II/base/multithread_info.h>
#include <deal.II/base/work_stream.h>

#include <deal.II/base/tensor_function.h>

#include <deal.II/numerics/error_estimator.h>

#include <ginkgo/ginkgo.hpp>

#include <fstream>
#include <iostream>


namespace Step9 {
using namespace dealii;


template <int dim>
class AdvectionProblem {
public:
```

```
    AdvectionProblem();
    ~AdvectionProblem();
    void run();

private:
    void setup_system();

    struct AssemblyScratchData {
        AssemblyScratchData(const FiniteElement<dim> &fe);
        AssemblyScratchData(const AssemblyScratchData &scratch_data);

        FEValues<dim> fe_values;
        FEFaceValues<dim> fe_face_values;
    };

    struct AssemblyCopyData {
        FullMatrix<double> cell_matrix;
        Vector<double> cell_rhs;
        std::vector<types::global_dof_index> local_dof_indices;
    };

    void assemble_system();
    void local_assemble_system(
        const typename DoFHandler<dim>::active_cell_iterator &cell,
        AssemblyScratchData &scratch, AssemblyCopyData &copy_data);
    void copy_local_to_global(const AssemblyCopyData &copy_data);


    void solve();
    void refine_grid();
    void output_results(const unsigned int cycle) const;

    Triangulation<dim> triangulation;
    DoFHandler<dim> dof_handler;

    FE_Q<dim> fe;

    ConstraintMatrix hanging_node_constraints;

    SparsityPattern sparsity_pattern;
    SparseMatrix<double> system_matrix;

    Vector<double> solution;
    Vector<double> system_rhs;
};



template <int dim>
class AdvectionField : public TensorFunction<1, dim> {
public:
    AdvectionField() : TensorFunction<1, dim>() {}

    virtual Tensor<1, dim> value(const Point<dim> &p) const;

    virtual void value_list(const std::vector<Point<dim>> &points,
                            std::vector<Tensor<1, dim>> &values) const;

    DeclException2(ExcDimensionMismatch, unsigned int, unsigned int,
                   << "The vector has size " << arg1 << " but should have "
                   << arg2 << " elements.");
};


template <int dim>
Tensor<1, dim> AdvectionField<dim>::value(const Point<dim> &p) const
{
    Point<dim> value;
    value[0] = 2;
    for (unsigned int i = 1; i < dim; ++i)
        value[i] = 1 + 0.8 * std::sin(8 * numbers::PI * p[0]);

    return value;
}


template <int dim>
void AdvectionField<dim>::value_list(const std::vector<Point<dim>> &points,
                                     std::vector<Tensor<1, dim>> &values) const
{
    Assert(values.size() == points.size(),
           ExcDimensionMismatch(values.size(), points.size()));

    for (unsigned int i = 0; i < points.size(); ++i)
        values[i] = AdvectionField<dim>::value(points[i]);
}
```

```
template <int dim>
class RightHandSide : public Function<dim> {
public:
    RightHandSide() : Function<dim>() {}

    virtual double value(const Point<dim> &p,
                         const unsigned int component = 0) const;

    virtual void value_list(const std::vector<Point<dim>> &points,
                            std::vector<double> &values,
                            const unsigned int component = 0) const;

private:
    static const Point<dim> center_point;
};


template <>
const Point<1> RightHandSide<1>::center_point = Point<1>(-0.75);

template <>
const Point<2> RightHandSide<2>::center_point = Point<2>(-0.75, -0.75);

template <>
const Point<3> RightHandSide<3>::center_point = Point<3>(-0.75, -0.75, -0.75);


template <int dim>
double RightHandSide<dim>::value(const Point<dim> &p,
                                 const unsigned int component) const
{
    (void)component;
    Assert(component == 0, ExcIndexRange(component, 0, 1));
    const double diameter = 0.1;
    return ((p - center_point).norm_square() < diameter * diameter
            ? .1 / std::pow(diameter, dim)
            : 0);
}


template <int dim>
void RightHandSide<dim>::value_list(const std::vector<Point<dim>> &points,
                                    std::vector<double> &values,
                                    const unsigned int component) const
{
    Assert(values.size() == points.size(),
           ExcDimensionMismatch(values.size(), points.size()));

    for (unsigned int i = 0; i < points.size(); ++i)
        values[i] = RightHandSide<dim>::value(points[i], component);
}


template <int dim>
class BoundaryValues : public Function<dim> {
public:
    BoundaryValues() : Function<dim>() {}

    virtual double value(const Point<dim> &p,
                         const unsigned int component = 0) const;

    virtual void value_list(const std::vector<Point<dim>> &points,
                            std::vector<double> &values,
                            const unsigned int component = 0) const;
};


template <int dim>
double BoundaryValues<dim>::value(const Point<dim> &p,
                                  const unsigned int component) const
{
    (void)component;
    Assert(component == 0, ExcIndexRange(component, 0, 1));

    const double sine_term =
        std::sin(16 * numbers::PI * std::sqrt(p.norm_square()));
    const double weight = std::exp(-5 * p.norm_square()) / std::exp(-5.);
    return sine_term * weight;
}


template <int dim>
void BoundaryValues<dim>::value_list(const std::vector<Point<dim>> &points,
                                     std::vector<double> &values,
                                     const unsigned int component) const
{
```

```
    Assert(values.size() == points.size(),
           ExcDimensionMismatch(values.size(), points.size()));

    for (unsigned int i = 0; i < points.size(); ++i)
        values[i] = BoundaryValues<dim>::value(points[i], component);
}



class GradientEstimation {
public:
    template <int dim>
    static void estimate(const DoFHandler<dim> &dof,
                         const Vector<double> &solution,
                         Vector<float> &error_per_cell);

    DeclException2(ExcInvalidVectorLength, int, int,
                   << "Vector has length " << arg1 << ", but should have "
                   << arg2);
    DeclException0(ExcInsufficientDirections);

private:
    template <int dim>
    struct EstimateScratchData {
        EstimateScratchData(const FiniteElement<dim> &fe,
                            const Vector<double> &solution,
                            Vector<float> &error_per_cell);
        EstimateScratchData(const EstimateScratchData &data);

        FEValues<dim> fe_midpoint_value;
        const Vector<double> &solution;
        Vector<float> &error_per_cell;
    };

    struct EstimateCopyData {};

    template <int dim>
    static void estimate_cell(
        const typename DoFHandler<dim>::active_cell_iterator &cell,
        EstimateScratchData<dim> &scratch_data,
        const EstimateCopyData &copy_data);
};




template <int dim>
AdvectionProblem<dim>::AdvectionProblem() : dof_handler(triangulation), fe(1)
{}


template <int dim>
AdvectionProblem<dim>::~AdvectionProblem()
{
    dof_handler.clear();
}


template <int dim>
void AdvectionProblem<dim>::setup_system()
{
    dof_handler.distribute_dofs(fe);
    hanging_node_constraints.clear();
    DoFTools::make_hanging_node_constraints(dof_handler,
                                            hanging_node_constraints);
    hanging_node_constraints.close();

    DynamicSparsityPattern dsp(dof_handler.n_dofs(), dof_handler.n_dofs());
    DoFTools::make_sparsity_pattern(dof_handler, dsp, hanging_node_constraints,
                                    /*keep_constrained_dofs = */ true);
    sparsity_pattern.copy_from(dsp);

    system_matrix.reinit(sparsity_pattern);

    solution.reinit(dof_handler.n_dofs());
    system_rhs.reinit(dof_handler.n_dofs());
}


template <int dim>
void AdvectionProblem<dim>::assemble_system()
{
    WorkStream::run(dof_handler.begin_active(), dof_handler.end(), *this,
                    &AdvectionProblem::local_assemble_system,
                    &AdvectionProblem::copy_local_to_global,
                    AssemblyScratchData(fe), AssemblyCopyData());
```

```
    hanging_node_constraints.condense(system_matrix);
    hanging_node_constraints.condense(system_rhs);
}


template <int dim>
AdvectionProblem<dim>::AssemblyScratchData::AssemblyScratchData(
    const FiniteElement<dim> &fe)
    : fe_values(fe, QGauss<dim>(2),
                update_values | update_gradients | update_quadrature_points |
                    update_JxW_values),
      fe_face_values(fe, QGauss<dim - 1>(2),
                     update_values | update_quadrature_points |
                         update_JxW_values | update_normal_vectors)
{}


template <int dim>
AdvectionProblem<dim>::AssemblyScratchData::AssemblyScratchData(
    const AssemblyScratchData &scratch_data)
    : fe_values(scratch_data.fe_values.get_fe(),
                scratch_data.fe_values.get_quadrature(),
                update_values | update_gradients | update_quadrature_points |
                    update_JxW_values),
      fe_face_values(scratch_data.fe_face_values.get_fe(),
                     scratch_data.fe_face_values.get_quadrature(),
                     update_values | update_quadrature_points |
                         update_JxW_values | update_normal_vectors)
{}


template <int dim>
void AdvectionProblem<dim>::local_assemble_system(
    const typename DoFHandler<dim>::active_cell_iterator &cell,
    AssemblyScratchData &scratch_data, AssemblyCopyData &copy_data)
{
    const AdvectionField<dim> advection_field;
    const RightHandSide<dim> right_hand_side;
    const BoundaryValues<dim> boundary_values;

    const unsigned int dofs_per_cell = fe.dofs_per_cell;
    const unsigned int n_q_points =
        scratch_data.fe_values.get_quadrature().size();
    const unsigned int n_face_q_points =
        scratch_data.fe_face_values.get_quadrature().size();

    copy_data.cell_matrix.reinit(dofs_per_cell, dofs_per_cell);
    copy_data.cell_rhs.reinit(dofs_per_cell);

    copy_data.local_dof_indices.resize(dofs_per_cell);

    std::vector<double> rhs_values(n_q_points);
    std::vector<Tensor<1, dim>> advection_directions(n_q_points);
    std::vector<double> face_boundary_values(n_face_q_points);
    std::vector<Tensor<1, dim>> face_advection_directions(n_face_q_points);


    scratch_data.fe_values.reinit(cell);

    advection_field.value_list(scratch_data.fe_values.get_quadrature_points(),
                               advection_directions);
    right_hand_side.value_list(scratch_data.fe_values.get_quadrature_points(),
                               rhs_values);

    const double delta = 0.1 * cell->diameter();

    for (unsigned int q_point = 0; q_point < n_q_points; ++q_point)
        for (unsigned int i = 0; i < dofs_per_cell; ++i) {
            for (unsigned int j = 0; j < dofs_per_cell; ++j)
                copy_data.cell_matrix(i, j) +=
                    ((advection_directions[q_point] *
                      scratch_data.fe_values.shape_grad(j, q_point) *
                      (scratch_data.fe_values.shape_value(i, q_point) +
                       delta *
                           (advection_directions[q_point] *
                            scratch_data.fe_values.shape_grad(i, q_point)))) *
                     scratch_data.fe_values.JxW(q_point));

            copy_data.cell_rhs(i) +=
                ((scratch_data.fe_values.shape_value(i, q_point) +
                  delta * (advection_directions[q_point] *
                           scratch_data.fe_values.shape_grad(i, q_point))) *
                 rhs_values[q_point] * scratch_data.fe_values.JxW(q_point));
        }

    for (unsigned int face = 0; face < GeometryInfo<dim>::faces_per_cell;
```

```
         ++face)
        if (cell->face(face)->at_boundary()) {
            scratch_data.fe_face_values.reinit(cell, face);

            boundary_values.value_list(
                scratch_data.fe_face_values.get_quadrature_points(),
                face_boundary_values);
            advection_field.value_list(
                scratch_data.fe_face_values.get_quadrature_points(),
                face_advection_directions);

            for (unsigned int q_point = 0; q_point < n_face_q_points; ++q_point)
                if (scratch_data.fe_face_values.normal_vector(q_point) *
                        face_advection_directions[q_point] <
                    0)
                    for (unsigned int i = 0; i < dofs_per_cell; ++i) {
                        for (unsigned int j = 0; j < dofs_per_cell; ++j)
                            copy_data.cell_matrix(i, j) -=
                                (face_advection_directions[q_point] *
                                 scratch_data.fe_face_values.normal_vector(
                                     q_point) *
                                 scratch_data.fe_face_values.shape_value(
                                     i, q_point) *
                                 scratch_data.fe_face_values.shape_value(
                                     j, q_point) *
                                 scratch_data.fe_face_values.JxW(q_point));

                        copy_data.cell_rhs(i) -=
                            (face_advection_directions[q_point] *
                             scratch_data.fe_face_values.normal_vector(
                                 q_point) *
                             face_boundary_values[q_point] *
                             scratch_data.fe_face_values.shape_value(i,
                                                                     q_point) *
                             scratch_data.fe_face_values.JxW(q_point));
                    }
        }


    cell->get_dof_indices(copy_data.local_dof_indices);
}


template <int dim>
void AdvectionProblem<dim>::copy_local_to_global(
    const AssemblyCopyData &copy_data)
{
    for (unsigned int i = 0; i < copy_data.local_dof_indices.size(); ++i) {
        for (unsigned int j = 0; j < copy_data.local_dof_indices.size(); ++j)
            system_matrix.add(copy_data.local_dof_indices[i],
                              copy_data.local_dof_indices[j],
                              copy_data.cell_matrix(i, j));

        system_rhs(copy_data.local_dof_indices[i]) += copy_data.cell_rhs(i);
    }
}

template <int dim>
void AdvectionProblem<dim>::solve()
{
    Assert(system_matrix.m() == system_matrix.n(), ExcNotQuadratic());
    auto num_rows = system_matrix.m();

    std::vector<double> rhs(num_rows);
    std::copy(system_rhs.begin(), system_rhs.begin() + num_rows, rhs.begin());

    using vec = gko::matrix::Dense<>;
    using mtx = gko::matrix::Csr<>;
    using bicgstab = gko::solver::Bicgstab<>;
    using bj = gko::preconditioner::Jacobi<>;
    using val_array = gko::Array<double>;

    std::shared_ptr<gko::Executor> exec = gko::ReferenceExecutor::create();

    auto b = vec::create(exec, gko::dim<2>(num_rows, 1),
                         val_array::view(exec, num_rows, rhs.data()), 1);
    auto x = vec::create(exec, gko::dim<2>(num_rows, 1));
    auto A = mtx::create(exec, gko::dim<2>(num_rows),
                         system_matrix.n_nonzero_elements());
    mtx::value_type *values = A->get_values();
    mtx::index_type *row_ptr = A->get_row_ptrs();
    mtx::index_type *col_idx = A->get_col_idxs();

    row_ptr[0] = 0;
    for (auto row = 1; row <= num_rows; ++row) {
        row_ptr[row] = row_ptr[row - 1] + system_matrix.get_row_length(row - 1);
    }
```

```
    std::vector<mtx::index_type> ptrs(num_rows + 1);
    std::copy(A->get_row_ptrs(), A->get_row_ptrs() + num_rows + 1,
              ptrs.begin());
    for (auto row = 0; row < system_matrix.m(); ++row) {
        for (auto p = system_matrix.begin(row); p != system_matrix.end(row);
             ++p) {
            col_idx[ptrs[row]] = p->column();
            values[ptrs[row]] = p->value();

            ++ptrs[row];
        }
    }

    auto solver_gen =
        bicgstab::build()
            .with_criteria(
                gko::stop::Iteration::build().with_max_iters(1000).on(exec),
                gko::stop::ResidualNormReduction<>::build()
                    .with_reduction_factor(1e-12)
                    .on(exec))
            .with_preconditioner(bj::build().on(exec))
            .on(exec);
    auto solver = solver_gen->generate(gko::give(A));

    solver->apply(gko::lend(b), gko::lend(x));

    std::copy(x->get_values(), x->get_values() + num_rows, solution.begin());

    /*******************************************************
     * deal.ii internal solver. Here for reference.
     SolverControl           solver_control (1000, 1e-12);
     SolverBicgstab<>        bicgstab (solver_control);

     PreconditionJacobi<> preconditioner;
     preconditioner.initialize(system_matrix, 1.0);

     bicgstab.solve (system_matrix, solution, system_rhs,
                     preconditioner);
    *******************************************************/

    hanging_node_constraints.distribute(solution);
}


template <int dim>
void AdvectionProblem<dim>::refine_grid()
{
    Vector<float> estimated_error_per_cell(triangulation.n_active_cells());

    GradientEstimation::estimate(dof_handler, solution,
                                 estimated_error_per_cell);

    GridRefinement::refine_and_coarsen_fixed_number(
        triangulation, estimated_error_per_cell, 0.5, 0.03);

    triangulation.execute_coarsening_and_refinement();
}


template <int dim>
void AdvectionProblem<dim>::output_results(const unsigned int cycle) const
{
    {
        GridOut grid_out;
        std::ofstream output("grid-" + std::to_string(cycle) + ".eps");
        grid_out.write_eps(triangulation, output);
    }

    {
        DataOut<dim> data_out;
        data_out.attach_dof_handler(dof_handler);
        data_out.add_data_vector(solution, "solution");
        data_out.build_patches();

        std::ofstream output("solution-" + std::to_string(cycle) + ".vtk");
        data_out.write_vtk(output);
    }
}


template <int dim>
void AdvectionProblem<dim>::run()
{
    for (unsigned int cycle = 0; cycle < 6; ++cycle) {
        std::cout << "Cycle " << cycle << ':' << std::endl;
```

```
        if (cycle == 0) {
            GridGenerator::hyper_cube(triangulation, -1, 1);
            triangulation.refine_global(4);
        } else {
            refine_grid();
        }


        std::cout << "   Number of active cells:       "
                  << triangulation.n_active_cells() << std::endl;

        setup_system();

        std::cout << "   Number of degrees of freedom: " << dof_handler.n_dofs()
                  << std::endl;

        assemble_system();
        solve();
        output_results(cycle);
    }
}



template <int dim>
GradientEstimation::EstimateScratchData<dim>::EstimateScratchData(
    const FiniteElement<dim> &fe, const Vector<double> &solution,
    Vector<float> &error_per_cell)
    : fe_midpoint_value(fe, QMidpoint<dim>(),
                        update_values | update_quadrature_points),
      solution(solution),
      error_per_cell(error_per_cell)
{}


template <int dim>
GradientEstimation::EstimateScratchData<dim>::EstimateScratchData(
    const EstimateScratchData &scratch_data)
    : fe_midpoint_value(scratch_data.fe_midpoint_value.get_fe(),
                        scratch_data.fe_midpoint_value.get_quadrature(),
                        update_values | update_quadrature_points),
      solution(scratch_data.solution),
      error_per_cell(scratch_data.error_per_cell)
{}


template <int dim>
void GradientEstimation::estimate(const DoFHandler<dim> &dof_handler,
                                  const Vector<double> &solution,
                                  Vector<float> &error_per_cell)
{
    Assert(error_per_cell.size() ==
               dof_handler.get_triangulation().n_active_cells(),
           ExcInvalidVectorLength(
               error_per_cell.size(),
               dof_handler.get_triangulation().n_active_cells()));

    WorkStream::run(dof_handler.begin_active(), dof_handler.end(),
                    &GradientEstimation::template estimate_cell<dim>,
                    std::function<void(const EstimateCopyData &)>(),
                    EstimateScratchData<dim>(dof_handler.get_fe(), solution,
                                             error_per_cell),
                    EstimateCopyData());
}


template <int dim>
void GradientEstimation::estimate_cell(
    const typename DoFHandler<dim>::active_cell_iterator &cell,
    EstimateScratchData<dim> &scratch_data, const EstimateCopyData &)
{
    Tensor<2, dim> Y;


    std::vector<typename DoFHandler<dim>::active_cell_iterator>
        active_neighbors;
    active_neighbors.reserve(GeometryInfo<dim>::faces_per_cell *
                             GeometryInfo<dim>::max_children_per_face);

    scratch_data.fe_midpoint_value.reinit(cell);

    Tensor<1, dim> projected_gradient;


    active_neighbors.clear();
    for (unsigned int face_no = 0; face_no < GeometryInfo<dim>::faces_per_cell;
         ++face_no)
```

```
        if (!cell->at_boundary(face_no)) {
            const typename DoFHandler<dim>::face_iterator face =
                cell->face(face_no);
            const typename DoFHandler<dim>::cell_iterator neighbor =
                cell->neighbor(face_no);

            if (neighbor->active())
                active_neighbors.push_back(neighbor);
            else {
                if (dim == 1) {
                    typename DoFHandler<dim>::cell_iterator neighbor_child =
                        neighbor;
                    while (neighbor_child->has_children())
                        neighbor_child =
                            neighbor_child->child(face_no == 0 ? 1 : 0);

                    Assert(
                        neighbor_child->neighbor(face_no == 0 ? 1 : 0) == cell,
                        ExcInternalError());

                    active_neighbors.push_back(neighbor_child);
                } else
                    for (unsigned int subface_no = 0;
                         subface_no < face->n_children(); ++subface_no)
                        active_neighbors.push_back(
                            cell->neighbor_child_on_subface(face_no,
                                                            subface_no));
            }
        }

    const Point<dim> this_center =
        scratch_data.fe_midpoint_value.quadrature_point(0);

    std::vector<double> this_midpoint_value(1);
    scratch_data.fe_midpoint_value.get_function_values(scratch_data.solution,
                                                       this_midpoint_value);


    std::vector<double> neighbor_midpoint_value(1);
    typename std::vector<typename DoFHandler<dim>::active_cell_iterator>::
        const_iterator neighbor_ptr = active_neighbors.begin();
    for (; neighbor_ptr != active_neighbors.end(); ++neighbor_ptr) {
        const typename DoFHandler<dim>::active_cell_iterator neighbor =
            *neighbor_ptr;

        scratch_data.fe_midpoint_value.reinit(neighbor);
        const Point<dim> neighbor_center =
            scratch_data.fe_midpoint_value.quadrature_point(0);

        scratch_data.fe_midpoint_value.get_function_values(
            scratch_data.solution, neighbor_midpoint_value);

        Tensor<1, dim> y = neighbor_center - this_center;
        const double distance = y.norm();
        y /= distance;

        for (unsigned int i = 0; i < dim; ++i)
            for (unsigned int j = 0; j < dim; ++j) Y[i][j] += y[i] * y[j];

        projected_gradient +=
            (neighbor_midpoint_value[0] - this_midpoint_value[0]) / distance *
            y;
    }

    AssertThrow(determinant(Y) != 0, ExcInsufficientDirections());

    const Tensor<2, dim> Y_inverse = invert(Y);

    Tensor<1, dim> gradient = Y_inverse * projected_gradient;

    scratch_data.error_per_cell(cell->active_cell_index()) =
        (std::pow(cell->diameter(), 1 + 1.0 * dim / 2) *
         std::sqrt(gradient.norm_square()));
}
}  // namespace Step9


int main()
{
    try {
        dealii::MultithreadInfo::set_thread_limit();

        Step9::AdvectionProblem<2> advection_problem_2d;
        advection_problem_2d.run();
    } catch (std::exception &exc) {
        std::cerr << std::endl
```

```
                    << std::endl
                    << "---------------------------------------------------"
                    << std::endl;
        std::cerr << "Exception on processing: " << std::endl
                    << exc.what() << std::endl
                    << "Aborting!" << std::endl
                    << "---------------------------------------------------"
                    << std::endl;
        return 1;
    } catch (...) {
        std::cerr << std::endl
                    << std::endl
                    << "---------------------------------------------------"
                    << std::endl;
        std::cerr << "Unknown exception!" << std::endl
                    << "Aborting!" << std::endl
                    << "---------------------------------------------------"
                    << std::endl;
        return 1;
    }

    return 0;
}
```

Chapter 10

The ginkgo-overhead program

The ginkgo overhead measurement example.

Introduction

About the example

The commented program

```
#include <ginkgo/ginkgo.hpp>


#include <chrono>
#include <cmath>
#include <iostream>


[[noreturn]] void print_usage_and_exit(const char *name)
{
    std::cerr << "Usage: " << name << " [NUM_ITERS]" << std::endl;
    std::exit(-1);
}


int main(int argc, char *argv[])
{
    using vec = gko::matrix::Dense<>;
    using mtx = gko::matrix::Dense<>;
    using cg = gko::solver::Cg<>;

    long unsigned num_iters = 1000000;
    if (argc > 2) {
        print_usage_and_exit(argv[0]);
    }
    if (argc == 2) {
        num_iters = std::atol(argv[1]);
        if (num_iters == 0) {
            print_usage_and_exit(argv[0]);
        }
    }

    std::cout << gko::version_info::get() << std::endl;

    auto exec = gko::ReferenceExecutor::create();

    auto cg_factory =
        cg::build()
            .with_criteria(
                gko::stop::Iteration::build().with_max_iters(num_iters).on(
                    exec))
            .on(exec);
```

```
    auto A = gko::initialize<mtx>({1.0}, exec);
    auto b = gko::initialize<vec>({std::nan("")}, exec);
    auto x = gko::initialize<vec>({0.0}, exec);

    auto tic = std::chrono::steady_clock::now();

    auto solver = cg_factory->generate(gko::give(A));
    solver->apply(lend(x), lend(b));
    exec->synchronize();

    auto tac = std::chrono::steady_clock::now();

    auto time = std::chrono::duration_cast<std::chrono::nanoseconds>(tac - tic);
    std::cout << "Running " << num_iters
              << " iterations of the CG solver took a total of "
              << 1.0 * time.count() / std::nano::den << " seconds." << std::endl
              << "\tAverage library overhead:     "
              << 1.0 * time.count() / num_iters << " [nanoseconds / iteration]"
              << std::endl;
}
```

Results

This is the expected output:

```
Running 1000000 iterations of the CG solver took a total of 1.50535 seconds.
        Average library overhead:     1505.35 [nanoseconds / iteration]
```

Comments about programming and debugging

The plain program

```
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#include <ginkgo/ginkgo.hpp>


#include <chrono>
#include <cmath>
#include <iostream>
```

```
[[noreturn]] void print_usage_and_exit(const char *name)
{
    std::cerr << "Usage: " << name << " [NUM_ITERS]" << std::endl;
    std::exit(-1);
}


int main(int argc, char *argv[])
{
    using vec = gko::matrix::Dense<>;
    using mtx = gko::matrix::Dense<>;
    using cg = gko::solver::Cg<>;

    long unsigned num_iters = 1000000;
    if (argc > 2) {
        print_usage_and_exit(argv[0]);
    }
    if (argc == 2) {
        num_iters = std::atol(argv[1]);
        if (num_iters == 0) {
            print_usage_and_exit(argv[0]);
        }
    }

    std::cout << gko::version_info::get() << std::endl;

    auto exec = gko::ReferenceExecutor::create();

    auto cg_factory =
        cg::build()
            .with_criteria(
                gko::stop::Iteration::build().with_max_iters(num_iters).on(
                    exec))
            .on(exec);
    auto A = gko::initialize<mtx>({1.0}, exec);
    auto b = gko::initialize<vec>({std::nan("")}, exec);
    auto x = gko::initialize<vec>({0.0}, exec);

    auto tic = std::chrono::steady_clock::now();

    auto solver = cg_factory->generate(gko::give(A));
    solver->apply(lend(x), lend(b));
    exec->synchronize();

    auto tac = std::chrono::steady_clock::now();

    auto time = std::chrono::duration_cast<std::chrono::nanoseconds>(tac - tic);
    std::cout << "Running " << num_iters
              << " iterations of the CG solver took a total of "
              << 1.0 * time.count() / std::nano::den << " seconds." << std::endl
              << "\tAverage library overhead:     "
              << 1.0 * time.count() / num_iters << " [nanoseconds / iteration]"
              << std::endl;
}
```

Chapter 11

The ginkgo-ranges program

The ranges and accessor example.

Introduction

About the example

The commented program

```
#include <ginkgo/ginkgo.hpp>
#include <iomanip>
#include <iostream>
```

LU factorization implementation using Ginkgo ranges For simplicity, we only consider square matrices, and no pivoting.

```
template <typename Accessor>
void factorize(const gko::range<Accessor> &A)
```

note: const means that the range (i.e. the data handler) is constant, not that the underlying data is constant!

```
{
    using gko::span;
    assert(A.length(0) == A.length(1));
    for (gko::size_type i = 0; i < A.length(0) - 1; ++i) {
        const auto trail = span{i + 1, A.length(0)};
```

note: neither of the lines below need additional memory to store intermediate arrays, all computation is done at the point of assignment

```
A(trail, i) = A(trail, i) / A(i, i);
```

caveat: operator $*$ is element-wise multiplication, mmul is matrix multiplication

```
        A(trail, trail) = A(trail, trail) - mmul(A(trail, i), A(i, trail));
    }
}
```

a utility function for printing the factorization on screen

```
template <typename Accessor>
void print_lu(const gko::range<Accessor> &A)
{
    std::cout << std::setprecision(2) << std::fixed;
    std::cout << "L = [";
    for (int i = 0; i < A.length(0); ++i) {
        std::cout << "\n  ";
        for (int j = 0; j < A.length(1); ++j) {
            std::cout << (i > j ? A(i, j) : (i == j) * 1.) << " ";
        }
    }
    std::cout << "\n]\n\nU = [";
    for (int i = 0; i < A.length(0); ++i) {
        std::cout << "\n  ";
        for (int j = 0; j < A.length(1); ++j) {
            std::cout << (i <= j ? A(i, j) : 0.) << " ";
        }
    }
    std::cout << "\n]" << std::endl;
}

int main(int argc, char *argv[])
{
```

Print version information

```
std::cout << gko::version_info::get() << std::endl;
```

Create some test data, add some padding just to demonstrate how to use it with ranges. clang-format off

```
double data[] = {
    2.,  4.,  5., -1.0,
    4., 11., 12., -1.0,
    6., 24., 24., -1.0
};
```

clang-format on

Create a 3-by-3 range, with a 2D row-major accessor using data as the underlying storage. Set the stride (a.k.a. "LDA") to 4.

```
auto A = gko::range<gko::accessor::row_major<double, 2>>(data
      , 3u, 3u, 4u);
```

use the LU factorization routine defined above to factorize the matrix

```
factorize(A);
```

print the factorization on screen

```
    print_lu(A);
}
```

Results

This is the expected output:

```
L = [
  1.00 0.00 0.00
  2.00 1.00 0.00
  3.00 4.00 1.00
]

U = [
  2.00 4.00 5.00
  0.00 3.00 2.00
  0.00 0.00 1.00
]
```

Comments about programming and debugging

The plain program

```
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#include <ginkgo/ginkgo.hpp>
#include <iomanip>
#include <iostream>


template <typename Accessor>
void factorize(const gko::range<Accessor> &A)
{
    using gko::span;
    assert(A.length(0) == A.length(1));
    for (gko::size_type i = 0; i < A.length(0) - 1; ++i) {
        const auto trail = span{i + 1, A.length(0)};
        A(trail, i) = A(trail, i) / A(i, i);
        A(trail, trail) = A(trail, trail) - mmul(A(trail, i), A(i, trail));
    }
}


template <typename Accessor>
void print_lu(const gko::range<Accessor> &A)
{
    std::cout << std::setprecision(2) << std::fixed;
    std::cout << "L = [";
    for (int i = 0; i < A.length(0); ++i) {
        std::cout << "\n  ";
```

```
        for (int j = 0; j < A.length(1); ++j) {
            std::cout << (i > j ? A(i, j) : (i == j) * 1.) << " ";
        }
    }
    std::cout << "\n]\n\nU = [";
    for (int i = 0; i < A.length(0); ++i) {
        std::cout << "\n  ";
        for (int j = 0; j < A.length(1); ++j) {
            std::cout << (i <= j ? A(i, j) : 0.) << " ";
        }
    }
    std::cout << "\n]" << std::endl;
}


int main(int argc, char *argv[])
{
    std::cout << gko::version_info::get() << std::endl;

    double data[] = {
        2.,  4.,  5., -1.0,
        4., 11., 12., -1.0,
        6., 24., 24., -1.0
    };

    auto A = gko::range<gko::accessor::row_major<double, 2>>(
      data, 3u, 3u, 4u);

    factorize(A);

    print_lu(A);
}
```

Chapter 12

The inverse-iteration program

The inverse iteration example.

This example depends on simple-solver, .

Introduction

This example shows how components available in Ginkgo can be used to implement higher-level numerical methods. The method used here will be the shifted inverse iteration method for eigenvalue computation which find the eigenvalue and eigenvector of A closest to z, for some scalar z. The method requires repeatedly solving the shifted linear system (A - zI)x = b, as well as performing matrix-vector products with the matrix `A`. Here is the complete pseudocode of the method:

```
x_0 = initial guess
for i = 0 .. max_iterations:
    solve (A - zI) y_i = x_i for y_i+1
    x_(i+1) = y_i / || y_i ||      # compute next eigenvector approximation
    g_(i+1) = x_(i+1)^* A x_(i+1)  # approximate eigenvalue (Rayleigh quotient)
    if ||A x_(i+1) - g_(i+1)x_(i+1)|| < tol * g_(i+1):  # check convergence
        break
```

About the example

The commented program

```
#include <ginkgo/ginkgo.hpp>


#include <cmath>
#include <complex>
#include <fstream>
#include <iomanip>
#include <iostream>
#include <string>


int main(int argc, char *argv[])
{
```

Some shortcuts

```
using precision = std::complex<double>;
using real_precision = double;
using vec = gko::matrix::Dense<precision>;
using mtx = gko::matrix::Csr<precision>;
using solver_type = gko::solver::Bicgstab<precision>;

using std::abs;
using std::sqrt;
```

Print version information

```
std::cout << gko::version_info::get() << std::endl;

std::cout << std::scientific << std::setprecision(8) << std::showpos;
```

Figure out where to run the code

```
std::shared_ptr<gko::Executor> exec;
if (argc == 1 || std::string(argv[1]) == "reference") {
    exec = gko::ReferenceExecutor::create();
} else if (argc == 2 && std::string(argv[1]) == "omp") {
    exec = gko::OmpExecutor::create();
} else if (argc == 2 && std::string(argv[1]) == "cuda" &&
           gko::CudaExecutor::get_num_devices() > 0) {
    exec = gko::CudaExecutor::create(0,
      gko::OmpExecutor::create());
} else {
    std::cerr << "Usage: " << argv[0] << " [executor]" << std::endl;
    std::exit(-1);
}

auto this_exec = exec->get_master();
```

linear system solver parameters

```
auto system_max_iterations = 100u;
auto system_residual_goal = real_precision{1e-16};
```

eigensolver parameters

```
auto max_iterations = 20u;
auto residual_goal = real_precision{1e-8};
auto z = precision{20.0, 2.0};
```

Read data

```
auto A = share(gko::read<mtx>(std::ifstream("data/A.mtx"), exec));
```

Generate shifted matrix A - zI

- we avoid duplicating memory by not storing both A and A - zI, but compute A - zI on the fly by using Ginkgo's utilities for creating linear combinations of operators

```
auto one = share(gko::initialize<vec>({precision{1.0}}, exec));
auto neg_one = share(gko::initialize<vec>({-precision{1.0}}, exec));
auto neg_z = gko::initialize<vec>({-z}, exec);

auto system_matrix = share(gko::Combination<precision>::create(
    one, A, gko::initialize<vec>({-z}, exec),
    gko::matrix::Identity<precision>::create(exec, A->get_size()[0]
      )));
```

Generate solver operator (A - zI)^-1

```
auto solver =
    solver_type::build()
        .with_criteria(gko::stop::Iteration::build()
                           .with_max_iters(system_max_iterations)
                           .on(exec),
                       gko::stop::ResidualNormReduction<precision>::build
      ()
                           .with_reduction_factor(system_residual_goal)
                           .on(exec))
        .on(exec)
        ->generate(system_matrix);
```

inverse iterations

start with guess [1, 1, ..., 1]

```
auto x = [&] {
    auto work = vec::create(this_exec, gko::dim<2>{A->get_size()[0], 1});
    const auto n = work->get_size()[0];
    for (int i = 0; i < n; ++i) {
        work->get_values()[i] = precision{1.0} / sqrt(n);
    }
    return clone(exec, work);
}();
auto y = clone(x);
auto tmp = clone(x);
auto norm = clone(one);
auto inv_norm = clone(this_exec, one);
auto g = clone(one);

for (auto i = 0u; i < max_iterations; ++i) {
    std::cout << "{ ";
```

(A - zI)y = x

```
solver->apply(lend(x), lend(y));
system_matrix->apply(lend(one), lend(y), lend(neg_one), lend(x));
x->compute_norm2(lend(norm));
std::cout << "\"system_residual\": "
          << clone(this_exec, norm)->get_values()[0] << ", ";
x->copy_from(lend(y));
```

x = y / || y ||

```
x->compute_norm2(lend(norm));
inv_norm->get_values()[0] =
    precision{1.0} / clone(this_exec, norm)->get_values()[0];
x->scale(lend(clone(exec, inv_norm)));
```

$g = x^\wedge * A x$

```
A->apply(lend(x), lend(tmp));
x->compute_dot(lend(tmp), lend(g));
auto g_val = clone(this_exec, g)->get_values()[0];
std::cout << "\"eigenvalue\": " << g_val << ", ";
```

$||Ax - gx|| < tol * g$

```
        auto v = gko::initialize<vec>({-g_val}, exec);
        tmp->add_scaled(lend(v), lend(x));
        tmp->compute_norm2(lend(norm));
        auto res_val = clone(exec->get_master(), norm)->get_values()[0];
        std::cout << "\"residual\": " << res_val / g_val << " }," << std::endl;
        if (abs(res_val) < residual_goal * abs(g_val)) {
            break;
        }
    }
}
```

Results

This is the expected output:

```
{ "system_residual": (+1.59066966e-14,+0.00000000e+00), "eigenvalue": (+2.03741410e+01,-5.42101086e-18), "
      residual": (+2.92231055e-01,+7.77548230e-20) },
{ "system_residual": (+6.38877157e-15,+0.00000000e+00), "eigenvalue": (+1.94878474e+01,-4.34534678e-16), "
      residual": (+7.94370276e-02,+1.77126506e-18) },
{ "system_residual": (+6.79215294e-15,+0.00000000e+00), "eigenvalue": (+1.93282121e+01,-3.68988781e-16), "
      residual": (+4.11149623e-02,+7.84912734e-19) },
{ "system_residual": (+3.54015578e-15,+0.00000000e+00), "eigenvalue": (+1.92638912e+01,+2.03949917e-16), "
      residual": (+2.34717040e-02,-2.48498708e-19) },
{ "system_residual": (+2.12400044e-15,+0.00000000e+00), "eigenvalue": (+1.92409166e+01,-7.59991100e-16), "
      residual": (+1.34709547e-02,+5.32085134e-19) },
{ "system_residual": (+3.29202859e-15,+0.00000000e+00), "eigenvalue": (+1.92331106e+01,+2.90110055e-15), "
      residual": (+7.72060707e-03,-1.16456760e-18) },
{ "system_residual": (+3.99088304e-15,+0.00000000e+00), "eigenvalue": (+1.92305014e+01,-3.21058733e-16), "
      residual": (+4.42106625e-03,+7.38109682e-20) },
{ "system_residual": (+2.02648035e-15,+0.00000000e+00), "eigenvalue": (+1.92296339e+01,+5.11222288e-16), "
      residual": (+2.53081312e-03,-6.72819919e-20) },
{ "system_residual": (+1.83840397e-15,+0.00000000e+00), "eigenvalue": (+1.92293461e+01,+3.51208924e-16), "
      residual": (+1.44862114e-03,-2.64579289e-20) },
{ "system_residual": (+1.60253167e-15,+0.00000000e+00), "eigenvalue": (+1.92292506e+01,-2.02284978e-15), "
      residual": (+8.29183451e-04,+8.72271932e-20) },
{ "system_residual": (+1.96758490e-15,+0.00000000e+00), "eigenvalue": (+1.92292190e+01,+8.90545453e-16), "
      residual": (+4.74636702e-04,-2.19814209e-20) },
{ "system_residual": (+1.53327380e-14,+0.00000000e+00), "eigenvalue": (+1.92292085e+01,-8.25871947e-17), "
      residual": (+2.71701077e-04,+1.16692425e-21) },
{ "system_residual": (+3.42985865e-15,+0.00000000e+00), "eigenvalue": (+1.92292051e+01,+1.63122796e-16), "
      residual": (+1.55539937e-04,-1.31945701e-21) },
{ "system_residual": (+3.30861071e-11,+0.00000000e+00), "eigenvalue": (+1.92292039e+01,-5.49102025e-16), "
      residual": (+8.90457139e-05,+2.54275643e-21) },
{ "system_residual": (+7.11155374e-14,+0.00000000e+00), "eigenvalue": (+1.92292035e+01,+1.16689376e-15), "
      residual": (+5.09805252e-05,-3.09367244e-21) },
{ "system_residual": (+2.68204494e-15,+0.00000000e+00), "eigenvalue": (+1.92292034e+01,-4.07084034e-17), "
      residual": (+2.91887365e-05,+6.17928281e-23) },
{ "system_residual": (+5.78377594e-13,+0.00000000e+00), "eigenvalue": (+1.92292034e+01,-3.38561848e-17), "
      residual": (+1.67126561e-05,+2.94253882e-23) },
{ "system_residual": (+6.26422040e-12,+0.00000000e+00), "eigenvalue": (+1.92292034e+01,-3.14429218e-18), "
      residual": (+9.56961199e-06,+1.56478953e-24) },
{ "system_residual": (+1.41104829e-12,+0.00000000e+00), "eigenvalue": (+1.92292033e+01,-6.54656730e-16), "
      residual": (+5.47975753e-06,+1.86557918e-22) },
{ "system_residual": (+1.97926842e-10,+0.00000000e+00), "eigenvalue": (+1.92292033e+01,+1.58008702e-16), "
      residual": (+3.13794996e-06,-2.57849164e-23) },
```

Comments about programming and debugging

The plain program

```
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```

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#include <ginkgo/ginkgo.hpp>


#include <cmath>
#include <complex>
#include <fstream>
#include <iomanip>
#include <iostream>
#include <string>


int main(int argc, char *argv[])
{
    using precision = std::complex<double>;
    using real_precision = double;
    using vec = gko::matrix::Dense<precision>;
    using mtx = gko::matrix::Csr<precision>;
    using solver_type = gko::solver::Bicgstab<precision>;

    using std::abs;
    using std::sqrt;

    std::cout << gko::version_info::get() << std::endl;

    std::cout << std::scientific << std::setprecision(8) << std::showpos;

    std::shared_ptr<gko::Executor> exec;
    if (argc == 1 || std::string(argv[1]) == "reference") {
        exec = gko::ReferenceExecutor::create();
    } else if (argc == 2 && std::string(argv[1]) == "omp") {
        exec = gko::OmpExecutor::create();
    } else if (argc == 2 && std::string(argv[1]) == "cuda" &&
               gko::CudaExecutor::get_num_devices() > 0) {
        exec = gko::CudaExecutor::create(0,
      gko::OmpExecutor::create());
    } else {
        std::cerr << "Usage: " << argv[0] << " [executor]" << std::endl;
        std::exit(-1);
    }

    auto this_exec = exec->get_master();

    auto system_max_iterations = 100u;
    auto system_residual_goal = real_precision{1e-16};

    auto max_iterations = 20u;
    auto residual_goal = real_precision{1e-8};
    auto z = precision{20.0, 2.0};

    auto A = share(gko::read<mtx>(std::ifstream("data/A.mtx"), exec));

    auto one = share(gko::initialize<vec>({precision{1.0}}, exec));
    auto neg_one = share(gko::initialize<vec>({-precision{1.0}}, exec));
    auto neg_z = gko::initialize<vec>({-z}, exec);

    auto system_matrix = share(gko::Combination<precision>::create(
        one, A, gko::initialize<vec>({-z}, exec),
        gko::matrix::Identity<precision>::create(exec, A->get_size(
      )[0])));

    auto solver =
        solver_type::build()
            .with_criteria(gko::stop::Iteration::build()
                               .with_max_iters(system_max_iterations)
                               .on(exec),
                           gko::stop::ResidualNormReduction<precision>::build
      ()
                               .with_reduction_factor(system_residual_goal)
                               .on(exec))
            .on(exec)
            ->generate(system_matrix);


    auto x = [&] {
        auto work = vec::create(this_exec, gko::dim<2>{A->get_size()[0], 1});
        const auto n = work->get_size()[0];
        for (int i = 0; i < n; ++i) {
            work->get_values()[i] = precision{1.0} / sqrt(n);
        }
        return clone(exec, work);
    }();
    auto y = clone(x);
    auto tmp = clone(x);
```

```
    auto norm = clone(one);
    auto inv_norm = clone(this_exec, one);
    auto g = clone(one);

    for (auto i = 0u; i < max_iterations; ++i) {
        std::cout << "{ ";
        solver->apply(lend(x), lend(y));
        system_matrix->apply(lend(one), lend(y), lend(neg_one), lend(x));
        x->compute_norm2(lend(norm));
        std::cout << "\"system_residual\": "
                  << clone(this_exec, norm)->get_values()[0] << ", ";
        x->copy_from(lend(y));
        x->compute_norm2(lend(norm));
        inv_norm->get_values()[0] =
            precision{1.0} / clone(this_exec, norm)->get_values()[0];
        x->scale(lend(clone(exec, inv_norm)));
        A->apply(lend(x), lend(tmp));
        x->compute_dot(lend(tmp), lend(g));
        auto g_val = clone(this_exec, g)->get_values()[0];
        std::cout << "\"eigenvalue\": " << g_val << ", ";
        auto v = gko::initialize<vec>({-g_val}, exec);
        tmp->add_scaled(lend(v), lend(x));
        tmp->compute_norm2(lend(norm));
        auto res_val = clone(exec->get_master(), norm)->get_values()[0];
        std::cout << "\"residual\": " << res_val / g_val << " }," << std::endl;
        if (abs(res_val) < residual_goal * abs(g_val)) {
            break;
        }
    }
}
```

Chapter 13

The minimal-cuda-solver program

The minimal CUDA solver example.

This example depends on simple-solver.

Introduction

This is a minimal example that solves a system with Ginkgo. The matrix, right hand side and initial guess are read from standard input, and the result is written to standard output. The system matrix is stored in CSR format, and the system solved using the CG method, preconditioned with the block-Jacobi preconditioner. All computations are done on the GPU.

The easiest way to use the example data from the data/ folder is to concatenate the matrix, the right hand side and the initial solution (in that exact order), and pipe the result to the minimal_solver_cuda executable:

```
cat data/A.mtx data/b.mtx data/x0.mtx | ./minimal_solver_cuda
```

About the example

The commented program

```
#include <ginkgo/ginkgo.hpp>
#include <iostream>

int main()
{
```

Instantiate a CUDA executor

```
auto gpu = gko::CudaExecutor::create(0,
      gko::OmpExecutor::create());
```

Read data

```
auto A = gko::read<gko::matrix::Csr<>>(std::cin, gpu);
auto b = gko::read<gko::matrix::Dense<>>(std::cin, gpu);
auto x = gko::read<gko::matrix::Dense<>>(std::cin, gpu);
```

Create the solver

```
auto solver =
    gko::solver::Cg<>::build()
        .with_preconditioner(gko::preconditioner::Jacobi<>::build().on(
      gpu))
        .with_criteria(
            gko::stop::Iteration::build().with_max_iters(20u).on(gpu),
            gko::stop::ResidualNormReduction<>::build()
                .with_reduction_factor(1e-15)
                .on(gpu))
        .on(gpu);
```

Solve system

```
solver->generate(give(A))->apply(lend(b), lend(x));
```

Write result

```
    write(std::cout, lend(x));
}
```

Results

The following is the expected result when using the data contained in the folder `data` as input:

```
%%MatrixMarket matrix array real general
19 1
0.252218
0.108645
0.0662811
0.0630433
0.0384088
0.0396536
0.0402648
0.0338935
0.0193098
0.0234653
0.0211499
0.0196413
0.0199151
0.0181674
0.0162722
0.0150714
0.0107016
0.0121141
0.0123025
```

Comments about programming and debugging

The plain program

```
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THEORY OF LIABILITY, WHETHER IN CONTRACT, STRICT LIABILITY, OR TORT
(INCLUDING NEGLIGENCE OR OTHERWISE) ARISING IN ANY WAY OUT OF THE USE
OF THIS SOFTWARE, EVEN IF ADVISED OF THE POSSIBILITY OF SUCH DAMAGE.
******************************<GINKGO LICENSE>*******************************/

#include <ginkgo/ginkgo.hpp>
#include <iostream>

int main()
{
    auto gpu = gko::CudaExecutor::create(0,
      gko::OmpExecutor::create());
    auto A = gko::read<gko::matrix::Csr<>>(std::cin, gpu);
    auto b = gko::read<gko::matrix::Dense<>>(std::cin, gpu);
    auto x = gko::read<gko::matrix::Dense<>>(std::cin, gpu);
    auto solver =
        gko::solver::Cg<>::build()
            .with_preconditioner(gko::preconditioner::Jacobi<>::build()
      .on(gpu))
            .with_criteria(
                gko::stop::Iteration::build().with_max_iters(20u).on(gpu),
                gko::stop::ResidualNormReduction<>::build()
                    .with_reduction_factor(1e-15)
                    .on(gpu))
            .on(gpu);
    solver->generate(give(A))->apply(lend(b), lend(x));
    write(std::cout, lend(x));
}
```

Chapter 14

The nine-pt-stencil-solver program

The 9-point stencil example.

This example depends on simple-solver, poisson-solver, three-pt-stencil-solve.

Introduction

This example solves a 2D Poisson equation:

[= (0,1)^2 \ = [0,1]^2 { (with boundary)} \ = \ u : -> R \ u'' = f \ u = u_D \ ]

using a finite difference method on an equidistant grid with `K` discretization points (`K` can be controlled with a command line parameter). The discretization may be done by any order Taylor polynomial. For an equidistant grid with K "inner" discretization points ((x1,y1), , (xk,y1),(x1,y2), , (xk,yk,z1)) step size (h = 1 / (K + 1)) and a stencil ({R}^{3 3}), the formula produces a system of linear equations

({a,b=-1}^1 stencil(a,b) $*$ u_{(i+a,j+b} = -f_k h^2), on any inner node with a neighborhood of inner nodes

On any node, where neighbor is on the border, the neighbor is replaced with a (-stencil(a,b) $*$ u_{i+a,j+b}) and added to the right hand side vector. For example a node with a neighborhood of only edge nodes may look like this

[{a,b=-1}^(1,0) stencil(a,b) $*$ u_{(i+a,j+b} = -f_k h^2 - {a=-1}^1 stencil(a,1) $*$ u_{(i+a,j+1}]

which is then solved using Ginkgo's implementation of the CG method preconditioned with block-Jacobi. It is also possible to specify on which executor Ginkgo will solve the system via the command line. The function `f` is set to (f(x,y) = 6x + 6y) (making the solution (u(x,y) = x^3

- y^3)), but that can be changed in the `main` function. Also the stencil values for the core, the faces, the edge and the corners can be changed when passing additional parameters.

The intention of this is to show how generation of stencil values and the right hand side vector changes when increasing the dimension.

About the example

The commented program

```
/ ****************************<DECSRIPTION>**********************************
This example solves a 2D Poisson equation:

    \Omega = (0,1)^2
    \Omega_b = [0,1]^2   (with boundary)
    \partial\Omega = \Omega_b \backslash \Omega
    u : \Omega_b -> R
    u'' = f in \Omega
    u = u_D on \partial\Omega

using a finite difference method on an equidistant grid with `K` discretization
points (`K` can be controlled with a command line parameter). The discretization
may be done by any order Taylor polynomial.
For an equidistant grid with K "inner" discretization points (x1,y1), ...,
(xk,y1),(x1,y2), ..., (xk,yk) step size h = 1 / (K + 1) and a stencil \in
\R^{3 x 3}, the formula produces a system of linear equations

\sum_{a,b=-1}^1 stencil(a,b) * u_{(i+a,j+b} = -f_k h^2,  on any inner node with
a neighborhood of inner nodes

On any node, where neighbor is on the border, the neighbor is replaced with a
'-stencil(a,b) * u_{i+a,j+b}' and added to the right hand side vector. For
example a node with a neighborhood of only edge nodes may look like this

\sum_{a,b=-1}^(1,0) stencil(a,b) * u_{(i+a,j+b} = -f_k h^2 - \sum_{a=-1}^1
stencil(a,1) * u_{(i+a,j+1}

which is then solved using Ginkgo's implementation of the CG method
preconditioned with block-Jacobi. It is also possible to specify on which
executor Ginkgo will solve the system via the command line.
The function `f` is set to `f(x,y) = 6x + 6y` (making the solution `u(x,y) = x^3
+ y^3`), but that can be changed in the `main` function. Also the stencil values
for the core, the faces, the edge and the corners can be changed when passing
additional parameters.

The intention of this is to show how generation of stencil values and the right
hand side vector changes when increasing the dimension.
*****************************<DECSRIPTION>******************************** /

#include <array>
#include <chrono>
#include <ginkgo/ginkgo.hpp>
#include <iostream>
#include <map>
#include <string>
#include <vector>
```

Stencil values. Ordering can be seen in the main function Can also be changed by passing additional parameter when executing

```
constexpr double default_alpha = 10.0 / 3.0;
constexpr double default_beta = -2.0 / 3.0;
constexpr double default_gamma = -1.0 / 6.0;

/ * Possible alternative default values are for example
 * default_alpha = 8.0;
 * default_beta = -1.0;
 * default_gamma = -1.0;
 * /
```

Creates a stencil matrix in CSR format for the given number of discretization points.

```
void generate_stencil_matrix(int dp, int *row_ptrs, int *col_idxs,
                             double *values, double *coefs)
{
    int pos = 0;
    const size_t dp_2 = dp * dp;
    row_ptrs[0] = pos;
    for (int k = 0; k < dp; ++k) {
        for (int i = 0; i < dp; ++i) {
            const size_t index = i + k * dp;
```

```
            for (int j = -1; j <= 1; ++j) {
                for (int l = -1; l <= 1; ++l) {
                    const int64_t offset = l + 1 + 3 * (j + 1);
                    if ((k + j) >= 0 && (k + j) < dp && (i + l) >= 0 &&
                        (i + l) < dp) {
                        values[pos] = coefs[offset];
                        col_idxs[pos] = index + l + dp * j;
                        ++pos;
                    }
                }
            }
            row_ptrs[index + 1] = pos;
        }
    }
}
```

Generates the RHS vector given `f` and the boundary conditions.

```
template <typename Closure, typename ClosureT>
void generate_rhs(int dp, Closure f, ClosureT u, double *rhs, double *coefs)
{
    const size_t dp_2 = dp * dp;
    const auto h = 1.0 / (dp + 1.0);
    for (int i = 0; i < dp; ++i) {
        const auto yi = (i + 1) * h;
        for (int j = 0; j < dp; ++j) {
            const auto xi = (j + 1) * h;
            const auto index = i * dp + j;
            rhs[index] = -f(xi, yi) * h * h;
        }
    }
```

Iterating over the edges to add boundary values and adding the overlapping 3x1 to the rhs

```
for (size_t i = 0; i < dp; ++i) {
    const auto xi = (i + 1) * h;
    const auto index_top = i;
    const auto index_bot = i + dp * (dp - 1);

    rhs[index_top] -= u(xi - h, 0.0) * coefs[0];
    rhs[index_top] -= u(xi, 0.0) * coefs[1];
    rhs[index_top] -= u(xi + h, 0.0) * coefs[2];

    rhs[index_bot] -= u(xi - h, 1.0) * coefs[6];
    rhs[index_bot] -= u(xi, 1.0) * coefs[7];
    rhs[index_bot] -= u(xi + h, 1.0) * coefs[8];
}
for (size_t i = 0; i < dp; ++i) {
    const auto yi = (i + 1) * h;
    const auto index_left = i * dp;
    const auto index_right = i * dp + (dp - 1);

    rhs[index_left] -= u(0.0, yi - h) * coefs[0];
    rhs[index_left] -= u(0.0, yi) * coefs[3];
    rhs[index_left] -= u(0.0, yi + h) * coefs[6];

    rhs[index_right] -= u(1.0, yi - h) * coefs[2];
    rhs[index_right] -= u(1.0, yi) * coefs[5];
    rhs[index_right] -= u(1.0, yi + h) * coefs[8];
}
```

remove the double corner values

```
    rhs[0] += u(0.0, 0.0) * coefs[0];
    rhs[(dp - 1)] += u(1.0, 0.0) * coefs[2];
    rhs[(dp - 1) * dp] += u(0.0, 1.0) * coefs[6];
    rhs[dp * dp - 1] += u(1.0, 1.0) * coefs[8];
}
```

Prints the solution `u`.

```
void print_solution(int dp, const double *u)
{
    for (int i = 0; i < dp; ++i) {
        for (int j = 0; j < dp; ++j) {
            std::cout << u[i * dp + j] << ' ';
        }
        std::cout << '\n';
    }
    std::cout << std::endl;
}
```

Computes the 1-norm of the error given the computed `u` and the correct solution function `correct_u`.

```
template <typename Closure>
double calculate_error(int dp, const double *u, Closure correct_u)
{
    const auto h = 1.0 / (dp + 1);
    auto error = 0.0;
    for (int j = 0; j < dp; ++j) {
        const auto xi = (j + 1) * h;
        for (int i = 0; i < dp; ++i) {
            using std::abs;
            const auto yi = (i + 1) * h;
            error +=
                abs(u[i * dp + j] - correct_u(xi, yi)) / abs(correct_u(xi, yi));
        }
    }
    return error;
}


void solve_system(const std::string &executor_string,
                  unsigned int discretization_points, int *row_ptrs,
                  int *col_idxs, double *values, double *rhs, double *u,
                  double accuracy)
{
```

Some shortcuts

```
using vec = gko::matrix::Dense<double>;
using mtx = gko::matrix::Csr<double, int>;
using cg = gko::solver::Cg<double>;
using bj = gko::preconditioner::Jacobi<double, int>;
using val_array = gko::Array<double>;
using idx_array = gko::Array<int>;
const auto &dp = discretization_points;
const size_t dp_2 = dp * dp;
```

Figure out where to run the code

```
const auto omp = gko::OmpExecutor::create();
std::map<std::string, std::shared_ptr<gko::Executor>> exec_map{
    {"omp", omp},
    {"cuda", gko::CudaExecutor::create(0, omp)},
    {"reference", gko::ReferenceExecutor::create()}};
```

executor where Ginkgo will perform the computation

```
const auto exec = exec_map.at(executor_string);  // throws if not valid
```

executor where the application initialized the data

```
const auto app_exec = exec_map["omp"];
```

Tell Ginkgo to use the data in our application

Matrix: we have to set the executor of the matrix to the one where we want SpMVs to run (in this case `exec`). When creating array views, we have to specify the executor where the data is (in this case `app_exec`).

If the two do not match, Ginkgo will automatically create a copy of the data on `exec` (however, it will not copy the data back once it is done

- here this is not important since we are not modifying the matrix).

```
auto matrix = mtx::create(
    exec, gko::dim<2>(dp_2),
    val_array::view(app_exec, (3 * dp - 2) * (3 * dp - 2), values),
    idx_array::view(app_exec, (3 * dp - 2) * (3 * dp - 2), col_idxs),
    idx_array::view(app_exec, dp_2 + 1, row_ptrs));
```

RHS: similar to matrix

```
auto b = vec::create(exec, gko::dim<2>(dp_2, 1),
                     val_array::view(app_exec, dp_2, rhs), 1);
```

Solution: we have to be careful here - if the executors are different, once we compute the solution the array will not be automatically copied back to the original memory locations. Fortunately, whenever `apply` is called on a linear operator (e.g. matrix, solver) the arguments automatically get copied to the executor where the operator is, and copied back once the operation is completed. Thus, in this case, we can just define the solution on `app_exec`, and it will be automatically transferred to/from `exec` if needed.

```
auto x = vec::create(app_exec, gko::dim<2>(dp_2, 1),
                     val_array::view(app_exec, dp_2, u), 1);
```

Generate solver

```
auto solver_gen =
    cg::build()
        .with_criteria(
            gko::stop::Iteration::build().with_max_iters(dp_2).on(exec),
            gko::stop::ResidualNormReduction<>::build()
                .with_reduction_factor(accuracy)
                .on(exec))
        .with_preconditioner(bj::build().on(exec))
        .on(exec);
auto solver = solver_gen->generate(gko::give(matrix));
```

Solve system

```
    solver->apply(gko::lend(b), gko::lend(x));
}


int main(int argc, char *argv[])
{
    if (argc < 2) {
        std::cerr << "Usage: " << argv[0] << " DISCRETIZATION_POINTS [executor]"
                  << " [stencil_alpha] [stencil_beta] [stencil_gamma]"
                  << std::endl;
        std::exit(-1);
    }

    const int discretization_points = argc >= 2 ? std::atoi(argv[1]) : 100;
    const auto executor_string = argc >= 3 ? argv[2] : "reference";
    const double alpha_c = argc >= 4 ? std::atof(argv[3]) : default_alpha;
    const double beta_c = argc >= 5 ? std::atof(argv[4]) : default_beta;
    const double gamma_c = argc >= 6 ? std::atof(argv[5]) : default_gamma;
```

clang-format off

```
std::array<double, 9> coefs{
    gamma_c, beta_c, gamma_c,
    beta_c, alpha_c, beta_c,
    gamma_c, beta_c, gamma_c};
```

clang-format on

```
const auto dp = discretization_points;
const size_t dp_2 = dp * dp;
```

problem:

```
auto correct_u = [](double x, double y) { return x * x * x + y * y * y; };
auto f = [](double x, double y) { return 6 * x + 6 * y; };
```

matrix

```
std::vector<int> row_ptrs(dp_2 + 1);
std::vector<int> col_idxs((3 * dp - 2) * (3 * dp - 2));
std::vector<double> values((3 * dp - 2) * (3 * dp - 2));
```

right hand side

```
std::vector<double> rhs(dp_2);
```

solution

```
std::vector<double> u(dp_2, 0.0);

generate_stencil_matrix(dp, row_ptrs.data(), col_idxs.data(), values.data(),
                        coefs.data());
```

looking for solution u = x^3: f = 6x, u(0) = 0, u(1) = 1

```
    generate_rhs(dp, f, correct_u, rhs.data(), coefs.data());

    auto start_time = std::chrono::steady_clock::now();

    solve_system(executor_string, dp, row_ptrs.data(), col_idxs.data(),
                 values.data(), rhs.data(), u.data(), 1e-12);

    auto stop_time = std::chrono::steady_clock::now();
    double runtime_duration =
        std::chrono::duration_cast<std::chrono::nanoseconds>(stop_time -
                                                             start_time)
            .count() *
        1e-6;

    print_solution(dp, u.data());
    std::cout << "The average relative error is "
              << calculate_error(dp, u.data(), correct_u) / dp_2 << std::endl;
    std::cout << "The runtime is " << std::to_string(runtime_duration) << " ms"
              << std::endl;
}
```

Results

The expected output of the relative error at K=10 should be

```
The average relative error is 1.45687e-13
```

Comments about programming and debugging

The plain program


```
/*****************************<DECSRIPTION>***********************************
This example solves a 2D Poisson equation:

    \Omega = (0,1)^2
    \Omega_b = [0,1]^2   (with boundary)
    \partial\Omega = \Omega_b \backslash \Omega
    u : \Omega_b -> R
    u'' = f in \Omega
    u = u_D on \partial\Omega

using a finite difference method on an equidistant grid with `K` discretization
points (`K` can be controlled with a command line parameter). The discretization
may be done by any order Taylor polynomial.
For an equidistant grid with K "inner" discretization points (x1,y1), ...,
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\R^{3 x 3}, the formula produces a system of linear equations

\sum_{a,b=-1}^1 stencil(a,b) * u_{(i+a,j+b} = -f_k h^2,  on any inner node with
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On any node, where neighbor is on the border, the neighbor is replaced with a
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example a node with a neighborhood of only edge nodes may look like this

\sum_{a,b=-1}^(1,0) stencil(a,b) * u_{(i+a,j+b} = -f_k h^2 - \sum_{a=-1}^1
stencil(a,1) * u_{(i+a,j+1}

which is then solved using Ginkgo's implementation of the CG method
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executor Ginkgo will solve the system via the command line.
The function `f` is set to `f(x,y) = 6x + 6y` (making the solution `u(x,y) = x^3
+ y^3`), but that can be changed in the `main` function. Also the stencil values
for the core, the faces, the edge and the corners can be changed when passing
additional parameters.
```

```
The intention of this is to show how generation of stencil values and the right
hand side vector changes when increasing the dimension.
*****************************<DECSRIPTION>**********************************/

#include <array>
#include <chrono>
#include <ginkgo/ginkgo.hpp>
#include <iostream>
#include <map>
#include <string>
#include <vector>

constexpr double default_alpha = 10.0 / 3.0;
constexpr double default_beta = -2.0 / 3.0;
constexpr double default_gamma = -1.0 / 6.0;

/* Possible alternative default values are for example
 * default_alpha = 8.0;
 * default_beta = -1.0;
 * default_gamma = -1.0;
 */

void generate_stencil_matrix(int dp, int *row_ptrs, int *col_idxs,
                             double *values, double *coefs)
{
    int pos = 0;
    const size_t dp_2 = dp * dp;
    row_ptrs[0] = pos;
    for (int k = 0; k < dp; ++k) {
        for (int i = 0; i < dp; ++i) {
            const size_t index = i + k * dp;
            for (int j = -1; j <= 1; ++j) {
                for (int l = -1; l <= 1; ++l) {
                    const int64_t offset = l + 1 + 3 * (j + 1);
                    if ((k + j) >= 0 && (k + j) < dp && (i + l) >= 0 &&
                        (i + l) < dp) {
                        values[pos] = coefs[offset];
                        col_idxs[pos] = index + l + dp * j;
                        ++pos;
                    }
                }
            }
            row_ptrs[index + 1] = pos;
        }
    }
}


template <typename Closure, typename ClosureT>
void generate_rhs(int dp, Closure f, ClosureT u, double *rhs, double *coefs)
{
    const size_t dp_2 = dp * dp;
    const auto h = 1.0 / (dp + 1.0);
    for (int i = 0; i < dp; ++i) {
        const auto yi = (i + 1) * h;
        for (int j = 0; j < dp; ++j) {
            const auto xi = (j + 1) * h;
            const auto index = i * dp + j;
            rhs[index] = -f(xi, yi) * h * h;
        }
    }

    for (size_t i = 0; i < dp; ++i) {
        const auto xi = (i + 1) * h;
        const auto index_top = i;
        const auto index_bot = i + dp * (dp - 1);

        rhs[index_top] -= u(xi - h, 0.0) * coefs[0];
        rhs[index_top] -= u(xi, 0.0) * coefs[1];
        rhs[index_top] -= u(xi + h, 0.0) * coefs[2];

        rhs[index_bot] -= u(xi - h, 1.0) * coefs[6];
        rhs[index_bot] -= u(xi, 1.0) * coefs[7];
        rhs[index_bot] -= u(xi + h, 1.0) * coefs[8];
    }
    for (size_t i = 0; i < dp; ++i) {
        const auto yi = (i + 1) * h;
        const auto index_left = i * dp;
        const auto index_right = i * dp + (dp - 1);

        rhs[index_left] -= u(0.0, yi - h) * coefs[0];
        rhs[index_left] -= u(0.0, yi) * coefs[3];
        rhs[index_left] -= u(0.0, yi + h) * coefs[6];

        rhs[index_right] -= u(1.0, yi - h) * coefs[2];
        rhs[index_right] -= u(1.0, yi) * coefs[5];
        rhs[index_right] -= u(1.0, yi + h) * coefs[8];
```

```
    }

    rhs[0] += u(0.0, 0.0) * coefs[0];
    rhs[(dp - 1)] += u(1.0, 0.0) * coefs[2];
    rhs[(dp - 1) * dp] += u(0.0, 1.0) * coefs[6];
    rhs[dp * dp - 1] += u(1.0, 1.0) * coefs[8];
}


void print_solution(int dp, const double *u)
{
    for (int i = 0; i < dp; ++i) {
        for (int j = 0; j < dp; ++j) {
            std::cout << u[i * dp + j] << ' ';
        }
        std::cout << '\n';
    }
    std::cout << std::endl;
}


template <typename Closure>
double calculate_error(int dp, const double *u, Closure correct_u)
{
    const auto h = 1.0 / (dp + 1);
    auto error = 0.0;
    for (int j = 0; j < dp; ++j) {
        const auto xi = (j + 1) * h;
        for (int i = 0; i < dp; ++i) {
            using std::abs;
            const auto yi = (i + 1) * h;
            error +=
                abs(u[i * dp + j] - correct_u(xi, yi)) / abs(correct_u(xi, yi));
        }
    }
    return error;
}


void solve_system(const std::string &executor_string,
                  unsigned int discretization_points, int *row_ptrs,
                  int *col_idxs, double *values, double *rhs, double *u,
                  double accuracy)
{
    using vec = gko::matrix::Dense<double>;
    using mtx = gko::matrix::Csr<double, int>;
    using cg = gko::solver::Cg<double>;
    using bj = gko::preconditioner::Jacobi<double, int>;
    using val_array = gko::Array<double>;
    using idx_array = gko::Array<int>;
    const auto &dp = discretization_points;
    const size_t dp_2 = dp * dp;

    const auto omp = gko::OmpExecutor::create();
    std::map<std::string, std::shared_ptr<gko::Executor>> exec_map{
        {"omp", omp},
        {"cuda", gko::CudaExecutor::create(0, omp)},
        {"reference", gko::ReferenceExecutor::create()}};
    const auto exec = exec_map.at(executor_string);  // throws if not valid
    const auto app_exec = exec_map["omp"];


    auto matrix = mtx::create(
        exec, gko::dim<2>(dp_2),
        val_array::view(app_exec, (3 * dp - 2) * (3 * dp - 2), values),
        idx_array::view(app_exec, (3 * dp - 2) * (3 * dp - 2), col_idxs),
        idx_array::view(app_exec, dp_2 + 1, row_ptrs));

    auto b = vec::create(exec, gko::dim<2>(dp_2, 1),
                         val_array::view(app_exec, dp_2, rhs), 1);

    auto x = vec::create(app_exec, gko::dim<2>(dp_2, 1),
                         val_array::view(app_exec, dp_2, u), 1);

    auto solver_gen =
        cg::build()
            .with_criteria(
                gko::stop::Iteration::build().with_max_iters(dp_2).on(exec),
                gko::stop::ResidualNormReduction<>::build()
                    .with_reduction_factor(accuracy)
                    .on(exec))
            .with_preconditioner(bj::build().on(exec))
            .on(exec);
    auto solver = solver_gen->generate(gko::give(matrix));

    solver->apply(gko::lend(b), gko::lend(x));
}
```

```
int main(int argc, char *argv[])
{
    if (argc < 2) {
        std::cerr << "Usage: " << argv[0] << " DISCRETIZATION_POINTS [executor]"
                  << " [stencil_alpha] [stencil_beta] [stencil_gamma]"
                  << std::endl;
        std::exit(-1);
    }

    const int discretization_points = argc >= 2 ? std::atoi(argv[1]) : 100;
    const auto executor_string = argc >= 3 ? argv[2] : "reference";
    const double alpha_c = argc >= 4 ? std::atof(argv[3]) : default_alpha;
    const double beta_c = argc >= 5 ? std::atof(argv[4]) : default_beta;
    const double gamma_c = argc >= 6 ? std::atof(argv[5]) : default_gamma;

    std::array<double, 9> coefs{
        gamma_c, beta_c, gamma_c,
    beta_c, alpha_c, beta_c,
        gamma_c, beta_c, gamma_c};

    const auto dp = discretization_points;
    const size_t dp_2 = dp * dp;

    auto correct_u = [](double x, double y) { return x * x * x + y * y * y; };
    auto f = [](double x, double y) { return 6 * x + 6 * y; };

    std::vector<int> row_ptrs(dp_2 + 1);
    std::vector<int> col_idxs((3 * dp - 2) * (3 * dp - 2));
    std::vector<double> values((3 * dp - 2) * (3 * dp - 2));
    std::vector<double> rhs(dp_2);
    std::vector<double> u(dp_2, 0.0);

    generate_stencil_matrix(dp, row_ptrs.data(), col_idxs.data(), values.data(),
                            coefs.data());
    generate_rhs(dp, f, correct_u, rhs.data(), coefs.data());

    auto start_time = std::chrono::steady_clock::now();

    solve_system(executor_string, dp, row_ptrs.data(), col_idxs.data(),
                 values.data(), rhs.data(), u.data(), 1e-12);

    auto stop_time = std::chrono::steady_clock::now();
    double runtime_duration =
        std::chrono::duration_cast<std::chrono::nanoseconds>(stop_time -
                                                             start_time)
            .count() *
        1e-6;

    print_solution(dp, u.data());
    std::cout << "The average relative error is "
              << calculate_error(dp, u.data(), correct_u) / dp_2 << std::endl;
    std::cout << "The runtime is " << std::to_string(runtime_duration) << " ms"
              << std::endl;
}
```

Chapter 15

The papi-logging program

The papi logging example.

This example depends on simple-solver-logging.

Introduction

About the example

The commented program

```
#include <ginkgo/ginkgo.hpp>


#include <papi.h>
#include <fstream>
#include <iostream>
#include <string>
#include <thread>


namespace {


void papi_add_event(const std::string &event_name, int &eventset)
{
    int code;
    int ret_val = PAPI_event_name_to_code(event_name.c_str(), &code);
    if (PAPI_OK != ret_val) {
        std::cerr << "Error at PAPI_name_to_code()" << std::endl;
        std::exit(-1);
    }

    ret_val = PAPI_add_event(eventset, code);
    if (PAPI_OK != ret_val) {
        std::cerr << "Error at PAPI_name_to_code()" << std::endl;
        std::exit(-1);
    }
}


template <typename T>
std::string to_string(T *ptr)
{
    std::ostringstream os;
    os << reinterpret_cast<gko::uintptr>(ptr);
    return os.str();
}


}  // namespace


int init_papi_counters(std::string solver_name, std::string A_name)
{
```

Initialize PAPI, add events and start it up

```
    int eventset = PAPI_NULL;
    int ret_val = PAPI_library_init(PAPI_VER_CURRENT);
    if (ret_val != PAPI_VER_CURRENT) {
        std::cerr << "Error at PAPI_library_init()" << std::endl;
        std::exit(-1);
    }
    ret_val = PAPI_create_eventset(&eventset);
    if (PAPI_OK != ret_val) {
        std::cerr << "Error at PAPI_create_eventset()" << std::endl;
        std::exit(-1);
    }

    std::string simple_apply_string("sde:::ginkgo0::linop_apply_completed::");
    std::string advanced_apply_string(
        "sde:::ginkgo0::linop_advanced_apply_completed::");
    papi_add_event(simple_apply_string + solver_name, eventset);
    papi_add_event(simple_apply_string + A_name, eventset);
    papi_add_event(advanced_apply_string + A_name, eventset);

    ret_val = PAPI_start(eventset);
    if (PAPI_OK != ret_val) {
        std::cerr << "Error at PAPI_start()" << std::endl;
        std::exit(-1);
    }
    return eventset;
}


void print_papi_counters(int eventset)
{
```

Stop PAPI and read the linop_apply_completed event for all of them

```
long long int values[3];
int ret_val = PAPI_stop(eventset, values);
if (PAPI_OK != ret_val) {
    std::cerr << "Error at PAPI_stop()" << std::endl;
    std::exit(-1);
}

PAPI_shutdown();
```

Print all values returned from PAPI

```
    std::cout << "PAPI SDE counters:" << std::endl;
    std::cout << "solver did " << values[0] << " applies." << std::endl;
    std::cout << "A did " << values[1] << " simple applies." << std::endl;
    std::cout << "A did " << values[2] << " advanced applies." << std::endl;
}


int main(int argc, char *argv[])
{
```

Some shortcuts

```
using vec = gko::matrix::Dense<>;
using mtx = gko::matrix::Csr<>;
using cg = gko::solver::Cg<>;
```

Print version information

```
std::cout << gko::version_info::get() << std::endl;
```

Figure out where to run the code

```
std::shared_ptr<gko::Executor> exec;
if (argc == 1 || std::string(argv[1]) == "reference") {
    exec = gko::ReferenceExecutor::create();
} else if (argc == 2 && std::string(argv[1]) == "omp") {
    exec = gko::OmpExecutor::create();
} else if (argc == 2 && std::string(argv[1]) == "cuda" &&
           gko::CudaExecutor::get_num_devices() > 0) {
    exec = gko::CudaExecutor::create(0,
      gko::OmpExecutor::create());
} else {
    std::cerr << "Usage: " << argv[0] << " [executor]" << std::endl;
    std::exit(-1);
}
```

Read data

```
auto A = share(gko::read<mtx>(std::ifstream("data/A.mtx"), exec));
auto b = gko::read<vec>(std::ifstream("data/b.mtx"), exec);
auto x = gko::read<vec>(std::ifstream("data/x0.mtx"), exec);
```

Generate solver

```
auto solver_gen =
    cg::build()
        .with_criteria(
            gko::stop::Iteration::build().with_max_iters(20u).on(exec),
            gko::stop::ResidualNormReduction<>::build()
                .with_reduction_factor(1e-20)
                .on(exec))
        .on(exec);
auto solver = solver_gen->generate(A);
```

In this example, we split as much as possible the Ginkgo solver/logger and the PAPI interface. Note that the PAPI ginkgo namespaces are of the form sde:::ginkgo<x> where <x> starts from 0 and is incremented with every new PAPI logger.

```
int eventset =
    init_papi_counters(to_string(solver.get()), to_string(A.get()));
```

Create a PAPI logger and add it to relevant LinOps

```
auto logger = gko::log::Papi<>::create(
    exec, gko::log::Logger::linop_apply_completed_mask |
              gko::log::Logger::linop_advanced_apply_completed_mask);
solver->add_logger(logger);
A->add_logger(logger);
```

Solve system

```
solver->apply(lend(b), lend(x));
```

Stop PAPI event gathering and print the counters

```
print_papi_counters(eventset);
```

Print solution

```
std::cout << "Solution (x): \n";
write(std::cout, lend(x));
```

Calculate residual

```
    auto one = gko::initialize<vec>({1.0}, exec);
    auto neg_one = gko::initialize<vec>({-1.0}, exec);
    auto res = gko::initialize<vec>({0.0}, exec);
    A->apply(lend(one), lend(x), lend(neg_one), lend(b));
    b->compute_norm2(lend(res));

    std::cout << "Residual norm sqrt(r^T r): \n";
    write(std::cout, lend(res));
}
```

Results

The following is the expected result:

```
PAPI SDE counters:
solver did 1 applies.
A did 20 simple applies.
A did 1 advanced applies.
Solution (x):
%%MatrixMarket matrix array real general
19 1
0.252218
0.108645
0.0662811
0.0630433
0.0384088
0.0396536
0.0402648
0.0338935
0.0193098
0.0234653
0.0211499
0.0196413
0.0199151
0.0181674
0.0162722
0.0150714
0.0107016
0.0121141
0.0123025
Residual norm sqrt(r^T r):
%%MatrixMarket matrix array real general
1 1
8.87107e-16
```

Comments about programming and debugging

The plain program

```
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#include <ginkgo/ginkgo.hpp>


#include <papi.h>
#include <fstream>
#include <iostream>
```

```
#include <string>
#include <thread>


namespace {


void papi_add_event(const std::string &event_name, int &eventset)
{
    int code;
    int ret_val = PAPI_event_name_to_code(event_name.c_str(), &code);
    if (PAPI_OK != ret_val) {
        std::cerr << "Error at PAPI_name_to_code()" << std::endl;
        std::exit(-1);
    }

    ret_val = PAPI_add_event(eventset, code);
    if (PAPI_OK != ret_val) {
        std::cerr << "Error at PAPI_name_to_code()" << std::endl;
        std::exit(-1);
    }
}


template <typename T>
std::string to_string(T *ptr)
{
    std::ostringstream os;
    os << reinterpret_cast<gko::uintptr>(ptr);
    return os.str();
}


}  // namespace


int init_papi_counters(std::string solver_name, std::string A_name)
{
    int eventset = PAPI_NULL;
    int ret_val = PAPI_library_init(PAPI_VER_CURRENT);
    if (ret_val != PAPI_VER_CURRENT) {
        std::cerr << "Error at PAPI_library_init()" << std::endl;
        std::exit(-1);
    }
    ret_val = PAPI_create_eventset(&eventset);
    if (PAPI_OK != ret_val) {
        std::cerr << "Error at PAPI_create_eventset()" << std::endl;
        std::exit(-1);
    }

    std::string simple_apply_string("sde:::ginkgo0::linop_apply_completed::");
    std::string advanced_apply_string(
        "sde:::ginkgo0::linop_advanced_apply_completed::");
    papi_add_event(simple_apply_string + solver_name, eventset);
    papi_add_event(simple_apply_string + A_name, eventset);
    papi_add_event(advanced_apply_string + A_name, eventset);

    ret_val = PAPI_start(eventset);
    if (PAPI_OK != ret_val) {
        std::cerr << "Error at PAPI_start()" << std::endl;
        std::exit(-1);
    }
    return eventset;
}


void print_papi_counters(int eventset)
{
    long long int values[3];
    int ret_val = PAPI_stop(eventset, values);
    if (PAPI_OK != ret_val) {
        std::cerr << "Error at PAPI_stop()" << std::endl;
        std::exit(-1);
    }

    PAPI_shutdown();

    std::cout << "PAPI SDE counters:" << std::endl;
    std::cout << "solver did " << values[0] << " applies." << std::endl;
    std::cout << "A did " << values[1] << " simple applies." << std::endl;
    std::cout << "A did " << values[2] << " advanced applies." << std::endl;
}


int main(int argc, char *argv[])
{
    using vec = gko::matrix::Dense<>;
```

```
    using mtx = gko::matrix::Csr<>;
    using cg = gko::solver::Cg<>;

    std::cout << gko::version_info::get() << std::endl;

    std::shared_ptr<gko::Executor> exec;
    if (argc == 1 || std::string(argv[1]) == "reference") {
        exec = gko::ReferenceExecutor::create();
    } else if (argc == 2 && std::string(argv[1]) == "omp") {
        exec = gko::OmpExecutor::create();
    } else if (argc == 2 && std::string(argv[1]) == "cuda" &&
               gko::CudaExecutor::get_num_devices() > 0) {
        exec = gko::CudaExecutor::create(0,
      gko::OmpExecutor::create());
    } else {
        std::cerr << "Usage: " << argv[0] << " [executor]" << std::endl;
        std::exit(-1);
    }

    auto A = share(gko::read<mtx>(std::ifstream("data/A.mtx"), exec));
    auto b = gko::read<vec>(std::ifstream("data/b.mtx"), exec);
    auto x = gko::read<vec>(std::ifstream("data/x0.mtx"), exec);

    auto solver_gen =
        cg::build()
            .with_criteria(
                gko::stop::Iteration::build().with_max_iters(20u).on(exec),
                gko::stop::ResidualNormReduction<>::build()
                    .with_reduction_factor(1e-20)
                    .on(exec))
            .on(exec);
    auto solver = solver_gen->generate(A);

    int eventset =
        init_papi_counters(to_string(solver.get()), to_string(A.get()));


    auto logger = gko::log::Papi<>::create(
        exec, gko::log::Logger::linop_apply_completed_mask |
                  gko::log::Logger::linop_advanced_apply_completed_mask);
    solver->add_logger(logger);
    A->add_logger(logger);

    solver->apply(lend(b), lend(x));


    print_papi_counters(eventset);

    std::cout << "Solution (x): \n";
    write(std::cout, lend(x));

    auto one = gko::initialize<vec>({1.0}, exec);
    auto neg_one = gko::initialize<vec>({-1.0}, exec);
    auto res = gko::initialize<vec>({0.0}, exec);
    A->apply(lend(one), lend(x), lend(neg_one), lend(b));
    b->compute_norm2(lend(res));

    std::cout << "Residual norm sqrt(r^T r): \n";
    write(std::cout, lend(res));
}
```

Chapter 16

The poisson-solver program

The poisson solver example.

This example depends on simple-solver.

Introduction

This example solves a 1D Poisson equation:

$$
\begin{aligned}
&u : [0, 1] \to R\\
&u'' = f\\
&u(0) = u0\\
&u(1) = u1
\end{aligned}
$$

using a finite difference method on an equidistant grid with `K` discretization points (`K` can be controlled with a command line parameter). The discretization is done via the second order Taylor polynomial:

$$
\begin{aligned}
&u(x + h) = u(x) - u'(x)h + 1/2u''(x)h^2 + O(h^3)\\
&u(x - h) = u(x) + u'(x)h + 1/2u''(x)h^2 + O(h^3)/+\\
&- -\\
&- u(x - h) + 2u(x) + -u(x + h) = -f(x)h^2 + O(h^3)
\end{aligned}
$$

For an equidistant grid with K "inner" discretization points $x1, ..., xk,$and step size $h = 1/(K + 1)$, the formula produces a system of linear equations

$$
\begin{aligned}
&2u_1 - u_2 = -f_1 h^2 + u0\\
&- u_(k - 1) + 2u_k - u_(k + 1) = -f_k h^2, k = 2, ..., K - 1\\
&- u_(K - 1) + 2u_K = -f_K h^2 + u1
\end{aligned}
$$

which is then solved using Ginkgo's implementation of the CG method preconditioned with block-Jacobi. It is also possible to specify on which executor Ginkgo will solve the system via the command line. The function 'f'is set to '$f(x) = 6x$' (making the solution '$u(x) = x^3$'), but that can be changed in the `main` function.

The intention of the example is to show how Ginkgo can be used to build an application solving a real-world problem, which includes a solution of a large, sparse linear system as a component.

About the example

The commented program

```
#include <ginkgo/ginkgo.hpp>
#include <iostream>
#include <map>
#include <string>
#include <vector>
```

Creates a stencil matrix in CSR format for the given number of discretization points.

```
void generate_stencil_matrix(gko::matrix::Csr<> *matrix)
{
    const auto discretization_points = matrix->get_size()[0];
    auto row_ptrs = matrix->get_row_ptrs();
    auto col_idxs = matrix->get_col_idxs();
    auto values = matrix->get_values();
    int pos = 0;
    const double coefs[] = {-1, 2, -1};
    row_ptrs[0] = pos;
    for (int i = 0; i < discretization_points; ++i) {
        for (auto ofs : {-1, 0, 1}) {
            if (0 <= i + ofs && i + ofs < discretization_points) {
                values[pos] = coefs[ofs + 1];
                col_idxs[pos] = i + ofs;
                ++pos;
            }
        }
        row_ptrs[i + 1] = pos;
    }
}
```

Generates the RHS vector given `f` and the boundary conditions.

```
template <typename Closure>
void generate_rhs(Closure f, double u0, double u1, gko::matrix::Dense<> *rhs)
{
    const auto discretization_points = rhs->get_size()[0];
    auto values = rhs->get_values();
    const auto h = 1.0 / (discretization_points + 1);
    for (int i = 0; i < discretization_points; ++i) {
        const auto xi = (i + 1) * h;
        values[i] = -f(xi) * h * h;
    }
    values[0] += u0;
    values[discretization_points - 1] += u1;
}
```

Prints the solution `u`.

```
void print_solution(double u0, double u1, const gko::matrix::Dense<> *u)
{
    std::cout << u0 << '\n';
    for (int i = 0; i < u->get_size()[0]; ++i) {
        std::cout << u->get_const_values()[i] << '\n';
    }
    std::cout << u1 << std::endl;
}
```

Computes the 1-norm of the error given the computed `u` and the correct solution function `correct_u`.

```
template <typename Closure>
double calculate_error(int discretization_points, const gko::matrix::Dense<> *u,
                       Closure correct_u)
{
    const auto h = 1.0 / (discretization_points + 1);
    auto error = 0.0;
    for (int i = 0; i < discretization_points; ++i) {
        using std::abs;
        const auto xi = (i + 1) * h;
        error +=
            abs(u->get_const_values()[i] - correct_u(xi)) /
      abs(correct_u(xi));
    }
    return error;
}


int main(int argc, char *argv[])
{
```

Some shortcuts

```
using vec = gko::matrix::Dense<double>;
using mtx = gko::matrix::Csr<double, int>;
using cg = gko::solver::Cg<double>;
using bj = gko::preconditioner::Jacobi<>;

if (argc < 2) {
    std::cerr << "Usage: " << argv[0] << " DISCRETIZATION_POINTS [executor]"
              << std::endl;
    std::exit(-1);
}
```

Get number of discretization points

```
const unsigned int discretization_points =
    argc >= 2 ? std::atoi(argv[1]) : 100;
const auto executor_string = argc >= 3 ? argv[2] : "reference";
```

Figure out where to run the code

```
const auto omp = gko::OmpExecutor::create();
std::map<std::string, std::shared_ptr<gko::Executor>> exec_map{
    {"omp", omp},
    {"cuda", gko::CudaExecutor::create(0, omp)},
    {"reference", gko::ReferenceExecutor::create()}};
```

executor where Ginkgo will perform the computation

```
const auto exec = exec_map.at(executor_string);  // throws if not valid
```

executor used by the application

```
const auto app_exec = exec_map["omp"];
```

problem:

```
auto correct_u = [](double x) { return x * x * x; };
auto f = [](double x) { return 6 * x; };
auto u0 = correct_u(0);
auto u1 = correct_u(1);
```

initialize matrix and vectors

```
auto matrix = mtx::create(app_exec, gko::dim<2>(discretization_points),
                          3 * discretization_points - 2);
generate_stencil_matrix(lend(matrix));
auto rhs = vec::create(app_exec, gko::dim<2>(discretization_points, 1));
generate_rhs(f, u0, u1, lend(rhs));
auto u = vec::create(app_exec, gko::dim<2>(discretization_points, 1));
for (int i = 0; i < u->get_size()[0]; ++i) {
    u->get_values()[i] = 0.0;
}
```

Generate solver and solve the system

```
    cg::build()
        .with_criteria(gko::stop::Iteration::build()
                           .with_max_iters(discretization_points)
                           .on(exec),
                       gko::stop::ResidualNormReduction<>::build()
                           .with_reduction_factor(1e-6)
                           .on(exec))
        .with_preconditioner(bj::build().on(exec))
        .on(exec)
        ->generate(clone(exec, matrix))  // copy the matrix to the executor
        ->apply(lend(rhs), lend(u));

    print_solution(u0, u1, lend(u));
    std::cout << "The average relative error is "
              << calculate_error(discretization_points, lend(u), correct_u) /
                     discretization_points
              << std::endl;
}
```

Results

This is the expected output:

```
0
0.00010798
0.000863838
0.00291545
0.0069107
0.0134975
0.0233236
0.037037
0.0552856
0.0787172
0.10798
0.143721
0.186589
0.237231
0.296296
0.364431
0.442285
0.530504
0.629738
0.740633
0.863838
1
The average relative error is 1.87318e-15
```

Comments about programming and debugging

The plain program

```
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```

```
#include <ginkgo/ginkgo.hpp>
#include <iostream>
#include <map>
#include <string>
#include <vector>


void generate_stencil_matrix(gko::matrix::Csr<> *matrix)
{
    const auto discretization_points = matrix->get_size()[0];
    auto row_ptrs = matrix->get_row_ptrs();
    auto col_idxs = matrix->get_col_idxs();
    auto values = matrix->get_values();
    int pos = 0;
    const double coefs[] = {-1, 2, -1};
    row_ptrs[0] = pos;
    for (int i = 0; i < discretization_points; ++i) {
        for (auto ofs : {-1, 0, 1}) {
            if (0 <= i + ofs && i + ofs < discretization_points) {
                values[pos] = coefs[ofs + 1];
                col_idxs[pos] = i + ofs;
                ++pos;
            }
        }
        row_ptrs[i + 1] = pos;
    }
}


template <typename Closure>
void generate_rhs(Closure f, double u0, double u1, gko::matrix::Dense<> *rhs)
{
    const auto discretization_points = rhs->get_size()[0];
    auto values = rhs->get_values();
    const auto h = 1.0 / (discretization_points + 1);
    for (int i = 0; i < discretization_points; ++i) {
        const auto xi = (i + 1) * h;
        values[i] = -f(xi) * h * h;
    }
    values[0] += u0;
    values[discretization_points - 1] += u1;
}


void print_solution(double u0, double u1, const gko::matrix::Dense<> *u)
{
    std::cout << u0 << '\n';
    for (int i = 0; i < u->get_size()[0]; ++i) {
        std::cout << u->get_const_values()[i] << '\n';
    }
    std::cout << u1 << std::endl;
}


template <typename Closure>
double calculate_error(int discretization_points, const gko::matrix::Dense<> *u,
                       Closure correct_u)
{
    const auto h = 1.0 / (discretization_points + 1);
    auto error = 0.0;
```

```
    for (int i = 0; i < discretization_points; ++i) {
        using std::abs;
        const auto xi = (i + 1) * h;
        error +=
            abs(u->get_const_values()[i] - correct_u(xi)) /
      abs(correct_u(xi));
    }
    return error;
}


int main(int argc, char *argv[])
{
    using vec = gko::matrix::Dense<double>;
    using mtx = gko::matrix::Csr<double, int>;
    using cg = gko::solver::Cg<double>;
    using bj = gko::preconditioner::Jacobi<>;

    if (argc < 2) {
        std::cerr << "Usage: " << argv[0] << " DISCRETIZATION_POINTS [executor]"
                  << std::endl;
        std::exit(-1);
    }

    const unsigned int discretization_points =
        argc >= 2 ? std::atoi(argv[1]) : 100;
    const auto executor_string = argc >= 3 ? argv[2] : "reference";

    const auto omp = gko::OmpExecutor::create();
    std::map<std::string, std::shared_ptr<gko::Executor>> exec_map{
        {"omp", omp},
        {"cuda", gko::CudaExecutor::create(0, omp)},
        {"reference", gko::ReferenceExecutor::create()}};

    const auto exec = exec_map.at(executor_string);  // throws if not valid
    const auto app_exec = exec_map["omp"];

    auto correct_u = [](double x) { return x * x * x; };
    auto f = [](double x) { return 6 * x; };
    auto u0 = correct_u(0);
    auto u1 = correct_u(1);

    auto matrix = mtx::create(app_exec, gko::dim<2>(discretization_points),
                              3 * discretization_points - 2);
    generate_stencil_matrix(lend(matrix));
    auto rhs = vec::create(app_exec, gko::dim<2>(discretization_points, 1));
    generate_rhs(f, u0, u1, lend(rhs));
    auto u = vec::create(app_exec, gko::dim<2>(discretization_points, 1));
    for (int i = 0; i < u->get_size()[0]; ++i) {
        u->get_values()[i] = 0.0;
    }

    cg::build()
        .with_criteria(gko::stop::Iteration::build()
                           .with_max_iters(discretization_points)
                           .on(exec),
                       gko::stop::ResidualNormReduction<>::build()
                           .with_reduction_factor(1e-6)
                           .on(exec))
        .with_preconditioner(bj::build().on(exec))
        .on(exec)
        ->generate(clone(exec, matrix))  // copy the matrix to the executor
        ->apply(lend(rhs), lend(u));

    print_solution(u0, u1, lend(u));
    std::cout << "The average relative error is "
              << calculate_error(discretization_points, lend(u), correct_u) /
                     discretization_points
              << std::endl;
}
```

Chapter 17

The preconditioned-solver program

The preconditioned solver example.

This example depends on simple-solver.

Introduction

About the example

The commented program

```
#include <ginkgo/ginkgo.hpp>


#include <fstream>
#include <iostream>
#include <string>


int main(int argc, char *argv[])
{
```

Some shortcuts

```
using vec = gko::matrix::Dense<>;
using mtx = gko::matrix::Csr<>;
using cg = gko::solver::Cg<>;
using bj = gko::preconditioner::Jacobi<>;
```

Print version information

```
std::cout << gko::version_info::get() << std::endl;
```

Figure out where to run the code

```
std::shared_ptr<gko::Executor> exec;
if (argc == 1 || std::string(argv[1]) == "reference") {
    exec = gko::ReferenceExecutor::create();
} else if (argc == 2 && std::string(argv[1]) == "omp") {
    exec = gko::OmpExecutor::create();
} else if (argc == 2 && std::string(argv[1]) == "cuda" &&
           gko::CudaExecutor::get_num_devices() > 0) {
    exec = gko::CudaExecutor::create(0,
      gko::OmpExecutor::create());
} else {
    std::cerr << "Usage: " << argv[0] << " [executor]" << std::endl;
    std::exit(-1);
}
```

Read data

```
auto A = share(gko::read<mtx>(std::ifstream("data/A.mtx"), exec));
auto b = gko::read<vec>(std::ifstream("data/b.mtx"), exec);
auto x = gko::read<vec>(std::ifstream("data/x0.mtx"), exec);
```

Create solver factory

```
auto solver_gen =
    cg::build()
        .with_criteria(
            gko::stop::Iteration::build().with_max_iters(20u).on(exec),
            gko::stop::ResidualNormReduction<>::build()
                .with_reduction_factor(1e-20)
                .on(exec))
```

Add preconditioner, these 2 lines are the only difference from the simple solver example

```
.with_preconditioner(bj::build().with_max_block_size(8u).on(exec))
.on(exec);
```

Create solver

```
auto solver = solver_gen->generate(A);
```

Solve system

```
solver->apply(lend(b), lend(x));
```

Print solution

```
std::cout << "Solution (x): \n";
write(std::cout, lend(x));
```

Calculate residual

```
    auto one = gko::initialize<vec>({1.0}, exec);
    auto neg_one = gko::initialize<vec>({-1.0}, exec);
    auto res = gko::initialize<vec>({0.0}, exec);
    A->apply(lend(one), lend(x), lend(neg_one), lend(b));
    b->compute_norm2(lend(res));

    std::cout << "Residual norm sqrt(r^T r): \n";
    write(std::cout, lend(res));
}
```

Results

This is the expected output:

```
Solution (x):
%%MatrixMarket matrix array real general
19 1
0.252218
0.108645
0.0662811
0.0630433
0.0384088
0.0396536
0.0402648
0.0338935
0.0193098
0.0234653
0.0211499
0.0196413
0.0199151
0.0181674
0.0162722
0.0150714
0.0107016
0.0121141
0.0123025
Residual norm sqrt(r^T r):
%%MatrixMarket matrix array real general
1 1
9.08137e-16
```

Comments about programming and debugging

The plain program

```
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#include <ginkgo/ginkgo.hpp>


#include <fstream>
#include <iostream>
#include <string>


int main(int argc, char *argv[])
```

```
{
    using vec = gko::matrix::Dense<>;
    using mtx = gko::matrix::Csr<>;
    using cg = gko::solver::Cg<>;
    using bj = gko::preconditioner::Jacobi<>;

    std::cout << gko::version_info::get() << std::endl;

    std::shared_ptr<gko::Executor> exec;
    if (argc == 1 || std::string(argv[1]) == "reference") {
        exec = gko::ReferenceExecutor::create();
    } else if (argc == 2 && std::string(argv[1]) == "omp") {
        exec = gko::OmpExecutor::create();
    } else if (argc == 2 && std::string(argv[1]) == "cuda" &&
               gko::CudaExecutor::get_num_devices() > 0) {
        exec = gko::CudaExecutor::create(0,
      gko::OmpExecutor::create());
    } else {
        std::cerr << "Usage: " << argv[0] << " [executor]" << std::endl;
        std::exit(-1);
    }

    auto A = share(gko::read<mtx>(std::ifstream("data/A.mtx"), exec));
    auto b = gko::read<vec>(std::ifstream("data/b.mtx"), exec);
    auto x = gko::read<vec>(std::ifstream("data/x0.mtx"), exec);

    auto solver_gen =
        cg::build()
            .with_criteria(
                gko::stop::Iteration::build().with_max_iters(20u).on(exec),
                gko::stop::ResidualNormReduction<>::build()
                    .with_reduction_factor(1e-20)
                    .on(exec))
            .with_preconditioner(bj::build().with_max_block_size(8u).on(exec))
            .on(exec);
    auto solver = solver_gen->generate(A);

    solver->apply(lend(b), lend(x));

    std::cout << "Solution (x): \n";
    write(std::cout, lend(x));

    auto one = gko::initialize<vec>({1.0}, exec);
    auto neg_one = gko::initialize<vec>({-1.0}, exec);
    auto res = gko::initialize<vec>({0.0}, exec);
    A->apply(lend(one), lend(x), lend(neg_one), lend(b));
    b->compute_norm2(lend(res));

    std::cout << "Residual norm sqrt(r^T r): \n";
    write(std::cout, lend(res));
}
```

Chapter 18

The simple-solver program

The simple solver example.

Introduction

This simple solver example should help you get started with Ginkgo. This example is meant for you to understand how Ginkgo works and how you can solve a simple linear system with Ginkgo. We encourage you to play with the code, change the parameters and see what is best suited for your purposes.

About the example

Each example has the following sections:

1. **Introduction:**This gives an overview of the example and mentions any interesting aspects in the example that might help the reader.
2. **The commented program:** This section is intended for you to understand the details of the example so that you can play with it and understand Ginkgo and its features better.
3. **Results:** This section shows the results of the code when run. Though the results may not be completely the same, you can expect the behaviour to be similar.
4. **The plain program:** This is the complete code without any comments to have an complete overview of the code.

The commented program

Include files

This is the main ginkgo header file.

```
#include <ginkgo/ginkgo.hpp>
```

Add the fstream header to read from data from files.

```
#include <fstream>
```

Add the C++ iostream header to output information to the console.

```
#include <iostream>
```

Add the string manipulation header to handle strings.

```
#include <string>
```

```
int main(int argc, char *argv[])
{
```

Use some shortcuts. In Ginkgo, vectors are seen as a gko::matrix::Dense with one column/one row. The advantage of this concept is that using multiple vectors is a now a natural extension of adding columns/rows are necessary.

```
using vec = gko::matrix::Dense<>;
```

The gko::matrix::Csr class is used here, but any other matrix class such as gko::matrix::Coo, gko::matrix::Hybrid, gko::matrix::Ell or gko::matrix::Sellp could also be used.

```
using mtx = gko::matrix::Csr<>;
```

The gko::solver::Cg is used here, but any other solver class can also be used.

```
using cg = gko::solver::Cg<>;
```

Print the ginkgo version information.

```
std::cout << gko::version_info::get() << std::endl;
```

Where do you want to run your solver ?

The gko::Executor class is one of the cornerstones of Ginkgo. Currently, we have support for an gko::Omp←Executor, which uses OpenMP multi-threading in most of its kernels, a gko::ReferenceExecutor, a single threaded specialization of the OpenMP executor and a gko::CudaExecutor which runs the code on a NVIDIA GPU if available.

Note

> With the help of C++, you see that you only ever need to change the executor and all the other functions/ routines within Ginkgo should automatically work and run on the executor with any other changes.

```
std::shared_ptr<gko::Executor> exec;
if (argc == 1 || std::string(argv[1]) == "reference") {
    exec = gko::ReferenceExecutor::create();
} else if (argc == 2 && std::string(argv[1]) == "omp") {
    exec = gko::OmpExecutor::create();
} else if (argc == 2 && std::string(argv[1]) == "cuda" &&
           gko::CudaExecutor::get_num_devices() > 0) {
    exec = gko::CudaExecutor::create(0,
      gko::OmpExecutor::create());
} else {
    std::cerr << "Usage: " << argv[0] << " [executor]" << std::endl;
    std::exit(-1);
}
```

Reading your data and transfer to the proper device.

Read the matrix, right hand side and the initial solution using the read function.

Note

> Ginkgo uses C++ smart pointers to automatically manage memory. To this end, we use our own object ownership transfer functions that under the hood call the required smart pointer functions to manage object ownership. The gko::share , gko::give and gko::lend are the functions that you would need to use.

```
auto A = share(gko::read<mtx>(std::ifstream("data/A.mtx"), exec));
auto b = gko::read<vec>(std::ifstream("data/b.mtx"), exec);
auto x = gko::read<vec>(std::ifstream("data/x0.mtx"), exec);
```

Creating the solver

Generate the gko::solver factory. Ginkgo uses the concept of Factories to build solvers with certain properties. Observe the Fluent interface used here. Here a cg solver is generated with a stopping criteria of maximum iterations of 20 and a residual norm reduction of 1e-15. You also observe that the stopping criteria(gko::stop) are also generated from factories using their build methods. You need to specify the executors which each of the object needs to be built on.

```
auto solver_gen =
    cg::build()
        .with_criteria(
            gko::stop::Iteration::build().with_max_iters(20u).on(exec),
            gko::stop::ResidualNormReduction<>::build()
                .with_reduction_factor(1e-15)
                .on(exec))
        .on(exec);
```

Generate the solver from the matrix. The solver factory built in the previous step takes a "matrix"(a gko::LinOp to be more general) as an input. In this case we provide it with a full matrix that we previously read, but as the solver only effectively uses the apply() method within the provided "matrix" object, you can effectively create a gko::LinOp class with your own apply implementation to accomplish more tasks. We will see an example of how this can be done in the custom-matrix-format example

```
auto solver = solver_gen->generate(A);
```

Finally, solve the system. The solver, being a gko::LinOp, can be applied to a right hand side, b to obtain the solution, x.

```
solver->apply(lend(b), lend(x));
```

Print the solution to the command line.

```
std::cout << "Solution (x): \n";
write(std::cout, lend(x));
```

To measure if your solution has actually converged, you can measure the error of the solution. one, neg_one are objects that represent the numbers which allow for a uniform interface when computing on any device. To compute the residual, all you need to do is call the apply method, which in this case is an spmv and equivalent to the LAPACK z_spmv routine. Finally, you compute the euclidean 2-norm with the compute_norm2 function.

```
    auto one = gko::initialize<vec>({1.0}, exec);
    auto neg_one = gko::initialize<vec>({-1.0}, exec);
    auto res = gko::initialize<vec>({0.0}, exec);
    A->apply(lend(one), lend(x), lend(neg_one), lend(b));
    b->compute_norm2(lend(res));

    std::cout << "Residual norm sqrt(r^T r): \n";
    write(std::cout, lend(res));
}
```

Results

The following is the expected result:

```
Solution (x):
%%MatrixMarket matrix array real general
19 1
0.252218
0.108645
0.0662811
0.0630433
0.0384088
0.0396536
0.0402648
0.0338935
0.0193098
0.0234653
0.0211499
0.0196413
0.0199151
0.0181674
0.0162722
0.0150714
0.0107016
0.0121141
0.0123025
Residual norm sqrt(r^T r):
%%MatrixMarket matrix array real general
1 1
2.10788e-15
```

Comments about programming and debugging

The plain program

```
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#include <ginkgo/ginkgo.hpp>

#include <fstream>
#include <iostream>
#include <string>


int main(int argc, char *argv[])
{
```

```
    using vec = gko::matrix::Dense<>;
    using mtx = gko::matrix::Csr<>;
    using cg = gko::solver::Cg<>;

    std::cout << gko::version_info::get() << std::endl;

    std::shared_ptr<gko::Executor> exec;
    if (argc == 1 || std::string(argv[1]) == "reference") {
        exec = gko::ReferenceExecutor::create();
    } else if (argc == 2 && std::string(argv[1]) == "omp") {
        exec = gko::OmpExecutor::create();
    } else if (argc == 2 && std::string(argv[1]) == "cuda" &&
               gko::CudaExecutor::get_num_devices() > 0) {
        exec = gko::CudaExecutor::create(0,
      gko::OmpExecutor::create());
    } else {
        std::cerr << "Usage: " << argv[0] << " [executor]" << std::endl;
        std::exit(-1);
    }

    auto A = share(gko::read<mtx>(std::ifstream("data/A.mtx"), exec));
    auto b = gko::read<vec>(std::ifstream("data/b.mtx"), exec);
    auto x = gko::read<vec>(std::ifstream("data/x0.mtx"), exec);

    auto solver_gen =
        cg::build()
            .with_criteria(
                gko::stop::Iteration::build().with_max_iters(20u).on(exec),
                gko::stop::ResidualNormReduction<>::build()
                    .with_reduction_factor(1e-15)
                    .on(exec))
            .on(exec);
    auto solver = solver_gen->generate(A);

    solver->apply(lend(b), lend(x));

    std::cout << "Solution (x): \n";
    write(std::cout, lend(x));

    auto one = gko::initialize<vec>({1.0}, exec);
    auto neg_one = gko::initialize<vec>({-1.0}, exec);
    auto res = gko::initialize<vec>({0.0}, exec);
    A->apply(lend(one), lend(x), lend(neg_one), lend(b));
    b->compute_norm2(lend(res));

    std::cout << "Residual norm sqrt(r^T r): \n";
    write(std::cout, lend(res));
}
```

Chapter 19

The simple-solver-logging program

The simple solver with logging example.

This example depends on simple-solver, minimal-cuda-solver.

Introduction

About the example

The commented program

```
#include <ginkgo/ginkgo.hpp>


#include <fstream>
#include <iomanip>
#include <iostream>
#include <string>


namespace {


void print_vector(const std::string &name, const gko::matrix::Dense<> *vec)
{
    std::cout << name << " = [" << std::endl;
    for (int i = 0; i < vec->get_size()[0]; ++i) {
        std::cout << "    " << vec->at(i, 0) << std::endl;
    }
    std::cout << "];" << std::endl;
}


}  // namespace


int main(int argc, char *argv[])
{
```

Some shortcuts

```
using vec = gko::matrix::Dense<>;
using mtx = gko::matrix::Csr<>;
using cg = gko::solver::Cg<>;
```

Print version information

```
std::cout << gko::version_info::get() << std::endl;
```

Figure out where to run the code

```
std::shared_ptr<gko::Executor> exec;
if (argc == 1 || std::string(argv[1]) == "reference") {
    exec = gko::ReferenceExecutor::create();
} else if (argc == 2 && std::string(argv[1]) == "omp") {
    exec = gko::OmpExecutor::create();
} else if (argc == 2 && std::string(argv[1]) == "cuda" &&
           gko::CudaExecutor::get_num_devices() > 0) {
    exec = gko::CudaExecutor::create(0,
      gko::OmpExecutor::create());
} else {
    std::cerr << "Usage: " << argv[0] << " [executor]" << std::endl;
    std::exit(-1);
}
```

Read data

```
auto A = share(gko::read<mtx>(std::ifstream("data/A.mtx"), exec));
auto b = gko::read<vec>(std::ifstream("data/b.mtx"), exec);
auto x = gko::read<vec>(std::ifstream("data/x0.mtx"), exec);
```

Let's declare a logger which prints to std::cout instead of printing to a file. We log all events except for all linop factory and polymorphic object events. Events masks are group of events which are provided for convenience.

```
std::shared_ptr<gko::log::Stream<>> stream_logger =
    gko::log::Stream<>::create(
        exec,
        gko::log::Logger::all_events_mask ^
            gko::log::Logger::linop_factory_events_mask ^
            gko::log::Logger::polymorphic_object_events_mask,
        std::cout);
```

Add stream_logger to the executor

```
exec->add_logger(stream_logger);
```

Add stream_logger only to the ResidualNormReduction criterion Factory Note that the logger will get automatically propagated to every criterion generated from this factory.

```
using ResidualCriterionFactory =
    gko::stop::ResidualNormReduction<>::Factory;
std::shared_ptr<ResidualCriterionFactory> residual_criterion =
    ResidualCriterionFactory::create().with_reduction_factor(1e-20).on(
        exec);
residual_criterion->add_logger(stream_logger);
```

Generate solver

```
auto solver_gen =
    cg::build()
        .with_criteria(
            residual_criterion,
            gko::stop::Iteration::build().with_max_iters(20u).on(exec))
        .on(exec);
auto solver = solver_gen->generate(A);
```

First we add facilities to only print to a file. It's possible to select events, using masks, e.g. only iterations mask: gko::log::Logger::iteration_complete_mask. See the documentation of Logger class for more information.

```
std::ofstream filestream("my_file.txt");
solver->add_logger(gko::log::Stream<>::create(
    exec, gko::log::Logger::all_events_mask, filestream));
solver->add_logger(stream_logger);
```

Add another logger which puts all the data in an object, we can later retrieve this object in our code. Here we only have want Executor and criterion check completed events.

```
std::shared_ptr<gko::log::Record> record_logger = gko::log::Record::create(
    exec, gko::log::Logger::executor_events_mask |
              gko::log::Logger::criterion_check_completed_mask);
exec->add_logger(record_logger);
residual_criterion->add_logger(record_logger);
```

Solve system

```
solver->apply(lend(b), lend(x));
```

Finally, get some data from `record_logger` and print the last memory location copied

```
auto &last_copy = record_logger->get().copy_completed.back();
std::cout << "Last memory copied was of size " << std::hex
          << std::get<0>(*last_copy).num_bytes << " FROM executor "
          << std::get<0>(*last_copy).exec << " pointer "
          << std::get<0>(*last_copy).location << " TO executor "
          << std::get<1>(*last_copy).exec << " pointer "
          << std::get<1>(*last_copy).location << std::dec << std::endl;
```

Also print the residual of the last criterion check event (where convergence happened)

```
auto residual =
    record_logger->get().criterion_check_completed.back()->residual.get();
auto residual_d = gko::as<gko::matrix::Dense<>>(residual);
print_vector("Residual", residual_d);
```

Print solution

```
std::cout << "Solution (x): \n";
write(std::cout, lend(x));
```

Calculate residual

```
    auto one = gko::initialize<vec>({1.0}, exec);
    auto neg_one = gko::initialize<vec>({-1.0}, exec);
    auto res = gko::initialize<vec>({0.0}, exec);
    A->apply(lend(one), lend(x), lend(neg_one), lend(b));
    b->compute_norm2(lend(res));

    std::cout << "Residual norm sqrt(r^T r): \n";
    write(std::cout, lend(res));
}
```

Results

This is the expected output:

```
[LOG] >>> apply started on A LinOp[gko::solver::Cg<double>,0x55ae09d923f0] with b LinOp[
      gko::matrix::Dense<double>,0x55ae09d928b0] and x LinOp[gko::matrix::Dense<double>,0x55ae09d92f10]
[LOG] >>> allocation started on Executor[gko::ReferenceExecutor,0x55ae09d8f2a0] with Bytes[8]
[LOG] >>> allocation completed on Executor[gko::ReferenceExecutor,0x55ae09d8f2a0] at Location[
      0x55ae09d91750] with Bytes[8]
[LOG] >>> allocation started on Executor[gko::ReferenceExecutor,0x55ae09d8f2a0] with Bytes[8]
[LOG] >>> allocation completed on Executor[gko::ReferenceExecutor,0x55ae09d8f2a0] at Location[
      0x55ae09d977e0] with Bytes[8]
[LOG] >>> allocation started on Executor[gko::ReferenceExecutor,0x55ae09d8f2a0] with Bytes[152]
[LOG] >>> allocation completed on Executor[gko::ReferenceExecutor,0x55ae09d8f2a0] at Location[
      0x55ae09d97b40] with Bytes[152]
[LOG] >>> allocation started on Executor[gko::ReferenceExecutor,0x55ae09d8f2a0] with Bytes[152]
[LOG] >>> allocation completed on Executor[gko::ReferenceExecutor,0x55ae09d8f2a0] at Location[
      0x55ae09d97d10] with Bytes[152]
[LOG] >>> allocation started on Executor[gko::ReferenceExecutor,0x55ae09d8f2a0] with Bytes[152]
[LOG] >>> allocation completed on Executor[gko::ReferenceExecutor,0x55ae09d8f2a0] at Location[
      0x55ae09d97ee0] with Bytes[152]
[LOG] >>> allocation started on Executor[gko::ReferenceExecutor,0x55ae09d8f2a0] with Bytes[152]
[LOG] >>> allocation completed on Executor[gko::ReferenceExecutor,0x55ae09d8f2a0] at Location[
      0x55ae09d980b0] with Bytes[152]
[LOG] >>> allocation started on Executor[gko::ReferenceExecutor,0x55ae09d8f2a0] with Bytes[8]
[LOG] >>> allocation completed on Executor[gko::ReferenceExecutor,0x55ae09d8f2a0] at Location[
      0x55ae09d98090] with Bytes[8]
[LOG] >>> allocation started on Executor[gko::ReferenceExecutor,0x55ae09d8f2a0] with Bytes[8]
[LOG] >>> allocation completed on Executor[gko::ReferenceExecutor,0x55ae09d8f2a0] at Location[
      0x55ae09d98260] with Bytes[8]
[LOG] >>> allocation started on Executor[gko::ReferenceExecutor,0x55ae09d8f2a0] with Bytes[8]
[LOG] >>> allocation completed on Executor[gko::ReferenceExecutor,0x55ae09d8f2a0] at Location[
      0x55ae09d983b0] with Bytes[8]
[LOG] >>> allocation started on Executor[gko::ReferenceExecutor,0x55ae09d8f2a0] with Bytes[8]
[LOG] >>> allocation completed on Executor[gko::ReferenceExecutor,0x55ae09d8f2a0] at Location[
      0x55ae09d98500] with Bytes[8]
[LOG] >>> allocation started on Executor[gko::ReferenceExecutor,0x55ae09d8f2a0] with Bytes[1]
[LOG] >>> allocation completed on Executor[gko::ReferenceExecutor,0x55ae09d8f2a0] at Location[
      0x55ae09d98650] with Bytes[1]
[LOG] >>> Operation[gko::solver::cg::initialize_operation<gko::matrix::Dense<double> const*&,
      gko::matrix::Dense<double>*, gko::matrix::Dense<double>*, gko::matrix::Dense<double>*, gko::matrix::Dense<double>*,
      gko::matrix::Dense<double>*, gko::matrix::Dense<double>*, gko:
:Array<gko::stopping_status>*>,0x7ffcab765d60] started on Executor[gko::ReferenceExecutor,0x55ae09d8f2a0]
[LOG] >>> Operation[gko::solver::cg::initialize_operation<gko::matrix::Dense<double> const*&,
      gko::matrix::Dense<double>*, gko::matrix::Dense<double>*, gko::matrix::Dense<double>*, gko::matrix::Dense<double>*,
      gko::matrix::Dense<double>*, gko::matrix::Dense<double>*, gko:
:Array<gko::stopping_status>*>,0x7ffcab765d60] completed on Executor[gko::ReferenceExecutor,0x55ae09d8f2a0]
[LOG] >>> Operation[gko::matrix::csr::advanced_spmv_operation<gko::matrix::Dense<double> const*,
      gko::matrix::Csr<double, int> const*, gko::matrix::Dense<double> const*, gko::matrix::Dense<double> const*,
      gko::matrix::Dense<double>*>,0x7ffcab765980] started on Executor[gk
o::ReferenceExecutor,0x55ae09d8f2a0]
[LOG] >>> Operation[gko::matrix::csr::advanced_spmv_operation<gko::matrix::Dense<double> const*,
      gko::matrix::Csr<double, int> const*, gko::matrix::Dense<double> const*, gko::matrix::Dense<double> const*,
      gko::matrix::Dense<double>*>,0x7ffcab765980] completed on Executor[
gko::ReferenceExecutor,0x55ae09d8f2a0]
[LOG] >>> allocation started on Executor[gko::ReferenceExecutor,0x55ae09d8f2a0] with Bytes[2]
[LOG] >>> allocation completed on Executor[gko::ReferenceExecutor,0x55ae09d8f2a0] at Location[
      0x55ae09d98690] with Bytes[2]
[LOG] >>> allocation started on Executor[gko::ReferenceExecutor,0x55ae09d8f2a0] with Bytes[8]
[LOG] >>> allocation completed on Executor[gko::ReferenceExecutor,0x55ae09d8f2a0] at Location[
      0x55ae09d99310] with Bytes[8]
[LOG] >>> allocation started on Executor[gko::ReferenceExecutor,0x55ae09d8f2a0] with Bytes[8]
[LOG] >>> allocation completed on Executor[gko::ReferenceExecutor,0x55ae09d8f2a0] at Location[
      0x55ae09d99350] with Bytes[8]
[LOG] >>> Operation[gko::matrix::dense::compute_norm2_operation<gko::matrix::Dense<double> const*,
      gko::matrix::Dense<double>*>,0x7ffcab7657c0] started on Executor[gko::ReferenceExecutor,0x55ae09d8f2a0]
[LOG] >>> Operation[gko::matrix::dense::compute_norm2_operation<gko::matrix::Dense<double> const*,
      gko::matrix::Dense<double>*>,0x7ffcab7657c0] completed on Executor[gko::ReferenceExecutor,0x55ae09d8f2a0]
[LOG] >>> copy started from Executor[gko::ReferenceExecutor,0x55ae09d8f2a0] to Executor[
      gko::ReferenceExecutor,0x55ae09d8f2a0] from Location[0x55ae09d97b40] to Location[0x55ae09d97d10] with Bytes[152]
[LOG] >>> copy completed from Executor[gko::ReferenceExecutor,0x55ae09d8f2a0] to Executor[
      gko::ReferenceExecutor,0x55ae09d8f2a0] from Location[0x55ae09d97b40] to Location[0x55ae09d97d10] with Bytes[152]
[LOG] >>> Operation[gko::matrix::dense::compute_dot_operation<gko::matrix::Dense<double> const*,
      gko::matrix::Dense<double> const*, gko::matrix::Dense<double>*>,0x7ffcab7659a0] started on Executor[
      gko::ReferenceExecutor,0x55ae09d8f2a0]
[LOG] >>> Operation[gko::matrix::dense::compute_dot_operation<gko::matrix::Dense<double> const*,
      gko::matrix::Dense<double> const*, gko::matrix::Dense<double>*>,0x7ffcab7659a0] completed on Executor[
      gko::ReferenceExecutor,0x55ae09d8f2a0]
[LOG] >>> iteration 0 completed with solver LinOp[gko::solver::Cg<double>,0x55ae09d923f0] with residual
      LinOp[gko::matrix::Dense<double>,0x55ae09d930c0], solution LinOp[gko::matrix::Dense<double>,0x55ae09d92f10] and
       residual_norm LinOp[gko::LinOp const*,0]
[LOG] >>> check started for stop::Criterion[gko::stop::ResidualNormReduction<double>,0x55ae09d99260] at
      iteration 0 with ID 1 and finalized set to 1
```

```
[LOG] >>> Operation[gko::matrix::dense::compute_norm2_operation<gko::matrix::Dense<double> const*,
      gko::matrix::Dense<double>*>,0x7ffcab765740] started on Executor[gko::ReferenceExecutor,0x55ae09d8f2a0]
[LOG] >>> Operation[gko::matrix::dense::compute_norm2_operation<gko::matrix::Dense<double> const*,
      gko::matrix::Dense<double>*>,0x7ffcab765740] completed on Executor[gko::ReferenceExecutor,0x55ae09d8f2a0]
[LOG] >>> Operation[
      gko::stop::residual_norm_reduction::residual_norm_reduction_operation<gko::matrix::Dense<double> const*&, gko::matrix::D
      gko::Array<gko::stopping_status>*&, gko::Array<bool>*, bool*, bool*&>,0x7ffcab765980]
 started on Executor[gko::ReferenceExecutor,0x55ae09d8f2a0]
[LOG] >>> Operation[
      gko::stop::residual_norm_reduction::residual_norm_reduction_operation<gko::matrix::Dense<double> const*&, gko::matrix::D
      gko::Array<gko::stopping_status>*&, gko::Array<bool>*, bool*, bool*&>,0x7ffcab765980]
 completed on Executor[gko::ReferenceExecutor,0x55ae09d8f2a0]
[LOG] >>> check completed for stop::Criterion[gko::stop::ResidualNormReduction<double>,0x55ae09d99260] at
      iteration 0 with ID 1 and finalized set to 1. It changed one RHS 0, stopped the iteration process 0
[LOG] >>> allocation started on Executor[gko::ReferenceExecutor,0x55ae09d8f2a0] with Bytes[152]
[LOG] >>> allocation completed on Executor[gko::ReferenceExecutor,0x55ae09d8f2a0] at Location[
      0x55ae09d99820] with Bytes[152]

.
.
.
.
.
.

[LOG] >>> free started on Executor[gko::ReferenceExecutor,0x55ae09d8f2a0] at Location[0x55ae09d98690]
[LOG] >>> free completed on Executor[gko::ReferenceExecutor,0x55ae09d8f2a0] at Location[0x55ae09d98690]
[LOG] >>> free started on Executor[gko::ReferenceExecutor,0x55ae09d8f2a0] at Location[0x55ae09d99350]
[LOG] >>> free completed on Executor[gko::ReferenceExecutor,0x55ae09d8f2a0] at Location[0x55ae09d99350]
[LOG] >>> free started on Executor[gko::ReferenceExecutor,0x55ae09d8f2a0] at Location[0x55ae09d99310]
[LOG] >>> free completed on Executor[gko::ReferenceExecutor,0x55ae09d8f2a0] at Location[0x55ae09d99310]
[LOG] >>> free started on Executor[gko::ReferenceExecutor,0x55ae09d8f2a0] at Location[0x55ae09d98650]
[LOG] >>> free completed on Executor[gko::ReferenceExecutor,0x55ae09d8f2a0] at Location[0x55ae09d98650]
[LOG] >>> free started on Executor[gko::ReferenceExecutor,0x55ae09d8f2a0] at Location[0x55ae09d98500]
[LOG] >>> free completed on Executor[gko::ReferenceExecutor,0x55ae09d8f2a0] at Location[0x55ae09d98500]
[LOG] >>> free started on Executor[gko::ReferenceExecutor,0x55ae09d8f2a0] at Location[0x55ae09d983b0]
[LOG] >>> free completed on Executor[gko::ReferenceExecutor,0x55ae09d8f2a0] at Location[0x55ae09d983b0]
[LOG] >>> free started on Executor[gko::ReferenceExecutor,0x55ae09d8f2a0] at Location[0x55ae09d98260]
[LOG] >>> free completed on Executor[gko::ReferenceExecutor,0x55ae09d8f2a0] at Location[0x55ae09d98260]
[LOG] >>> free started on Executor[gko::ReferenceExecutor,0x55ae09d8f2a0] at Location[0x55ae09d98090]
[LOG] >>> free completed on Executor[gko::ReferenceExecutor,0x55ae09d8f2a0] at Location[0x55ae09d98090]
[LOG] >>> free started on Executor[gko::ReferenceExecutor,0x55ae09d8f2a0] at Location[0x55ae09d980b0]
[LOG] >>> free completed on Executor[gko::ReferenceExecutor,0x55ae09d8f2a0] at Location[0x55ae09d980b0]
[LOG] >>> free started on Executor[gko::ReferenceExecutor,0x55ae09d8f2a0] at Location[0x55ae09d97ee0]
[LOG] >>> free completed on Executor[gko::ReferenceExecutor,0x55ae09d8f2a0] at Location[0x55ae09d97ee0]
[LOG] >>> free started on Executor[gko::ReferenceExecutor,0x55ae09d8f2a0] at Location[0x55ae09d97d10]
[LOG] >>> free completed on Executor[gko::ReferenceExecutor,0x55ae09d8f2a0] at Location[0x55ae09d97d10]
[LOG] >>> free started on Executor[gko::ReferenceExecutor,0x55ae09d8f2a0] at Location[0x55ae09d97b40]
[LOG] >>> free completed on Executor[gko::ReferenceExecutor,0x55ae09d8f2a0] at Location[0x55ae09d97b40]
[LOG] >>> free started on Executor[gko::ReferenceExecutor,0x55ae09d8f2a0] at Location[0x55ae09d977e0]
[LOG] >>> free completed on Executor[gko::ReferenceExecutor,0x55ae09d8f2a0] at Location[0x55ae09d977e0]
[LOG] >>> free started on Executor[gko::ReferenceExecutor,0x55ae09d8f2a0] at Location[0x55ae09d91750]
[LOG] >>> free completed on Executor[gko::ReferenceExecutor,0x55ae09d8f2a0] at Location[0x55ae09d91750]
[LOG] >>> apply completed on A LinOp[gko::solver::Cg<double>,0x55ae09d923f0] with b LinOp[
      gko::matrix::Dense<double>,0x55ae09d928b0] and x LinOp[gko::matrix::Dense<double>,0x55ae09d92f10]
Last memory copied was of size 98 FROM executor 0x55ae09d8f2a0 pointer 55ae09d931d0 TO executor
      0x55ae09d8f2a0 pointer 55ae09d998c0
Residual = [
    1.3067e-18
    -1.34263e-18
    -2.7754e-19
    2.35392e-20
    -2.25114e-19
    -1.35474e-20
    -1.82049e-19
    -2.48092e-19
    -4.57754e-19
    -1.28163e-18
    -1.04918e-18
    -5.88231e-19
    -8.463e-19
    -2.87785e-18
    -4.06072e-18
    -9.40979e-18
    -1.07071e-17
    -4.14666e-17
    -2.75923e-17
];
Solution (x):
%%MatrixMarket matrix array real general
19 1
0.252218
0.108645
0.0662811
0.0630433
0.0384088
0.0396536
```

```
0.0402648
0.0338935
0.0193098
0.0234653
0.0211499
0.0196413
0.0199151
0.0181674
0.0162722
0.0150714
0.0107016
0.0121141
0.0123025
[LOG] >>> allocation started on Executor[gko::ReferenceExecutor,0x55ae09d8f2a0] with Bytes[8]
[LOG] >>> allocation completed on Executor[gko::ReferenceExecutor,0x55ae09d8f2a0] at Location[0
      x55ae09d9a310] with Bytes[8]
[LOG] >>> allocation started on Executor[gko::ReferenceExecutor,0x55ae09d8f2a0] with Bytes[8]
[LOG] >>> allocation completed on Executor[gko::ReferenceExecutor,0x55ae09d8f2a0] at Location[0
      x55ae09d97ec0] with Bytes[8]
[LOG] >>> allocation started on Executor[gko::ReferenceExecutor,0x55ae09d8f2a0] with Bytes[8]
[LOG] >>> allocation completed on Executor[gko::ReferenceExecutor,0x55ae09d8f2a0] at Location[0
      x55ae09d99370] with Bytes[8]
[LOG] >>> Operation[gko::matrix::csr::advanced_spmv_operation<gko::matrix::Dense<double> const*,
      gko::matrix::Csr<double, int> const*, gko::matrix::Dense<double> const*,
      gko::matrix::Dense<double> const*, gko::matrix::Dense<double>*>,0x7ffcab765d50] started on Executor[
      gk
o::ReferenceExecutor,0x55ae09d8f2a0]
[LOG] >>> Operation[gko::matrix::csr::advanced_spmv_operation<gko::matrix::Dense<double> const*,
      gko::matrix::Csr<double, int> const*, gko::matrix::Dense<double> const*,
      gko::matrix::Dense<double> const*, gko::matrix::Dense<double>*>,0x7ffcab765d50] completed on Executor
      [
gko::ReferenceExecutor,0x55ae09d8f2a0]
[LOG] >>> Operation[gko::matrix::dense::compute_norm2_operation<gko::matrix::Dense<double> const*,
      gko::matrix::Dense<double>*>,0x7ffcab765dc0] started on Executor[gko::ReferenceExecutor,0
      x55ae09d8f2a0]
[LOG] >>> Operation[gko::matrix::dense::compute_norm2_operation<gko::matrix::Dense<double> const*,
      gko::matrix::Dense<double>*>,0x7ffcab765dc0] completed on Executor[gko::ReferenceExecutor,0
      x55ae09d8f2a0]
Residual norm sqrt(r^T r):
%%MatrixMarket matrix array real general
1 1
8.87107e-16
[LOG] >>> free started on Executor[gko::ReferenceExecutor,0x55ae09d8f2a0] at Location[0x55ae09d99370]
[LOG] >>> free completed on Executor[gko::ReferenceExecutor,0x55ae09d8f2a0] at Location[0x55ae09d99370]
[LOG] >>> free started on Executor[gko::ReferenceExecutor,0x55ae09d8f2a0] at Location[0x55ae09d97ec0]
[LOG] >>> free completed on Executor[gko::ReferenceExecutor,0x55ae09d8f2a0] at Location[0x55ae09d97ec0]
[LOG] >>> free started on Executor[gko::ReferenceExecutor,0x55ae09d8f2a0] at Location[0x55ae09d9a310]
[LOG] >>> free completed on Executor[gko::ReferenceExecutor,0x55ae09d8f2a0] at Location[0x55ae09d9a310]
[LOG] >>> free started on Executor[gko::ReferenceExecutor,0x55ae09d8f2a0] at Location[0x55ae09d931d0]
[LOG] >>> free completed on Executor[gko::ReferenceExecutor,0x55ae09d8f2a0] at Location[0x55ae09d931d0]
[LOG] >>> free started on Executor[gko::ReferenceExecutor,0x55ae09d8f2a0] at Location[0x55ae09d93020]
[LOG] >>> free completed on Executor[gko::ReferenceExecutor,0x55ae09d8f2a0] at Location[0x55ae09d93020]
[LOG] >>> free started on Executor[gko::ReferenceExecutor,0x55ae09d8f2a0] at Location[0x55ae09d92830]
[LOG] >>> free completed on Executor[gko::ReferenceExecutor,0x55ae09d8f2a0] at Location[0x55ae09d92830]
[LOG] >>> free started on Executor[gko::ReferenceExecutor,0x55ae09d8f2a0] at Location[0x55ae09d925b0]
[LOG] >>> free completed on Executor[gko::ReferenceExecutor,0x55ae09d8f2a0] at Location[0x55ae09d925b0]
[LOG] >>> free started on Executor[gko::ReferenceExecutor,0x55ae09d8f2a0] at Location[0x55ae09d93360]
[LOG] >>> free completed on Executor[gko::ReferenceExecutor,0x55ae09d8f2a0] at Location[0x55ae09d93360]
```

Comments about programming and debugging

The plain program

```
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```

```
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#include <ginkgo/ginkgo.hpp>


#include <fstream>
#include <iomanip>
#include <iostream>
#include <string>


namespace {


void print_vector(const std::string &name, const gko::matrix::Dense<> *vec)
{
    std::cout << name << " = [" << std::endl;
    for (int i = 0; i < vec->get_size()[0]; ++i) {
        std::cout << "    " << vec->at(i, 0) << std::endl;
    }
    std::cout << "];" << std::endl;
}


}  // namespace


int main(int argc, char *argv[])
{
    using vec = gko::matrix::Dense<>;
    using mtx = gko::matrix::Csr<>;
    using cg = gko::solver::Cg<>;

    std::cout << gko::version_info::get() << std::endl;

    std::shared_ptr<gko::Executor> exec;
    if (argc == 1 || std::string(argv[1]) == "reference") {
        exec = gko::ReferenceExecutor::create();
    } else if (argc == 2 && std::string(argv[1]) == "omp") {
        exec = gko::OmpExecutor::create();
    } else if (argc == 2 && std::string(argv[1]) == "cuda" &&
               gko::CudaExecutor::get_num_devices() > 0) {
        exec = gko::CudaExecutor::create(0,
      gko::OmpExecutor::create());
    } else {
        std::cerr << "Usage: " << argv[0] << " [executor]" << std::endl;
        std::exit(-1);
    }

    auto A = share(gko::read<mtx>(std::ifstream("data/A.mtx"), exec));
    auto b = gko::read<vec>(std::ifstream("data/b.mtx"), exec);
    auto x = gko::read<vec>(std::ifstream("data/x0.mtx"), exec);

    std::shared_ptr<gko::log::Stream<>> stream_logger =
        gko::log::Stream<>::create(
            exec,
            gko::log::Logger::all_events_mask ^
                gko::log::Logger::linop_factory_events_mask ^
                gko::log::Logger::polymorphic_object_events_mask,
            std::cout);

    exec->add_logger(stream_logger);

    using ResidualCriterionFactory =
        gko::stop::ResidualNormReduction<>::Factory;
    std::shared_ptr<ResidualCriterionFactory> residual_criterion =
        ResidualCriterionFactory::create().with_reduction_factor(1e-20).on(
            exec);
    residual_criterion->add_logger(stream_logger);

    auto solver_gen =
        cg::build()
            .with_criteria(
                residual_criterion,
```

```
                gko::stop::Iteration::build().with_max_iters(20u).on(exec))
            .on(exec);
    auto solver = solver_gen->generate(A);


    std::ofstream filestream("my_file.txt");
    solver->add_logger(gko::log::Stream<>::create(
        exec, gko::log::Logger::all_events_mask, filestream));
    solver->add_logger(stream_logger);

    std::shared_ptr<gko::log::Record> record_logger = gko::log::Record::create(
        exec, gko::log::Logger::executor_events_mask |
                  gko::log::Logger::criterion_check_completed_mask);
    exec->add_logger(record_logger);
    residual_criterion->add_logger(record_logger);

    solver->apply(lend(b), lend(x));

    auto &last_copy = record_logger->get().copy_completed.back();
    std::cout << "Last memory copied was of size " << std::hex
              << std::get<0>(*last_copy).num_bytes << " FROM executor "
              << std::get<0>(*last_copy).exec << " pointer "
              << std::get<0>(*last_copy).location << " TO executor "
              << std::get<1>(*last_copy).exec << " pointer "
              << std::get<1>(*last_copy).location << std::dec << std::endl;
    auto residual =
        record_logger->get().criterion_check_completed.back()->residual.get();
    auto residual_d = gko::as<gko::matrix::Dense<>>(residual);
    print_vector("Residual", residual_d);

    std::cout << "Solution (x): \n";
    write(std::cout, lend(x));

    auto one = gko::initialize<vec>({1.0}, exec);
    auto neg_one = gko::initialize<vec>({-1.0}, exec);
    auto res = gko::initialize<vec>({0.0}, exec);
    A->apply(lend(one), lend(x), lend(neg_one), lend(b));
    b->compute_norm2(lend(res));

    std::cout << "Residual norm sqrt(r^T r): \n";
    write(std::cout, lend(res));
}
```

Chapter 20

The three-pt-stencil-solver program

The 3-point stencil example.

This example depends on simple-solver, poisson-solver.

Introduction

This example solves a 1D Poisson equation:

$u : [0, 1] \rightarrow R$
$u'' = f$
$u(0) = u0$
$u(1) = u1$

using a finite difference method on an equidistant grid with `K` discretization points (`K` can be controlled with a command line parameter). The discretization is done via the second order Taylor polynomial:

$u(x + h) = u(x) - u'(x)h + 1/2u''(x)h^2 + O(h^3)$
$u(x - h) = u(x) + u'(x)h + 1/2u''(x)h^2 + O(h^3)/+$
$------------------------$
$-u(x - h) + 2u(x) + -u(x + h) = -f(x)h^2 + O(h^3)$

For an equidistant grid with K "inner" discretization points $x1, ..., xk$,and step size $h = 1/(K + 1)$, the formula produces a system of linear equations

$2u_1 - u_2 = -f_1h^2 + u0$
$-u_(k - 1) + 2u_k - u_(k + 1) = -f_kh^2, k = 2, ..., K - 1$
$-u_(K - 1) + 2u_K = -f_Kh^2 + u1$

which is then solved using Ginkgo's implementation of the CG method preconditioned with block-Jacobi. It is also possible to specify on which executor Ginkgo will solve the system via the command line. The function 'f'is set to '$f(x) = 6x$' (making the solution '$u(x) = x^3$'), but that can be changed in the `main` function.

The intention of the example is to show how Ginkgo can be integrated into existing software - the `generate_stencil_matrix`, `generate_rhs`, `print_solution`, `compute_error` and `main` function do not reference Ginkgo at all (i.e. they could have been there before the application developer decided to use Ginkgo, and the only part where Ginkgo is introduced is inside the `solve_system` function.

About the example

The commented program

```
/ *****************************<DECSRIPTION>***********************************
This example solves a 1D Poisson equation:

    u : [0, 1] -> R
    u'' = f
    u(0) = u0
    u(1) = u1

using a finite difference method on an equidistant grid with `K` discretization
points (`K` can be controlled with a command line parameter). The discretization
is done via the second order Taylor polynomial:

u(x + h) = u(x) - u'(x)h + 1/2 u''(x)h^2 + O(h^3)
u(x - h) = u(x) + u'(x)h + 1/2 u''(x)h^2 + O(h^3)  / +
---------------------------------------------
-u(x - h) + 2u(x) + -u(x + h) = -f(x)h^2 + O(h^3)

For an equidistant grid with K "inner" discretization points x1, ..., xk, and
step size h = 1 / (K + 1), the formula produces a system of linear equations

           2u_1 - u_2     = -f_1 h^2 + u0
-u_(k-1) + 2u_k - u_(k+1) = -f_k h^2,       k = 2, ..., K - 1
-u_(K-1) + 2u_K           = -f_K h^2 + u1


which is then solved using Ginkgo's implementation of the CG method
preconditioned with block-Jacobi. It is also possible to specify on which
executor Ginkgo will solve the system via the command line.
The function `f` is set to `f(x) = 6x` (making the solution `u(x) = x^3`), but
that can be changed in the `main` function.

The intention of the example is to show how Ginkgo can be integrated into
existing software - the `generate_stencil_matrix`, `generate_rhs`,
`print_solution`, `compute_error` and `main` function do not reference Ginkgo at
all (i.e. they could have been there before the application developer decided to
use Ginkgo, and the only part where Ginkgo is introduced is inside the
`solve_system` function.
****************************<DECSRIPTION>********************************** /

#include <ginkgo/ginkgo.hpp>
#include <iostream>
#include <map>
#include <string>
#include <vector>
```

Creates a stencil matrix in CSR format for the given number of discretization points.

```
void generate_stencil_matrix(int discretization_points, int *row_ptrs,
                             int *col_idxs, double *values)
{
    int pos = 0;
    const double coefs[] = {-1, 2, -1};
    row_ptrs[0] = pos;
    for (int i = 0; i < discretization_points; ++i) {
        for (auto ofs : {-1, 0, 1}) {
            if (0 <= i + ofs && i + ofs < discretization_points) {
                values[pos] = coefs[ofs + 1];
                col_idxs[pos] = i + ofs;
                ++pos;
            }
        }
        row_ptrs[i + 1] = pos;
    }
}
```

Generates the RHS vector given `f` and the boundary conditions.

```
template <typename Closure>
void generate_rhs(int discretization_points, Closure f, double u0, double u1,
                  double *rhs)
{
```

```
    const auto h = 1.0 / (discretization_points + 1);
    for (int i = 0; i < discretization_points; ++i) {
        const auto xi = (i + 1) * h;
        rhs[i] = -f(xi) * h * h;
    }
    rhs[0] += u0;
    rhs[discretization_points - 1] += u1;
}
```

Prints the solution `u`.

```
void print_solution(int discretization_points, double u0, double u1,
                    const double *u)
{
    std::cout << u0 << '\n';
    for (int i = 0; i < discretization_points; ++i) {
        std::cout << u[i] << '\n';
    }
    std::cout << u1 << std::endl;
}
```

Computes the 1-norm of the error given the computed `u` and the correct solution function `correct_u`.

```
template <typename Closure>
double calculate_error(int discretization_points, const double *u,
                       Closure correct_u)
{
    const auto h = 1.0 / (discretization_points + 1);
    auto error = 0.0;
    for (int i = 0; i < discretization_points; ++i) {
        using std::abs;
        const auto xi = (i + 1) * h;
        error += abs(u[i] - correct_u(xi)) / abs(correct_u(xi));
    }
    return error;
}

void solve_system(const std::string &executor_string,
                  unsigned int discretization_points, int *row_ptrs,
                  int *col_idxs, double *values, double *rhs, double *u,
                  double accuracy)
{
```

Some shortcuts

```
using vec = gko::matrix::Dense<double>;
using mtx = gko::matrix::Csr<double, int>;
using cg = gko::solver::Cg<double>;
using bj = gko::preconditioner::Jacobi<double, int>;
using val_array = gko::Array<double>;
using idx_array = gko::Array<int>;
const auto &dp = discretization_points;
```

Figure out where to run the code

```
const auto omp = gko::OmpExecutor::create();
std::map<std::string, std::shared_ptr<gko::Executor>> exec_map{
    {"omp", omp},
    {"cuda", gko::CudaExecutor::create(0, omp)},
    {"reference", gko::ReferenceExecutor::create()}};
```

executor where Ginkgo will perform the computation

```
const auto exec = exec_map.at(executor_string);  // throws if not valid
```

executor where the application initialized the data

```
const auto app_exec = exec_map["omp"];
```

Tell Ginkgo to use the data in our application

Matrix: we have to set the executor of the matrix to the one where we want SpMVs to run (in this case `exec`). When creating array views, we have to specify the executor where the data is (in this case `app_exec`).

If the two do not match, Ginkgo will automatically create a copy of the data on `exec` (however, it will not copy the data back once it is done

- here this is not important since we are not modifying the matrix).

```
auto matrix = mtx::create(exec, gko::dim<2>(dp),
                          val_array::view(app_exec, 3 * dp - 2, values),
                          idx_array::view(app_exec, 3 * dp - 2, col_idxs),
                          idx_array::view(app_exec, dp + 1, row_ptrs));
```

RHS: similar to matrix

```
auto b = vec::create(exec, gko::dim<2>(dp, 1),
                     val_array::view(app_exec, dp, rhs), 1);
```

Solution: we have to be careful here - if the executors are different, once we compute the solution the array will not be automatically copied back to the original memory locations. Fortunately, whenever `apply` is called on a linear operator (e.g. matrix, solver) the arguments automatically get copied to the executor where the operator is, and copied back once the operation is completed. Thus, in this case, we can just define the solution on `app_exec`, and it will be automatically transferred to/from `exec` if needed.

```
auto x = vec::create(app_exec, gko::dim<2>(dp, 1),
                     val_array::view(app_exec, dp, u), 1);
```

Generate solver

```
auto solver_gen =
    cg::build()
        .with_criteria(
            gko::stop::Iteration::build().with_max_iters(dp).on(exec),
            gko::stop::ResidualNormReduction<>::build()
                .with_reduction_factor(accuracy)
                .on(exec))
        .with_preconditioner(bj::build().on(exec))
        .on(exec);
auto solver = solver_gen->generate(gko::give(matrix));
```

Solve system

```
    solver->apply(gko::lend(b), gko::lend(x));
}


int main(int argc, char *argv[])
{
    if (argc < 2) {
        std::cerr << "Usage: " << argv[0] << " DISCRETIZATION_POINTS [executor]"
                  << std::endl;
        std::exit(-1);
    }

    const int discretization_points = argc >= 2 ? std::atoi(argv[1]) : 100;
    const auto executor_string = argc >= 3 ? argv[2] : "reference";
```

problem:

```
auto correct_u = [](double x) { return x * x * x; };
auto f = [](double x) { return 6 * x; };
auto u0 = correct_u(0);
auto u1 = correct_u(1);
```

matrix

```
std::vector<int> row_ptrs(discretization_points + 1);
std::vector<int> col_idxs(3 * discretization_points - 2);
std::vector<double> values(3 * discretization_points - 2);
```

right hand side

```
std::vector<double> rhs(discretization_points);
```

solution

```
std::vector<double> u(discretization_points, 0.0);

generate_stencil_matrix(discretization_points, row_ptrs.data(),
                        col_idxs.data(), values.data());
```

looking for solution u = x^3: f = 6x, u(0) = 0, u(1) = 1

```
    generate_rhs(discretization_points, f, u0, u1, rhs.data());

    solve_system(executor_string, discretization_points, row_ptrs.data(),
                 col_idxs.data(), values.data(), rhs.data(), u.data(), 1e-12);

    print_solution(discretization_points, 0, 1, u.data());
    std::cout << "The average relative error is "
              << calculate_error(discretization_points, u.data(), correct_u) /
                     discretization_points
              << std::endl;
}
```

Results

This is the expected output:

```
0
0.00010798
0.000863838
0.00291545
0.0069107
0.0134975
0.0233236
0.037037
0.0552856
0.0787172
0.10798
0.143721
0.186589
0.237231
0.296296
0.364431
0.442285
0.530504
0.629738
0.740633
0.863838
1
The average relative error is 1.87318e-15
```

Comments about programming and debugging

The plain program

```
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/******************************<DECSRIPTION>*********************************
This example solves a 1D Poisson equation:

    u : [0, 1] -> R
    u'' = f
    u(0) = u0
    u(1) = u1

using a finite difference method on an equidistant grid with `K` discretization
points (`K` can be controlled with a command line parameter). The discretization
is done via the second order Taylor polynomial:

u(x + h) = u(x) - u'(x)h + 1/2 u''(x)h^2 + O(h^3)
u(x - h) = u(x) + u'(x)h + 1/2 u''(x)h^2 + O(h^3)  / +
---------------------------------------------
-u(x - h) + 2u(x) + -u(x + h) = -f(x)h^2 + O(h^3)

For an equidistant grid with K "inner" discretization points x1, ..., xk, and
step size h = 1 / (K + 1), the formula produces a system of linear equations

           2u_1 - u_2     = -f_1 h^2 + u0
-u_(k-1) + 2u_k - u_(k+1) = -f_k h^2,       k = 2, ..., K - 1
-u_(K-1) + 2u_K           = -f_K h^2 + u1


which is then solved using Ginkgo's implementation of the CG method
preconditioned with block-Jacobi. It is also possible to specify on which
executor Ginkgo will solve the system via the command line.
The function `f` is set to `f(x) = 6x` (making the solution `u(x) = x^3`), but
that can be changed in the `main` function.

The intention of the example is to show how Ginkgo can be integrated into
existing software - the `generate_stencil_matrix`, `generate_rhs`,
`print_solution`, `compute_error` and `main` function do not reference Ginkgo at
all (i.e. they could have been there before the application developer decided to
use Ginkgo, and the only part where Ginkgo is introduced is inside the
`solve_system` function.
*****************************<DECSRIPTION>**********************************/

#include <ginkgo/ginkgo.hpp>
#include <iostream>
#include <map>
#include <string>
#include <vector>


void generate_stencil_matrix(int discretization_points, int *row_ptrs,
```

```
                             int *col_idxs, double *values)
{
    int pos = 0;
    const double coefs[] = {-1, 2, -1};
    row_ptrs[0] = pos;
    for (int i = 0; i < discretization_points; ++i) {
        for (auto ofs : {-1, 0, 1}) {
            if (0 <= i + ofs && i + ofs < discretization_points) {
                values[pos] = coefs[ofs + 1];
                col_idxs[pos] = i + ofs;
                ++pos;
            }
        }
        row_ptrs[i + 1] = pos;
    }
}


template <typename Closure>
void generate_rhs(int discretization_points, Closure f, double u0, double u1,
                  double *rhs)
{
    const auto h = 1.0 / (discretization_points + 1);
    for (int i = 0; i < discretization_points; ++i) {
        const auto xi = (i + 1) * h;
        rhs[i] = -f(xi) * h * h;
    }
    rhs[0] += u0;
    rhs[discretization_points - 1] += u1;
}


void print_solution(int discretization_points, double u0, double u1,
                    const double *u)
{
    std::cout << u0 << '\n';
    for (int i = 0; i < discretization_points; ++i) {
        std::cout << u[i] << '\n';
    }
    std::cout << u1 << std::endl;
}


template <typename Closure>
double calculate_error(int discretization_points, const double *u,
                       Closure correct_u)
{
    const auto h = 1.0 / (discretization_points + 1);
    auto error = 0.0;
    for (int i = 0; i < discretization_points; ++i) {
        using std::abs;
        const auto xi = (i + 1) * h;
        error += abs(u[i] - correct_u(xi)) / abs(correct_u(xi));
    }
    return error;
}


void solve_system(const std::string &executor_string,
                  unsigned int discretization_points, int *row_ptrs,
                  int *col_idxs, double *values, double *rhs, double *u,
                  double accuracy)
{
    using vec = gko::matrix::Dense<double>;
    using mtx = gko::matrix::Csr<double, int>;
    using cg = gko::solver::Cg<double>;
    using bj = gko::preconditioner::Jacobi<double, int>;
    using val_array = gko::Array<double>;
    using idx_array = gko::Array<int>;
    const auto &dp = discretization_points;

    const auto omp = gko::OmpExecutor::create();
    std::map<std::string, std::shared_ptr<gko::Executor>> exec_map{
        {"omp", omp},
        {"cuda", gko::CudaExecutor::create(0, omp)},
        {"reference", gko::ReferenceExecutor::create()}};
    const auto exec = exec_map.at(executor_string);  // throws if not valid
    const auto app_exec = exec_map["omp"];


    auto matrix = mtx::create(exec, gko::dim<2>(dp),
                              val_array::view(app_exec, 3 * dp - 2, values),
                              idx_array::view(app_exec, 3 * dp - 2, col_idxs),
                              idx_array::view(app_exec, dp + 1, row_ptrs));

    auto b = vec::create(exec, gko::dim<2>(dp, 1),
                         val_array::view(app_exec, dp, rhs), 1);
```

```
    auto x = vec::create(app_exec, gko::dim<2>(dp, 1),
                         val_array::view(app_exec, dp, u), 1);

    auto solver_gen =
        cg::build()
            .with_criteria(
                gko::stop::Iteration::build().with_max_iters(dp).on(exec),
                gko::stop::ResidualNormReduction<>::build()
                    .with_reduction_factor(accuracy)
                    .on(exec))
            .with_preconditioner(bj::build().on(exec))
            .on(exec);
    auto solver = solver_gen->generate(gko::give(matrix));

    solver->apply(gko::lend(b), gko::lend(x));
}


int main(int argc, char *argv[])
{
    if (argc < 2) {
        std::cerr << "Usage: " << argv[0] << " DISCRETIZATION_POINTS [executor]"
                  << std::endl;
        std::exit(-1);
    }

    const int discretization_points = argc >= 2 ? std::atoi(argv[1]) : 100;
    const auto executor_string = argc >= 3 ? argv[2] : "reference";

    auto correct_u = [](double x) { return x * x * x; };
    auto f = [](double x) { return 6 * x; };
    auto u0 = correct_u(0);
    auto u1 = correct_u(1);

    std::vector<int> row_ptrs(discretization_points + 1);
    std::vector<int> col_idxs(3 * discretization_points - 2);
    std::vector<double> values(3 * discretization_points - 2);
    std::vector<double> rhs(discretization_points);
    std::vector<double> u(discretization_points, 0.0);

    generate_stencil_matrix(discretization_points, row_ptrs.data(),
                            col_idxs.data(), values.data());
    generate_rhs(discretization_points, f, u0, u1, rhs.data());

    solve_system(executor_string, discretization_points, row_ptrs.data(),
                 col_idxs.data(), values.data(), rhs.data(), u.data(), 1e-12);

    print_solution(discretization_points, 0, 1, u.data());
    std::cout << "The average relative error is "
              << calculate_error(discretization_points, u.data(), correct_u) /
                     discretization_points
              << std::endl;
}
```

Chapter 21

The twentyseven-pt-stencil-solver program

The 27-point stencil example.

This example depends on simple-solver, poisson-solver, three-pt-stencil-solver, nine-pt-stencil-solve.

Introduction

This example solves a 3D Poisson equation:

[= (0,1)^3 \ = [0,1]^3 { (with boundary)} \ = \ u : R \ u'' = f \ u = u_D \ ]

using a finite difference method on an equidistant grid with `K` discretization points (`K` can be controlled with a command line parameter). The discretization may be done by any order Taylor polynomial. For an equidistant grid with K "inner" discretization points ((x1,y1,z1), , (xk,y1,z1),(x1,y2,z1), , (xk,yk,z1), (x1,y1,z2), , (xk,yk,zk)), step size (h = 1 / (K + 1)) and a stencil ({R}^{3 3 3}), the formula produces a system of linear equations

({a,b,c=-1}^1 stencil(a,b,c) ∗ u_{(i+a,j+b,k+c} = -f_k h^2), on any inner node with a neighborhood of inner nodes

On any node, where neighbor is on the border, the neighbor is replaced with a (-stencil(a,b,c) ∗ u_{i+a,j+b,k+c}) and added to the right hand side vector. For example a node with a neighborhood of only face nodes may look like this

[{a,b,c=-1}^(1,1,0) stencil(a,b,c) ∗ u_{(i+a,j+b,k+c} = -f_k h^2

- {a,b=-1}^(1,1) stencil(a,b,1) ∗ u_{(i+a,j+b,k+1}]

which is then solved using Ginkgo's implementation of the CG method preconditioned with block-Jacobi. It is also possible to specify on which executor Ginkgo will solve the system via the command line. The function `f` is set to (f(x,y,z) = 6x + 6y + 6z) (making the solution (u(x,y,z) = x^3 + y^3 + z^3)), but that can be changed in the `main` function. Also the stencil values for the core, the faces, the edge and the corners can be changed when passing additional parameters.

The intention of this is to show how generation of stencil values and the right hand side vector changes when increasing the dimension.

About the example

The commented program

```
/ *****************************<DECSRIPTION>**********************************
This example solves a 3D Poisson equation:

    \Omega = (0,1)^3
    \Omega_b = [0,1]^3   (with boundary)
    \partial\Omega = \Omega_b \backslash \Omega
    u : \Omega_b -> R
    u'' = f in \Omega
    u = u_D on \partial\Omega

using a finite difference method on an equidistant grid with `K` discretization
points (`K` can be controlled with a command line parameter). The discretization
may be done by any order Taylor polynomial.
For an equidistant grid with K "inner" discretization points (x1,y1,z1), ...,
(xk,y1,z1),(x1,y2,z1), ..., (xk,yk,z1), (x1,y1,z2), ..., (xk,yk,zk), step size h
= 1 / (K + 1) and a stencil \in \R^{3 x 3 x 3}, the formula produces a system of
linear equations

\sum_{a,b,c=-1}^1 stencil(a,b,c) * u_{(i+a,j+b,k+c} = -f_k h^2,  on any inner
node with a neighborhood of inner nodes

On any node, where neighbor is on the border, the neighbor is replaced with a
'-stencil(a,b,c) * u_{i+a,j+b,k+c}' and added to the right hand side vector.
For example a node with a neighborhood of only face nodes may look like this

\sum_{a,b,c=-1}^(1,1,0) stencil(a,b,c) * u_{(i+a,j+b,k+c} = -f_k h^2 -
\sum_{a,b=-1}^(1,1) stencil(a,b,1) * u_{(i+a,j+b,k+1}

which is then solved using Ginkgo's implementation of the CG method
preconditioned with block-Jacobi. It is also possible to specify on which
executor Ginkgo will solve the system via the command line.
The function `f` is set to `f(x,y,z) = 6x + 6y + 6z` (making the solution
`u(x,y,z) = x^3 + y^3 + z^3`), but that can be changed in the `main` function.
Also the stencil values for the core, the faces, the edge and the corners can be
changed when passing additional parameters.

The intention of this is to show how generation of stencil values and the right
hand side vector changes when increasing the dimension.
*****************************<DECSRIPTION>********************************** /

#include <array>
#include <chrono>
#include <ginkgo/ginkgo.hpp>
#include <iostream>
#include <map>
#include <string>
#include <vector>
```

Can be changed by passing additional parameters when executing the program

```
constexpr double default_alpha = 38 / 6.0;
constexpr double default_beta = -4.0 / 6.0;
constexpr double default_gamma = -1.0 / 6.0;
constexpr double default_delta = -1.0 / 24.0;

/ * Possible alternative values can be for example
 * default_alpha = 28.0;
 * default_beta = -1.0;
 * default_gamma = -1.0;
 * default_delta = -1.0;
 * /
```

Creates a stencil matrix in CSR format for the given number of discretization points.

```
void generate_stencil_matrix(int dp, int *row_ptrs, int *col_idxs,
                             double *values, double *coefs)
{
    int pos = 0;
    size_t dp_2 = dp * dp;
```

```
    row_ptrs[0] = pos;
    for (int64_t z = 0; z < dp; ++z) {
        for (int64_t y = 0; y < dp; ++y) {
            for (int64_t x = 0; x < dp; ++x) {
                const auto index = x + dp * (y + dp * z);
                for (int k = -1; k <= 1; ++k) {
                    for (int j = -1; j <= 1; ++j) {
                        for (int i = -1; i <= 1; ++i) {
                            const int64_t offset =
                                i + 1 + 3 * (j + 1 + 3 * (k + 1));
                            if ((x + i) >= 0 && (x + i) < dp && (y + j) >= 0 &&
                                (y + j) < dp && (z + k) >= 0 && (z + k) < dp) {
                                values[pos] = coefs[offset];
                                col_idxs[pos] = index + i + dp * (j + dp * k);
                                ++pos;
                            }
                        }
                    }
                }
                row_ptrs[index + 1] = pos;
            }
        }
    }
}
```

Generates the RHS vector given `f` and the boundary conditions.

```
template <typename Closure, typename ClosureT>
void generate_rhs(int dp, Closure f, ClosureT u, double *rhs, double *coefs)
{
    const size_t dp_2 = dp * dp;
    const auto h = 1.0 / (dp + 1.0);
    for (size_t k = 0; k < dp; ++k) {
        const auto zi = (k + 1) * h;
        for (size_t j = 0; j < dp; ++j) {
            const auto yi = (j + 1) * h;
            for (size_t i = 0; i < dp; ++i) {
                const auto xi = (i + 1) * h;
                const auto index = i + dp * (j + dp * k);
                rhs[index] = -f(xi, yi, zi) * h * h;
            }
        }
    }
```

This is the iteration over the surface of left and right side of the cube x - ortho to left, right y - ortho to top, bottom z - ortho to front, back

```
for (size_t j = 0; j < dp; ++j) {
    for (size_t k = 0; k < dp; ++k) {
        const auto yi = (j + 1) * h;
        const auto zi = (k + 1) * h;
        const auto index_left = dp * j + dp * dp * k;
        const auto index_right = dp * j + dp * dp * k + (dp - 1);

        for (int b = -1; b <= 1; ++b) {
            for (int c = -1; c <= 1; ++c) {
                rhs[index_left] -= u(0.0, yi + b * h, zi + c * h) *
                                   coefs[3 * (b + 1) + 3 * 3 * (c + 1)];
                rhs[index_right] -=
                    u(1.0, yi + b * h, zi + c * h) *
                    coefs[3 * (b + 1) + 3 * 3 * (c + 1) + 2];
            }
        }
    }
}
```

To avoid double counting we have to check if our previous calculations included this case

```
for (size_t i = 0; i < dp; ++i) {
    for (size_t k = 0; k < dp; ++k) {
        const auto xi = (i + 1) * h;
        const auto zi = (k + 1) * h;
        const auto index_top = i + dp * dp * k;
        const auto index_bot = i + dp * dp * k + dp * (dp - 1);

        for (int a = -1; a <= 1; ++a) {
```

```
            if ((i < (dp - 1) || a < 1) && (i > 0 || a > -1)) {
                for (int c = -1; c <= 1; ++c) {
                    rhs[index_top] -= u(xi + a * h, 0.0, zi + c * h) *
                                      coefs[(a + 1) + 3 * 3 * (c + 1)];
                    rhs[index_bot] -=
                        u(xi + a * h, 1.0, zi + c * h) *
                        coefs[(a + 1) + 3 * 3 * (c + 1) + 3 * 2];
                }
            }
        }
    }
}
```

Now every side has to be checked

```
    for (size_t i = 0; i < dp; ++i) {
        for (size_t j = 0; j < dp; ++j) {
            const auto xi = (i + 1) * h;
            const auto yi = (j + 1) * h;
            const auto index_front = i + dp * j;
            const auto index_back = i + dp * j + dp * dp * (dp - 1);

            for (int a = -1; a <= 1; ++a) {
                if ((i < (dp - 1) || a < 1) && (i > 0 || a > -1)) {
                    for (int b = -1; b <= 1; ++b) {
                        if ((j < (dp - 1) || b < 1) && (j > 0 || j > -1)) {
                            rhs[index_front] -= u(xi + a * h, yi + b * h, 0.0) *
                                                coefs[(a + 1) + 3 * (b + 1)];
                            rhs[index_back] -=
                                u(xi + a * h, yi + b * h, 1.0) *
                                coefs[(a + 1) + 3 * (b + 1) + 3 * 3 * 2];
                        }
                    }
                }
            }
        }
    }
}
```

Prints the solution `u`.

```
void print_solution(int dp, const double *u)
{
    for (size_t k = 0; k < dp; ++k) {
        for (size_t j = 0; j < dp; ++j) {
            for (size_t i = 0; i < dp; ++i) {
                std::cout << u[i + dp * (j + dp * k)] << ' ';
            }
            std::cout << '\n';
        }
        std::cout << ":\n";
    }
    std::cout << std::endl;
}
```

Computes the 1-norm of the error given the computed `u` and the correct solution function `correct_u`.

```
template <typename Closure>
double calculate_error(int dp, const double *u, Closure correct_u)
{
    using std::abs;
    const auto h = 1.0 / (dp + 1);
    auto error = 0.0;
    for (int k = 0; k < dp; ++k) {
        const auto zi = (k + 1) * h;
        for (int j = 0; j < dp; ++j) {
            const auto yi = (j + 1) * h;
            for (int i = 0; i < dp; ++i) {
                const auto xi = (i + 1) * h;
                error +=
                    abs(u[k * dp * dp + i * dp + j] - correct_u(xi, yi, zi)) /
                    abs(correct_u(xi, yi, zi));
            }
        }
    }
    return error;
```

```
}

void solve_system(const std::string &executor_string,
                  unsigned int discretization_points, int *row_ptrs,
                  int *col_idxs, double *values, double *rhs, double *u,
                  double accuracy)
{
```

Some shortcuts

```
using vec = gko::matrix::Dense<double>;
using mtx = gko::matrix::Csr<double, int>;
using cg = gko::solver::Cg<double>;
using bj = gko::preconditioner::Jacobi<double, int>;
using val_array = gko::Array<double>;
using idx_array = gko::Array<int>;
const auto &dp = discretization_points;
const size_t dp_2 = dp * dp;
const size_t dp_3 = dp * dp * dp;
```

Figure out where to run the code

```
const auto omp = gko::OmpExecutor::create();
std::map<std::string, std::shared_ptr<gko::Executor>> exec_map{
    {"omp", omp},
    {"cuda", gko::CudaExecutor::create(0, omp)},
    {"reference", gko::ReferenceExecutor::create()}};
```

executor where Ginkgo will perform the computation

```
const auto exec = exec_map.at(executor_string);  // throws if not valid
```

executor where the application initialized the data

```
const auto app_exec = exec_map["omp"];
```

Tell Ginkgo to use the data in our application

Matrix: we have to set the executor of the matrix to the one where we want SpMVs to run (in this case `exec`). When creating array views, we have to specify the executor where the data is (in this case `app_exec`).

If the two do not match, Ginkgo will automatically create a copy of the data on `exec` (however, it will not copy the data back once it is done

- here this is not important since we are not modifying the matrix).

```
auto matrix = mtx::create(
    exec, gko::dim<2>(dp_3),
    val_array::view(app_exec, (3 * dp - 2) * (3 * dp - 2) * (3 * dp - 2),
                    values),
    idx_array::view(app_exec, (3 * dp - 2) * (3 * dp - 2) * (3 * dp - 2),
                    col_idxs),
    idx_array::view(app_exec, dp_3 + 1, row_ptrs));
```

RHS: similar to matrix

```
auto b = vec::create(exec, gko::dim<2>(dp_3, 1),
                     val_array::view(app_exec, dp_3, rhs), 1);
```

Solution: we have to be careful here - if the executors are different, once we compute the solution the array will not be automatically copied back to the original memory locations. Fortunately, whenever `apply` is called on a linear operator (e.g. matrix, solver) the arguments automatically get copied to the executor where the operator is, and copied back once the operation is completed. Thus, in this case, we can just define the solution on `app_exec`, and it will be automatically transferred to/from `exec` if needed.

```
auto x = vec::create(app_exec, gko::dim<2>(dp_3, 1),
                     val_array::view(app_exec, dp_3, u), 1);
```

Generate solver

```
auto solver_gen =
    cg::build()
        .with_criteria(
            gko::stop::Iteration::build().with_max_iters(dp_3).on(exec),
            gko::stop::ResidualNormReduction<>::build()
                .with_reduction_factor(accuracy)
                .on(exec))
        .with_preconditioner(bj::build().on(exec))
        .on(exec);
auto solver = solver_gen->generate(gko::give(matrix));
```

Solve system

```
    solver->apply(gko::lend(b), gko::lend(x));
}

int main(int argc, char *argv[])
{
    if (argc < 2) {
        std::cerr
            << "Usage: " << argv[0] << " DISCRETIZATION_POINTS [executor]"
            << " [stencil_alpha] [stencil_beta] [stencil_gamma] [stencil_delta]"
            << std::endl;
        std::exit(-1);
    }

    const int discretization_points = argc >= 2 ? std::atoi(argv[1]) : 100;
    const auto executor_string = argc >= 3 ? argv[2] : "reference";
    const double alpha_c = argc >= 4 ? std::atof(argv[3]) : default_alpha;
    const double beta_c = argc >= 5 ? std::atof(argv[4]) : default_beta;
    const double gamma_c = argc >= 6 ? std::atof(argv[5]) : default_gamma;
    const double delta_c = argc >= 7 ? std::atof(argv[6]) : default_delta;
```

clang-format off

```
std::array<double,27> coefs{
    delta_c, gamma_c, delta_c,
    gamma_c, beta_c, gamma_c,
    delta_c, gamma_c, delta_c,

    gamma_c, beta_c,  gamma_c,
    beta_c,  alpha_c, beta_c,
    gamma_c, beta_c,  gamma_c,

    delta_c, gamma_c, delta_c,
    gamma_c, beta_c, gamma_c,
    delta_c, gamma_c, delta_c
};
```

clang-format on

```
const auto dp = discretization_points;
const size_t dp_2 = dp * dp;
const size_t dp_3 = dp * dp * dp;
```

problem:

```
auto correct_u = [](double x, double y, double z) {
    return x * x * x + y * y * y + z * z * z;
};
auto f = [](double x, double y, double z) { return 6 * x + 6 * y + 6 * z; };
```

matrix

```
std::vector<int> row_ptrs(dp_3 + 1);
std::vector<int> col_idxs((3 * dp - 2) * (3 * dp - 2) * (3 * dp - 2));
std::vector<double> values((3 * dp - 2) * (3 * dp - 2) * (3 * dp - 2));
```

right hand side

```
std::vector<double> rhs(dp_3);
```

solution

```
std::vector<double> u(dp_3, 0.0);

generate_stencil_matrix(dp, row_ptrs.data(), col_idxs.data(), values.data(),
                        coefs.data());
```

looking for solution u = x^3: f = 6x, u(0) = 0, u(1) = 1

```
    generate_rhs(dp, f, correct_u, rhs.data(), coefs.data());

    auto start_time = std::chrono::steady_clock::now();

    solve_system(executor_string, dp, row_ptrs.data(), col_idxs.data(),
                 values.data(), rhs.data(), u.data(), 1e-12);

    auto stop_time = std::chrono::steady_clock::now();
    double runtime_duration =
        std::chrono::duration_cast<std::chrono::nanoseconds>(stop_time -
                                                             start_time)
            .count() *
        1e-6;

    print_solution(dp, u.data());
    std::cout << "The average relative error is "
              << calculate_error(dp, u.data(), correct_u) / dp_3 << std::endl;

    std::cout << "The runtime is " << std::to_string(runtime_duration) << " ms"
              << std::endl;
}
```

Results

The expected output of the relative error at K=10 should be

```
The average relative error is 1.87318e-15
```

Comments about programming and debugging

The plain program

```
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/****************************<DECSRIPTION>***********************************
This example solves a 3D Poisson equation:

    \Omega = (0,1)^3
    \Omega_b = [0,1]^3   (with boundary)
    \partial\Omega = \Omega_b \backslash \Omega
    u : \Omega_b -> R
    u'' = f in \Omega
    u = u_D on \partial\Omega

using a finite difference method on an equidistant grid with `K` discretization
points (`K` can be controlled with a command line parameter). The discretization
may be done by any order Taylor polynomial.
For an equidistant grid with K "inner" discretization points (x1,y1,z1), ...,
(xk,y1,z1),(x1,y2,z1), ..., (xk,yk,z1), (x1,y1,z2), ..., (xk,yk,zk), step size h
= 1 / (K + 1) and a stencil \in \R^{3 x 3 x 3}, the formula produces a system of
linear equations

\sum_{a,b,c=-1}^1 stencil(a,b,c) * u_{(i+a,j+b,k+c} = -f_k h^2,  on any inner
node with a neighborhood of inner nodes

On any node, where neighbor is on the border, the neighbor is replaced with a
'-stencil(a,b,c) * u_{i+a,j+b,k+c}' and added to the right hand side vector.
For example a node with a neighborhood of only face nodes may look like this

\sum_{a,b,c=-1}^(1,1,0) stencil(a,b,c) * u_{(i+a,j+b,k+c} = -f_k h^2 -
\sum_{a,b=-1}^(1,1) stencil(a,b,1) * u_{(i+a,j+b,k+1}

which is then solved using Ginkgo's implementation of the CG method
preconditioned with block-Jacobi. It is also possible to specify on which
executor Ginkgo will solve the system via the command line.
The function `f` is set to `f(x,y,z) = 6x + 6y + 6z` (making the solution
`u(x,y,z) = x^3 + y^3 + z^3`), but that can be changed in the `main` function.
Also the stencil values for the core, the faces, the edge and the corners can be
changed when passing additional parameters.

The intention of this is to show how generation of stencil values and the right
hand side vector changes when increasing the dimension.
*****************************<DECSRIPTION>**********************************/

#include <array>
#include <chrono>
#include <ginkgo/ginkgo.hpp>
#include <iostream>
#include <map>
#include <string>
#include <vector>
```

```
constexpr double default_alpha = 38 / 6.0;
constexpr double default_beta = -4.0 / 6.0;
constexpr double default_gamma = -1.0 / 6.0;
constexpr double default_delta = -1.0 / 24.0;

/* Possible alternative values can be for example
 * default_alpha = 28.0;
 * default_beta = -1.0;
 * default_gamma = -1.0;
 * default_delta = -1.0;
 */

void generate_stencil_matrix(int dp, int *row_ptrs, int *col_idxs,
                             double *values, double *coefs)
{
    int pos = 0;
    size_t dp_2 = dp * dp;


    row_ptrs[0] = pos;
    for (int64_t z = 0; z < dp; ++z) {
        for (int64_t y = 0; y < dp; ++y) {
            for (int64_t x = 0; x < dp; ++x) {
                const auto index = x + dp * (y + dp * z);
                for (int k = -1; k <= 1; ++k) {
                    for (int j = -1; j <= 1; ++j) {
                        for (int i = -1; i <= 1; ++i) {
                            const int64_t offset =
                                i + 1 + 3 * (j + 1 + 3 * (k + 1));
                            if ((x + i) >= 0 && (x + i) < dp && (y + j) >= 0 &&
                                (y + j) < dp && (z + k) >= 0 && (z + k) < dp) {
                                values[pos] = coefs[offset];
                                col_idxs[pos] = index + i + dp * (j + dp * k);
                                ++pos;
                            }
                        }
                    }
                }
                row_ptrs[index + 1] = pos;
            }
        }
    }
}


template <typename Closure, typename ClosureT>
void generate_rhs(int dp, Closure f, ClosureT u, double *rhs, double *coefs)
{
    const size_t dp_2 = dp * dp;
    const auto h = 1.0 / (dp + 1.0);
    for (size_t k = 0; k < dp; ++k) {
        const auto zi = (k + 1) * h;
        for (size_t j = 0; j < dp; ++j) {
            const auto yi = (j + 1) * h;
            for (size_t i = 0; i < dp; ++i) {
                const auto xi = (i + 1) * h;
                const auto index = i + dp * (j + dp * k);
                rhs[index] = -f(xi, yi, zi) * h * h;
            }
        }
    }

    for (size_t j = 0; j < dp; ++j) {
        for (size_t k = 0; k < dp; ++k) {
            const auto yi = (j + 1) * h;
            const auto zi = (k + 1) * h;
            const auto index_left = dp * j + dp * dp * k;
            const auto index_right = dp * j + dp * dp * k + (dp - 1);

            for (int b = -1; b <= 1; ++b) {
                for (int c = -1; c <= 1; ++c) {
                    rhs[index_left] -= u(0.0, yi + b * h, zi + c * h) *
                                       coefs[3 * (b + 1) + 3 * 3 * (c + 1)];
                    rhs[index_right] -=
                        u(1.0, yi + b * h, zi + c * h) *
                        coefs[3 * (b + 1) + 3 * 3 * (c + 1) + 2];
                }
            }
        }
    }

    for (size_t i = 0; i < dp; ++i) {
        for (size_t k = 0; k < dp; ++k) {
            const auto xi = (i + 1) * h;
            const auto zi = (k + 1) * h;
            const auto index_top = i + dp * dp * k;
```

```
            const auto index_bot = i + dp * dp * k + dp * (dp - 1);

            for (int a = -1; a <= 1; ++a) {
                if ((i < (dp - 1) || a < 1) && (i > 0 || a > -1)) {
                    for (int c = -1; c <= 1; ++c) {
                        rhs[index_top] -= u(xi + a * h, 0.0, zi + c * h) *
                                          coefs[(a + 1) + 3 * 3 * (c + 1)];
                        rhs[index_bot] -=
                            u(xi + a * h, 1.0, zi + c * h) *
                            coefs[(a + 1) + 3 * 3 * (c + 1) + 3 * 2];
                    }
                }
            }
        }
    }

    for (size_t i = 0; i < dp; ++i) {
        for (size_t j = 0; j < dp; ++j) {
            const auto xi = (i + 1) * h;
            const auto yi = (j + 1) * h;
            const auto index_front = i + dp * j;
            const auto index_back = i + dp * j + dp * dp * (dp - 1);

            for (int a = -1; a <= 1; ++a) {
                if ((i < (dp - 1) || a < 1) && (i > 0 || a > -1)) {
                    for (int b = -1; b <= 1; ++b) {
                        if ((j < (dp - 1) || b < 1) && (j > 0 || j > -1)) {
                            rhs[index_front] -= u(xi + a * h, yi + b * h, 0.0) *
                                                coefs[(a + 1) + 3 * (b + 1)];
                            rhs[index_back] -=
                                u(xi + a * h, yi + b * h, 1.0) *
                                coefs[(a + 1) + 3 * (b + 1) + 3 * 3 * 2];
                        }
                    }
                }
            }
        }
    }
}


void print_solution(int dp, const double *u)
{
    for (size_t k = 0; k < dp; ++k) {
        for (size_t j = 0; j < dp; ++j) {
            for (size_t i = 0; i < dp; ++i) {
                std::cout << u[i + dp * (j + dp * k)] << ' ';
            }
            std::cout << '\n';
        }
        std::cout << ":\n";
    }
    std::cout << std::endl;
}


template <typename Closure>
double calculate_error(int dp, const double *u, Closure correct_u)
{
    using std::abs;
    const auto h = 1.0 / (dp + 1);
    auto error = 0.0;
    for (int k = 0; k < dp; ++k) {
        const auto zi = (k + 1) * h;
        for (int j = 0; j < dp; ++j) {
            const auto yi = (j + 1) * h;
            for (int i = 0; i < dp; ++i) {
                const auto xi = (i + 1) * h;
                error +=
                    abs(u[k * dp * dp + i * dp + j] - correct_u(xi, yi, zi)) /
                    abs(correct_u(xi, yi, zi));
            }
        }
    }
    return error;
}


void solve_system(const std::string &executor_string,
                  unsigned int discretization_points, int *row_ptrs,
                  int *col_idxs, double *values, double *rhs, double *u,
                  double accuracy)
{
    using vec = gko::matrix::Dense<double>;
    using mtx = gko::matrix::Csr<double, int>;
    using cg = gko::solver::Cg<double>;
    using bj = gko::preconditioner::Jacobi<double, int>;
```

```
    using val_array = gko::Array<double>;
    using idx_array = gko::Array<int>;
    const auto &dp = discretization_points;
    const size_t dp_2 = dp * dp;
    const size_t dp_3 = dp * dp * dp;

    const auto omp = gko::OmpExecutor::create();
    std::map<std::string, std::shared_ptr<gko::Executor>> exec_map{
        {"omp", omp},
        {"cuda", gko::CudaExecutor::create(0, omp)},
        {"reference", gko::ReferenceExecutor::create()}};
    const auto exec = exec_map.at(executor_string);  // throws if not valid
    const auto app_exec = exec_map["omp"];


    auto matrix = mtx::create(
        exec, gko::dim<2>(dp_3),
        val_array::view(app_exec, (3 * dp - 2) * (3 * dp - 2) * (3 * dp - 2),
                        values),
        idx_array::view(app_exec, (3 * dp - 2) * (3 * dp - 2) * (3 * dp - 2),
                        col_idxs),
        idx_array::view(app_exec, dp_3 + 1, row_ptrs));

    auto b = vec::create(exec, gko::dim<2>(dp_3, 1),
                         val_array::view(app_exec, dp_3, rhs), 1);

    auto x = vec::create(app_exec, gko::dim<2>(dp_3, 1),
                         val_array::view(app_exec, dp_3, u), 1);

    auto solver_gen =
        cg::build()
            .with_criteria(
                gko::stop::Iteration::build().with_max_iters(dp_3).on(exec),
                gko::stop::ResidualNormReduction<>::build()
                    .with_reduction_factor(accuracy)
                    .on(exec))
            .with_preconditioner(bj::build().on(exec))
            .on(exec);
    auto solver = solver_gen->generate(gko::give(matrix));

    solver->apply(gko::lend(b), gko::lend(x));
}

int main(int argc, char *argv[])
{
    if (argc < 2) {
        std::cerr
            << "Usage: " << argv[0] << " DISCRETIZATION_POINTS [executor]"
            << " [stencil_alpha] [stencil_beta] [stencil_gamma] [stencil_delta]"
            << std::endl;
        std::exit(-1);
    }

    const int discretization_points = argc >= 2 ? std::atoi(argv[1]) : 100;
    const auto executor_string = argc >= 3 ? argv[2] : "reference";
    const double alpha_c = argc >= 4 ? std::atof(argv[3]) : default_alpha;
    const double beta_c = argc >= 5 ? std::atof(argv[4]) : default_beta;
    const double gamma_c = argc >= 6 ? std::atof(argv[5]) : default_gamma;
    const double delta_c = argc >= 7 ? std::atof(argv[6]) : default_delta;

    std::array<double,27> coefs{
        delta_c, gamma_c, delta_c,
        gamma_c, beta_c, gamma_c,
        delta_c, gamma_c, delta_c,

        gamma_c, beta_c,  gamma_c,
        beta_c,  alpha_c, beta_c,
        gamma_c, beta_c,  gamma_c,

        delta_c, gamma_c, delta_c,
        gamma_c, beta_c, gamma_c,
        delta_c, gamma_c, delta_c
    };

    const auto dp = discretization_points;
    const size_t dp_2 = dp * dp;
    const size_t dp_3 = dp * dp * dp;

    auto correct_u = [](double x, double y, double z) {
        return x * x * x + y * y * y + z * z * z;
    };
    auto f = [](double x, double y, double z) { return 6 * x + 6 * y + 6 * z; };

    std::vector<int> row_ptrs(dp_3 + 1);
    std::vector<int> col_idxs((3 * dp - 2) * (3 * dp - 2) * (3 * dp - 2));
    std::vector<double> values((3 * dp - 2) * (3 * dp - 2) * (3 * dp - 2));
    std::vector<double> rhs(dp_3);
```

```
    std::vector<double> u(dp_3, 0.0);

    generate_stencil_matrix(dp, row_ptrs.data(), col_idxs.data(), values.data(),
                            coefs.data());
    generate_rhs(dp, f, correct_u, rhs.data(), coefs.data());

    auto start_time = std::chrono::steady_clock::now();

    solve_system(executor_string, dp, row_ptrs.data(), col_idxs.data(),
                 values.data(), rhs.data(), u.data(), 1e-12);

    auto stop_time = std::chrono::steady_clock::now();
    double runtime_duration =
        std::chrono::duration_cast<std::chrono::nanoseconds>(stop_time -
                                                             start_time)
            .count() *
        1e-6;

    print_solution(dp, u.data());
    std::cout << "The average relative error is "
              << calculate_error(dp, u.data(), correct_u) / dp_3 << std::endl;

    std::cout << "The runtime is " << std::to_string(runtime_duration) << " ms"
              << std::endl;
}
```

Chapter 22

Module Documentation

22.1 CUDA Executor

A module dedicated to the implementation and usage of the CUDA executor in Ginkgo.

Classes

- class gko::CudaExecutor

  This is the Executor subclass which represents the CUDA device.

22.1.1 Detailed Description

A module dedicated to the implementation and usage of the CUDA executor in Ginkgo.

22.2 Executors

A module dedicated to the implementation and usage of the executors in Ginkgo.

Modules

- CUDA Executor

    A module dedicated to the implementation and usage of the CUDA executor in Ginkgo.
- OpenMP Executor

    A module dedicated to the implementation and usage of the OpenMP executor in Ginkgo.
- Reference Executor

    A module dedicated to the implementation and usage of the Reference executor in Ginkgo.

Classes

- class gko::Operation

    Operations can be used to define functionalities whose implementations differ among devices.
- class gko::Executor

    The first step in using the Ginkgo library consists of creating an executor.
- class gko::executor_deleter< T >

    This is a deleter that uses an executor's `free` method to deallocate the data.
- class gko::OmpExecutor

    This is the Executor subclass which represents the OpenMP device (typically CPU).
- class gko::ReferenceExecutor

    This is a specialization of the OmpExecutor, which runs the reference implementations of the kernels used for debugging purposes.
- class gko::CudaExecutor

    This is the Executor subclass which represents the CUDA device.

Macros

- #define GKO_REGISTER_OPERATION(_name, _kernel)

    Binds a set of device-specific kernels to an Operation.

22.2.1 Detailed Description

A module dedicated to the implementation and usage of the executors in Ginkgo.

Below, we provide a brief introduction to executors in Ginkgo, how they have been implemented, how to best make use of them and how to add new executors.

22.2.2 Executors in Ginkgo.

The first step in using the Ginkgo library consists of creating an executor. Executors are used to specify the location for the data of linear algebra objects, and to determine where the operations will be executed. Ginkgo currently supports three different executor types:

- OpenMP Executor specifies that the data should be stored and the associated operations executed on an OpenMP-supporting device (e.g. host CPU);
- CUDA Executor specifies that the data should be stored and the operations executed on the NVIDIA GPU accelerator;
- Reference Executor executes a non-optimized reference implementation, which can be used to debug the library.

22.2.3 Macro Definition Documentation

22.2.3.1 GKO_REGISTER_OPERATION

```
#define GKO_REGISTER_OPERATION(
                _name,
                _kernel )
```

Binds a set of device-specific kernels to an Operation.

It also defines a helper function which creates the associated operation. Any input arguments passed to the helper function are forwarded to the kernel when the operation is executed.

The kernels used to bind the operation are searched in `kernels::DEV_TYPE` namespace, where `DEV_TYPE` is replaced by `omp`, `cuda` and `reference`.

Parameters

_name	operation name
_kernel	kernel which will be bound to the operation

Example

```
{c++}
// define the omp, cuda and reference kernels which will be bound to the
// operation
namespace kernels {
namespace omp {
void my_kernel(int x) {
     // omp code
}
}
namespace cuda {
void my_kernel(int x) {
     // cuda code
}
}
namespace reference {
```

```
void my_kernel(int x) {
    // reference code
}
}

// Bind the kernels to the operation
GKO_REGISTER_OPERATION(my_op, my_kernel);

int main() {
    // create executors
    auto omp = OmpExecutor::create();
    auto cuda = CudaExecutor::create(omp, 0);
    auto ref = ReferenceExecutor::create();

    // create the operation
    auto op = make_my_op(5); // x = 5

    omp->run(op);  // run omp kernel
    cuda->run(op);  // run cuda kernel
    ref->run(op);  // run reference kernel
}
```

22.3 Factorizations

A module dedicated to the implementation and usage of the Factorizations in Ginkgo.

Namespaces

- gko::factorization

  The Factorization namespace.

Classes

- class gko::factorization::ParIlu< ValueType, IndexType >

  ParILU is an incomplete LU factorization which is computed in parallel.

22.3.1 Detailed Description

A module dedicated to the implementation and usage of the Factorizations in Ginkgo.

22.4 Linear Operators

A module dedicated to the implementation and usage of the Linear operators in Ginkgo.

Modules

- Factorizations

  A module dedicated to the implementation and usage of the Factorizations in Ginkgo.
- SpMV employing different Matrix formats

  A module dedicated to the implementation and usage of the various Matrix Formats in Ginkgo.
- Preconditioners

  A module dedicated to the implementation and usage of the Preconditioners in Ginkgo.
- Solvers

  A module dedicated to the implementation and usage of the Solvers in Ginkgo.

Classes

- class gko::Combination< ValueType >

  The Combination class can be used to construct a linear combination of multiple linear operators 'c1 ∗ op1 + c2 ∗ op2 + ...
- class gko::Composition< ValueType >

  The Composition class can be used to compose linear operators `op1, op2, ..., opn` and obtain the operator 'op1 ∗ op2 ∗ ...
- class gko::LinOpFactory

  A LinOpFactory represents a higher order mapping which transforms one linear operator into another.
- class gko::ReadableFromMatrixData< ValueType, IndexType >

  A LinOp implementing this interface can read its data from a matrix_data structure.
- class gko::WritableToMatrixData< ValueType, IndexType >

  A LinOp implementing this interface can write its data to a matrix_data structure.
- class gko::Preconditionable

  A LinOp implementing this interface can be preconditioned.
- class gko::EnableLinOp< ConcreteLinOp, PolymorphicBase >

  The EnableLinOp mixin can be used to provide sensible default implementations of the majority of the LinOp and PolymorphicObject interface.
- class gko::Perturbation< ValueType >

  The Perturbation class can be used to construct a LinOp to represent the operation `(identity + scalar * basis * projector)`.
- class gko::matrix::Coo< ValueType, IndexType >

  COO stores a matrix in the coordinate matrix format.
- class gko::matrix::Csr< ValueType, IndexType >

  CSR is a matrix format which stores only the nonzero coefficients by compressing each row of the matrix (compressed sparse row format).
- class gko::matrix::Dense< ValueType >

  Dense is a matrix format which explicitly stores all values of the matrix.
- class gko::matrix::Ell< ValueType, IndexType >

  ELL is a matrix format where stride with explicit zeros is used such that all rows have the same number of stored elements.
- class gko::matrix::Hybrid< ValueType, IndexType >

  HYBRID is a matrix format which splits the matrix into ELLPACK and COO format.
- class gko::matrix::Identity< ValueType >

This class is a utility which efficiently implements the identity matrix (a linear operator which maps each vector to itself).

- class gko::matrix::IdentityFactory< ValueType >

  This factory is a utility which can be used to generate Identity operators.
- class gko::matrix::Sellp< ValueType, IndexType >

  SELL-P is a matrix format similar to ELL format.
- class gko::preconditioner::Ilu< LSolverType, USolverType, ReverseApply >

  The Incomplete LU (ILU) preconditioner solves the equation $LUx = b$ for a given lower triangular matrix L, an upper triangular matrix U and the right hand side b (can contain multiple right hand sides).
- struct gko::preconditioner::block_interleaved_storage_scheme< IndexType >

  Defines the parameters of the interleaved block storage scheme used by block-Jacobi blocks.
- class gko::preconditioner::Jacobi< ValueType, IndexType >

  A block-Jacobi preconditioner is a block-diagonal linear operator, obtained by inverting the diagonal blocks of the source operator.
- class gko::solver::Bicgstab< ValueType >

  BiCGSTAB or the Bi-Conjugate Gradient-Stabilized is a Krylov subspace solver.
- class gko::solver::Cg< ValueType >

  CG or the conjugate gradient method is an iterative type Krylov subspace method which is suitable for symmetric positive definite methods.
- class gko::solver::Cgs< ValueType >

  CGS or the conjugate gradient square method is an iterative type Krylov subspace method which is suitable for general systems.
- class gko::solver::Fcg< ValueType >

  FCG or the flexible conjugate gradient method is an iterative type Krylov subspace method which is suitable for symmetric positive definite methods.
- class gko::solver::Gmres< ValueType >

  GMRES or the generalized minimal residual method is an iterative type Krylov subspace method which is suitable for nonsymmetric linear systems.
- class gko::solver::LowerTrs< ValueType, IndexType >

  LowerTrs is the triangular solver which solves the system L x = b, when L is a lower triangular matrix.
- class gko::solver::UpperTrs< ValueType, IndexType >

  UpperTrs is the triangular solver which solves the system U x = b, when U is an upper triangular matrix.

Macros

- #define GKO_CREATE_FACTORY_PARAMETERS(_parameters_name, _factory_name)

  This Macro will generate a new type containing the parameters for the factory `_factory_name`.
- #define GKO_ENABLE_LIN_OP_FACTORY(_lin_op, _parameters_name, _factory_name)

  This macro will generate a default implementation of a LinOpFactory for the LinOp subclass it is defined in.
- #define GKO_ENABLE_BUILD_METHOD(_factory_name)

  Defines a build method for the factory, simplifying its construction by removing the repetitive typing of factory's name.
- #define GKO_FACTORY_PARAMETER(_name, ...)

  Creates a factory parameter in the factory parameters structure.

Typedefs

- template<typename ConcreteFactory , typename ConcreteLinOp , typename ParametersType , typename PolymorphicBase = Lin↩ OpFactory>
  using gko::EnableDefaultLinOpFactory = EnableDefaultFactory< ConcreteFactory, ConcreteLinOp, ParametersType, PolymorphicBase >

  This is an alias for the EnableDefaultFactory mixin, which correctly sets the template parameters to enable a subclass of LinOpFactory.

22.4.1 Detailed Description

A module dedicated to the implementation and usage of the Linear operators in Ginkgo.

Below we elaborate on one of the most important concepts of Ginkgo, the linear operator. The linear operator (LinOp) is a base class for all linear algebra objects in Ginkgo. The main benefit of having a single base class for the entire collection of linear algebra objects (as opposed to having separate hierarchies for matrices, solvers and preconditioners) is the generality it provides.

22.4.2 Advantages of this approach and usage

A common interface often allows for writing more generic code. If a user's routine requires only operations provided by the LinOp interface, the same code can be used for any kind of linear operators, independent of whether these are matrices, solvers or preconditioners. This feature is also extensively used in Ginkgo itself. For example, a preconditioner used inside a Krylov solver is a LinOp. This allows the user to supply a wide variety of preconditioners: either the ones which were designed to be used in this scenario (like ILU or block-Jacobi), a user-supplied matrix which is known to be a good preconditioner for the specific problem, or even another solver (e.g., if constructing a flexible GMRES solver).

For example, a matrix free implementation would require the user to provide an apply implementation and instead of passing the generated matrix to the solver, they would have to provide their apply implementation for all the executors needed and no other code needs to be changed. See The custom-matrix-format program example for more details.

22.4.3 Linear operator as a concept

The linear operator (LinOp) is a base class for all linear algebra objects in Ginkgo. The main benefit of having a single base class for the entire collection of linear algebra objects (as opposed to having separate hierarchies for matrices, solvers and preconditioners) is the generality it provides.

First, since all subclasses provide a common interface, the library users are exposed to a smaller set of routines. For example, a matrix-vector product, a preconditioner application, or even a system solve are just different terms given to the operation of applying a certain linear operator to a vector. As such, Ginkgo uses the same routine name, LinOp::apply() for each of these operations, where the actual operation performed depends on the type of linear operator involved in the operation.

Second, a common interface often allows for writing more generic code. If a user's routine requires only operations provided by the LinOp interface, the same code can be used for any kind of linear operators, independent of whether these are matrices, solvers or preconditioners. This feature is also extensively used in Ginkgo itself. For example, a preconditioner used inside a Krylov solver is a LinOp. This allows the user to supply a wide variety of preconditioners: either the ones which were designed to be used in this scenario (like ILU or block-Jacobi), a user-supplied matrix which is known to be a good preconditioner for the specific problem, or even another solver (e.g., if constructing a flexible GMRES solver).

A key observation for providing a unified interface for matrices, solvers, and preconditioners is that the most common operation performed on all of them can be expressed as an application of a linear operator to a vector:

- the sparse matrix-vector product with a matrix A is a linear operator application $y = Ax$;
- the application of a preconditioner is a linear operator application $y = M^{-1}x$, where M is an approximation of the original system matrix A (thus a preconditioner represents an "approximate inverse" operator M^{-1}).
- the system solve $Ax = b$ can be viewed as linear operator application $x = A^{-1}b$ (it goes without saying that the implementation of linear system solves does not follow this conceptual idea), so a linear system solver can be viewed as a representation of the operator A^{-1}.

Finally, direct manipulation of LinOp objects is rarely required in simple scenarios. As an illustrative example, one could construct a fixed-point iteration routine $x_{k+1} = Lx_k + b$ as follows:

```
std::unique_ptr<matrix::Dense<>> calculate_fixed_point(
        int iters, const LinOp *L, const matrix::Dense<> *x0
        const matrix::Dense<> *b)
{
    auto x = gko::clone(x0);
    auto tmp = gko::clone(x0);
    auto one = Dense<>::create(L->get_executor(), {1.0,});
    for (int i = 0; i < iters; ++i) {
        L->apply(gko::lend(tmp), gko::lend(x));
        x->add_scaled(gko::lend(one), gko::lend(b));
        tmp->copy_from(gko::lend(x));
    }
    return x;
}
```

Here, if L is a matrix, LinOp::apply() refers to the matrix vector product, and `L->apply(a, b)` computes $b = L \cdot a$. `x->add_scaled(one.get(), b.get())` is the `axpy` vector update $x := x + b$.

The interesting part of this example is the apply() routine at line 4 of the function body. Since this routine is part of the LinOp base class, the fixed-point iteration routine can calculate a fixed point not only for matrices, but for any type of linear operator.

Linear Operators

22.4.4 Macro Definition Documentation

22.4.4.1 GKO_CREATE_FACTORY_PARAMETERS

```
#define GKO_CREATE_FACTORY_PARAMETERS(
                _parameters_name,
                _factory_name )
```

Value:

```
public:                                                                    \
    class _factory_name;                                                   \
    struct _parameters_name##_type                                         \
        : ::gko::enable_parameters_type<_parameters_name##_type,           \
                                        _factory_name>
```

This Macro will generate a new type containing the parameters for the factory `_factory_name`.

For more details, see GKO_ENABLE_LIN_OP_FACTORY(). It is required to use this macro **before** calling the macro GKO_ENABLE_LIN_OP_FACTORY(). It is also required to use the same names for all parameters between both macros.

Parameters

_parameters_name	name of the parameters member in the class
_factory_name	name of the generated factory type

Referenced by gko::solver::Gmres< ValueType >::get_krylov_dim(), gko::preconditioner::Jacobi< ValueType, IndexType >::get_num_stored_elements(), gko::solver::Cgs< ValueType >::get_preconditioner(), gko::solver::Cg< ValueType >::get_preconditioner(), gko::solver::Bicgstab< ValueType >::get_preconditioner(), gko::solver::Fcg< ValueType >::get_preconditioner(), gko::solver::LowerTrs< ValueType, IndexType >::get_preconditioner(), gko::solver::UpperTrs< ValueType, IndexType >::get_preconditioner(), and gko::solver::Ir< ValueType >::get_solver().

22.4.4.2 GKO_ENABLE_BUILD_METHOD

```
#define GKO_ENABLE_BUILD_METHOD(
                _factory_name )
```

Value:

```
static auto build()->decltype(_factory_name::create())                  \
    {                                                                    \
        return _factory_name::create();                                  \
    }                                                                    \
    static_assert(true,                                                  \
                  "This assert is used to counter the false positive extra " \
                  "semi-colon warnings")
```

Defines a build method for the factory, simplifying its construction by removing the repetitive typing of factory's name.

Parameters

_factory_name	the factory for which to define the method

Referenced by gko::solver::Gmres< ValueType >::get_krylov_dim(), gko::preconditioner::Jacobi< ValueType, IndexType >::get_num_stored_elements(), gko::solver::Cgs< ValueType >::get_preconditioner(), gko::solver::Cg< ValueType >::get_preconditioner(), gko::solver::Bicgstab< ValueType >::get_preconditioner(), gko::solver::Fcg< ValueType >::get_preconditioner(), gko::solver::LowerTrs< ValueType, IndexType >::get_preconditioner(), gko::solver::UpperTrs< ValueType, IndexType >::get_preconditioner(), and gko::solver::Ir< ValueType >::get_solver().

22.4.4.3 GKO_ENABLE_LIN_OP_FACTORY

```
#define GKO_ENABLE_LIN_OP_FACTORY(
                _lin_op,
                _parameters_name,
                _factory_name )
```

Value:

```
public:                                                                  \
    const _parameters_name##_type &get_##_parameters_name() const        \
    {                                                                    \
        return _parameters_name##_;                                      \
    }                                                                    \
                                                                         \
    class _factory_name                                                  \
        : public ::gko::EnableDefaultLinOpFactory<_factory_name,
      _lin_op,    \
                                                  _parameters_name##_type> { \
        friend class ::gko::EnablePolymorphicObject<_factory_name,       \
```

```
                                                  ::gko::LinOpFactory>;     \
        friend class ::gko::enable_parameters_type<_parameters_name##_type,  \
                                                  _factory_name>;           \
        using ::gko::EnableDefaultLinOpFactory<
                      \
            _factory_name, _lin_op,                                         \
            _parameters_name##_type>::EnableDefaultLinOpFactory;            \
    };                                                                      \
    friend ::gko::EnableDefaultLinOpFactory<_factory_name,
      _lin_op,            \
                                        _parameters_name##_type>;           \
                                                                            \
                                                                            \
private:                                                                    \
    _parameters_name##_type _parameters_name##_;                            \
                                                                            \
public:                                                                     \
    static_assert(true,                                                     \
                  "This assert is used to counter the false positive extra " \
                  "semi-colon warnings")
```

This macro will generate a default implementation of a LinOpFactory for the LinOp subclass it is defined in.

It is required to first call the macro GKO_CREATE_FACTORY_PARAMETERS() before this one in order to instantiate the parameters type first.

The list of parameters for the factory should be defined in a code block after the macro definition, and should contain a list of GKO_FACTORY_PARAMETER declarations. The class should provide a constructor with signature _lin↩ _op(const _factory_name ∗, std::shared_ptr<const LinOp>) which the factory will use a callback to construct the object.

A minimal example of a linear operator is the following:

```
{c++}
struct MyLinOp : public EnableLinOp<MyLinOp> {
    GKO_ENABLE_LIN_OP_FACTORY(MyLinOp, my_parameters, Factory) {
        // a factory parameter named "my_value", of type int and default
        // value of 5
        int GKO_FACTORY_PARAMETER(my_value, 5);
    };
    // constructor needed by EnableLinOp
    explicit MyLinOp(std::shared_ptr<const Executor> exec) {
        : EnableLinOp<MyLinOp>(exec) {}
    // constructor needed by the factory
    explicit MyLinOp(const Factory *factory,
                     std::shared_ptr<const LinOp> matrix)
        : EnableLinOp<MyLinOp>(factory->get_executor()), matrix->get_size()),
          // store factory's parameters locally
          my_parameters_{factory->get_parameters()},
    {
         int value = my_parameters_.my_value;
         // do something with value
    }
```

MyLinOp can then be created as follows:

```
{c++}
auto exec = gko::ReferenceExecutor::create();
// create a factory with default `my_value` parameter
auto fact = MyLinOp::build().on(exec);
// create a operator using the factory:
auto my_op = fact->generate(gko::matrix::Identity::create(exec, 2));
std::cout << my_op->get_my_parameters().my_value;  // prints 5

// create a factory with custom `my_value` parameter
auto fact = MyLinOp::build().with_my_value(0).on(exec);
// create a operator using the factory:
auto my_op = fact->generate(gko::matrix::Identity::create(exec, 2));
std::cout << my_op->get_my_parameters().my_value;  // prints 0
```

Note

It is possible to combine both the #GKO_CREATE_FACTORY_PARAMETER() macro with this one in a unique macro for class **templates** (not with regular classes). Splitting this into two distinct macros allows to use them in all contexts. See https://stackoverflow.com/q/50202718/9385966 for more details.

Parameters

_lin_op	concrete operator for which the factory is to be created [CRTP parameter]
_parameters_name	name of the parameters member in the class (its type is `<_parameters_name>_type`, the protected member's name is `<_parameters_name>_`, and the public getter's name is `get_<_parameters_name>()`)
_factory_name	name of the generated factory type

Referenced by gko::solver::Gmres< ValueType >::get_krylov_dim(), gko::preconditioner::Jacobi< ValueType, IndexType >::get_num_stored_elements(), gko::solver::Cgs< ValueType >::get_preconditioner(), gko::solver::Cg< ValueType >::get_preconditioner(), gko::solver::Bicgstab< ValueType >::get_preconditioner(), gko::solver::Fcg< ValueType >::get_preconditioner(), gko::solver::LowerTrs< ValueType, IndexType >::get_preconditioner(), gko::solver::UpperTrs< ValueType, IndexType >::get_preconditioner(), and gko::solver::Ir< ValueType >::get_solver().

22.4.4.4 GKO_FACTORY_PARAMETER

```
#define GKO_FACTORY_PARAMETER(
                _name,
                ... )
```

Value:

```
mutable _name{__VA_ARGS__};                                                    \
                                                                                   \
    template <typename... Args>                                                    \
    auto with_##_name(Args &&... _value)                                           \
        const->const ::gko::xstd::decay_t<decltype(*this)> &                       \
    {                                                                              \
        using type = decltype(this->_name);                                        \
        this->_name = type{std::forward<Args>(_value)...};                         \
        return *this;                                                              \
    }                                                                              \
    static_assert(true,                                                            \
                  "This assert is used to counter the false positive extra " \
                  "semi-colon warnings")
```

Creates a factory parameter in the factory parameters structure.

Parameters

_name	name of the parameter
VA_ARGS	default value of the parameter

See also

GKO_ENABLE_LIN_OP_FACTORY for more details, and usage example

Referenced by gko::solver::Gmres< ValueType >::get_krylov_dim(), gko::preconditioner::Jacobi< ValueType, IndexType >::get_num_stored_elements(), gko::solver::Cgs< ValueType >::get_preconditioner(), gko::solver::Cg< ValueType >::get_preconditioner(), gko::solver::Bicgstab< ValueType >::get_preconditioner(), gko::solver::Fcg< ValueType >::get_preconditioner(), gko::solver::LowerTrs< ValueType, IndexType >::get_preconditioner(), gko::solver::UpperTrs< ValueType, IndexType >::get_preconditioner(), and gko::solver::Ir< ValueType >::get_solver().

22.4.5 Typedef Documentation

22.4.5.1 EnableDefaultLinOpFactory

```
template<typename ConcreteFactory , typename ConcreteLinOp , typename ParametersType , typename
PolymorphicBase = LinOpFactory>
using gko::EnableDefaultLinOpFactory = typedef EnableDefaultFactory<ConcreteFactory, Concrete↩
LinOp, ParametersType, PolymorphicBase>
```

This is an alias for the EnableDefaultFactory mixin, which correctly sets the template parameters to enable a subclass of LinOpFactory.

Template Parameters

ConcreteFactory	the concrete factory which is being implemented [CRTP parmeter]
ConcreteLinOp	the concrete LinOp type which this factory produces, needs to have a constructor which takes a const ConcreteFactory $*$, and an std::shared_ptr$<$const LinOp$>$ as parameters.
ParametersType	a subclass of enable_parameters_type template which defines all of the parameters of the factory
PolymorphicBase	parent of ConcreteFactory in the polymorphic hierarchy, has to be a subclass of LinOpFactory

22.5 Logging

A module dedicated to the implementation and usage of the Logging in Ginkgo.

Namespaces

- gko::log

    The logger namespace .

Classes

- class gko::log::Convergence< ValueType >

    Convergence is a Logger which logs data strictly from the `criterion_check_completed` event.
- class gko::log::Stream< ValueType >

    Stream is a Logger which logs every event to a stream.

22.5.1 Detailed Description

A module dedicated to the implementation and usage of the Logging in Ginkgo.

The Logger class represents a simple Logger object.

It comprises all masks and events internally. Every new logging event addition should be done here. The Logger class also provides a default implementation for most events which do nothing, therefore it is not an obligation to change all classes which derive from Logger, although it is good practice. The logger class is built using event masks to control which events should be logged, and which should not.

22.6 SpMV employing different Matrix formats

A module dedicated to the implementation and usage of the various Matrix Formats in Ginkgo.

Classes

- class gko::matrix::Coo< ValueType, IndexType >

  COO stores a matrix in the coordinate matrix format.
- class gko::matrix::Csr< ValueType, IndexType >

  CSR is a matrix format which stores only the nonzero coefficients by compressing each row of the matrix (compressed sparse row format).
- class gko::matrix::Dense< ValueType >

  Dense is a matrix format which explicitly stores all values of the matrix.
- class gko::matrix::Ell< ValueType, IndexType >

  ELL is a matrix format where stride with explicit zeros is used such that all rows have the same number of stored elements.
- class gko::matrix::Hybrid< ValueType, IndexType >

  HYBRID is a matrix format which splits the matrix into ELLPACK and COO format.
- class gko::matrix::Identity< ValueType >

  This class is a utility which efficiently implements the identity matrix (a linear operator which maps each vector to itself).
- class gko::matrix::IdentityFactory< ValueType >

  This factory is a utility which can be used to generate Identity operators.
- class gko::matrix::Sellp< ValueType, IndexType >

  SELL-P is a matrix format similar to ELL format.

Functions

- template<typename Matrix , typename... TArgs>
  std::unique_ptr< Matrix > gko::initialize (size_type stride, std::initializer_list< typename Matrix::value_type > vals, std::shared_ptr< const Executor > exec, TArgs &&... create_args)

  Creates and initializes a column-vector.
- template<typename Matrix , typename... TArgs>
  std::unique_ptr< Matrix > gko::initialize (std::initializer_list< typename Matrix::value_type > vals, std::shared_ptr< const Executor > exec, TArgs &&... create_args)

  Creates and initializes a column-vector.
- template<typename Matrix , typename... TArgs>
  std::unique_ptr< Matrix > gko::initialize (size_type stride, std::initializer_list< std::initializer_list< typename Matrix::value_type >> vals, std::shared_ptr< const Executor > exec, TArgs &&... create_args)

  Creates and initializes a matrix.
- template<typename Matrix , typename... TArgs>
  std::unique_ptr< Matrix > gko::initialize (std::initializer_list< std::initializer_list< typename Matrix::value_type >> vals, std::shared_ptr< const Executor > exec, TArgs &&... create_args)

  Creates and initializes a matrix.

22.6.1 Detailed Description

A module dedicated to the implementation and usage of the various Matrix Formats in Ginkgo.

22.6.2 Function Documentation

22.6.2.1 initialize() [1/4]

```
template<typename Matrix , typename... TArgs>
std::unique_ptr<Matrix> gko::initialize (
            size_type stride,
            std::initializer_list< typename Matrix::value_type > vals,
            std::shared_ptr< const Executor > exec,
            TArgs &&... create_args )
```

Creates and initializes a column-vector.

This function first creates a temporary Dense matrix, fills it with passed in values, and then converts the matrix to the requested type.

Template Parameters

Matrix	matrix type to initialize (Dense has to implement the ConvertibleTo<Matrix> interface)
TArgs	argument types for Matrix::create method (not including the implied Executor as the first argument)

Parameters

stride	row stride for the temporary Dense matrix
vals	values used to initialize the vector
exec	Executor associated to the vector
create_args	additional arguments passed to Matrix::create, not including the Executor, which is passed as the first argument

References gko::matrix::Dense< ValueType >::at().

```
{
    using dense = matrix::Dense<typename Matrix::value_type>;
    size_type num_rows = vals.size();
    auto tmp = dense::create(exec->get_master(), dim<2>{num_rows, 1}, stride);
    size_type idx = 0;
    for (const auto &elem : vals) {
        tmp->at(idx) = elem;
        ++idx;
    }
    auto mtx = Matrix::create(exec, std::forward<TArgs>(create_args)...);
    tmp->move_to(mtx.get());
    return mtx;
}
```

22.6.2.2 initialize() [2/4]

```
template<typename Matrix , typename... TArgs>
std::unique_ptr<Matrix> gko::initialize (
```

```
            std::initializer_list< typename Matrix::value_type > vals,
            std::shared_ptr< const Executor > exec,
            TArgs &&... create_args )
```

Creates and initializes a column-vector.

This function first creates a temporary Dense matrix, fills it with passed in values, and then converts the matrix to the requested type. The stride of the intermediate Dense matrix is set to 1.

Template Parameters

Matrix	matrix type to initialize (Dense has to implement the ConvertibleTo<Matrix> interface)
TArgs	argument types for Matrix::create method (not including the implied Executor as the first argument)

Parameters

vals	values used to initialize the vector
exec	Executor associated to the vector
create_args	additional arguments passed to Matrix::create, not including the Executor, which is passed as the first argument

```
{
    return initialize<Matrix>(1, vals, std::move(exec),
                              std::forward<TArgs>(create_args)...);
}
```

22.6.2.3 initialize() [3/4]

```
template<typename Matrix , typename... TArgs>
std::unique_ptr<Matrix> gko::initialize (
            size_type stride,
            std::initializer_list< std::initializer_list< typename Matrix::value_type >>
vals,
            std::shared_ptr< const Executor > exec,
            TArgs &&... create_args )
```

Creates and initializes a matrix.

This function first creates a temporary Dense matrix, fills it with passed in values, and then converts the matrix to the requested type.

Template Parameters

Matrix	matrix type to initialize (Dense has to implement the ConvertibleTo<Matrix> interface)
TArgs	argument types for Matrix::create method (not including the implied Executor as the first argument)

Parameters

stride	row stride for the temporary Dense matrix

Parameters

vals	values used to initialize the matrix
exec	Executor associated to the matrix
create_args	additional arguments passed to Matrix::create, not including the Executor, which is passed as the first argument

References gko::matrix::Dense< ValueType >::at().

```
{
    using dense = matrix::Dense<typename Matrix::value_type>;
    size_type num_rows = vals.size();
    size_type num_cols = num_rows > 0 ? begin(vals)->size() : 1;
    auto tmp =
        dense::create(exec->get_master(), dim<2>{num_rows, num_cols}, stride);
    size_type ridx = 0;
    for (const auto &row : vals) {
        size_type cidx = 0;
        for (const auto &elem : row) {
            tmp->at(ridx, cidx) = elem;
            ++cidx;
        }
        ++ridx;
    }
    auto mtx = Matrix::create(exec, std::forward<TArgs>(create_args)...);
    tmp->move_to(mtx.get());
    return mtx;
}
```

22.6.2.4 initialize() [4/4]

```
template<typename Matrix , typename...  TArgs>
std::unique_ptr<Matrix> gko::initialize (
            std::initializer_list< std::initializer_list< typename Matrix::value_type >>
vals,
            std::shared_ptr< const Executor > exec,
            TArgs &&...  create_args )
```

Creates and initializes a matrix.

This function first creates a temporary Dense matrix, fills it with passed in values, and then converts the matrix to the requested type. The stride of the intermediate Dense matrix is set to the number of columns of the initializer list.

Template Parameters

Matrix	matrix type to initialize (Dense has to implement the ConvertibleTo<Matrix> interface)
TArgs	argument types for Matrix::create method (not including the implied Executor as the first argument)

Parameters

vals	values used to initialize the matrix
exec	Executor associated to the matrix
create_args	additional arguments passed to Matrix::create, not including the Executor, which is passed as the first argument

```
{
    return initialize<Matrix>(vals.size() > 0 ? begin(vals)->size() : 0, vals,
                              std::move(exec),
                              std::forward<TArgs>(create_args)...);
}
```

22.7 OpenMP Executor

A module dedicated to the implementation and usage of the OpenMP executor in Ginkgo.

Classes

- class gko::OmpExecutor

  This is the Executor subclass which represents the OpenMP device (typically CPU).

22.7.1 Detailed Description

A module dedicated to the implementation and usage of the OpenMP executor in Ginkgo.

22.8 Preconditioners

A module dedicated to the implementation and usage of the Preconditioners in Ginkgo.

Namespaces

- gko::preconditioner

  The Preconditioner namespace.

Classes

- class gko::Preconditionable

  A LinOp implementing this interface can be preconditioned.
- class gko::preconditioner::Ilu< LSolverType, USolverType, ReverseApply >

  The Incomplete LU (ILU) preconditioner solves the equation $LUx = b$ for a given lower triangular matrix L, an upper triangular matrix U and the right hand side b (can contain multiple right hand sides).
- struct gko::preconditioner::block_interleaved_storage_scheme< IndexType >

  Defines the parameters of the interleaved block storage scheme used by block-Jacobi blocks.
- class gko::preconditioner::Jacobi< ValueType, IndexType >

  A block-Jacobi preconditioner is a block-diagonal linear operator, obtained by inverting the diagonal blocks of the source operator.

22.8.1 Detailed Description

A module dedicated to the implementation and usage of the Preconditioners in Ginkgo.

22.9 Reference Executor

A module dedicated to the implementation and usage of the Reference executor in Ginkgo.

Classes

- class gko::ReferenceExecutor

  This is a specialization of the OmpExecutor, which runs the reference implementations of the kernels used for debugging purposes.

22.9.1 Detailed Description

A module dedicated to the implementation and usage of the Reference executor in Ginkgo.

22.10 Solvers

A module dedicated to the implementation and usage of the Solvers in Ginkgo.

Namespaces

- gko::solver

  The ginkgo Solve namespace.

Classes

- class gko::solver::Bicgstab< ValueType >

  BiCGSTAB or the Bi-Conjugate Gradient-Stabilized is a Krylov subspace solver.
- class gko::solver::Cg< ValueType >

  CG or the conjugate gradient method is an iterative type Krylov subspace method which is suitable for symmetric positive definite methods.
- class gko::solver::Cgs< ValueType >

  CGS or the conjugate gradient square method is an iterative type Krylov subspace method which is suitable for general systems.
- class gko::solver::Fcg< ValueType >

  FCG or the flexible conjugate gradient method is an iterative type Krylov subspace method which is suitable for symmetric positive definite methods.
- class gko::solver::Gmres< ValueType >

  GMRES or the generalized minimal residual method is an iterative type Krylov subspace method which is suitable for nonsymmetric linear systems.
- class gko::solver::LowerTrs< ValueType, IndexType >

  LowerTrs is the triangular solver which solves the system L x = b, when L is a lower triangular matrix.
- class gko::solver::UpperTrs< ValueType, IndexType >

  UpperTrs is the triangular solver which solves the system U x = b, when U is an upper triangular matrix.

22.10.1 Detailed Description

A module dedicated to the implementation and usage of the Solvers in Ginkgo.

22.11 Stopping criteria

A module dedicated to the implementation and usage of the Stopping Criteria in Ginkgo.

Namespaces

- gko::stop

  The Stopping criterion namespace.

Classes

- class gko::stop::Combined

  The Combined class is used to combine multiple criterions together through an OR operation.
- class gko::stop::Iteration

  The Iteration class is a stopping criterion which stops the iteration process after a preset number of iterations.
- class gko::stop::ResidualNormReduction< ValueType >

  The ResidualNormReduction class is a stopping criterion which stops the iteration process when the relative residual norm is below a certain threshold.
- class gko::stopping_status

  This class is used to keep track of the stopping status of one vector.
- class gko::stop::Time

  The Time class is a stopping criterion which stops the iteration process after a certain amout of time has passed.

Macros

- #define GKO_ENABLE_CRITERION_FACTORY(_criterion, _parameters_name, _factory_name)

  This macro will generate a default implementation of a CriterionFactory for the Criterion subclass it is defined in.

Functions

- template<typename FactoryContainer >
  std::shared_ptr< const CriterionFactory > gko::stop::combine (FactoryContainer &&factories)

  Combines multiple criterion factories into a single combined criterion factory.

22.11.1 Detailed Description

A module dedicated to the implementation and usage of the Stopping Criteria in Ginkgo.

22.11.2 Macro Definition Documentation

22.11.2.1 GKO_ENABLE_CRITERION_FACTORY

```
#define GKO_ENABLE_CRITERION_FACTORY(
                _criterion,
                _parameters_name,
                _factory_name )
```

Value:

```
public:                                                                          \
    const _parameters_name##_type &get_##_parameters_name() const              \
    {                                                                           \
        return _parameters_name##_;                                            \
    }                                                                           \
                                                                                \
    class _factory_name                                                         \
        : public ::gko::stop::EnableDefaultCriterionFactory<                   \
              _factory_name, _criterion, _parameters_name##_type> {            \
        friend class ::gko::EnablePolymorphicObject<                           \
            _factory_name, ::gko::stop::CriterionFactory>;                     \
        friend class ::gko::enable_parameters_type<_parameters_name##_type,   \
                                                   _factory_name>;             \
        using ::gko::stop::EnableDefaultCriterionFactory<                      \
            _factory_name, _criterion,                                         \
            _parameters_name##_type>::EnableDefaultCriterionFactory;           \
    };                                                                          \
    friend ::gko::stop::EnableDefaultCriterionFactory<                         \
        _factory_name, _criterion, _parameters_name##_type>;                   \
                                                                                \
private:                                                                        \
    _parameters_name##_type _parameters_name##_;                               \
                                                                                \
public:                                                                         \
    static_assert(true,                                                         \
                  "This assert is used to counter the false positive extra " \
                  "semi-colon warnings")
```

This macro will generate a default implementation of a CriterionFactory for the Criterion subclass it is defined in.

This macro is very similar to the macro #ENABLE_LIN_OP_FACTORY(). A more detailed description of the use of these type of macros can be found there.

Parameters

_criterion	concrete operator for which the factory is to be created [CRTP parameter]
_parameters_name	name of the parameters member in the class (its type is `<_parameters_name>_type`, the protected member's name is `<_parameters_name>_`, and the public getter's name is `get_<_parameters_name>()`)
_factory_name	name of the generated factory type

22.11.3 Function Documentation

22.11.3.1 combine()

```
template<typename FactoryContainer >
std::shared_ptr<const CriterionFactory> gko::stop::combine (
            FactoryContainer && factories )
```

Combines multiple criterion factories into a single combined criterion factory.

This function treats a singleton container as a special case and avoids creating an additional object and just returns the input factory.

Template Parameters

FactoryContainer	a random access container type

Parameters

factories	a list of factories to combined

Returns

a combined criterion factory if the input contains multiple factories or the input factory if the input contains only one factory

Referenced by gko::solver::Gmres< ValueType >::get_krylov_dim(), gko::solver::Cgs< ValueType >::get_preconditioner(), gko::solver::Cg< ValueType >::get_preconditioner(), gko::solver::Fcg< ValueType >::get_preconditioner(), gko::solver::Bicgstab< ValueType >::get_preconditioner(), and gko::solver::Ir< ValueType >::get_solver().

```
{
    switch (factories.size()) {
    case 0:
        GKO_NOT_SUPPORTED(nullptr);
        return nullptr;
    case 1:
        return factories[0];
    default:
        auto exec = factories[0]->get_executor();
        return Combined::build()
            .with_criteria(std::forward<FactoryContainer>(factories))
            .on(exec);
    }
}
```

Chapter 23

Namespace Documentation

23.1 gko Namespace Reference

The Ginkgo namespace.

Namespaces

- accessor

    The accessor namespace.
- factorization

    The Factorization namespace.
- log

    The logger namespace .
- matrix

    The matrix namespace.
- name_demangling

    The name demangling namespace.
- preconditioner

    The Preconditioner namespace.
- solver

    The ginkgo Solve namespace.
- stop

    The Stopping criterion namespace.
- syn

    The Synthesizer namespace.
- xstd

    The namespace for functionalities after C++11 standard.

Classes

- class AbstractFactory

  The AbstractFactory is a generic interface template that enables easy implementation of the abstract factory design pattern.
- class AllocationError

  AllocationError is thrown if a memory allocation fails.
- class Array

  An Array is a container which encapsulates fixed-sized arrays, stored on the Executor tied to the Array.
- class BadDimension

  BadDimension is thrown if an operation is being applied to a LinOp with bad dimensions.
- class Combination

  The Combination class can be used to construct a linear combination of multiple linear operators 'c1 ∗ op1 + c2 ∗ op2 + ...
- class Composition

  The Composition class can be used to compose linear operators `op1, op2, ..., opn` *and obtain the operator 'op1 ∗ op2 ∗ ...*
- class ConvertibleTo

  ConvertibleTo interface is used to mark that the implementer can be converted to the object of ResultType.
- class copy_back_deleter

  A copy_back_deleter is a type of deleter that copies the data to an internally referenced object before performing the deletion.
- class CublasError

  CublasError is thrown when a cuBLAS routine throws a non-zero error code.
- class CudaError

  CudaError is thrown when a CUDA routine throws a non-zero error code.
- class CudaExecutor

  This is the Executor subclass which represents the CUDA device.
- class CusparseError

  CusparseError is thrown when a cuSPARSE routine throws a non-zero error code.
- struct default_converter

  Used to convert objects of type `S` *to objects of type* `R` *using static_cast.*
- struct dim

  A type representing the dimensions of a multidimensional object.
- class DimensionMismatch

  DimensionMismatch is thrown if an operation is being applied to LinOps of incompatible size.
- struct enable_parameters_type

  The enable_parameters_type mixin is used to create a base implementation of the factory parameters structure.
- class EnableAbstractPolymorphicObject

  This mixin inherits from (a subclass of) PolymorphicObject and provides a base implementation of a new abstract object.
- class EnableCreateMethod

  This mixin implements a static `create()` *method on* `ConcreteType` *that dynamically allocates the memory, uses the passed-in arguments to construct the object, and returns an std::unique_ptr to such an object.*
- class EnableDefaultFactory

  This mixin provides a default implementation of a concrete factory.
- class EnableLinOp

  The EnableLinOp mixin can be used to provide sensible default implementations of the majority of the LinOp and PolymorphicObject interface.
- class EnablePolymorphicAssignment

  This mixin is used to enable a default PolymorphicObject::copy_from() implementation for objects that have implemented conversions between them.
- class EnablePolymorphicObject

This mixin inherits from (a subclass of) PolymorphicObject and provides a base implementation of a new concrete polymorphic object.

- class Error

  The Error class is used to report exceptional behaviour in library functions.
- class Executor

  The first step in using the Ginkgo library consists of creating an executor.
- class executor_deleter

  This is a deleter that uses an executor's `free` method to deallocate the data.
- class KernelNotFound

  KernelNotFound is thrown if Ginkgo cannot find a kernel which satisfies the criteria imposed by the input arguments.
- class LinOpFactory

  A LinOpFactory represents a higher order mapping which transforms one linear operator into another.
- struct matrix_data

  This structure is used as an intermediate data type to store a sparse matrix.
- class NotCompiled

  NotCompiled is thrown when attempting to call an operation which is a part of a module that was not compiled on the system.
- class NotImplemented

  NotImplemented is thrown in case an operation has not yet been implemented (but will be implemented in the future).
- class NotSupported

  NotSupported is thrown in case it is not possible to perform the requested operation on the given object type.
- class null_deleter

  This is a deleter that does not delete the object.
- class OmpExecutor

  This is the Executor subclass which represents the OpenMP device (typically CPU).
- class Operation

  Operations can be used to define functionalities whose implementations differ among devices.
- class OutOfBoundsError

  OutOfBoundsError is thrown if a memory access is detected to be out-of-bounds.
- class Perturbation

  The Perturbation class can be used to construct a LinOp to represent the operation `(identity + scalar * basis * projector)`.
- class PolymorphicObject

  A PolymorphicObject is the abstract base for all "heavy" objects in Ginkgo that behave polymorphically.
- class precision_reduction

  This class is used to encode storage precisions of low precision algorithms.
- class Preconditionable

  A LinOp implementing this interface can be preconditioned.
- class range

  A range is a multidimensional view of the memory.
- class ReadableFromMatrixData

  A LinOp implementing this interface can read its data from a matrix_data structure.
- class ReferenceExecutor

  This is a specialization of the OmpExecutor, which runs the reference implementations of the kernels used for debugging purposes.
- struct span

  A span is a lightweight structure used to create sub-ranges from other ranges.
- class stopping_status

  This class is used to keep track of the stopping status of one vector.
- class StreamError

  StreamError is thrown if accessing a stream failed.

- class temporary_clone

    A temporary_clone is a special smart pointer-like object that is designed to hold an object temporarily copied to another executor.
- class Transposable

    Linear operators which support transposition should implement the Transposable interface.
- struct version

    This structure is used to represent versions of various Ginkgo modules.
- class version_info

    Ginkgo uses version numbers to label new features and to communicate backward compatibility guarantees:
- class WritableToMatrixData

    A LinOp implementing this interface can write its data to a matrix_data structure.

Typedefs

- template< typename ConcreteFactory , typename ConcreteLinOp , typename ParametersType , typename PolymorphicBase = LinOp↩ Factory>
  using EnableDefaultLinOpFactory = EnableDefaultFactory< ConcreteFactory, ConcreteLinOp, Parameters↩ Type, PolymorphicBase >

    This is an alias for the EnableDefaultFactory mixin, which correctly sets the template parameters to enable a subclass of LinOpFactory.
- template< typename T >
  using remove_complex = typename detail::remove_complex_impl< T >::type

    Obtains a real counterpart of a std::complex type, and leaves the type unchanged if it is not a complex type.
- template< typename T >
  using is_complex_s = detail::is_complex_impl< T >

    Allows to check if T is a complex value during compile time by accessing the `value` attribute of this struct.
- template< typename T >
  using reduce_precision = typename detail::reduce_precision_impl< T >::type

    Obtains the next type in the hierarchy with lower precision than T.
- template< typename T >
  using increase_precision = typename detail::increase_precision_impl< T >::type

    Obtains the next type in the hierarchy with higher precision than T.
- template< typename T , size_type Limit = sizeof(uint16) ∗ byte_size>
  using truncate_type = xstd::conditional_t< detail::type_size_impl< T >::value >=2 ∗Limit, typename detail↩ ::truncate_type_impl< T >::type, T >

    Truncates the type by half (by dropping bits), but ensures that it is at least `Limit` bits wide.
- using size_type = std::size_t

    Integral type used for allocation quantities.
- using int8 = std::int8_t

    8-bit signed integral type.
- using int16 = std::int16_t

    16-bit signed integral type.
- using int32 = std::int32_t

    32-bit signed integral type.
- using int64 = std::int64_t

    64-bit signed integral type.
- using uint8 = std::uint8_t

    8-bit unsigned integral type.
- using uint16 = std::uint16_t

    16-bit unsigned integral type.
- using uint32 = std::uint32_t

32-bit unsigned integral type.

- using uint64 = std::uint64_t

    64-bit unsigned integral type.
- using float16 = half

    Half precision floating point type.
- using float32 = float

    Single precision floating point type.
- using float64 = double

    Double precision floating point type.
- using full_precision = double

    The most precise floating-point type.
- using default_precision = double

    Precision used if no precision is explicitly specified.

Enumerations

- enum layout_type { layout_type::array, layout_type::coordinate }

    Specifies the layout type when writing data in matrix market format.

Functions

- template< size_type Dimensionality, typename DimensionType >
  constexpr bool operator!= (const dim< Dimensionality, DimensionType > &x, const dim< Dimensionality, DimensionType > &y)

    Checks if two dim objects are different.
- template< typename DimensionType >
  constexpr dim< 2, DimensionType > transpose (const dim< 2, DimensionType > &dimensions) noexcept

    Returns a dim<2> object with its dimensions swapped.
- template< typename T >
  constexpr bool is_complex ()

    Checks if T is a complex type.
- template< typename T >
  constexpr reduce_precision< T > round_down (T val)

    Reduces the precision of the input parameter.
- template< typename T >
  constexpr increase_precision< T > round_up (T val)

    Increases the precision of the input parameter.
- constexpr int64 ceildiv (int64 num, int64 den)

    Performs integer division with rounding up.
- template< typename T >
  constexpr T zero ()

    Returns the additive identity for T.
- template< typename T >
  constexpr T zero (const T &)

    Returns the additive identity for T.
- template< typename T >
  constexpr T one ()

    Returns the multiplicative identity for T.
- template< typename T >
  constexpr T one (const T &)

    Returns the multiplicative identity for T.

- template<typename T >
  constexpr T abs (const T &x)

  Returns the absolute value of the object.
- template<typename T >
  constexpr T max (const T &x, const T &y)

  Returns the larger of the arguments.
- template<typename T >
  constexpr T min (const T &x, const T &y)

  Returns the smaller of the arguments.
- template<typename T >
  constexpr T real (const T &x)

  Returns the real part of the object.
- template<typename T >
  constexpr T imag (const T &)

  Returns the imaginary part of the object.
- template<typename T >
  T conj (const T &x)

  Returns the conjugate of an object.
- template<typename T >
  constexpr auto squared_norm (const T &x) -> decltype(real(conj(x) *x))

  Returns the squared norm of the object.
- template<typename T >
  constexpr uint32 get_significant_bit (const T &n, uint32 hint=0u) noexcept

  Returns the position of the most significant bit of the number.
- template<typename T >
  constexpr T get_superior_power (const T &base, const T &limit, const T &hint=T{1}) noexcept

  Returns the smallest power of `base` not smaller than `limit`.
- template<typename T >
  xstd::enable_if_t< is_complex_s< T >::value, bool > isfinite (const T &value)

  Checks if all components of a complex value are finite, meaning they are neither +/- infinity nor NaN.
- template<typename ValueType = default_precision, typename IndexType = int32>
  matrix_data< ValueType, IndexType > read_raw (std::istream &is)

  Reads a matrix stored in matrix market format from an input stream.
- template<typename ValueType , typename IndexType >
  void write_raw (std::ostream &os, const matrix_data< ValueType, IndexType > &data, layout_type layout=layout_type::array)

  Writes a matrix_data structure to a stream in matrix market format.
- template<typename MatrixType , typename StreamType , typename... MatrixArgs>
  std::unique_ptr< MatrixType > read (StreamType &&is, MatrixArgs &&... args)

  Reads a matrix stored in matrix market format from an input stream.
- template<typename MatrixType , typename StreamType >
  void write (StreamType &&os, MatrixType *matrix, layout_type layout=layout_type::array)

  Reads a matrix stored in matrix market format from an input stream.
- template<typename R , typename T >
  std::unique_ptr< R, std::function< void(R *)> > copy_and_convert_to (std::shared_ptr< const Executor > exec, T *obj)

  Converts the object to R and places it on Executor exec.
- template<typename R , typename T >
  std::unique_ptr< const R, std::function< void(const R *)> > copy_and_convert_to (std::shared_ptr< const Executor > exec, const T *obj)

  Converts the object to R and places it on Executor exec.
- template<typename R , typename T >
  std::shared_ptr< R > copy_and_convert_to (std::shared_ptr< const Executor > exec, std::shared_ptr< T > obj)

Converts the object to R and places it on Executor exec.

- template< typename R , typename T >
  std::shared_ptr< const R > copy_and_convert_to (std::shared_ptr< const Executor > exec, std::shared_ptr< const T > obj)
- constexpr bool operator== (precision_reduction x, precision_reduction y) noexcept

  Checks if two precision_reduction encodings are equal.
- constexpr bool operator!= (precision_reduction x, precision_reduction y) noexcept

  Checks if two precision_reduction encodings are different.
- template< typename Pointer >
  detail::cloned_type< Pointer > clone (const Pointer &p)

  Creates a unique clone of the object pointed to by p.
- template< typename Pointer >
  detail::cloned_type< Pointer > clone (std::shared_ptr< const Executor > exec, const Pointer &p)

  Creates a unique clone of the object pointed to by p on Executor $exec$.
- template< typename OwningPointer >
  detail::shared_type< OwningPointer > share (OwningPointer &&p)

  Marks the object pointed to by p as shared.
- template< typename OwningPointer >
  std::remove_reference< OwningPointer >::type && give (OwningPointer &&p)

  Marks that the object pointed to by p can be given to the callee.
- template< typename Pointer >
  std::enable_if< detail::have_ownership< Pointer >), detail::pointee< Pointer > ∗ >::type lend (const Pointer &p)

  Returns a non-owning (plain) pointer to the object pointed to by p.
- template< typename Pointer >
  std::enable_if<!detail::have_ownership< Pointer >), detail::pointee< Pointer > ∗ >::type lend (const Pointer &p)

  Returns a non-owning (plain) pointer to the object pointed to by p.
- template< typename T , typename U >
  std::decay< T >::type ∗ as (U ∗obj)

  Performs polymorphic type conversion.
- template< typename T , typename U >
  const std::decay< T >::type ∗ as (const U ∗obj)

  Performs polymorphic type conversion.
- template< typename T >
  temporary_clone< T > make_temporary_clone (std::shared_ptr< const Executor > exec, T ∗ptr)

  Creates a temporary_clone.
- std::ostream & operator<< (std::ostream &os, const version &ver)

  Prints version information to a stream.
- std::ostream & operator<< (std::ostream &os, const version_info &ver_info)

  Prints library version information in human-readable format to a stream.
- template< typename Matrix , typename... TArgs>
  std::unique_ptr< Matrix > initialize (size_type stride, std::initializer_list< typename Matrix::value_type > vals, std::shared_ptr< const Executor > exec, TArgs &&... create_args)

  Creates and initializes a column-vector.
- template< typename Matrix , typename... TArgs>
  std::unique_ptr< Matrix > initialize (std::initializer_list< typename Matrix::value_type > vals, std::shared_ptr< const Executor > exec, TArgs &&... create_args)

  Creates and initializes a column-vector.
- template< typename Matrix , typename... TArgs>
  std::unique_ptr< Matrix > initialize (size_type stride, std::initializer_list< std::initializer_list< typename Matrix::value_type >> vals, std::shared_ptr< const Executor > exec, TArgs &&... create_args)

  Creates and initializes a matrix.

- template<typename Matrix , typename... TArgs>
  std::unique_ptr< Matrix > initialize (std::initializer_list< std::initializer_list< typename Matrix::value_type >> vals, std::shared_ptr< const Executor > exec, TArgs &&... create_args)

  Creates and initializes a matrix.
- bool operator== (const stopping_status &x, const stopping_status &y) noexcept

  Checks if two stopping statuses are equivalent.
- bool operator!= (const stopping_status &x, const stopping_status &y) noexcept

  Checks if two stopping statuses are different.

Variables

- constexpr size_type byte_size = CHAR_BIT

  Number of bits in a byte.

23.1.1 Detailed Description

The Ginkgo namespace.

23.1.2 Typedef Documentation

23.1.2.1 is_complex_s

```
template<typename T >
using gko::is_complex_s = typedef detail::is_complex_impl<T>
```

Allows to check if T is a complex value during compile time by accessing the `value` attribute of this struct.

If `value` is `true`, T is a complex type, if it is `false`, T is not a complex type.

Template Parameters

T	type to check

23.1.3 Enumeration Type Documentation

23.1.3.1 layout_type

```
enum gko::layout_type [strong]
```

Specifies the layout type when writing data in matrix market format.

Enumerator

array	The matrix should be written as dense matrix in column-major order.
coordinate	The matrix should be written as a sparse matrix in coordinate format.

```
{
    array,
    coordinate
};
```

23.1.4 Function Documentation

23.1.4.1 abs()

```
template<typename T >
constexpr T gko::abs (
            const T & x ) [inline]
```

Returns the absolute value of the object.

Template Parameters

T	the type of the object

Parameters

x	the object

Returns

x >= zero<T>() ? x : -x;

```
{
    return x >= zero<T>() ? x : -x;
}
```

23.1.4.2 as() [1/2]

```
template<typename T , typename U >
std::decay<T>::type* gko::as (
            U * obj ) [inline]
```

Performs polymorphic type conversion.

Template Parameters

T	requested result type
U	static type of the passed object

Parameters

obj	the object which should be converted

Returns

If successful, returns a pointer to the subtype, otherwise throws NotSupported.

```
{
    if (auto p = dynamic_cast<typename std::decay<T>::type *>(obj)) {
        return p;
    } else {
        throw NotSupported(__FILE__, __LINE__, __func__, typeid(obj).name());
    }
}
```

23.1.4.3 as() [2/2]

```
template<typename T , typename U >
const std::decay<T>::type* gko::as (
            const U * obj )  [inline]
```

Performs polymorphic type conversion.

This is the constant version of the function.

Template Parameters

T	requested result type
U	static type of the passed object

Parameters

obj	the object which should be converted

Returns

If successful, returns a pointer to the subtype, otherwise throws NotSupported.

```
{
    if (auto p = dynamic_cast<const typename std::decay<T>::type *>(obj)) {
        return p;
    } else {
        throw NotSupported(__FILE__, __LINE__, __func__, typeid(obj).name());
    }
}
```

23.1.4.4 ceildiv()

```
constexpr int64 gko::ceildiv (
            int64 num,
            int64 den ) [inline]
```

Performs integer division with rounding up.

Parameters

num	numerator
den	denominator

Returns

returns the ceiled quotient.

Referenced by gko::matrix::Sellp< ValueType, IndexType >::col_at(), and gko::preconditioner::block_interleaved←_storage_scheme< index_type >::compute_storage_space().

```
292 {
293     return (num + den - 1) / den;
294 }
```

23.1.4.5 clone() [1/2]

```
template<typename Pointer >
detail::cloned_type<Pointer> gko::clone (
            const Pointer & p ) [inline]
```

Creates a unique clone of the object pointed to by p.

The pointee (i.e. *p) needs to have a clone method that returns a std::unique_ptr in order for this method to work.

Template Parameters

Pointer	type of pointer to the object (plain or smart pointer)

Parameters

p	a pointer to the object

Note

The difference between this function and directly calling LinOp::clone() is that this one preserves the static type of the object.

Referenced by gko::temporary_clone< T >::temporary_clone().

```
{
    static_assert(detail::is_clonable<detail::pointee<Pointer>>(),
                  "Object is not clonable");
    return detail::cloned_type<Pointer>(
        static_cast<typename std::remove_cv<detail::pointee<Pointer>>::type *>(
            p->clone().release()));
}
```

23.1.4.6 clone() [2/2]

```
template<typename Pointer >
detail::cloned_type<Pointer> gko::clone (
            std::shared_ptr< const Executor > exec,
            const Pointer & p ) [inline]
```

Creates a unique clone of the object pointed to by `p` on Executor `exec`.

The pointee (i.e. `*p`) needs to have a clone method that takes an executor and returns a std::unique_ptr in order for this method to work.

Template Parameters

Pointer	type of pointer to the object (plain or smart pointer)

Parameters

exec	the executor where the cloned object should be stored
p	a pointer to the object

Note

The difference between this function and directly calling LinOp::clone() is that this one preserves the static type of the object.

```
{
    static_assert(detail::is_clonable_to<detail::pointee<Pointer>>(),
                  "Object is not clonable");
    return detail::cloned_type<Pointer>(
        static_cast<typename std::remove_cv<detail::pointee<Pointer>>::type *>(
            p->clone(std::move(exec)).release()));
}
```

23.1.4.7 conj()

```
template<typename T >
T gko::conj (
            const T & x ) [inline]
```

Returns the conjugate of an object.

Parameters

x	the number to conjugate

Returns

conjugate of the object (by default, the object itself)

Referenced by gko::matrix_data< ValueType, IndexType >::ensure_row_major_order(), and squared_norm().

```
{
    return x;
}
```

23.1.4.8 copy_and_convert_to() [1/4]

```
template<typename R , typename T >
std::unique_ptr<R, std::function<void(R *)> > gko::copy_and_convert_to (
            std::shared_ptr< const Executor > exec,
            T * obj )
```

Converts the object to R and places it on Executor exec.

If the object is already of the requested type and on the requested executor, the copy and conversion is avoided and a reference to the original object is returned instead.

Template Parameters

R	the type to which the object should be converted
T	the type of the input object

Parameters

exec	the executor where the result should be placed
obj	the object that should be converted

Returns

a unique pointer (with dynamically bound deleter) to the converted object

```
{
    return detail::copy_and_convert_to_impl<R>(std::move(exec), obj);
}
```

23.1.4.9 copy_and_convert_to() [2/4]

```
template<typename R , typename T >
std::unique_ptr<const R, std::function<void(const R *)> > gko::copy_and_convert_to (
            std::shared_ptr< const Executor > exec,
            const T * obj )
```

Converts the object to R and places it on Executor exec.

If the object is already of the requested type and on the requested executor, the copy and conversion is avoided and a reference to the original object is returned instead.

Template Parameters

R	the type to which the object should be converted
T	the type of the input object

Parameters

exec	the executor where the result should be placed
obj	the object that should be converted

Returns

a unique pointer (with dynamically bound deleter) to the converted object

Note

This is a version of the function which adds the const qualifier to the result if the input had the same qualifier.

```
483 {
484     return detail::copy_and_convert_to_impl<const R>(std::move(exec), obj);
485 }
```

23.1.4.10 copy_and_convert_to() [3/4]

```
template<typename R , typename T >
std::shared_ptr<R> gko::copy_and_convert_to (
            std::shared_ptr< const Executor > exec,
            std::shared_ptr< T > obj )
```

Converts the object to R and places it on Executor exec.

This is the version that takes in the std::shared_ptr and returns a std::shared_ptr

If the object is already of the requested type and on the requested executor, the copy and conversion is avoided and a reference to the original object is returned instead.

Template Parameters

R	the type to which the object should be converted
T	the type of the input object

Parameters

exec	the executor where the result should be placed
obj	the object that should be converted

Returns

a shared pointer to the converted object

```
{
    return detail::copy_and_convert_to_impl<R>(std::move(exec), obj);
}
```

23.1.4.11 copy_and_convert_to() [4/4]

```
template<typename R , typename T >
std::shared_ptr<const R> gko::copy_and_convert_to (
            std::shared_ptr< const Executor > exec,
            std::shared_ptr< const T > obj )
```

This is the version that takes in the std::shared_ptr and returns a std::shared_ptr

If the object is already of the requested type and on the requested executor, the copy and conversion is avoided and a reference to the original object is returned instead.

Template Parameters

R	the type to which the object should be converted
T	the type of the input object

Parameters

exec	the executor where the result should be placed
obj	the object that should be converted

Returns

a shared pointer to the converted object

Note

This is a version of the function which adds the const qualifier to the result if the input had the same qualifier.

```
{
    return detail::copy_and_convert_to_impl<const R>(std::move(exec), obj);
}
```

23.1.4.12 get_significant_bit()

```
template<typename T >
constexpr uint32 gko::get_significant_bit (
            const T & n,
            uint32 hint = 0u ) [inline], [noexcept]
```

Returns the position of the most significant bit of the number.

This is the same as the rounded down base-2 logarithm of the number.

Template Parameters

T	a numeric type supporting bit shift and comparison

Parameters

n	a number
hint	a lower bound for the position o the significant bit

Returns

maximum of `hint` and the significant bit position of `n`

Referenced by gko::preconditioner::Jacobi< ValueType, IndexType >::get_num_stored_elements().

```
{
    return (T{1} << (hint + 1)) > n ? hint : get_significant_bit(n, hint + 1u);
}
```

23.1.4.13 get_superior_power()

```
template<typename T >
constexpr T gko::get_superior_power (
            const T & base,
            const T & limit,
            const T & hint = T{1} ) [inline], [noexcept]
```

Returns the smallest power of `base` not smaller than `limit`.

Template Parameters

T	a numeric type supporting multiplication and comparison

Parameters

base	the base of the power to be returned
limit	the lower limit on the size of the power returned
hint	a lower bound on the result, has to be a power of base

Returns

the smallest power of `base` not smaller than `limit`

Referenced by gko::preconditioner::Jacobi< ValueType, IndexType >::get_num_stored_elements().

```
                                                     {1}) noexcept
{
    return hint >= limit ? hint : get_superior_power(base, limit, hint * base);
}
```

23.1.4.14 give()

```
template<typename OwningPointer >
std::remove_reference<OwningPointer>::type&& gko::give (
              OwningPointer && p )  [inline]
```

Marks that the object pointed to by `p` can be given to the callee.

Effectively calls `std::move(p).`

Template Parameters

OwningPointer	type of pointer with ownership to the object (has to be a smart pointer)

Parameters

p	a pointer to the object

Note

The original pointer `p` becomes invalid after this call.

```
{
    static_assert(detail::have_ownership<OwningPointer>(),
                  "OwningPointer does not have ownership of the object");
    return std::move(p);
}
```

23.1.4.15 imag()

```
template<typename T >
constexpr T gko::imag (
            const T & )  [inline]
```

Returns the imaginary part of the object.

Template Parameters

T	type of the object

Parameters

x	the object

Returns

imaginary part of the object (by default, zero<T>())

```
{
    return zero<T>();
}
```

23.1.4.16 is_complex()

```
template<typename T >
constexpr bool gko::is_complex ( )  [inline]
```

Checks if T is a complex type.

Template Parameters

T	type to check

Returns

`true` if T is a complex type, `false` otherwise

```
{
    return detail::is_complex_impl<T>::value;
}
```

23.1.4.17 isfinite()

```
template<typename T >
xstd::enable_if_t<is_complex_s<T>::value, bool> gko::isfinite (
            const T & value ) [inline]
```

Checks if all components of a complex value are finite, meaning they are neither +/- infinity nor NaN.

Template Parameters

T	complex type of the value to check

Parameters

value	complex value to check

returns `true` if both components of the given value are finite, meaning they are neither +/- infinity nor NaN.

```
540 {
541     return isfinite(value.real()) && isfinite(value.imag());
542 }
```

23.1.4.18 lend() [1/2]

```
template<typename Pointer >
std::enable_if<detail::have_ownership<Pointer>(), detail::pointee<Pointer> *>::type gko::lend
(
            const Pointer & p ) [inline]
```

Returns a non-owning (plain) pointer to the object pointed to by `p`.

Template Parameters

Pointer	type of pointer to the object (plain or smart pointer)

Parameters

p	a pointer to the object

Note

This is the overload for owning (smart) pointers, that behaves the same as calling .get() on the smart pointer.

Referenced by gko::preconditioner::Jacobi< ValueType, IndexType >::get_num_stored_elements(), gko::Perturbation< ValueType >::get_scalar(), and gko::log::EnableLogging< Executor >::remove_logger().

```
250 {
251     return p.get();
252 }
```

23.1.4.19 lend() [2/2]

```
template<typename Pointer >
std::enable_if<!detail::have_ownership<Pointer>(), detail::pointee<Pointer> *>::type gko↩
::lend (
            const Pointer & p )  [inline]
```

Returns a non-owning (plain) pointer to the object pointed to by `p`.

Template Parameters

Pointer	type of pointer to the object (plain or smart pointer)

Parameters

p	a pointer to the object

Note

This is the overload for non-owning (plain) pointers, that just returns `p`.

```
268 {
269     return p;
270 }
```

23.1.4.20 make_temporary_clone()

```
template<typename T >
temporary_clone<T> gko::make_temporary_clone (
            std::shared_ptr< const Executor > exec,
            T * ptr )
```

Creates a temporary_clone.

This is a helper function which avoids the need to explicitly specify the type of the object, as would be the case if using the constructor of temporary_clone.

Parameters

exec	the executor where the clone will be created
ptr	a pointer to the object of which the clone will be created

Referenced by gko::matrix::Dense< ValueType >::add_scaled(), gko::matrix::Coo< ValueType, IndexType >↩
::apply2(), gko::matrix::Dense< ValueType >::compute_dot(), gko::matrix::Dense< ValueType >::compute_↩
norm2(), and gko::matrix::Dense< ValueType >::scale().

```
{
    return temporary_clone<T>(std::move(exec), ptr);
}
```

23.1.4.21 max()

```
template<typename T >
constexpr T gko::max (
            const T & x,
            const T & y ) [inline]
```

Returns the larger of the arguments.

Template Parameters

T	type of the arguments

Parameters

x	first argument
y	second argument

Returns

x >= y ? x : y

Note

C++11 version of this function is not constexpr, thus we provide our own implementation.

```
{
    return x >= y ? x : y;
}
```

23.1.4.22 min()

```
template<typename T >
constexpr T gko::min (
            const T & x,
            const T & y ) [inline]
```

Returns the smaller of the arguments.

Template Parameters

T	type of the arguments

Parameters

x	first argument
y	second argument

Returns

x <= y ? x : y

Note

C++11 version of this function is not `constexpr`, thus we provide our own implementation.

```
{
    return x <= y ? x : y;
}
```

23.1.4.23 one() [1/2]

```
template<typename T >
constexpr T gko::one ( ) [inline]
```

Returns the multiplicative identity for T.

Returns

the multiplicative identity for T

Referenced by gko::matrix_data< ValueType, IndexType >::ensure_row_major_order(), gko::Combination< ValueType >::get_operators(), and gko::Perturbation< ValueType >::get_scalar().

```
{
    return T(1);
}
```

23.1.4.24 one() [2/2]

```
template<typename T >
constexpr T gko::one (
            const T & ) [inline]
```

Returns the multiplicative identity for T.

Returns

the multiplicative identity for T

Note

This version takes an unused reference argument to avoid complicated calls like one<decltype(x)>(). Instead, it allows one(x).

```
{
    return one<T>();
}
```

23.1.4.25 operator"!=() [1/3]

```
bool gko::operator!= (
            const stopping_status & x,
            const stopping_status & y ) [inline], [noexcept]
```

Checks if two stopping statuses are different.

Parameters

x	a stopping status
y	a stopping status

Returns

true if and only if `!(x == y)`

```
{
    return x.data_ != y.data_;
}
```

23.1.4.26 operator"!=() [2/3]

```
template<size_type Dimensionality, typename DimensionType >
constexpr bool gko::operator!= (
            const dim< Dimensionality, DimensionType > & x,
            const dim< Dimensionality, DimensionType > & y ) [inline]
```

Checks if two dim objects are different.

Template Parameters

Dimensionality	number of dimensions of the dim objects
DimensionType	datatype used to represent each dimension

Parameters

x	first object
y	second object

Returns

`!(x == y)`

```
{
    return !(x == y);
}
```

23.1.4.27 operator"!=() [3/3]

```
constexpr bool gko::operator!= (
            precision_reduction x,
            precision_reduction y ) [noexcept]
```

Checks if two precision_reduction encodings are different.

Parameters

x	an encoding
y	an encoding

Returns

true if and only if x and y are different encodings.

```
{
    using st = precision_reduction::storage_type;
    return static_cast<st>(x) != static_cast<st>(y);
}
```

23.1.4.28 operator<<() [1/2]

```
std::ostream& gko::operator<< (
            std::ostream & os,
            const version & ver ) [inline]
```

Prints version information to a stream.

Parameters

os	output stream
ver	version structure

Returns

os

References gko::version::major, gko::version::minor, gko::version::patch, and gko::version::tag.

```
{
    os << ver.major << "." << ver.minor << "." << ver.patch;
    if (ver.tag) {
        os << " (" << ver.tag << ")";
    }
    return os;
}
```

23.1.4.29 operator<<() [2/2]

```
std::ostream& gko::operator<< (
            std::ostream & os,
            const version_info & ver_info )
```

Prints library version information in human-readable format to a stream.

Parameters

os	output stream
ver_info	version information

Returns

os

23.1.4.30 operator==() [1/2]

```
bool gko::operator== (
            const stopping_status & x,
            const stopping_status & y )  [inline], [noexcept]
```

Checks if two stopping statuses are equivalent.

Parameters

x	a stopping status
y	a stopping status

Returns

true if and only if both x and y have the same mask and converged and finalized state

```
164 {
165     return x.data_ == y.data_;
166 }
```

23.1.4.31 operator==() [2/2]

```
constexpr bool gko::operator== (
            precision_reduction x,
            precision_reduction y )  [noexcept]
```

Checks if two precision_reduction encodings are equal.

Parameters

x	an encoding
y	an encoding

Returns

true if and only if `x` and `y` are the same encodings

```
{
    using st = precision_reduction::storage_type;
    return static_cast<st>(x) == static_cast<st>(y);
}
```

23.1.4.32 read()

```
template<typename MatrixType , typename StreamType , typename... MatrixArgs>
std::unique_ptr<MatrixType> gko::read (
            StreamType && is,
            MatrixArgs &&... args ) [inline]
```

Reads a matrix stored in matrix market format from an input stream.

Template Parameters

MatrixType	a ReadableFromMatrixData LinOp type used to store the matrix once it's been read from disk.
StreamType	type of stream used to write the data to
MatrixArgs	additional argument types passed to MatrixType constructor

Parameters

is	input stream from which to read the data
args	additional arguments passed to MatrixType constructor

Returns

A MatrixType LinOp filled with data from filename

References read_raw().

```
{
    auto mtx = MatrixType::create(std::forward<MatrixArgs>(args)...);
    mtx->read(read_raw<typename MatrixType::value_type,
                       typename MatrixType::index_type>(is));
    return mtx;
}
```

23.1.4.33 read_raw()

```
template<typename ValueType = default_precision, typename IndexType = int32>
matrix_data<ValueType, IndexType> gko::read_raw (
            std::istream & is )
```

Reads a matrix stored in matrix market format from an input stream.

Template Parameters

ValueType	type of matrix values
IndexType	type of matrix indexes

Parameters

is	input stream from which to read the data

Returns

A matrix_data structure containing the matrix. The nonzero elements are sorted in lexicographic order of their (row, colum) indexes.

Note

This is an advanced routine that will return the raw matrix data structure. Consider using gko::read instead.

Referenced by read().

23.1.4.34 real()

```
template<typename T >
constexpr T gko::real (
            const T & x ) [inline]
```

Returns the real part of the object.

Template Parameters

T	type of the object

Parameters

x	the object

Returns

real part of the object (by default, the object itself)

Referenced by squared_norm().

```
{
    return x;
}
```

23.1.4.35 round_down()

```
template<typename T >
constexpr reduce_precision<T> gko::round_down (
            T val )  [inline]
```

Reduces the precision of the input parameter.

Template Parameters

T	the original precision

Parameters

val	the value to round down

Returns

the rounded down value

```
{
    return static_cast<reduce_precision<T>>(val);
}
```

23.1.4.36 round_up()

```
template<typename T >
constexpr increase_precision<T> gko::round_up (
            T val )  [inline]
```

Increases the precision of the input parameter.

Template Parameters

T	the original precision

Parameters

val	the value to round up

Returns

the rounded up value

References byte_size.

```
{
    return static_cast<increase_precision<T>>(val);
}
```

23.1.4.37 share()

```
template<typename OwningPointer >
detail::shared_type<OwningPointer> gko::share (
            OwningPointer && p ) [inline]
```

Marks the object pointed to by `p` as shared.

Effectively converts a pointer with ownership to std::shared_ptr.

Template Parameters

OwningPointer	type of pointer with ownership to the object (has to be a smart pointer)

Parameters

p	a pointer to the object

Note

The original pointer `p` becomes invalid after this call.

```
{
    static_assert(detail::have_ownership<OwningPointer>(),
                  "OwningPointer does not have ownership of the object");
    return detail::shared_type<OwningPointer>(std::move(p));
}
```

23.1.4.38 squared_norm()

```
template<typename T >
constexpr auto gko::squared_norm (
            const T & x ) -> decltype(real(conj(x) * x)) [inline]
```

Returns the squared norm of the object.

Template Parameters

T	type of the object.

Returns

The squared norm of the object.

References conj(), and real().

```
{
    return real(conj(x) * x);
}
```

23.1.4.39 transpose()

```
template<typename DimensionType >
constexpr dim<2, DimensionType> gko::transpose (
            const dim< 2, DimensionType > & dimensions )  [inline], [noexcept]
```

Returns a dim<2> object with its dimensions swapped.

Template Parameters

DimensionType	datatype used to represent each dimension

Parameters

dimensions	original object

Returns

a dim<2> object with its dimensions swapped

Referenced by gko::matrix_data< ValueType, IndexType >::ensure_row_major_order(), gko::solver::Gmres< ValueType >::get_krylov_dim(), gko::preconditioner::Jacobi< ValueType, IndexType >::get_num_stored_elements(), gko::solver::Cgs< ValueType >::get_preconditioner(), gko::solver::Cg< ValueType >::get_preconditioner(), gko::solver::Bicgstab< ValueType >::get_preconditioner(), gko::solver::Fcg< ValueType >::get_preconditioner(), gko::solver::UpperTrs< ValueType, IndexType >::get_preconditioner(), gko::solver::LowerTrs< ValueType, IndexType >::get_preconditioner(), and gko::solver::Ir< ValueType >::get_solver().

```
{
    return {dimensions[1], dimensions[0]};
}
```

23.1.4.40 write()

```
template<typename MatrixType , typename StreamType >
void gko::write (
            StreamType && os,
            MatrixType * matrix,
            layout_type layout = layout_type::array ) [inline]
```

Reads a matrix stored in matrix market format from an input stream.

Template Parameters

MatrixType	a ReadableFromMatrixData LinOp type used to store the matrix once it's been read from disk.
StreamType	type of stream used to write the data to

Parameters

os	output stream where the data is to be written
matrix	the matrix to write
layout	the layout used in the output

References write_raw().

Referenced by gko::preconditioner::Jacobi< ValueType, IndexType >::get_num_stored_elements().

```
{
    matrix_data<typename MatrixType::value_type,
                typename MatrixType::index_type>
        data{};
    matrix->write(data);
    write_raw(os, data, layout);
}
```

23.1.4.41 write_raw()

```
template<typename ValueType , typename IndexType >
void gko::write_raw (
            std::ostream & os,
            const matrix_data< ValueType, IndexType > & data,
            layout_type layout = layout_type::array )
```

Writes a matrix_data structure to a stream in matrix market format.

Template Parameters

ValueType	type of matrix values
IndexType	type of matrix indexes

Parameters

os	output stream where the data is to be written
data	the matrix data to write
layout	the layout used in the output

Note

This is an advanced routine that writes the raw matrix data structure. If you are trying to write an existing matrix, consider using gko::write instead.

Referenced by write().

23.1.4.42 zero() [1/2]

```
template<typename T >
constexpr T gko::zero ( ) [inline]
```

Returns the additive identity for T.

Returns

additive identity for T

Referenced by gko::matrix_data< ValueType, IndexType >::ensure_row_major_order(), and gko::Combination< ValueType >::get_operators().

```
{
    return T(0);
}
```

23.1.4.43 zero() [2/2]

```
template<typename T >
constexpr T gko::zero (
            const T & ) [inline]
```

Returns the additive identity for T.

Returns

additive identity for T

Note

This version takes an unused reference argument to avoid complicated calls like `zero<decltype(x)>()`. Instead, it allows `zero(x)`.

```
{
    return zero<T>();
}
```

23.2 gko::accessor Namespace Reference

The accessor namespace.

Classes

- class row_major

    A row_major accessor is a bridge between a range and the row-major memory layout.

23.2.1 Detailed Description

The accessor namespace.

23.3 gko::factorization Namespace Reference

The Factorization namespace.

Classes

- class ParIlu

    ParILU is an incomplete LU factorization which is computed in parallel.

23.3.1 Detailed Description

The Factorization namespace.

23.4 gko::log Namespace Reference

The logger namespace .

Classes

- class Convergence

  Convergence is a Logger which logs data strictly from the `criterion_check_completed` event.
- struct criterion_data

  Struct representing Criterion related data.
- class EnableLogging

  EnableLogging is a mixin which should be inherited by any class which wants to enable logging.
- struct executor_data

  Struct representing Executor related data.
- struct iteration_complete_data

  Struct representing iteration complete related data.
- struct linop_data

  Struct representing LinOp related data.
- struct linop_factory_data

  Struct representing LinOp factory related data.
- class Loggable

  Loggable class is an interface which should be implemented by classes wanting to support logging.
- struct operation_data

  Struct representing Operator related data.
- struct polymorphic_object_data

  Struct representing PolymorphicObject related data.
- class Record

  Record is a Logger which logs every event to an object.
- class Stream

  Stream is a Logger which logs every event to a stream.

23.4.1 Detailed Description

The logger namespace .

The Logging namespace.

Logging

23.5 gko::matrix Namespace Reference

The matrix namespace.

Classes

- class Coo

  COO stores a matrix in the coordinate matrix format.
- class Csr

  CSR is a matrix format which stores only the nonzero coefficients by compressing each row of the matrix (compressed sparse row format).
- class Dense

  Dense is a matrix format which explicitly stores all values of the matrix.
- class Ell

  ELL is a matrix format where stride with explicit zeros is used such that all rows have the same number of stored elements.
- class Hybrid

  HYBRID is a matrix format which splits the matrix into ELLPACK and COO format.
- class Identity

  This class is a utility which efficiently implements the identity matrix (a linear operator which maps each vector to itself).
- class IdentityFactory

  This factory is a utility which can be used to generate Identity operators.
- class Sellp

  SELL-P is a matrix format similar to ELL format.

23.5.1 Detailed Description

The matrix namespace.

23.6 gko::name_demangling Namespace Reference

The name demangling namespace.

Functions

- template<typename T >
  std::string get_static_type (const T &)

  This function uses name demangling facilities to get the name of the static type (`T`) of the object passed in arguments.
- template<typename T >
  std::string get_dynamic_type (const T &t)

  This function uses name demangling facilities to get the name of the dynamic type of the object passed in arguments.

23.6.1 Detailed Description

The name demangling namespace.

23.6.2 Function Documentation

23.6.2.1 get_dynamic_type()

```
template<typename T >
std::string gko::name_demangling::get_dynamic_type (
            const T & t )
```

This function uses name demangling facilities to get the name of the dynamic type of the object passed in arguments.

Template Parameters

T	the type of the object to demangle

Parameters

t	the object we get the dynamic type of

```
{
    return get_type_name(typeid(t));
}
```

23.6.2.2 get_static_type()

```
template<typename T >
std::string gko::name_demangling::get_static_type (
            const T & )
```

This function uses name demangling facilities to get the name of the static type (`T`) of the object passed in arguments.

Template Parameters

T	the type of the object to demangle

Parameters

unused	

```
{
    return get_type_name(typeid(T));
}
```

23.7 gko::preconditioner Namespace Reference

The Preconditioner namespace.

Classes

- struct block_interleaved_storage_scheme

  Defines the parameters of the interleaved block storage scheme used by block-Jacobi blocks.
- class Ilu

  The Incomplete LU (ILU) preconditioner solves the equation $LUx = b$ for a given lower triangular matrix L, an upper triangular matrix U and the right hand side b (can contain multiple right hand sides).
- class Jacobi

  A block-Jacobi preconditioner is a block-diagonal linear operator, obtained by inverting the diagonal blocks of the source operator.

23.7.1 Detailed Description

The Preconditioner namespace.

23.8 gko::solver Namespace Reference

The ginkgo Solve namespace.

Classes

- class Bicgstab

    BiCGSTAB or the Bi-Conjugate Gradient-Stabilized is a Krylov subspace solver.
- class Cg

    CG or the conjugate gradient method is an iterative type Krylov subspace method which is suitable for symmetric positive definite methods.
- class Cgs

    CGS or the conjugate gradient square method is an iterative type Krylov subspace method which is suitable for general systems.
- class Fcg

    FCG or the flexible conjugate gradient method is an iterative type Krylov subspace method which is suitable for symmetric positive definite methods.
- class Gmres

    GMRES or the generalized minimal residual method is an iterative type Krylov subspace method which is suitable for nonsymmetric linear systems.
- class Ir

    Iterative refinement (IR) is an iterative method that uses another coarse method to approximate the error of the current solution via the current residual.
- class LowerTrs

    LowerTrs is the triangular solver which solves the system L x = b, when L is a lower triangular matrix.
- class UpperTrs

    UpperTrs is the triangular solver which solves the system U x = b, when U is an upper triangular matrix.

23.8.1 Detailed Description

The ginkgo Solve namespace.

23.9 gko::stop Namespace Reference

The Stopping criterion namespace.

Classes

- class Combined

  The Combined class is used to combine multiple criterions together through an OR operation.
- class Criterion

  The Criterion class is a base class for all stopping criteria.
- struct CriterionArgs

  This struct is used to pass parameters to the EnableDefaultCriterionFactoryCriterionFactory::generate() method.
- class Iteration

  The Iteration class is a stopping criterion which stops the iteration process after a preset number of iterations.
- class ResidualNormReduction

  The ResidualNormReduction class is a stopping criterion which stops the iteration process when the relative residual norm is below a certain threshold.
- class Time

  The Time class is a stopping criterion which stops the iteration process after a certain amout of time has passed.

Typedefs

- using CriterionFactory = AbstractFactory< Criterion, CriterionArgs >

  Declares an Abstract Factory specialized for Criterions.
- template<typename ConcreteFactory , typename ConcreteCriterion , typename ParametersType , typename PolymorphicBase = CriterionFactory>
  using EnableDefaultCriterionFactory = EnableDefaultFactory< ConcreteFactory, ConcreteCriterion, ParametersType, PolymorphicBase >

  This is an alias for the EnableDefaultFactory mixin, which correctly sets the template parameters to enable a subclass of CriterionFactory.

Functions

- template<typename FactoryContainer >
  std::shared_ptr< const CriterionFactory > combine (FactoryContainer &&factories)

  Combines multiple criterion factories into a single combined criterion factory.

23.9.1 Detailed Description

The Stopping criterion namespace.

Stopping criteria

23.9.2 Typedef Documentation

23.9.2.1 EnableDefaultCriterionFactory

```
template<typename ConcreteFactory , typename ConcreteCriterion , typename ParametersType ,
typename PolymorphicBase = CriterionFactory>
using gko::stop::EnableDefaultCriterionFactory = typedef EnableDefaultFactory<ConcreteFactory,
ConcreteCriterion, ParametersType, PolymorphicBase>
```

This is an alias for the EnableDefaultFactory mixin, which correctly sets the template parameters to enable a subclass of CriterionFactory.

Template Parameters

ConcreteFactory	the concrete factory which is being implemented [CRTP parmeter]
ConcreteCriterion	the concrete Criterion type which this factory produces, needs to have a constructor which takes a const ConcreteFactory $*$, and a const CriterionArgs $*$ as parameters.
ParametersType	a subclass of enable_parameters_type template which defines all of the parameters of the factory
PolymorphicBase	parent of ConcreteFactory in the polymorphic hierarchy, has to be a subclass of CriterionFactory

23.10 gko::syn Namespace Reference

The Synthesizer namespace.

23.10.1 Detailed Description

The Synthesizer namespace.

23.11 gko::xstd Namespace Reference

The namespace for functionalities after C++11 standard.

23.11.1 Detailed Description

The namespace for functionalities after C++11 standard.

Chapter 24

Class Documentation

24.1 gko::AbstractFactory< AbstractProductType, ComponentsType > Class Template Reference

The AbstractFactory is a generic interface template that enables easy implementation of the abstract factory design pattern.

```
#include <ginkgo/core/base/abstract_factory.hpp>
```

Public Member Functions

- template<typename... Args>
  std::unique_ptr< AbstractProductType > generate (Args &&... args) const

  Creates a new product from the given components.

24.1.1 Detailed Description

template<typename AbstractProductType, typename ComponentsType>
class gko::AbstractFactory< AbstractProductType, ComponentsType >

The AbstractFactory is a generic interface template that enables easy implementation of the abstract factory design pattern.

The interface provides the AbstractFactory::generate() method that can produce products of type `AbstractProductType` using an object of `ComponentsType` (which can be constructed on the fly from parameters to its constructors). The generate() method is not declared as virtual, as this allows subclasses to hide the method with a variant that preserves the compile-time type of the objects. Instead, implementers should override the generate_impl() method, which is declared virtual.

Implementers of concrete factories should consider using the EnableDefaultFactory mixin to obtain default implementations of utility methods of PolymorphicObject and AbstractFactory.

Template Parameters

AbstractProductType	the type of products the factory produces
ComponentsType	the type of components the factory needs to produce the product

24.1.2 Member Function Documentation

24.1.2.1 generate()

```
template<typename AbstractProductType, typename ComponentsType>
template<typename... Args>
std::unique_ptr<AbstractProductType> gko::AbstractFactory< AbstractProductType, ComponentsType >::generate (
            Args &&... args ) const [inline]
```

Creates a new product from the given components.

The method will create an ComponentsType object from the arguments of this method, and pass it to the generate_impl() function which will create a new AbstractProductType.

Template Parameters

Args	types of arguments passed to the constructor of ComponentsType

Parameters

args	arguments passed to the constructor of ComponentsType

Returns

an instance of AbstractProductType

```
{
    auto product = this->generate_impl({std::forward<Args>(args)...});
    for (auto logger : this->loggers_) {
        product->add_logger(logger);
    }
    return product;
}
```

The documentation for this class was generated from the following file:

- ginkgo/core/base/abstract_factory.hpp (8045ac75)

24.2 gko::AllocationError Class Reference

AllocationError is thrown if a memory allocation fails.

```
#include <ginkgo/core/base/exception.hpp>
```

Public Member Functions

- AllocationError (const std::string &file, int line, const std::string &device, size_type bytes)

  Initializes an allocation error.

24.2.1 Detailed Description

AllocationError is thrown if a memory allocation fails.

24.2.2 Constructor & Destructor Documentation

24.2.2.1 AllocationError()

```
gko::AllocationError::AllocationError (
            const std::string & file,
            int line,
            const std::string & device,
            size_type bytes )  [inline]
```

Initializes an allocation error.

Parameters

file	The name of the offending source file
line	The source code line number where the error occurred
device	The device on which the error occurred
bytes	The size of the memory block whose allocation failed.

```
        : Error(file, line,
                device + ": failed to allocate memory block of " +
                    std::to_string(bytes) + "B")
    {}
```

The documentation for this class was generated from the following file:

- ginkgo/core/base/exception.hpp (8fbad33a)

24.3 gko::Array< ValueType > Class Template Reference

An Array is a container which encapsulates fixed-sized arrays, stored on the Executor tied to the Array.

```
#include <ginkgo/core/base/array.hpp>
```

Public Types

- using value_type = ValueType

  The type of elements stored in the array.
- using default_deleter = executor_deleter< value_type[ ]>

  The default deleter type used by Array.
- using view_deleter = null_deleter< value_type[ ]>

  The deleter type used for views.

Public Member Functions

- Array () noexcept

  Creates an empty Array not tied to any executor.
- Array (std::shared_ptr< const Executor > exec) noexcept

  Creates an empty Array tied to the specified Executor.
- Array (std::shared_ptr< const Executor > exec, size_type num_elems)

  Creates an Array on the specified Executor.
- template<typename DeleterType >
  Array (std::shared_ptr< const Executor > exec, size_type num_elems, value_type ∗data, DeleterType deleter)

  Creates an Array from existing memory.
- Array (std::shared_ptr< const Executor > exec, size_type num_elems, value_type ∗data)

  Creates an Array from existing memory.
- template<typename RandomAccessIterator >
  Array (std::shared_ptr< const Executor > exec, RandomAccessIterator begin, RandomAccessIterator end)

  Creates an array on the specified Executor and initializes it with values.
- template<typename T >
  Array (std::shared_ptr< const Executor > exec, std::initializer_list< T > init_list)

  Creates an array on the specified Executor and initializes it with values.
- Array (std::shared_ptr< const Executor > exec, const Array &other)

  Creates a copy of another array on a different executor.
- Array (const Array &other)

  Creates a copy of another array.
- Array (std::shared_ptr< const Executor > exec, Array &&other)

  Moves another array to a different executor.
- Array (Array &&other)

  Moves another array.
- Array & operator= (const Array &other)

  Copies data from another array.
- Array & operator= (Array &&other)

  Moves data from another array.
- void clear () noexcept

  Deallocates all data used by the Array.
- void resize_and_reset (size_type num_elems)

  Resizes the array so it is able to hold the specified number of elements.
- size_type get_num_elems () const noexcept

  Returns the number of elements in the Array.
- value_type ∗ get_data () noexcept

  Returns a pointer to the block of memory used to store the elements of the Array.
- const value_type ∗ get_const_data () const noexcept

  Returns a constant pointer to the block of memory used to store the elements of the Array.
- std::shared_ptr< const Executor > get_executor () const noexcept

  Returns the Executor associated with the array.
- void set_executor (std::shared_ptr< const Executor > exec)

  Changes the Executor of the Array, moving the allocated data to the new Executor.

Static Public Member Functions

- static Array view (std::shared_ptr< const Executor > exec, size_type num_elems, value_type ∗data)

  Creates an Array from existing memory.

24.3.1 Detailed Description

template<typename ValueType>
class gko::Array< ValueType >

An Array is a container which encapsulates fixed-sized arrays, stored on the Executor tied to the Array.

The array stores and transfers its data as **raw** memory, which means that the constructors of its elements are not called when constructing, copying or moving the Array. Thus, the Array class is most suitable for storing POD types.

Template Parameters

ValueType	the type of elements stored in the array

24.3.2 Constructor & Destructor Documentation

24.3.2.1 Array() [1/11]

```
template<typename ValueType>
gko::Array< ValueType >::Array ( )  [inline], [noexcept]
```

Creates an empty Array not tied to any executor.

An array without an assigned executor can only be empty. Attempts to change its size (e.g. via the resize_and_↩
reset method) will result in an exception. If such an array is used as the right hand side of an assignment or move assignment expression, the data of the target array will be cleared, but its executor will not be modified.

The executor can later be set by using the set_executor method. If an Array with no assigned executor is assigned or moved to, it will inherit the executor of the source Array.

```
        : num_elems_(0),
          data_(nullptr, default_deleter{nullptr}),
          exec_(nullptr)
    {}
```

24.3.2.2 Array() [2/11]

```
template<typename ValueType>
gko::Array< ValueType >::Array (
            std::shared_ptr< const Executor > exec )  [inline], [noexcept]
```

Creates an empty Array tied to the specified Executor.

Parameters

exec	the Executor where the array data is allocated

```
        : num_elems_(0),
          data_(nullptr, default_deleter{exec}),
          exec_(std::move(exec))
    {}
```

24.3.2.3 Array() [3/11]

```
template<typename ValueType>
gko::Array< ValueType >::Array (
            std::shared_ptr< const Executor > exec,
            size_type num_elems )  [inline]
```

Creates an Array on the specified Executor.

Parameters

exec	the Executor where the array data will be allocated
num_elems	the amount of memory (expressed as the number of `value_type` elements) allocated on the Executor

```
        : num_elems_(num_elems),
          data_(nullptr, default_deleter{exec}),
          exec_(std::move(exec))
    {
        if (num_elems > 0) {
            data_.reset(exec_->alloc<value_type>(num_elems));
        }
    }
```

24.3.2.4 Array() [4/11]

```
template<typename ValueType>
template<typename DeleterType >
gko::Array< ValueType >::Array (
            std::shared_ptr< const Executor > exec,
            size_type num_elems,
            value_type * data,
            DeleterType deleter )  [inline]
```

Creates an Array from existing memory.

The memory will be managed by the array, and deallocated using the specified deleter (e.g. use std::default_delete for data allocated with new).

Template Parameters

DeleterType	type of the deleter

Parameters

exec	executor where `data` is located
num_elems	number of elements in `data`
data	chunk of memory used to create the array
deleter	the deleter used to free the memory

See also

Array::view() to create an array that does not deallocate memory
Array(std::shared_ptr<cont Executor>, size_type, value_type*) to deallocate the memory using Executor::free() method

```
        : num_elems_{num_elems}, data_(data, deleter), exec_{exec}
    {}
```

24.3.2.5 Array() [5/11]

```
template<typename ValueType>
gko::Array< ValueType >::Array (
            std::shared_ptr< const Executor > exec,
            size_type num_elems,
            value_type * data ) [inline]
```

Creates an Array from existing memory.

The memory will be managed by the array, and deallocated using the Executor::free method.

Parameters

exec	executor where `data` is located
num_elems	number of elements in `data`
data	chunk of memory used to create the array

```
        : Array(exec, num_elems, data, default_deleter{exec})
    {}
```

24.3.2.6 Array() [6/11]

```
template<typename ValueType>
template<typename RandomAccessIterator >
```

```
gko::Array< ValueType >::Array (
        std::shared_ptr< const Executor > exec,
        RandomAccessIterator begin,
        RandomAccessIterator end ) [inline]
```

Creates an array on the specified Executor and initializes it with values.

Template Parameters

RandomAccessIterator	type of the iterators

Parameters

exec	the Executor where the array data will be allocated
begin	start of range of values
end	end of range of values

```
        : Array(exec)
    {
        Array tmp(exec->get_master(), end - begin);
        int i = 0;
        for (auto it = begin; it != end; ++it, ++i) {
            tmp.data_[i] = *it;
        }
        *this = std::move(tmp);
    }
```

24.3.2.7 Array() [7/11]

```
template<typename ValueType>
template<typename T >
gko::Array< ValueType >::Array (
        std::shared_ptr< const Executor > exec,
        std::initializer_list< T > init_list ) [inline]
```

Creates an array on the specified Executor and initializes it with values.

Template Parameters

T	type of values used to initialize the array (T has to be implicitly convertible to value_type)

Parameters

exec	the Executor where the array data will be allocated
init_list	list of values used to initialize the Array

```
        : Array(exec, begin(init_list), end(init_list))
    {}
```

24.3.2.8 Array() [8/11]

```
template<typename ValueType>
gko::Array< ValueType >::Array (
            std::shared_ptr< const Executor > exec,
            const Array< ValueType > & other ) [inline]
```

Creates a copy of another array on a different executor.

This does not invoke the constructors of the elements, instead they are copied as POD types.

Parameters

exec	the executor where the new array will be created
other	the Array to copy from

```
        : Array(exec)
    {
        *this = other;
    }
```

24.3.2.9 Array() [9/11]

```
template<typename ValueType>
gko::Array< ValueType >::Array (
            const Array< ValueType > & other ) [inline]
```

Creates a copy of another array.

This does not invoke the constructors of the elements, instead they are copied as POD types.

Parameters

other	the Array to copy from

```
: Array(other.get_executor(), other) {}
```

24.3.2.10 Array() [10/11]

```
template<typename ValueType>
gko::Array< ValueType >::Array (
            std::shared_ptr< const Executor > exec,
            Array< ValueType > && other ) [inline]
```

Moves another array to a different executor.

This does not invoke the constructors of the elements, instead they are copied as POD types.

Parameters

exec	the executor where the new array will be moved
other	the Array to move

```
                                                    : Array(exec)
    {
        *this = std::move(other);
    }
```

24.3.2.11 Array() [11/11]

```
template<typename ValueType>
gko::Array< ValueType >::Array (
            Array< ValueType > && other ) [inline]
```

Moves another array.

This does not invoke the constructors of the elements, instead they are copied as POD types.

Parameters

other	the Array to move

```
: Array(other.get_executor(), std::move(other)) {}
```

24.3.3 Member Function Documentation

24.3.3.1 clear()

```
template<typename ValueType>
void gko::Array< ValueType >::clear ( ) [inline], [noexcept]
```

Deallocates all data used by the Array.

The array is left in a valid, but empty state, so the same array can be used to allocate new memory. Calls to Array::get_data() will return a `nullptr`.

```
    {
        num_elems_ = 0;
        data_.reset(nullptr);
    }
```

24.3.3.2 get_const_data()

```
template<typename ValueType>
const value_type* gko::Array< ValueType >::get_const_data ( ) const [inline], [noexcept]
```

Returns a constant pointer to the block of memory used to store the elements of the Array.

Returns

a constant pointer to the block of memory used to store the elements of the Array

Referenced by gko::matrix::Dense< ValueType >::at(), gko::matrix::Sellp< ValueType, IndexType >::get_const_col_idxs(), gko::matrix::Ell< ValueType, IndexType >::get_const_col_idxs(), gko::matrix::Coo< ValueType, IndexType >::get_const_col_idxs(), gko::matrix::Coo< ValueType, IndexType >::get_const_row_idxs(), gko::matrix::Sellp< ValueType, IndexType >::get_const_slice_lengths(), gko::matrix::Sellp< ValueType, IndexType >::get_const_slice_sets(), gko::matrix::Sellp< ValueType, IndexType >::get_const_values(), gko::matrix::Ell< ValueType, IndexType >::get_const_values(), gko::matrix::Coo< ValueType, IndexType >::get_const_values(), gko::matrix::Dense< ValueType >::get_const_values(), gko::matrix::Hybrid< ValueType, IndexType >::strategy_type::get_coo_nnz(), gko::Array< index_type >::operator=(), gko::matrix::Ell< ValueType, IndexType >::val_at(), and gko::matrix::Sellp< ValueType, IndexType >::val_at().

```
406 { return data_.get(); }
```

24.3.3.3 get_data()

```
template<typename ValueType>
value_type* gko::Array< ValueType >::get_data ( ) [inline], [noexcept]
```

Returns a pointer to the block of memory used to store the elements of the Array.

Returns

a pointer to the block of memory used to store the elements of the Array

Referenced by gko::matrix::Dense< ValueType >::at(), gko::matrix::Hybrid< ValueType, IndexType >::imbalance_limit::compute_ell_num_stored_elements_per_row(), gko::matrix::Sellp< ValueType, IndexType >::get_col_idxs(), gko::matrix::Ell< ValueType, IndexType >::get_col_idxs(), gko::matrix::Coo< ValueType, IndexType >::get_col_idxs(), gko::matrix::Coo< ValueType, IndexType >::get_row_idxs(), gko::matrix::Sellp< ValueType, IndexType >::get_slice_lengths(), gko::matrix::Sellp< ValueType, IndexType >::get_slice_sets(), gko::matrix::Sellp< ValueType, IndexType >::get_values(), gko::matrix::Ell< ValueType, IndexType >::get_values(), gko::matrix::Coo< ValueType, IndexType >::get_values(), gko::matrix::Dense< ValueType >::get_values(), gko::Array< index_type >::operator=(), gko::matrix::Ell< ValueType, IndexType >::val_at(), and gko::matrix::Sellp< ValueType, IndexType >::val_at().

```
397 { return data_.get(); }
```

24.3.3.4 get_executor()

```
template<typename ValueType>
std::shared_ptr<const Executor> gko::Array< ValueType >::get_executor ( ) const [inline],
[noexcept]
```

Returns the Executor associated with the array.

Returns

the Executor associated with the array

Referenced by gko::matrix::Hybrid< ValueType, IndexType >::strategy_type::compute_hybrid_config(), and gko::Array< index_type >::operator=().

```
{
    return exec_;
}
```

24.3.3.5 get_num_elems()

```
template<typename ValueType>
size_type gko::Array< ValueType >::get_num_elems ( ) const [inline], [noexcept]
```

Returns the number of elements in the Array.

Returns

the number of elements in the Array

Referenced by gko::matrix::Coo< ValueType, IndexType >::apply2(), gko::matrix::Ell< ValueType, IndexType >::col_at(), gko::matrix::Hybrid< ValueType, IndexType >::imbalance_limit::compute_ell_num_stored_elements_per_row(), gko::matrix::Hybrid< ValueType, IndexType >::imbalance_bounded_limit::compute_ell_num_stored_elements_per_row(), gko::matrix::Hybrid< ValueType, IndexType >::strategy_type::compute_hybrid_config(), gko::matrix::Dense< ValueType >::create_submatrix(), gko::matrix::Hybrid< ValueType, IndexType >::strategy_type::get_coo_nnz(), gko::matrix::Ell< ValueType, IndexType >::get_num_stored_elements(), gko::matrix::Coo< ValueType, IndexType >::get_num_stored_elements(), gko::matrix::Sellp< ValueType, IndexType >::get_num_stored_elements(), gko::matrix::Dense< ValueType >::get_num_stored_elements(), gko::preconditioner::Jacobi< ValueType, IndexType >::get_num_stored_elements(), and gko::Array< index_type >::operator=().

```
{ return num_elems_; }
```

24.3.3.6 operator=() [1/2]

```
template<typename ValueType>
Array& gko::Array< ValueType >::operator= (
            const Array< ValueType > & other ) [inline]
```

Copies data from another array.

This does not invoke the constructors of the elements, instead they are copied as POD types.

The executor of this is preserved. In case this does not have an assigned executor, it will inherit the executor of other.

Parameters

other	the Array to copy from

Returns

this

```
    {
        if (&other == this) {
            return *this;
        }
        if (exec_ == nullptr) {
            exec_ = other.get_executor();
            data_ = data_manager{nullptr, other.data_.get_deleter()};
        }
        if (other.get_executor() == nullptr) {
            this->resize_and_reset(0);
            return *this;
        }
        this->resize_and_reset(other.get_num_elems());
        exec_->copy_from(other.get_executor().get(), num_elems_,
                         other.get_const_data(), this->get_data());
        return *this;
    }
```

24.3.3.7 operator=() [2/2]

```
template<typename ValueType>
Array& gko::Array< ValueType >::operator= (
            Array< ValueType > && other )  [inline]
```

Moves data from another array.

This does not invoke the constructors of the elements, instead they are copied as POD types.

The executor of this is preserved. In case this does not have an assigned executor, it will inherit the executor of other.

Parameters

other	the Array to move data from

Returns

this

```
    {
        if (&other == this) {
            return *this;
        }
        if (exec_ == nullptr) {
            exec_ = other.get_executor();
            data_ = data_manager{nullptr, other.data_.get_deleter()};
        }
        if (other.get_executor() == nullptr) {
            this->resize_and_reset(0);
            return *this;
        }
```

```
        if (exec_ == other.get_executor() &&
            data_.get_deleter().target_type() != typeid(view_deleter)) {
            // same device and not a view, only move the pointer
            using std::swap;
            swap(data_, other.data_);
            swap(num_elems_, other.num_elems_);
        } else {
            // different device or a view, copy the data
            *this = other;
        }
        return *this;
    }
```

24.3.3.8 resize_and_reset()

```
template<typename ValueType>
void gko::Array< ValueType >::resize_and_reset (
            size_type num_elems ) [inline]
```

Resizes the array so it is able to hold the specified number of elements.

All data stored in the array will be lost.

If the Array is not assigned an executor, an exception will be thrown.

Parameters

num_elems	the amount of memory (expressed as the number of `value_type` elements) allocated on the Executor

Referenced by gko::Array< index_type >::operator=().

```
    {
        if (num_elems == num_elems_) {
            return;
        }
        if (exec_ == nullptr) {
            throw gko::NotSupported(__FILE__, __LINE__, __func__,
                                    "gko::Executor (nullptr)");
        }
        num_elems_ = num_elems;
        if (num_elems > 0) {
            data_.reset(exec_->alloc<value_type>(num_elems));
        } else {
            data_.reset(nullptr);
        }
    }
```

24.3.3.9 set_executor()

```
template<typename ValueType>
void gko::Array< ValueType >::set_executor (
            std::shared_ptr< const Executor > exec ) [inline]
```

Changes the Executor of the Array, moving the allocated data to the new Executor.

Parameters

exec	the Executor where the data will be moved to

```
{
    if (exec == exec_) {
        // moving to the same executor, no-op
        return;
    }
    Array tmp(std::move(exec));
    tmp = *this;
    exec_ = std::move(tmp.exec_);
    data_ = std::move(tmp.data_);
}
```

24.3.3.10 view()

```
template<typename ValueType>
static Array gko::Array< ValueType >::view (
            std::shared_ptr< const Executor > exec,
            size_type num_elems,
            value_type * data ) [inline], [static]
```

Creates an Array from existing memory.

The Array does not take ownership of the memory, and will not deallocate it once it goes out of scope.

Parameters

exec	executor where `data` is located
num_elems	number of elements in `data`
data	chunk of memory used to create the array

Returns

an Array constructed from `data`

Referenced by gko::matrix::Dense< ValueType >::create_submatrix().

```
{
    return Array{exec, num_elems, data, view_deleter{}};
}
```

The documentation for this class was generated from the following file:

- ginkgo/core/base/array.hpp (8045ac75)

24.4 gko::matrix::Hybrid< ValueType, IndexType >::automatic Class Reference

automatic is a stratgy_type which decides the number of stored elements per row of the ell part automatically.

`#include <ginkgo/core/matrix/hybrid.hpp>`

Public Member Functions

- automatic ()

  Creates an automatic strategy.
- size_type compute_ell_num_stored_elements_per_row (Array< size_type > ∗row_nnz) const override

  Computes the number of stored elements per row of the ell part.

24.4.1 Detailed Description

template<typename ValueType = default_precision, typename IndexType = int32>
class gko::matrix::Hybrid< ValueType, IndexType >::automatic

automatic is a stratgy_type which decides the number of stored elements per row of the ell part automatically.

24.4.2 Member Function Documentation

24.4.2.1 compute_ell_num_stored_elements_per_row()

```
template<typename ValueType = default_precision, typename IndexType = int32>
size_type gko::matrix::Hybrid< ValueType, IndexType >::automatic::compute_ell_num_stored_↩
elements_per_row (
            Array< size_type > * row_nnz ) const  [inline], [override], [virtual]
```

Computes the number of stored elements per row of the ell part.

Parameters

row_nnz	the number of nonzeros of each row

Returns

the number of stored elements per row of the ell part

Implements gko::matrix::Hybrid< ValueType, IndexType >::strategy_type.

References gko::matrix::Hybrid< ValueType, IndexType >::read(), and gko::matrix::Hybrid< ValueType, IndexType >::write().

```
        {
            return strategy_.compute_ell_num_stored_elements_per_row
    (row_nnz);
        }
```

The documentation for this class was generated from the following file:

- ginkgo/core/matrix/hybrid.hpp (3e51a52b)

24.5 gko::BadDimension Class Reference

BadDimension is thrown if an operation is being applied to a LinOp with bad dimensions.

```
#include <ginkgo/core/base/exception.hpp>
```

Public Member Functions

- BadDimension (const std::string &file, int line, const std::string &func, const std::string &op_name, size_type op_num_rows, size_type op_num_cols, const std::string &clarification)

  Initializes a bad dimension error.

24.5.1 Detailed Description

BadDimension is thrown if an operation is being applied to a LinOp with bad dimensions.

24.5.2 Constructor & Destructor Documentation

24.5.2.1 BadDimension()

```
gko::BadDimension::BadDimension (
            const std::string & file,
            int line,
            const std::string & func,
            const std::string & op_name,
            size_type op_num_rows,
            size_type op_num_cols,
            const std::string & clarification )  [inline]
```

Initializes a bad dimension error.

Parameters

file	The name of the offending source file
line	The source code line number where the error occurred
func	The function name where the error occurred
op_name	The name of the operator
op_num_rows	The row dimension of the operator
op_num_cols	The column dimension of the operator
clarification	An additional message further describing the error

```
        : Error(file, line,
                func + ": Object " + op_name + " has dimensions [" +
                    std::to_string(op_num_rows) + " x " +
                    std::to_string(op_num_cols) + "]: " + clarification)
    {}
```

The documentation for this class was generated from the following file:

- ginkgo/core/base/exception.hpp (8fbad33a)

24.6 gko::solver::Bicgstab< ValueType > Class Template Reference

BiCGSTAB or the Bi-Conjugate Gradient-Stabilized is a Krylov subspace solver.

`#include <ginkgo/core/solver/bicgstab.hpp>`

Public Member Functions

- std::shared_ptr< const LinOp > get_system_matrix () const
  Gets the system operator (matrix) of the linear system.
- std::shared_ptr< const LinOp > get_preconditioner () const override
  Returns the preconditioner operator used by the solver.

24.6.1 Detailed Description

template<typename ValueType = default_precision>
class gko::solver::Bicgstab< ValueType >

BiCGSTAB or the Bi-Conjugate Gradient-Stabilized is a Krylov subspace solver.

Being a generic solver, it is capable of solving general matrices, including non-s.p.d matrices. Though, the memory and the computational requirement of the BiCGSTAB solver are higher than of its s.p.d solver counterpart, it has the capability to solve generic systems. It was developed by stabilizing the BiCG method.

Template Parameters

ValueType	precision of the elements of the system matrix.

24.6.2 Member Function Documentation

24.6.2.1 get_preconditioner()

```
template<typename ValueType = default_precision>
std::shared_ptr<const LinOp> gko::solver::Bicgstab< ValueType >::get_preconditioner ( ) const
[inline], [override], [virtual]
```

Returns the preconditioner operator used by the solver.

Returns

the preconditioner operator used by the solver

Implements gko::Preconditionable.

References gko::stop::combine(), gko::PolymorphicObject::get_executor(), GKO_CREATE_FACTORY_PARAMETERS, GKO_ENABLE_BUILD_METHOD, GKO_ENABLE_LIN_OP_FACTORY, GKO_FACTORY_PARAMETER, and gko::transpose().

```
{
    return preconditioner_;
}
```

24.6.2.2 get_system_matrix()

```
template<typename ValueType = default_precision>
std::shared_ptr<const LinOp> gko::solver::Bicgstab< ValueType >::get_system_matrix ( ) const
[inline]
```

Gets the system operator (matrix) of the linear system.

Returns

the system operator (matrix)

```
{
    return system_matrix_;
}
```

The documentation for this class was generated from the following file:

- ginkgo/core/solver/bicgstab.hpp (f1a4eb68)

24.7 gko::preconditioner::block_interleaved_storage_scheme< IndexType > Struct Template Reference

Defines the parameters of the interleaved block storage scheme used by block-Jacobi blocks.

```
#include <ginkgo/core/preconditioner/jacobi.hpp>
```

Public Member Functions

- IndexType get_group_size () const noexcept
  Returns the number of elements in the group.
- size_type compute_storage_space (size_type num_blocks) const noexcept
  Computes the storage space required for the requested number of blocks.
- IndexType get_group_offset (IndexType block_id) const noexcept
  Returns the offset of the group belonging to the block with the given ID.
- IndexType get_block_offset (IndexType block_id) const noexcept
  Returns the offset of the block with the given ID within its group.
- IndexType get_global_block_offset (IndexType block_id) const noexcept
  Returns the offset of the block with the given ID.
- IndexType get_stride () const noexcept
  Returns the stride between columns of the block.

Public Attributes

- IndexType block_offset

  The offset between consecutive blocks within the group.
- IndexType group_offset

  The offset between two block groups.
- uint32 group_power

  Then base 2 power of the group.

24.7.1 Detailed Description

template<typename IndexType>
struct gko::preconditioner::block_interleaved_storage_scheme< IndexType >

Defines the parameters of the interleaved block storage scheme used by block-Jacobi blocks.

Template Parameters

IndexType	type used for storing indices of the matrix

24.7.2 Member Function Documentation

24.7.2.1 compute_storage_space()

```
template<typename IndexType>
size_type gko::preconditioner::block_interleaved_storage_scheme< IndexType >::compute_storage↩
_space (
            size_type num_blocks ) const  [inline], [noexcept]
```

Computes the storage space required for the requested number of blocks.

Parameters

num_blocks	the total number of blocks that needs to be stored

Returns

the total memory (as the number of elements) that need to be allocated for the scheme

Note

To simplify using the method in situations where the number of blocks is not known, for a special input `size↩_type{} - 1` the method returns `0` to avoid overallocation of memory.

```
{
    return (num_blocks + 1 == size_type{0})
               ? size_type{0}
               : ceildiv(num_blocks, this->get_group_size()) *
group_offset;
}
```

24.7.2.2 get_block_offset()

```
template<typename IndexType>
IndexType gko::preconditioner::block_interleaved_storage_scheme< IndexType >::get_block_offset
(
            IndexType block_id ) const  [inline], [noexcept]
```

Returns the offset of the block with the given ID within its group.

Parameters

block_id	the ID of the block

Returns

the offset of the block with ID `block_id` within its group

Referenced by gko::preconditioner::block_interleaved_storage_scheme< index_type >::get_global_block_offset().

```
{
    return block_offset * (block_id & (this->get_group_size() - 1));
}
```

24.7.2.3 get_global_block_offset()

```
template<typename IndexType>
IndexType gko::preconditioner::block_interleaved_storage_scheme< IndexType >::get_global_block_offset (
            IndexType block_id ) const  [inline], [noexcept]
```

Returns the offset of the block with the given ID.

Parameters

block_id	the ID of the block

Returns

the offset of the block with ID `block_id`

```
{
    return this->get_group_offset(block_id) +
           this->get_block_offset(block_id);
}
```

24.7.2.4 get_group_offset()

```
template<typename IndexType>
IndexType gko::preconditioner::block_interleaved_storage_scheme< IndexType >::get_group_offset
(
            IndexType block_id ) const  [inline], [noexcept]
```

Returns the offset of the group belonging to the block with the given ID.

Parameters

block_id	the ID of the block

Returns

the offset of the group belonging to block with ID `block_id`

Referenced by gko::preconditioner::block_interleaved_storage_scheme< index_type >::get_global_block_offset().

```
{
    return group_offset * (block_id >> group_power);
}
```

24.7.2.5 get_group_size()

```
template<typename IndexType>
IndexType gko::preconditioner::block_interleaved_storage_scheme< IndexType >::get_group_size (
) const  [inline], [noexcept]
```

Returns the number of elements in the group.

Returns

the number of elements in the group

Referenced by gko::preconditioner::block_interleaved_storage_scheme< index_type >::compute_storage_space(), and gko::preconditioner::block_interleaved_storage_scheme< index_type >::get_block_offset().

```
{
    return one<IndexType>() << group_power;
}
```

24.7.2.6 get_stride()

```
template<typename IndexType>
IndexType gko::preconditioner::block_interleaved_storage_scheme< IndexType >::get_stride ( )
const [inline], [noexcept]
```

Returns the stride between columns of the block.

Returns

stride between columns of the block

```
164     {
165         return block_offset << group_power;
166     }
```

24.7.3 Member Data Documentation

24.7.3.1 group_power

```
template<typename IndexType>
uint32 gko::preconditioner::block_interleaved_storage_scheme< IndexType >::group_power
```

Then base 2 power of the group.

I.e. the group contains `1 << group_power` elements.

Referenced by gko::preconditioner::block_interleaved_storage_scheme< index_type >::get_group_offset(), and gko::preconditioner::block_interleaved_storage_scheme< index_type >::get_stride().

The documentation for this struct was generated from the following file:

- ginkgo/core/preconditioner/jacobi.hpp (9c2e5ae6)

24.8 gko::solver::Cg< ValueType > Class Template Reference

CG or the conjugate gradient method is an iterative type Krylov subspace method which is suitable for symmetric positive definite methods.

`#include <ginkgo/core/solver/cg.hpp>`

Public Member Functions

- std::shared_ptr< const LinOp > get_system_matrix () const
  Gets the system operator (matrix) of the linear system.
- std::shared_ptr< const LinOp > get_preconditioner () const override
  Returns the preconditioner operator used by the solver.

24.8.1 Detailed Description

template<typename ValueType = default_precision>
class gko::solver::Cg< ValueType >

CG or the conjugate gradient method is an iterative type Krylov subspace method which is suitable for symmetric positive definite methods.

Though this method performs very well for symmetric positive definite matrices, it is in general not suitable for general matrices.

The implementation in Ginkgo makes use of the merged kernel to make the best use of data locality. The inner operations in one iteration of CG are merged into 2 separate steps.

Template Parameters

ValueType	precision of matrix elements

24.8.2 Member Function Documentation

24.8.2.1 get_preconditioner()

```
template<typename ValueType = default_precision>
std::shared_ptr<const LinOp> gko::solver::Cg< ValueType >::get_preconditioner ( ) const [inline],
[override], [virtual]
```

Returns the preconditioner operator used by the solver.

Returns

the preconditioner operator used by the solver

Implements gko::Preconditionable.

References gko::stop::combine(), gko::PolymorphicObject::get_executor(), GKO_CREATE_FACTORY_PARAM←ETERS, GKO_ENABLE_BUILD_METHOD, GKO_ENABLE_LIN_OP_FACTORY, GKO_FACTORY_PARAMETER, and gko::transpose().

```
{
    return preconditioner_;
}
```

24.8.2.2 get_system_matrix()

```
template<typename ValueType = default_precision>
std::shared_ptr<const LinOp> gko::solver::Cg< ValueType >::get_system_matrix ( ) const  [inline]
```

Gets the system operator (matrix) of the linear system.

Returns

the system operator (matrix)

```
{
    return system_matrix_;
}
```

The documentation for this class was generated from the following file:

- ginkgo/core/solver/cg.hpp (f1a4eb68)

24.9 gko::solver::Cgs< ValueType > Class Template Reference

CGS or the conjugate gradient square method is an iterative type Krylov subspace method which is suitable for general systems.

```
#include <ginkgo/core/solver/cgs.hpp>
```

Public Member Functions

- std::shared_ptr< const LinOp > get_system_matrix () const
  Gets the system operator (matrix) of the linear system.
- std::shared_ptr< const LinOp > get_preconditioner () const override
  Returns the preconditioner operator used by the solver.

24.9.1 Detailed Description

template<typename ValueType = default_precision>
class gko::solver::Cgs< ValueType >

CGS or the conjugate gradient square method is an iterative type Krylov subspace method which is suitable for general systems.

The implementation in Ginkgo makes use of the merged kernel to make the best use of data locality. The inner operations in one iteration of CGS are merged into 3 separate steps.

Template Parameters

ValueType	precision of matrix elements

24.9.2 Member Function Documentation

24.9.2.1 get_preconditioner()

```
template<typename ValueType = default_precision>
std::shared_ptr<const LinOp> gko::solver::Cgs< ValueType >::get_preconditioner ( ) const
[inline], [override], [virtual]
```

Returns the preconditioner operator used by the solver.

Returns

the preconditioner operator used by the solver

Implements gko::Preconditionable.

References gko::stop::combine(), gko::PolymorphicObject::get_executor(), GKO_CREATE_FACTORY_PARAMETERS, GKO_ENABLE_BUILD_METHOD, GKO_ENABLE_LIN_OP_FACTORY, GKO_FACTORY_PARAMETER, and gko::transpose().

```
91     {
92         return preconditioner_;
93     }
```

24.9.2.2 get_system_matrix()

```
template<typename ValueType = default_precision>
std::shared_ptr<const LinOp> gko::solver::Cgs< ValueType >::get_system_matrix ( ) const  [inline]
```

Gets the system operator (matrix) of the linear system.

Returns

the system operator (matrix)

```
81     {
82         return system_matrix_;
83     }
```

The documentation for this class was generated from the following file:

- ginkgo/core/solver/cgs.hpp (f1a4eb68)

24.10 gko::matrix::Hybrid< ValueType, IndexType >::column_limit Class Reference

column_limit is a strategy_type which decides the number of stored elements per row of the ell part by specifying the number of columns.

```
#include <ginkgo/core/matrix/hybrid.hpp>
```

Public Member Functions

- column_limit (size_type num_column=0)

  Creates a column_limit strategy.
- size_type compute_ell_num_stored_elements_per_row (Array< size_type > ∗row_nnz) const override

  Computes the number of stored elements per row of the ell part.

24.10.1 Detailed Description

template<typename ValueType = default_precision, typename IndexType = int32>
class gko::matrix::Hybrid< ValueType, IndexType >::column_limit

column_limit is a strategy_type which decides the number of stored elements per row of the ell part by specifying the number of columns.

24.10.2 Constructor & Destructor Documentation

24.10.2.1 column_limit()

```
template<typename ValueType = default_precision, typename IndexType = int32>
gko::matrix::Hybrid< ValueType, IndexType >::column_limit::column_limit (
            size_type num_column = 0 )  [inline], [explicit]
```

Creates a column_limit strategy.

Parameters

num_column	the specified number of columns of the ell part

```
203             : num_columns_(num_column)
204         {}
```

24.10.3 Member Function Documentation

24.10.3.1 compute_ell_num_stored_elements_per_row()

```
template<typename ValueType = default_precision, typename IndexType = int32>
size_type gko::matrix::Hybrid< ValueType, IndexType >::column_limit::compute_ell_num_stored_↩
elements_per_row (
            Array< size_type > * row_nnz ) const  [inline], [override], [virtual]
```

Computes the number of stored elements per row of the ell part.

Parameters

row_nnz	the number of nonzeros of each row

Returns

the number of stored elements per row of the ell part

Implements gko::matrix::Hybrid< ValueType, IndexType >::strategy_type.

```
        {
            return num_columns_;
        }
```

The documentation for this class was generated from the following file:

- ginkgo/core/matrix/hybrid.hpp (3e51a52b)

24.11 gko::Combination< ValueType > Class Template Reference

The Combination class can be used to construct a linear combination of multiple linear operators ‘c1 ∗ op1 + c2 ∗ op2 + ...

```
#include <ginkgo/core/base/combination.hpp>
```

Public Member Functions

- const std::vector< std::shared_ptr< const LinOp > > & get_coefficients () const noexcept
    Returns a list of coefficients of the combination.
- const std::vector< std::shared_ptr< const LinOp > > & get_operators () const noexcept
    Returns a list of operators of the combination.

24.11.1 Detailed Description

template<typename ValueType = default_precision>
class gko::Combination< ValueType >

The Combination class can be used to construct a linear combination of multiple linear operators ‘c1 ∗ op1 + c2 ∗ op2 + ...

- ck ∗ opk‘.

Template Parameters

ValueType	precision of input and result vectors

24.11.2 Member Function Documentation

24.11.2.1 get_coefficients()

```
template<typename ValueType = default_precision>
const std::vector<std::shared_ptr<const LinOp> >& gko::Combination< ValueType >::get_↩
coefficients ( ) const [inline], [noexcept]
```

Returns a list of coefficients of the combination.

Returns

a list of coefficients

```
{
    return coefficients_;
}
```

24.11.2.2 get_operators()

```
template<typename ValueType = default_precision>
const std::vector<std::shared_ptr<const LinOp> >& gko::Combination< ValueType >::get_↩
operators ( ) const [inline], [noexcept]
```

Returns a list of operators of the combination.

Returns

a list of operators

References gko::one(), and gko::zero().

```
{
    return operators_;
}
```

The documentation for this class was generated from the following file:

- ginkgo/core/base/combination.hpp (f9f0549a)

24.12 gko::stop::Combined Class Reference

The Combined class is used to combine multiple criterions together through an OR operation.

`#include <ginkgo/core/stop/combined.hpp>`

24.12.1 Detailed Description

The Combined class is used to combine multiple criterions together through an OR operation.

The typical use case is to stop the iteration process if any of the criteria is fulfilled, e.g. a number of iterations, the relative residual norm has reached a threshold, etc.

The documentation for this class was generated from the following file:

- ginkgo/core/stop/combined.hpp (f1a4eb68)

24.13 gko::Composition< ValueType > Class Template Reference

The Composition class can be used to compose linear operators `op1, op2, ..., opn` and obtain the operator 'op1 * op2 * ...

`#include <ginkgo/core/base/composition.hpp>`

Public Member Functions

- const std::vector< std::shared_ptr< const LinOp > > & get_operators () const noexcept

  Returns a list of operators of the composition.

24.13.1 Detailed Description

template<typename ValueType = default_precision>
class gko::Composition< ValueType >

The Composition class can be used to compose linear operators `op1, op2, ..., opn` and obtain the operator 'op1 * op2 * ...

- opn'.

Template Parameters

ValueType	precision of input and result vectors

24.13.2 Member Function Documentation

24.13.2.1 get_operators()

```
template<typename ValueType = default_precision>
const std::vector<std::shared_ptr<const LinOp> >& gko::Composition< ValueType >::get_↩
operators ( ) const  [inline], [noexcept]
```

Returns a list of operators of the composition.

Returns

a list of operators

```
{
    return operators_;
}
```

The documentation for this class was generated from the following file:

- ginkgo/core/base/composition.hpp (f9f0549a)

24.14 gko::log::Convergence< ValueType > Class Template Reference

Convergence is a Logger which logs data strictly from the `criterion_check_completed` event.

`#include <ginkgo/core/log/convergence.hpp>`

Public Member Functions

- const size_type & get_num_iterations () const noexcept
  Returns the number of iterations.
- const LinOp ∗ get_residual () const noexcept
  Returns the residual.
- const LinOp ∗ get_residual_norm () const noexcept
  Returns the residual norm.

Static Public Member Functions

- static std::unique_ptr< Convergence > create (std::shared_ptr< const Executor > exec, const mask_type &enabled_events=Logger::all_events_mask)
  Creates a convergence logger.

24.14.1 Detailed Description

template<typename ValueType = default_precision>
class gko::log::Convergence< ValueType >

Convergence is a Logger which logs data strictly from the `criterion_check_completed` event.

The purpose of this logger is to give a simple access to standard data generated by the solver once it has converged with minimal overhead.

This logger also computes the residual norm from the residual when the residual norm was not available. This can add some slight overhead.

24.14.2 Member Function Documentation

24.14.2.1 create()

```
template<typename ValueType = default_precision>
static std::unique_ptr<Convergence> gko::log::Convergence< ValueType >::create (
            std::shared_ptr< const Executor > exec,
            const mask_type & enabled_events = Logger::all_events_mask )  [inline], [static]
```

Creates a convergence logger.

This dynamically allocates the memory, constructs the object and returns an std::unique_ptr to this object.

Parameters

exec	the executor
enabled_events	the events enabled for this logger. By default all events.

Returns

an std::unique_ptr to the the constructed object

```
94     {
95         return std::unique_ptr<Convergence>(
96             new Convergence(exec, enabled_events));
97     }
```

24.14.2.2 get_num_iterations()

```
template<typename ValueType = default_precision>
const size_type& gko::log::Convergence< ValueType >::get_num_iterations ( ) const  [inline],
[noexcept]
```

Returns the number of iterations.

Returns

the number of iterations

```
{
    return num_iterations_;
}
```

24.14.2.3 get_residual()

```
template<typename ValueType = default_precision>
const LinOp* gko::log::Convergence< ValueType >::get_residual ( ) const  [inline], [noexcept]
```

Returns the residual.

Returns

the residual

```
{ return residual_.get(); }
```

24.14.2.4 get_residual_norm()

```
template<typename ValueType = default_precision>
const LinOp* gko::log::Convergence< ValueType >::get_residual_norm ( ) const  [inline], [noexcept]
```

Returns the residual norm.

Returns

the residual norm

```
{
    return residual_norm_.get();
}
```

The documentation for this class was generated from the following file:

- ginkgo/core/log/convergence.hpp (f1a4eb68)

24.15 gko::ConvertibleTo< ResultType > Class Template Reference

ConvertibleTo interface is used to mark that the implementer can be converted to the object of ResultType.

```
#include <ginkgo/core/base/polymorphic_object.hpp>
```

Public Member Functions

- virtual void convert_to (result_type *result) const =0

  Converts the implementer to an object of type result_type.
- virtual void move_to (result_type *result)=0

  Converts the implementer to an object of type result_type by moving data from this object.

24.15.1 Detailed Description

template<typename ResultType>
class gko::ConvertibleTo< ResultType >

ConvertibleTo interface is used to mark that the implementer can be converted to the object of ResultType.

This interface is used to enable conversions between polymorphic objects. To mark that an object of type `U` can be converted to an object of type `V`, `U` should implement ConvertibleTo<V>. Then, the implementation of `PolymorphicObject::copy_from` automatically generated by `EnablePolymorphicObject` mixin will use RTTI to figure out that `U` implements the interface and convert it using the convert_to / move_to methods of the interface.

As an example, the following function:

```
{c++}
void my_function(const U *u, V *v) {
    v->copy_from(u);
}
```

will convert object `u` to object `v` by checking that `u` can be dynamically casted to `ConvertibleTo\<V\>`, and calling ConvertibleTo<V>::convert_to(V*)' to do the actual conversion.

In case `u` is passed as a unique_ptr, call to `convert_to` will be replaced by a call to `move_to` and trigger move semantics.

Template Parameters

ResultType	the type to which the implementer can be converted to, has to be a subclass of PolymorphicObject

24.15.2 Member Function Documentation

24.15.2.1 convert_to()

```
template<typename ResultType>
virtual void gko::ConvertibleTo< ResultType >::convert_to (
            result_type * result ) const  [pure virtual]
```

Converts the implementer to an object of type result_type.

Parameters

result	the object used to store the result of the conversion

Implemented in gko::EnablePolymorphicAssignment< ConcreteType, ResultType >, gko::EnablePolymorphicAssignment< Dense< ValueType > >, gko::EnablePolymorphicAssignment< UpperTrs< ValueType, IndexType > >, gko::EnablePolymorphicAssignment< Hybrid< ValueType, IndexType > >, gko::EnablePolymorphicAssignment< Identity< ValueType > >, gko::EnablePolymorphicAssignment< ConcreteLinOp >, gko::EnablePolymorphicAssignment< Composition< ValueType > >, gko::EnablePolymorphicAssignment< Bicgstab< ValueType > >, gko::EnablePolymorphicAssignment< LowerTrs< ValueType, IndexType > >, gko::EnablePolymorphicAssignment< Combination< ValueType > >, gko::EnablePolymorphicAssignment< Gmres< ValueType > >, gko::EnablePolymorphicAssignment< Csr< ValueType, IndexType > >, gko::EnablePolymorphicAssignment< Ir< ValueType > >, gko::EnablePolymorphicAssignment< Coo< ValueType, IndexType > >, gko::EnablePolymorphicAssignment< Fcg< ValueType > >, gko::EnablePolymorphicAssignment< Ilu< LSolverType, USolverType, ReverseApply > >, gko::EnablePolymorphicAssignment< ConcreteFactory >, gko::EnablePolymorphicAssignment< Cgs< ValueType > >, gko::EnablePolymorphicAssignment< Ell< ValueType, IndexType > >, gko::EnablePolymorphicAssignment< Jacobi< ValueType, IndexType > >, gko::EnablePolymorphicAssignment< Cg< ValueType > >, gko::EnablePolymorphicAssignment< Sellp< ValueType, IndexType > >, gko::EnablePolymorphicAssignment< Perturbation< ValueType > >, and gko::preconditioner::Jacobi< ValueType, IndexType >.

24.15.2.2 move_to()

```
template<typename ResultType>
virtual void gko::ConvertibleTo< ResultType >::move_to (
            result_type * result )  [pure virtual]
```

Converts the implementer to an object of type result_type by moving data from this object.

This method is used when the implementer is a temporary object, and move semantics can be used.

Parameters

result	the object used to emplace the result of the conversion

Note

ConvertibleTo::move_to can be implemented by simply calling ConvertibleTo::convert_to. However, this operation can often be optimized by exploiting the fact that implementer's data can be moved to the result.

Implemented in gko::EnablePolymorphicAssignment< ConcreteType, ResultType >, gko::EnablePolymorphicAssignment< Dense< ValueType > >, gko::EnablePolymorphicAssignment< UpperTrs< ValueType, IndexType > >, gko::EnablePolymorphicAssignment< Hybrid< ValueType, IndexType > >, gko::EnablePolymorphicAssignment< Identity< ValueType > >, gko::EnablePolymorphicAssignment< ConcreteLinOp >, gko::EnablePolymorphicAssignment< Composition< ValueType > >, gko::EnablePolymorphicAssignment< Bicgstab< ValueType > >, gko::EnablePolymorphicAssignment< LowerTrs< ValueType, IndexType > >, gko::EnablePolymorphicAssignment< Combination< ValueType > >, gko::EnablePolymorphicAssignment< Gmres< ValueType > >, gko::EnablePolymorphicAssignment< Csr< ValueType, IndexType > >, gko::EnablePolymorphicAssignment< Ir< ValueType > >, gko::EnablePolymorphicAssignment< Coo< ValueType, IndexType > >, gko::EnablePolymorphicAssignment< Fcg< ValueType > >, gko::EnablePolymorphicAssignment< Ilu< L←SolverType, USolverType, ReverseApply > >, gko::EnablePolymorphicAssignment< ConcreteFactory >, gko←::EnablePolymorphicAssignment< Cgs< ValueType > >, gko::EnablePolymorphicAssignment< Ell< Value←Type, IndexType > >, gko::EnablePolymorphicAssignment< Jacobi< ValueType, IndexType > >, gko::Enable←PolymorphicAssignment< Cg< ValueType > >, gko::EnablePolymorphicAssignment< Sellp< ValueType, Index←Type > >, gko::EnablePolymorphicAssignment< Perturbation< ValueType > >, and gko::preconditioner::Jacobi< ValueType, IndexType >.

The documentation for this class was generated from the following file:

- ginkgo/core/base/polymorphic_object.hpp (3f08cf0a)

24.16 gko::matrix::Coo< ValueType, IndexType > Class Template Reference

COO stores a matrix in the coordinate matrix format.

`#include <ginkgo/core/matrix/coo.hpp>`

Public Member Functions

- void read (const mat_data &data) override
  Reads a matrix from a matrix_data structure.
- void write (mat_data &data) const override
  Writes a matrix to a matrix_data structure.
- value_type ∗ get_values () noexcept
  Returns the values of the matrix.
- const value_type ∗ get_const_values () const noexcept
  Returns the values of the matrix.
- index_type ∗ get_col_idxs () noexcept
  Returns the column indexes of the matrix.
- const index_type ∗ get_const_col_idxs () const noexcept
  Returns the column indexes of the matrix.
- index_type ∗ get_row_idxs () noexcept
  Returns the row indexes of the matrix.
- const index_type ∗ get_const_row_idxs () const noexcept
- size_type get_num_stored_elements () const noexcept
  Returns the number of elements explicitly stored in the matrix.
- LinOp ∗ apply2 (const LinOp ∗b, LinOp ∗x)
  Applies Coo matrix axpy to a vector (or a sequence of vectors).
- const LinOp ∗ apply2 (const LinOp ∗b, LinOp ∗x) const
- LinOp ∗ apply2 (const LinOp ∗alpha, const LinOp ∗b, LinOp ∗x)
  Performs the operation x = alpha ∗ Coo ∗ b + x.
- const LinOp ∗ apply2 (const LinOp ∗alpha, const LinOp ∗b, LinOp ∗x) const
  Performs the operation x = alpha ∗ Coo ∗ b + x.

24.16.1 Detailed Description

template<typename ValueType = default_precision, typename IndexType = int32>
class gko::matrix::Coo< ValueType, IndexType >

COO stores a matrix in the coordinate matrix format.

The nonzero elements are stored in an array row-wise (but not neccessarily sorted by column index within a row). Two extra arrays contain the row and column indexes of each nonzero element of the matrix.

Template Parameters

ValueType	precision of matrix elements
IndexType	precision of matrix indexes

24.16.2 Member Function Documentation

24.16.2.1 apply2() [1/4]

```
template<typename ValueType = default_precision, typename IndexType = int32>
LinOp* gko::matrix::Coo< ValueType, IndexType >::apply2 (
            const LinOp * b,
            LinOp * x )  [inline]
```

Applies Coo matrix axpy to a vector (or a sequence of vectors).

Performs the operation x = Coo ∗ b + x

Parameters

b	the input vector(s) on which the operator is applied
x	the output vector(s) where the result is stored

Returns

this

References gko::PolymorphicObject::get_executor(), and gko::make_temporary_clone().

```
{
    this->validate_application_parameters(b, x);
    auto exec = this->get_executor();
    this->apply2_impl(make_temporary_clone(exec, b).get(),
                      make_temporary_clone(exec, x).get());
    return this;
}
```

24.16.2.2 apply2() [2/4]

```
template<typename ValueType = default_precision, typename IndexType = int32>
const LinOp* gko::matrix::Coo< ValueType, IndexType >::apply2 (
            const LinOp * b,
            LinOp * x ) const  [inline]
```

References gko::PolymorphicObject::get_executor(), and gko::make_temporary_clone().

```
{
    this->validate_application_parameters(b, x);
    auto exec = this->get_executor();
    this->apply2_impl(make_temporary_clone(exec, b).get(),
                      make_temporary_clone(exec, x).get());
    return this;
}
```

24.16.2.3 apply2() [3/4]

```
template<typename ValueType = default_precision, typename IndexType = int32>
LinOp* gko::matrix::Coo< ValueType, IndexType >::apply2 (
            const LinOp * alpha,
            const LinOp * b,
            LinOp * x ) [inline]
```

Performs the operation x = alpha ∗ Coo ∗ b + x.

Parameters

alpha	scaling of the result of Coo ∗ b
b	vector(s) on which the operator is applied
x	output vector(s)

Returns

this

References gko::PolymorphicObject::get_executor(), and gko::make_temporary_clone().

```
{
    this->validate_application_parameters(b, x);
    GKO_ASSERT_EQUAL_DIMENSIONS(alpha, dim<2>(1, 1));
    auto exec = this->get_executor();
    this->apply2_impl(make_temporary_clone(exec, alpha).get(),
                      make_temporary_clone(exec, b).get(),
                      make_temporary_clone(exec, x).get());
    return this;
}
```

24.16.2.4 apply2() [4/4]

```
template<typename ValueType = default_precision, typename IndexType = int32>
const LinOp* gko::matrix::Coo< ValueType, IndexType >::apply2 (
            const LinOp * alpha,
            const LinOp * b,
            LinOp * x ) const [inline]
```

Performs the operation x = alpha ∗ Coo ∗ b + x.

Parameters

alpha	scaling of the result of Coo ∗ b
b	vector(s) on which the operator is applied
x	output vector(s)

Returns

this

References gko::PolymorphicObject::get_executor(), gko::Array< ValueType >::get_num_elems(), and gko::make_temporary_clone().

```
{
    this->validate_application_parameters(b, x);
    GKO_ASSERT_EQUAL_DIMENSIONS(alpha, dim<2>(1, 1));
    auto exec = this->get_executor();
    this->apply2_impl(make_temporary_clone(exec, alpha).get(),
                      make_temporary_clone(exec, b).get(),
                      make_temporary_clone(exec, x).get());
    return this;
}
```

24.16.2.5 get_col_idxs()

```
template<typename ValueType = default_precision, typename IndexType = int32>
index_type* gko::matrix::Coo< ValueType, IndexType >::get_col_idxs ( )  [inline], [noexcept]
```

Returns the column indexes of the matrix.

Returns

the column indexes of the matrix.

References gko::Array< ValueType >::get_data().

```
{ return col_idxs_.get_data(); }
```

24.16.2.6 get_const_col_idxs()

```
template<typename ValueType = default_precision, typename IndexType = int32>
const index_type* gko::matrix::Coo< ValueType, IndexType >::get_const_col_idxs ( ) const  [inline],
[noexcept]
```

Returns the column indexes of the matrix.

Returns

the column indexes of the matrix.

Note

This is the constant version of the function, which can be significantly more memory efficient than the non-constant version, so always prefer this version.

References gko::Array< ValueType >::get_const_data().

```
{
    return col_idxs_.get_const_data();
}
```

24.16.2.7 get_const_row_idxs()

```
template<typename ValueType = default_precision, typename IndexType = int32>
const index_type* gko::matrix::Coo< ValueType, IndexType >::get_const_row_idxs ( ) const [inline],
[noexcept]
```

Note

This is the constant version of the function, which can be significantly more memory efficient than the non-constant version, so always prefer this version.

References gko::Array< ValueType >::get_const_data().

```
{
    return row_idxs_.get_const_data();
}
```

24.16.2.8 get_const_values()

```
template<typename ValueType = default_precision, typename IndexType = int32>
const value_type* gko::matrix::Coo< ValueType, IndexType >::get_const_values ( ) const [inline],
[noexcept]
```

Returns the values of the matrix.

Returns

the values of the matrix.

Note

This is the constant version of the function, which can be significantly more memory efficient than the non-constant version, so always prefer this version.

References gko::Array< ValueType >::get_const_data().

```
{
    return values_.get_const_data();
}
```

24.16.2.9 get_num_stored_elements()

```
template<typename ValueType = default_precision, typename IndexType = int32>
size_type gko::matrix::Coo< ValueType, IndexType >::get_num_stored_elements ( ) const [inline],
[noexcept]
```

Returns the number of elements explicitly stored in the matrix.

Returns

the number of elements explicitly stored in the matrix

References gko::Array< ValueType >::get_num_elems().

```
{
    return values_.get_num_elems();
}
```

24.16.2.10 get_row_idxs()

```
template<typename ValueType = default_precision, typename IndexType = int32>
index_type* gko::matrix::Coo< ValueType, IndexType >::get_row_idxs ( ) [inline], [noexcept]
```

Returns the row indexes of the matrix.

Returns

the row indexes of the matrix.

References gko::Array< ValueType >::get_data().

```
{ return row_idxs_.get_data(); }
```

24.16.2.11 get_values()

```
template<typename ValueType = default_precision, typename IndexType = int32>
value_type* gko::matrix::Coo< ValueType, IndexType >::get_values ( ) [inline], [noexcept]
```

Returns the values of the matrix.

Returns

the values of the matrix.

References gko::Array< ValueType >::get_data().

```
{ return values_.get_data(); }
```

24.16.2.12 read()

```
template<typename ValueType = default_precision, typename IndexType = int32>
void gko::matrix::Coo< ValueType, IndexType >::read (
            const mat_data & data ) [override], [virtual]
```

Reads a matrix from a matrix_data structure.

Parameters

data	the matrix_data structure

Implements gko::ReadableFromMatrixData< ValueType, IndexType >.

24.16.2.13 write()

```
template<typename ValueType = default_precision, typename IndexType = int32>
void gko::matrix::Coo< ValueType, IndexType >::write (
            mat_data & data ) const  [override], [virtual]
```

Writes a matrix to a matrix_data structure.

Parameters

data	the matrix_data structure

Implements gko::WritableToMatrixData< ValueType, IndexType >.

The documentation for this class was generated from the following file:

- ginkgo/core/matrix/coo.hpp (5545d209)

24.17 gko::copy_back_deleter< T > Class Template Reference

A copy_back_deleter is a type of deleter that copies the data to an internally referenced object before performing the deletion.

`#include <ginkgo/core/base/utils.hpp>`

Public Member Functions

- copy_back_deleter (pointer original)

  Creates a new deleter object.
- void operator() (pointer ptr) const

  Deletes the object.

24.17.1 Detailed Description

template<typename T>
class gko::copy_back_deleter< T >

A copy_back_deleter is a type of deleter that copies the data to an internally referenced object before performing the deletion.

The deleter will use the `copy_from` method to perform the copy, and then delete the passed object using the `delete` keyword. This kind of deleter is useful when temporarily copying an object with the intent of copying it back once it goes out of scope.

There is also a specialization for constant objects that does not perform the copy, since a constant object couldn't have been changed.

Template Parameters

T	the type of object being deleted

24.17.2 Constructor & Destructor Documentation

24.17.2.1 copy_back_deleter()

```
template<typename T >
gko::copy_back_deleter< T >::copy_back_deleter (
            pointer original )  [inline]
```

Creates a new deleter object.

Parameters

original	the origin object where the data will be copied before deletion

```
: original_{original} {}
```

24.17.3 Member Function Documentation

24.17.3.1 operator()()

```
template<typename T >
void gko::copy_back_deleter< T >::operator() (
            pointer ptr ) const  [inline]
```

Deletes the object.

Parameters

ptr	pointer to the object being deleted

```
    {
        original_->copy_from(ptr);
        delete ptr;
    }
```

The documentation for this class was generated from the following file:

- ginkgo/core/base/utils.hpp (4bde4271)

24.18 gko::stop::Criterion Class Reference

The Criterion class is a base class for all stopping criteria.

`#include <ginkgo/core/stop/criterion.hpp>`

Classes

- class Updater

    The Updater class serves for convenient argument passing to the Criterion's check function.

Public Member Functions

- Updater update ()

    Returns the updater object.
- bool check (uint8 stoppingId, bool setFinalized, Array< stopping_status > ∗stop_status, bool ∗one_changed, const Updater &updater)

    This checks whether convergence was reached for a certain criterion.

24.18.1 Detailed Description

The Criterion class is a base class for all stopping criteria.

It contains a factory to instantiate criteria. It is up to each specific stopping criterion to decide what to do with the data that is passed to it.

Note that depending on the criterion, convergence may not have happened after stopping.

24.18.2 Member Function Documentation

24.18.2.1 check()

```
bool gko::stop::Criterion::check (
            uint8 stoppingId,
            bool setFinalized,
            Array< stopping_status > * stop_status,
            bool * one_changed,
            const Updater & updater ) [inline]
```

This checks whether convergence was reached for a certain criterion.

The actual implantation of the criterion goes here.

Parameters

stoppingId	id of the stopping criterion
setFinalized	Controls if the current version should count as finalized or not
stop_status	status of the stopping criterion
one_changed	indicates if one vector's status changed
updater	the Updater object containing all the information

Returns

whether convergence was completely reached

Referenced by gko::stop::Criterion::Updater::check().

```
{
    this->template log<log::Logger::criterion_check_started>(
        this, updater.num_iterations_, updater.residual_,
        updater.residual_norm_, updater.solution_, stoppingId,
        setFinalized);
    auto all_converged = this->check_impl(
        stoppingId, setFinalized, stop_status, one_changed, updater);
    this->template log<log::Logger::criterion_check_completed>(
        this, updater.num_iterations_, updater.residual_,
        updater.residual_norm_, updater.solution_, stoppingId, setFinalized,
        stop_status, *one_changed, all_converged);
    return all_converged;
}
```

24.18.2.2 update()

```
Updater gko::stop::Criterion::update ( ) [inline]
```

Returns the updater object.

Returns

the updater object

```
{ return {this}; }
```

The documentation for this class was generated from the following file:

- ginkgo/core/stop/criterion.hpp (f0a50f96)

24.19 gko::log::criterion_data Struct Reference

Struct representing Criterion related data.

`#include <ginkgo/core/log/record.hpp>`

24.19.1 Detailed Description

Struct representing Criterion related data.

The documentation for this struct was generated from the following file:

- ginkgo/core/log/record.hpp (f0a50f96)

24.20 gko::stop::CriterionArgs Struct Reference

This struct is used to pass parameters to the EnableDefaultCriterionFactoryCriterionFactory::generate() method.

`#include <ginkgo/core/stop/criterion.hpp>`

24.20.1 Detailed Description

This struct is used to pass parameters to the EnableDefaultCriterionFactoryCriterionFactory::generate() method.

It is the ComponentsType of CriterionFactory.

Note

Dependly on the use case, some of these parameters can be `nullptr` as only some stopping criterion require them to be set. An example is the `ResidualNormReduction` which really requires the `initial_residual` to be set.

The documentation for this struct was generated from the following file:

- ginkgo/core/stop/criterion.hpp (f0a50f96)

24.21 gko::matrix::Csr< ValueType, IndexType > Class Template Reference

CSR is a matrix format which stores only the nonzero coefficients by compressing each row of the matrix (compressed sparse row format).

`#include <ginkgo/core/matrix/csr.hpp>`

Public Member Functions

- void read (const mat_data &data) override

  Reads a matrix from a matrix_data structure.
- void write (mat_data &data) const override

  Writes a matrix to a matrix_data structure.
- std::unique_ptr< LinOp > transpose () const override

  Returns a LinOp representing the transpose of the Transposable object.
- std::unique_ptr< LinOp > conj_transpose () const override

  Returns a LinOp representing the conjugate transpose of the Transposable object.
- void sort_by_column_index ()

  Sorts all (value, col_idx) pairs in each row by column index.
- value_type * get_values () noexcept

  Returns the values of the matrix.
- const value_type * get_const_values () const noexcept

  Returns the values of the matrix.
- index_type * get_col_idxs () noexcept

  Returns the column indexes of the matrix.
- const index_type * get_const_col_idxs () const noexcept

  Returns the column indexes of the matrix.
- index_type * get_row_ptrs () noexcept

  Returns the row pointers of the matrix.
- const index_type * get_const_row_ptrs () const noexcept

  Returns the row pointers of the matrix.
- index_type * get_srow () noexcept

  Returns the starting rows.
- const index_type * get_const_srow () const noexcept

  Returns the starting rows.
- size_type get_num_srow_elements () const noexcept

  Returns the number of the srow stored elements (involved warps)
- size_type get_num_stored_elements () const noexcept

  Returns the number of elements explicitly stored in the matrix.
- std::shared_ptr< strategy_type > get_strategy () const noexcept

  Returns the strategy.

24.21.1 Detailed Description

template<typename ValueType = default_precision, typename IndexType = int32>
class gko::matrix::Csr< ValueType, IndexType >

CSR is a matrix format which stores only the nonzero coefficients by compressing each row of the matrix (compressed sparse row format).

The nonzero elements are stored in a 1D array row-wise, and accompanied with a row pointer array which stores the starting index of each row. An additional column index array is used to identify the column of each nonzero element.

Template Parameters

ValueType	precision of matrix elements
IndexType	precision of matrix indexes

24.21.2 Member Function Documentation

24.21.2.1 conj_transpose()

```
template<typename ValueType = default_precision, typename IndexType = int32>
std::unique_ptr<LinOp> gko::matrix::Csr< ValueType, IndexType >::conj_transpose ( ) const
[override], [virtual]
```

Returns a LinOp representing the conjugate transpose of the Transposable object.

Returns

a pointer to the new conjugate transposed object

Implements gko::Transposable.

24.21.2.2 get_col_idxs()

```
template<typename ValueType = default_precision, typename IndexType = int32>
index_type* gko::matrix::Csr< ValueType, IndexType >::get_col_idxs ( ) [inline], [noexcept]
```

Returns the column indexes of the matrix.

Returns

the column indexes of the matrix.

```
{ return col_idxs_.get_data(); }
```

24.21.2.3 get_const_col_idxs()

```
template<typename ValueType = default_precision, typename IndexType = int32>
const index_type* gko::matrix::Csr< ValueType, IndexType >::get_const_col_idxs ( ) const [inline],
[noexcept]
```

Returns the column indexes of the matrix.

Returns

the column indexes of the matrix.

Note

This is the constant version of the function, which can be significantly more memory efficient than the non-constant version, so always prefer this version.

```
{
    return col_idxs_.get_const_data();
}
```

24.21.2.4 get_const_row_ptrs()

```
template<typename ValueType = default_precision, typename IndexType = int32>
const index_type* gko::matrix::Csr< ValueType, IndexType >::get_const_row_ptrs ( ) const [inline],
[noexcept]
```

Returns the row pointers of the matrix.

Returns

the row pointers of the matrix.

Note

This is the constant version of the function, which can be significantly more memory efficient than the non-constant version, so always prefer this version.

```
{
    return row_ptrs_.get_const_data();
}
```

24.21.2.5 get_const_srow()

```
template<typename ValueType = default_precision, typename IndexType = int32>
const index_type* gko::matrix::Csr< ValueType, IndexType >::get_const_srow ( ) const [inline],
[noexcept]
```

Returns the starting rows.

Returns

the starting rows.

Note

This is the constant version of the function, which can be significantly more memory efficient than the non-constant version, so always prefer this version.

```
{
    return srow_.get_const_data();
}
```

24.21.2.6 get_const_values()

```
template<typename ValueType = default_precision, typename IndexType = int32>
const value_type* gko::matrix::Csr< ValueType, IndexType >::get_const_values ( ) const [inline],
[noexcept]
```

Returns the values of the matrix.

Returns

the values of the matrix.

Note

This is the constant version of the function, which can be significantly more memory efficient than the non-constant version, so always prefer this version.

```
{
    return values_.get_const_data();
}
```

24.21.2.7 get_num_srow_elements()

```
template<typename ValueType = default_precision, typename IndexType = int32>
size_type gko::matrix::Csr< ValueType, IndexType >::get_num_srow_elements ( ) const [inline],
[noexcept]
```

Returns the number of the srow stored elements (involved warps)

Returns

the number of the srow stored elements (involved warps)

```
{
    return srow_.get_num_elems();
}
```

24.21.2.8 get_num_stored_elements()

```
template<typename ValueType = default_precision, typename IndexType = int32>
size_type gko::matrix::Csr< ValueType, IndexType >::get_num_stored_elements ( ) const [inline],
[noexcept]
```

Returns the number of elements explicitly stored in the matrix.

Returns

the number of elements explicitly stored in the matrix

```
{
    return values_.get_num_elems();
}
```

24.21.2.9 get_row_ptrs()

```
template<typename ValueType = default_precision, typename IndexType = int32>
index_type* gko::matrix::Csr< ValueType, IndexType >::get_row_ptrs ( ) [inline], [noexcept]
```

Returns the row pointers of the matrix.

Returns

the row pointers of the matrix.

```
366 { return row_ptrs_.get_data(); }
```

24.21.2.10 get_srow()

```
template<typename ValueType = default_precision, typename IndexType = int32>
index_type* gko::matrix::Csr< ValueType, IndexType >::get_srow ( ) [inline], [noexcept]
```

Returns the starting rows.

Returns

the starting rows.

```
385 { return srow_.get_data(); }
```

24.21.2.11 get_strategy()

```
template<typename ValueType = default_precision, typename IndexType = int32>
std::shared_ptr<strategy_type> gko::matrix::Csr< ValueType, IndexType >::get_strategy ( )
const [inline], [noexcept]
```

Returns the strategy.

Returns

the strategy

```
424     {
425         return strategy_;
426     }
```

24.21.2.12 get_values()

```
template<typename ValueType = default_precision, typename IndexType = int32>
value_type* gko::matrix::Csr< ValueType, IndexType >::get_values ( )  [inline], [noexcept]
```

Returns the values of the matrix.

Returns

the values of the matrix.

```
328 { return values_.get_data(); }
```

24.21.2.13 read()

```
template<typename ValueType = default_precision, typename IndexType = int32>
void gko::matrix::Csr< ValueType, IndexType >::read (
            const mat_data & data )  [override], [virtual]
```

Reads a matrix from a matrix_data structure.

Parameters

data	the matrix_data structure

Implements gko::ReadableFromMatrixData< ValueType, IndexType >.

24.21.2.14 transpose()

```
template<typename ValueType = default_precision, typename IndexType = int32>
std::unique_ptr<LinOp> gko::matrix::Csr< ValueType, IndexType >::transpose ( ) const  [override],
[virtual]
```

Returns a LinOp representing the transpose of the Transposable object.

Returns

a pointer to the new transposed object

Implements gko::Transposable.

24.21.2.15 write()

```
template<typename ValueType = default_precision, typename IndexType = int32>
void gko::matrix::Csr< ValueType, IndexType >::write (
            mat_data & data ) const  [override], [virtual]
```

Writes a matrix to a matrix_data structure.

Parameters

data	the matrix_data structure

Implements gko::WritableToMatrixData< ValueType, IndexType >.

The documentation for this class was generated from the following files:

- ginkgo/core/matrix/coo.hpp (5545d209)
- ginkgo/core/matrix/csr.hpp (ec6dbb34)

24.22 gko::CublasError Class Reference

CublasError is thrown when a cuBLAS routine throws a non-zero error code.

`#include <ginkgo/core/base/exception.hpp>`

Public Member Functions

- CublasError (const std::string &file, int line, const std::string &func, int64 error_code)
  Initializes a cuBLAS error.

24.22.1 Detailed Description

CublasError is thrown when a cuBLAS routine throws a non-zero error code.

24.22.2 Constructor & Destructor Documentation

24.22.2.1 CublasError()

```
gko::CublasError::CublasError (
            const std::string & file,
            int line,
            const std::string & func,
            int64 error_code )  [inline]
```

Initializes a cuBLAS error.

Parameters

file	The name of the offending source file
line	The source code line number where the error occurred
func	The name of the cuBLAS routine that failed
error_code	The resulting cuBLAS error code

```
        : Error(file, line, func + ": " + get_error(error_code))
    {}
```

The documentation for this class was generated from the following file:

- ginkgo/core/base/exception.hpp (8fbad33a)

24.23 gko::CudaError Class Reference

CudaError is thrown when a CUDA routine throws a non-zero error code.

```
#include <ginkgo/core/base/exception.hpp>
```

Public Member Functions

- CudaError (const std::string &file, int line, const std::string &func, int64 error_code)
  Initializes a CUDA error.

24.23.1 Detailed Description

CudaError is thrown when a CUDA routine throws a non-zero error code.

24.23.2 Constructor & Destructor Documentation

24.23.2.1 CudaError()

```
gko::CudaError::CudaError (
            const std::string & file,
            int line,
            const std::string & func,
            int64 error_code )  [inline]
```

Initializes a CUDA error.

Parameters

file	The name of the offending source file
line	The source code line number where the error occurred
func	The name of the CUDA routine that failed
error_code	The resulting CUDA error code

```
        : Error(file, line, func + ": " + get_error(error_code))
    {}
```

The documentation for this class was generated from the following file:

- ginkgo/core/base/exception.hpp (8fbad33a)

24.24 gko::CudaExecutor Class Reference

This is the Executor subclass which represents the CUDA device.

`#include <ginkgo/core/base/executor.hpp>`

Public Member Functions

- std::shared_ptr< Executor > get_master () noexcept override
  Returns the master OmpExecutor of this Executor.
- std::shared_ptr< const Executor > get_master () const noexcept override
  Returns the master OmpExecutor of this Executor.
- void synchronize () const override
  Synchronize the operations launched on the executor with its master.
- void run (const Operation &op) const override
  Runs the specified Operation using this Executor.
- int get_device_id () const noexcept
  Get the CUDA device id of the device associated to this executor.
- int get_num_cores_per_sm () const noexcept
  Get the number of cores per SM of this executor.
- int get_num_multiprocessor () const noexcept
  Get the number of multiprocessor of this executor.
- int get_num_warps () const noexcept
  Get the number of warps of this executor.
- int get_major_version () const noexcept
  Get the major verion of compute capability.
- int get_minor_version () const noexcept
  Get the minor verion of compute capability.
- cublasContext * get_cublas_handle () const
  Get the cublas handle for this executor.
- cusparseContext * get_cusparse_handle () const
  Get the cusparse handle for this executor.

Static Public Member Functions

- static std::shared_ptr< CudaExecutor > create (int device_id, std::shared_ptr< Executor > master)
  Creates a new CudaExecutor.
- static int get_num_devices ()
  Get the number of devices present on the system.

24.24.1 Detailed Description

This is the Executor subclass which represents the CUDA device.

24.24.2 Member Function Documentation

24.24.2.1 create()

```
static std::shared_ptr<CudaExecutor> gko::CudaExecutor::create (
            int device_id,
            std::shared_ptr< Executor > master )  [static]
```

Creates a new CudaExecutor.

Parameters

device_id	the CUDA device id of this device
master	an executor on the host that is used to invoke the device kernels

24.24.2.2 get_cublas_handle()

```
cublasContext* gko::CudaExecutor::get_cublas_handle ( ) const  [inline]
```

Get the cublas handle for this executor.

Returns

the cublas handle (cublasContext*) for this executor

```
{ return cublas_handle_.get(); }
```

24.24.2.3 get_cusparse_handle()

```
cusparseContext* gko::CudaExecutor::get_cusparse_handle ( ) const  [inline]
```

Get the cusparse handle for this executor.

Returns

the cusparse handle (cusparseContext*) for this executor

```
    {
        return cusparse_handle_.get();
    }
```

24.24.2.4 get_master() [1/2]

```
std::shared_ptr<Executor> gko::CudaExecutor::get_master ( ) [override], [virtual], [noexcept]
```

Returns the master OmpExecutor of this Executor.

Returns

the master OmpExecutor of this Executor.

Implements gko::Executor.

24.24.2.5 get_master() [2/2]

```
std::shared_ptr<const Executor> gko::CudaExecutor::get_master ( ) const [override], [virtual],
[noexcept]
```

Returns the master OmpExecutor of this Executor.

Returns

the master OmpExecutor of this Executor.

Implements gko::Executor.

24.24.2.6 run()

```
void gko::CudaExecutor::run (
            const Operation & op ) const [override], [virtual]
```

Runs the specified Operation using this Executor.

Parameters

op	the operation to run

Implements gko::Executor.

The documentation for this class was generated from the following file:

- ginkgo/core/base/executor.hpp (f1a4eb68)

24.25 gko::CusparseError Class Reference

CusparseError is thrown when a cuSPARSE routine throws a non-zero error code.

`#include <ginkgo/core/base/exception.hpp>`

Public Member Functions

- CusparseError (const std::string &file, int line, const std::string &func, int64 error_code)
  Initializes a cuSPARSE error.

24.25.1 Detailed Description

CusparseError is thrown when a cuSPARSE routine throws a non-zero error code.

24.25.2 Constructor & Destructor Documentation

24.25.2.1 CusparseError()

```
gko::CusparseError::CusparseError (
            const std::string & file,
            int line,
            const std::string & func,
            int64 error_code )  [inline]
```

Initializes a cuSPARSE error.

Parameters

file	The name of the offending source file
line	The source code line number where the error occurred
func	The name of the cuSPARSE routine that failed
error_code	The resulting cuSPARSE error code

```
237         : Error(file, line, func + ": " + get_error(error_code))
238     {}
```

The documentation for this class was generated from the following file:

- ginkgo/core/base/exception.hpp (8fbad33a)

24.26 gko::default_converter< S, R > Struct Template Reference

Used to convert objects of type S to objects of type R using static_cast.

`#include <ginkgo/core/base/math.hpp>`

Public Member Functions

- R operator() (S val)
  Converts the object to result type.

24.26.1 Detailed Description

template<typename S, typename R>
struct gko::default_converter< S, R >

Used to convert objects of type `S` to objects of type `R` using static_cast.

Template Parameters

S	source type
R	result type

24.26.2 Member Function Documentation

24.26.2.1 operator()()

```
template<typename S , typename R >
R gko::default_converter< S, R >::operator() (
            S val )  [inline]
```

Converts the object to result type.

Parameters

val	the object to convert

Returns

the converted object

```
276 { return static_cast<R>(val); }
```

The documentation for this struct was generated from the following file:

- ginkgo/core/base/math.hpp (1c8cd641)

24.27 gko::matrix::Dense< ValueType > Class Template Reference

Dense is a matrix format which explicitly stores all values of the matrix.

```
#include <ginkgo/core/matrix/dense.hpp>
```

Public Member Functions

- std::unique_ptr< LinOp > transpose () const override
    Returns a LinOp representing the transpose of the Transposable object.
- std::unique_ptr< LinOp > conj_transpose () const override
    Returns a LinOp representing the conjugate transpose of the Transposable object.
- value_type * get_values () noexcept
    Returns a pointer to the array of values of the matrix.
- const value_type * get_const_values () const noexcept
    Returns a pointer to the array of values of the matrix.
- size_type get_stride () const noexcept
    Returns the stride of the matrix.
- size_type get_num_stored_elements () const noexcept
    Returns the number of elements explicitly stored in the matrix.
- value_type & at (size_type row, size_type col) noexcept
    Returns a single element of the matrix.
- value_type at (size_type row, size_type col) const noexcept
    Returns a single element of the matrix.
- ValueType & at (size_type idx) noexcept
    Returns a single element of the matrix.
- ValueType at (size_type idx) const noexcept
    Returns a single element of the matrix.
- void scale (const LinOp *alpha)
    Scales the matrix with a scalar (aka: BLAS scal).
- void add_scaled (const LinOp *alpha, const LinOp *b)
    Adds `b` scaled by `alpha` to the matrix (aka: BLAS axpy).
- void compute_dot (const LinOp *b, LinOp *result) const
    Computes the column-wise dot product of this matrix and `b`.
- void compute_norm2 (LinOp *result) const
    Computes the Euclidian (L^2) norm of this matrix.
- std::unique_ptr< Dense > create_submatrix (const span &rows, const span &columns, const size_type stride)
    Create a submatrix from the original matrix.

Static Public Member Functions

- static std::unique_ptr< Dense > create_with_config_of (const Dense *other)
    Creates a Dense matrix with the configuration of another Dense matrix.

24.27.1 Detailed Description

template<typename ValueType = default_precision>
class gko::matrix::Dense< ValueType >

Dense is a matrix format which explicitly stores all values of the matrix.

The values are stored in row-major format (values belonging to the same row appear consecutive in the memory). Optionally, rows can be padded for better memory access.

Template Parameters

ValueType	precision of matrix elements

Note

While this format is not very useful for storing sparse matrices, it is often suitable to store vectors, and sets of vectors.

24.27.2 Member Function Documentation

24.27.2.1 add_scaled()

```
template<typename ValueType = default_precision>
void gko::matrix::Dense< ValueType >::add_scaled (
            const LinOp * alpha,
            const LinOp * b )  [inline]
```

Adds `b` scaled by `alpha` to the matrix (aka: BLAS axpy).

Parameters

alpha	If alpha is 1x1 Dense matrix, the entire matrix is scaled by alpha. If it is a Dense row vector of values, then i-th column of the matrix is scaled with the i-th element of alpha (the number of columns of alpha has to match the number of columns of the matrix).
b	a matrix of the same dimension as this

References gko::PolymorphicObject::get_executor(), and gko::make_temporary_clone().

```
{
    auto exec = this->get_executor();
    this->add_scaled_impl(make_temporary_clone(exec, alpha).get(),
                          make_temporary_clone(exec, b).get());
}
```

24.27.2.2 at() [1/4]

```
template<typename ValueType = default_precision>
value_type& gko::matrix::Dense< ValueType >::at (
            size_type row,
            size_type col )  [inline], [noexcept]
```

Returns a single element of the matrix.

Parameters

row	the row of the requested element
col	the column of the requested element

Note

the method has to be called on the same Executor the matrix is stored at (e.g. trying to call this method on a GPU matrix from the OMP results in a runtime error)

References gko::Array< ValueType >::get_data().

Referenced by gko::initialize().

```
{
    return values_.get_data()[linearize_index(row, col)];
}
```

24.27.2.3 at() [2/4]

```
template<typename ValueType = default_precision>
value_type gko::matrix::Dense< ValueType >::at (
            size_type row,
            size_type col ) const  [inline], [noexcept]
```

Returns a single element of the matrix.

Parameters

row	the row of the requested element
col	the column of the requested element

Note

the method has to be called on the same Executor the matrix is stored at (e.g. trying to call this method on a GPU matrix from the OMP results in a runtime error)

References gko::Array< ValueType >::get_const_data().

```
{
    return values_.get_const_data()[linearize_index(row, col)];
}
```

24.27.2.4 at() [3/4]

```
template<typename ValueType = default_precision>
ValueType& gko::matrix::Dense< ValueType >::at (
            size_type idx ) [inline], [noexcept]
```

Returns a single element of the matrix.

Useful for iterating across all elements of the matrix. However, it is less efficient than the two-parameter variant of this method.

Parameters

idx	a linear index of the requested element (ignoring the stride)

Note

the method has to be called on the same Executor the matrix is stored at (e.g. trying to call this method on a GPU matrix from the OMP results in a runtime error)

References gko::Array< ValueType >::get_data().

```
{
    return values_.get_data()[linearize_index(idx)];
}
```

24.27.2.5 at() [4/4]

```
template<typename ValueType = default_precision>
ValueType gko::matrix::Dense< ValueType >::at (
            size_type idx ) const [inline], [noexcept]
```

Returns a single element of the matrix.

Useful for iterating across all elements of the matrix. However, it is less efficient than the two-parameter variant of this method.

Parameters

idx	a linear index of the requested element (ignoring the stride)

Note

the method has to be called on the same Executor the matrix is stored at (e.g. trying to call this method on a GPU matrix from the OMP results in a runtime error)

References gko::Array< ValueType >::get_const_data().

```
{
    return values_.get_const_data()[linearize_index(idx)];
}
```

24.27.2.6 compute_dot()

```
template<typename ValueType = default_precision>
void gko::matrix::Dense< ValueType >::compute_dot (
            const LinOp * b,
            LinOp * result ) const [inline]
```

Computes the column-wise dot product of this matrix and `b`.

The conjugate of this is taken.

Parameters

b	a Dense matrix of same dimension as this
result	a Dense row vector, used to store the dot product (the number of column in the vector must match the number of columns of this)

References gko::PolymorphicObject::get_executor(), and gko::make_temporary_clone().

```
{
    auto exec = this->get_executor();
    this->compute_dot_impl(make_temporary_clone(exec, b).get(),
                           make_temporary_clone(exec, result).get());
}
```

24.27.2.7 compute_norm2()

```
template<typename ValueType = default_precision>
void gko::matrix::Dense< ValueType >::compute_norm2 (
            LinOp * result ) const [inline]
```

Computes the Euclidian (L^2) norm of this matrix.

Parameters

result	a Dense row vector, used to store the norm (the number of columns in the vector must match the number of columns of this)

References gko::PolymorphicObject::get_executor(), and gko::make_temporary_clone().

```
{
    auto exec = this->get_executor();
    this->compute_norm2_impl(make_temporary_clone(exec, result).get());
}
```

24.27.2.8 conj_transpose()

```
template<typename ValueType = default_precision>
std::unique_ptr<LinOp> gko::matrix::Dense< ValueType >::conj_transpose ( ) const [override],
[virtual]
```

Returns a LinOp representing the conjugate transpose of the Transposable object.

Returns

a pointer to the new conjugate transposed object

Implements gko::Transposable.

Referenced by gko::matrix::Dense< ValueType >::create_with_config_of().

24.27.2.9 create_submatrix()

```
template<typename ValueType = default_precision>
std::unique_ptr<Dense> gko::matrix::Dense< ValueType >::create_submatrix (
            const span & rows,
            const span & columns,
            const size_type stride ) [inline]
```

Create a submatrix from the original matrix.

Warning: defining stride for this create_submatrix method might cause wrong memory access. Better use the create_submatrix(rows, columns) method instead.

Parameters

rows	row span
columns	column span
stride	stride of the new submatrix.

References gko::span::begin, gko::PolymorphicObject::get_executor(), gko::Array< ValueType >::get_num_elems(), gko::matrix::Dense< ValueType >::get_stride(), gko::matrix::Dense< ValueType >::get_values(), and gko::Array< ValueType >::view().

```
    {
        row_major_range range_this{this->get_values(), this->get_size()[0],
                                   this->get_size()[1], this->get_stride()};
        auto range_result = range_this(rows, columns);
        // TODO: can result in HUGE padding - which will be copied with the
        // vector
        return Dense::create(
            this->get_executor(),
            dim<2>{range_result.length(0), range_result.length(1)},
            Array<ValueType>::view(
                this->get_executor(),
                range_result.length(0) * range_this.length(1) - columns.begin,
                range_result->data),
            stride);
    }
```

24.27.2.10 create_with_config_of()

```
template<typename ValueType = default_precision>
static std::unique_ptr<Dense> gko::matrix::Dense< ValueType >::create_with_config_of (
            const Dense< ValueType > * other ) [inline], [static]
```

Creates a Dense matrix with the configuration of another Dense matrix.

Parameters

other	The other matrix whose configuration needs to copied.

References gko::matrix::Dense< ValueType >::conj_transpose(), and gko::matrix::Dense< ValueType >↩ ::transpose().

```
{
    // De-referencing `other` before calling the functions (instead of
    // using operator `->`) is currently required to be compatible with
    // CUDA 10.1.
    // Otherwise, it results in a compile error.
    // TODO Check if the compiler error is fixed and revert to `operator->`.
    return Dense::create((*other).get_executor(), (*other).get_size(),
                         (*other).get_stride());
}
```

24.27.2.11 get_const_values()

```
template<typename ValueType = default_precision>
const value_type* gko::matrix::Dense< ValueType >::get_const_values ( ) const [inline], [noexcept]
```

Returns a pointer to the array of values of the matrix.

Returns

the pointer to the array of values

Note

This is the constant version of the function, which can be significantly more memory efficient than the non-constant version, so always prefer this version.

References gko::Array< ValueType >::get_const_data().

```
{
    return values_.get_const_data();
}
```

24.27.2.12 get_num_stored_elements()

```
template<typename ValueType = default_precision>
size_type gko::matrix::Dense< ValueType >::get_num_stored_elements ( ) const [inline], [noexcept]
```

Returns the number of elements explicitly stored in the matrix.

Returns

the number of elements explicitly stored in the matrix

References gko::Array< ValueType >::get_num_elems().

```
{
    return values_.get_num_elems();
}
```

24.27.2.13 get_stride()

```
template<typename ValueType = default_precision>
size_type gko::matrix::Dense< ValueType >::get_stride ( ) const [inline], [noexcept]
```

Returns the stride of the matrix.

Returns

the stride of the matrix.

Referenced by gko::matrix::Dense< ValueType >::create_submatrix().

```
{ return stride_; }
```

24.27.2.14 get_values()

```
template<typename ValueType = default_precision>
value_type* gko::matrix::Dense< ValueType >::get_values ( ) [inline], [noexcept]
```

Returns a pointer to the array of values of the matrix.

Returns

the pointer to the array of values

References gko::Array< ValueType >::get_data().

Referenced by gko::matrix::Dense< ValueType >::create_submatrix().

```
{ return values_.get_data(); }
```

24.27.2.15 scale()

```
template<typename ValueType = default_precision>
void gko::matrix::Dense< ValueType >::scale (
            const LinOp * alpha ) [inline]
```

Scales the matrix with a scalar (aka: BLAS scal).

Parameters

alpha	If alpha is 1x1 Dense matrix, the entire matrix is scaled by alpha. If it is a Dense row vector of values, then i-th column of the matrix is scaled with the i-th element of alpha (the number of columns of alpha has to match the number of columns of the matrix).

References gko::PolymorphicObject::get_executor(), and gko::make_temporary_clone().

```
{
    auto exec = this->get_executor();
    this->scale_impl(make_temporary_clone(exec, alpha).get());
}
```

24.27.2.16 transpose()

```
template<typename ValueType = default_precision>
std::unique_ptr<LinOp> gko::matrix::Dense< ValueType >::transpose ( ) const [override],
[virtual]
```

Returns a LinOp representing the transpose of the Transposable object.

Returns

a pointer to the new transposed object

Implements gko::Transposable.

Referenced by gko::matrix::Dense< ValueType >::create_with_config_of().

The documentation for this class was generated from the following files:

- ginkgo/core/matrix/coo.hpp (5545d209)
- ginkgo/core/matrix/dense.hpp (664ab4d8)

24.28 gko::dim< Dimensionality, DimensionType > Struct Template Reference

A type representing the dimensions of a multidimensional object.

```
#include <ginkgo/core/base/dim.hpp>
```

Public Member Functions

- constexpr dim (const dimension_type &size=dimension_type{})
  Creates a dimension object with all dimensions set to the same value.
- template<typename... Rest>
  constexpr dim (const dimension_type &first, const Rest &... rest)
  Creates a dimension object with the specified dimensions.
- constexpr const dimension_type & operator[ ] (const size_type &dimension) const noexcept
  Returns the requested dimension.
- dimension_type & operator[ ] (const size_type &dimension) noexcept
- constexpr operator bool () const
  Checks if all dimensions evaluate to true.

Friends

- constexpr bool operator== (const dim &x, const dim &y)

  Checks if two dim objects are equal.
- constexpr dim operator* (const dim &x, const dim &y)

  Multiplies two dim objects.

24.28.1 Detailed Description

template<size_type Dimensionality, typename DimensionType = size_type>
struct gko::dim< Dimensionality, DimensionType >

A type representing the dimensions of a multidimensional object.

Template Parameters

Dimensionality	number of dimensions of the object
DimensionType	datatype used to represent each dimension

24.28.2 Constructor & Destructor Documentation

24.28.2.1 dim() [1/2]

```
template<size_type Dimensionality, typename DimensionType = size_type>
constexpr gko::dim< Dimensionality, DimensionType >::dim (
            const dimension_type & size = dimension_type{} )  [inline]
```

Creates a dimension object with all dimensions set to the same value.

Parameters

size	the size of each dimension

```
                                                                    {})
        : first_{size}, rest_{size}
    {}
```

24.28.2.2 dim() [2/2]

```
template<size_type Dimensionality, typename DimensionType = size_type>
template<typename... Rest>
```

```
constexpr gko::dim< Dimensionality, DimensionType >::dim (
            const dimension_type & first,
            const Rest &... rest ) [inline]
```

Creates a dimension object with the specified dimensions.

If the number of dimensions given is less than the dimensionality of the object, the remaining dimensions are set to the same value as the last value given.

For example, in the context of matrices `dim<2>{2, 3}` creates the dimensions for a 2-by-3 matrix.

Parameters

first	first dimension
rest	other dimensions

```
    : first_{first}, rest_{static_cast<dimension_type>(rest)...}
{}
```

24.28.3 Member Function Documentation

24.28.3.1 operator bool()

```
template<size_type Dimensionality, typename DimensionType = size_type>
constexpr gko::dim< Dimensionality, DimensionType >::operator bool ( ) const [inline]
```

Checks if all dimensions evaluate to true.

For standard arithmetic types, this is equivalent to all dimensions being different than zero.

Returns

true if and only if all dimensions evaluate to true

```
{
    return static_cast<bool>(first_) && static_cast<bool>(rest_);
}
```

24.28.3.2 operator[]() [1/2]

```
template<size_type Dimensionality, typename DimensionType = size_type>
constexpr const dimension_type& gko::dim< Dimensionality, DimensionType >::operator[] (
            const size_type & dimension ) const [inline], [noexcept]
```

Returns the requested dimension.

For example, if `d` is a dim<2> object representing matrix dimensions, `d[0]` returns the number of rows, and `d[1]` returns the number of columns.

Parameters

dimension	the requested dimension

Returns

the `dimension`-th dimension

```
{
    return GKO_ASSERT(dimension < dimensionality), *(&first_ + dimension);
}
```

24.28.3.3 operator[]() [2/2]

```
template<size_type Dimensionality, typename DimensionType = size_type>
dimension_type& gko::dim< Dimensionality, DimensionType >::operator[] (
            const size_type & dimension ) [inline], [noexcept]
```

```
{
    return GKO_ASSERT(dimension < dimensionality), *(&first_ + dimension);
}
```

24.28.4 Friends And Related Function Documentation

24.28.4.1 operator*

```
template<size_type Dimensionality, typename DimensionType = size_type>
constexpr dim operator* (
            const dim< Dimensionality, DimensionType > & x,
            const dim< Dimensionality, DimensionType > & y ) [friend]
```

Multiplies two dim objects.

Parameters

x	first object
y	second object

Returns

a dim object representing the size of the tensor product `x * y`

```
{
    return dim(x.first_ * y.first_, x.rest_ * y.rest_);
}
```

24.28.4.2 operator==

```
template<size_type Dimensionality, typename DimensionType = size_type>
constexpr bool operator== (
            const dim< Dimensionality, DimensionType > & x,
            const dim< Dimensionality, DimensionType > & y )  [friend]
```

Checks if two dim objects are equal.

Parameters

x	first object
y	second object

Returns

true if and only if all dimensions of both objects are equal.

```
{
    return x.first_ == y.first_ && x.rest_ == y.rest_;
}
```

The documentation for this struct was generated from the following file:

- ginkgo/core/base/dim.hpp (f1a4eb68)

24.29 gko::DimensionMismatch Class Reference

DimensionMismatch is thrown if an operation is being applied to LinOps of incompatible size.

```
#include <ginkgo/core/base/exception.hpp>
```

Public Member Functions

- DimensionMismatch (const std::string &file, int line, const std::string &func, const std::string &first_name, size_type first_rows, size_type first_cols, const std::string &second_name, size_type second_rows, size_↩ type second_cols, const std::string &clarification)

  Initializes a dimension mismatch error.

24.29.1 Detailed Description

DimensionMismatch is thrown if an operation is being applied to LinOps of incompatible size.

24.29.2 Constructor & Destructor Documentation

24.29.2.1 DimensionMismatch()

```
gko::DimensionMismatch::DimensionMismatch (
            const std::string & file,
            int line,
            const std::string & func,
            const std::string & first_name,
            size_type first_rows,
            size_type first_cols,
            const std::string & second_name,
            size_type second_rows,
            size_type second_cols,
            const std::string & clarification )  [inline]
```

Initializes a dimension mismatch error.

Parameters

file	The name of the offending source file
line	The source code line number where the error occurred
func	The function name where the error occurred
first_name	The name of the first operator
first_rows	The output dimension of the first operator
first_cols	The input dimension of the first operator
second_name	The name of the second operator
second_rows	The output dimension of the second operator
second_cols	The input dimension of the second operator
clarification	An additional message describing the error further

```
        : Error(file, line,
                func + ": attempting to combine operators " + first_name +
                    " [" + std::to_string(first_rows) + " x " +
                    std::to_string(first_cols) + "] and " + second_name + " [" +
                    std::to_string(second_rows) + " x " +
                    std::to_string(second_cols) + "]: " + clarification)
    {}
```

The documentation for this class was generated from the following file:

- ginkgo/core/base/exception.hpp (8fbad33a)

24.30 gko::matrix::Ell< ValueType, IndexType > Class Template Reference

ELL is a matrix format where stride with explicit zeros is used such that all rows have the same number of stored elements.

```
#include <ginkgo/core/matrix/ell.hpp>
```

Public Member Functions

- void read (const mat_data &data) override

    Reads a matrix from a matrix_data structure.
- void write (mat_data &data) const override

    Writes a matrix to a matrix_data structure.
- value_type ∗ get_values () noexcept

    Returns the values of the matrix.
- const value_type ∗ get_const_values () const noexcept

    Returns the values of the matrix.
- index_type ∗ get_col_idxs () noexcept

    Returns the column indexes of the matrix.
- const index_type ∗ get_const_col_idxs () const noexcept

    Returns the column indexes of the matrix.
- size_type get_num_stored_elements_per_row () const noexcept

    Returns the number of stored elements per row.
- size_type get_stride () const noexcept

    Returns the stride of the matrix.
- size_type get_num_stored_elements () const noexcept

    Returns the number of elements explicitly stored in the matrix.
- value_type & val_at (size_type row, size_type idx) noexcept

    Returns the `idx`-th non-zero element of the `row`-th row .
- value_type val_at (size_type row, size_type idx) const noexcept

    Returns the `idx`-th non-zero element of the `row`-th row .
- index_type & col_at (size_type row, size_type idx) noexcept

    Returns the `idx`-th column index of the `row`-th row .
- index_type col_at (size_type row, size_type idx) const noexcept

    Returns the `idx`-th column index of the `row`-th row .

24.30.1 Detailed Description

template<typename ValueType = default_precision, typename IndexType = int32>
class gko::matrix::Ell< ValueType, IndexType >

ELL is a matrix format where stride with explicit zeros is used such that all rows have the same number of stored elements.

The number of elements stored in each row is the largest number of nonzero elements in any of the rows (obtainable through get_num_stored_elements_per_row() method). This removes the need of a row pointer like in the CSR format, and allows for SIMD processing of the distinct rows. For efficient processing, the nonzero elements and the corresponding column indices are stored in column-major fashion. The columns are padded to the length by user-defined stride parameter whose default value is the number of rows of the matrix.

Template Parameters

ValueType	precision of matrix elements
IndexType	precision of matrix indexes

24.30.2 Member Function Documentation

24.30.2.1 col_at() [1/2]

```
template<typename ValueType = default_precision, typename IndexType = int32>
index_type& gko::matrix::Ell< ValueType, IndexType >::col_at (
            size_type row,
            size_type idx ) [inline], [noexcept]
```

Returns the `idx`-th column index of the `row`-th row .

Parameters

row	the row of the requested element
idx	the idx-th stored element of the row

Note

the method has to be called on the same Executor the matrix is stored at (e.g. trying to call this method on a GPU matrix from the OMP results in a runtime error)

References gko::matrix::Ell< ValueType, IndexType >::get_col_idxs().

```
201     {
202         return this->get_col_idxs()[this->linearize_index(row, idx)];
203     }
```

24.30.2.2 col_at() [2/2]

```
template<typename ValueType = default_precision, typename IndexType = int32>
index_type gko::matrix::Ell< ValueType, IndexType >::col_at (
            size_type row,
            size_type idx ) const [inline], [noexcept]
```

Returns the `idx`-th column index of the `row`-th row .

Parameters

row	the row of the requested element
idx	the idx-th stored element of the row

Note

the method has to be called on the same Executor the matrix is stored at (e.g. trying to call this method on a GPU matrix from the OMP results in a runtime error)

References gko::matrix::Ell< ValueType, IndexType >::get_const_col_idxs(), and gko::Array< ValueType >::get↩
_num_elems().

```
{
    return this->get_const_col_idxs()[this->linearize_index(row, idx)];
}
```

24.30.2.3 get_col_idxs()

```
template<typename ValueType = default_precision, typename IndexType = int32>
index_type* gko::matrix::Ell< ValueType, IndexType >::get_col_idxs ( )  [inline], [noexcept]
```

Returns the column indexes of the matrix.

Returns

the column indexes of the matrix.

References gko::Array< ValueType >::get_data().

Referenced by gko::matrix::Ell< ValueType, IndexType >::col_at().

```
{ return col_idxs_.get_data(); }
```

24.30.2.4 get_const_col_idxs()

```
template<typename ValueType = default_precision, typename IndexType = int32>
const index_type* gko::matrix::Ell< ValueType, IndexType >::get_const_col_idxs ( ) const  [inline],
[noexcept]
```

Returns the column indexes of the matrix.

Returns

the column indexes of the matrix.

Note

This is the constant version of the function, which can be significantly more memory efficient than the non-constant version, so always prefer this version.

References gko::Array< ValueType >::get_const_data().

Referenced by gko::matrix::Ell< ValueType, IndexType >::col_at().

```
{
    return col_idxs_.get_const_data();
}
```

24.30.2.5 get_const_values()

```
template<typename ValueType = default_precision, typename IndexType = int32>
const value_type* gko::matrix::Ell< ValueType, IndexType >::get_const_values ( ) const [inline],
[noexcept]
```

Returns the values of the matrix.

Returns

the values of the matrix.

Note

This is the constant version of the function, which can be significantly more memory efficient than the non-constant version, so always prefer this version.

References gko::Array< ValueType >::get_const_data().

```
{
    return values_.get_const_data();
}
```

24.30.2.6 get_num_stored_elements()

```
template<typename ValueType = default_precision, typename IndexType = int32>
size_type gko::matrix::Ell< ValueType, IndexType >::get_num_stored_elements ( ) const [inline],
[noexcept]
```

Returns the number of elements explicitly stored in the matrix.

Returns

the number of elements explicitly stored in the matrix

References gko::Array< ValueType >::get_num_elems().

```
{
    return values_.get_num_elems();
}
```

24.30.2.7 get_num_stored_elements_per_row()

```
template<typename ValueType = default_precision, typename IndexType = int32>
size_type gko::matrix::Ell< ValueType, IndexType >::get_num_stored_elements_per_row ( ) const
[inline], [noexcept]
```

Returns the number of stored elements per row.

Returns

the number of stored elements per row.

```
{
    return num_stored_elements_per_row_;
}
```

24.30.2.8 get_stride()

```
template<typename ValueType = default_precision, typename IndexType = int32>
size_type gko::matrix::Ell< ValueType, IndexType >::get_stride ( ) const [inline], [noexcept]
```

Returns the stride of the matrix.

Returns

the stride of the matrix.

```
155 { return stride_; }
```

24.30.2.9 get_values()

```
template<typename ValueType = default_precision, typename IndexType = int32>
value_type* gko::matrix::Ell< ValueType, IndexType >::get_values ( ) [inline], [noexcept]
```

Returns the values of the matrix.

Returns

the values of the matrix.

References gko::Array< ValueType >::get_data().

```
107 { return values_.get_data(); }
```

24.30.2.10 read()

```
template<typename ValueType = default_precision, typename IndexType = int32>
void gko::matrix::Ell< ValueType, IndexType >::read (
            const mat_data & data ) [override], [virtual]
```

Reads a matrix from a matrix_data structure.

Parameters

data	the matrix_data structure

Implements gko::ReadableFromMatrixData< ValueType, IndexType >.

24.30.2.11 val_at() [1/2]

```
template<typename ValueType = default_precision, typename IndexType = int32>
value_type& gko::matrix::Ell< ValueType, IndexType >::val_at (
            size_type row,
            size_type idx ) [inline], [noexcept]
```

Returns the `idx`-th non-zero element of the `row`-th row .

Parameters

row	the row of the requested element
idx	the idx-th stored element of the row

Note

the method has to be called on the same Executor the matrix is stored at (e.g. trying to call this method on a GPU matrix from the OMP results in a runtime error)

References gko::Array< ValueType >::get_data().

```
{
    return values_.get_data()[this->linearize_index(row, idx)];
}
```

24.30.2.12 val_at() [2/2]

```
template<typename ValueType = default_precision, typename IndexType = int32>
value_type gko::matrix::Ell< ValueType, IndexType >::val_at (
            size_type row,
            size_type idx ) const [inline], [noexcept]
```

Returns the `idx`-th non-zero element of the `row`-th row .

Parameters

row	the row of the requested element
idx	the idx-th stored element of the row

Note

the method has to be called on the same Executor the matrix is stored at (e.g. trying to call this method on a GPU matrix from the OMP results in a runtime error)

References gko::Array< ValueType >::get_const_data().

```
{
    return values_.get_const_data()[this->linearize_index(row, idx)];
}
```

24.30.2.13 write()

```
template<typename ValueType = default_precision, typename IndexType = int32>
void gko::matrix::Ell< ValueType, IndexType >::write (
            mat_data & data ) const  [override], [virtual]
```

Writes a matrix to a matrix_data structure.

Parameters

data	the matrix_data structure

Implements gko::WritableToMatrixData< ValueType, IndexType >.

The documentation for this class was generated from the following files:

- ginkgo/core/matrix/csr.hpp (ec6dbb34)
- ginkgo/core/matrix/ell.hpp (8045ac75)

24.31 gko::enable_parameters_type< ConcreteParametersType, Factory > Struct Template Reference

The enable_parameters_type mixin is used to create a base implementation of the factory parameters structure.

```
#include <ginkgo/core/base/abstract_factory.hpp>
```

Public Member Functions

- std::unique_ptr< Factory > on (std::shared_ptr< const Executor > exec) const
  Creates a new factory on the specified executor.

24.31.1 Detailed Description

template< typename ConcreteParametersType, typename Factory >
struct gko::enable_parameters_type< ConcreteParametersType, Factory >

The enable_parameters_type mixin is used to create a base implementation of the factory parameters structure.

It provides only the on() method which can be used to instantiate the factory give the parameters stored in the structure.

Template Parameters

ConcreteParametersType	the concrete parameters type which is being implemented [CRTP parameter]
Factory	the concrete factory for which these parameters are being used

24.31.2 Member Function Documentation

24.31.2.1 on()

```
template<typename ConcreteParametersType, typename Factory>
std::unique_ptr<Factory> gko::enable_parameters_type< ConcreteParametersType, Factory >::on (
            std::shared_ptr< const Executor > exec ) const  [inline]
```

Creates a new factory on the specified executor.

Parameters

exec	the executor where the factory will be created

Returns

a new factory instance

```
{
    return std::unique_ptr<Factory>(new Factory(exec, *self()));
}
```

The documentation for this struct was generated from the following file:

- ginkgo/core/base/abstract_factory.hpp (8045ac75)

24.32 gko::EnableAbstractPolymorphicObject< AbstactObject, PolymorphicBase > Class Template Reference

This mixin inherits from (a subclass of) PolymorphicObject and provides a base implementation of a new abstract object.

```
#include <ginkgo/core/base/polymorphic_object.hpp>
```

24.32.1 Detailed Description

template<typename AbstactObject, typename PolymorphicBase = PolymorphicObject>
class gko::EnableAbstractPolymorphicObject< AbstactObject, PolymorphicBase >

This mixin inherits from (a subclass of) PolymorphicObject and provides a base implementation of a new abstract object.

It uses method hiding to update the parameter and return types from `PolymorphicObject to`AbstractObject' wherever it makes sense. As opposed to EnablePolymorphicObject, it does not implement PolymorphicObject's virtual methods.

Template Parameters

AbstractObject	the abstract class which is being implemented [CRTP parameter]
PolymorphicBase	parent of AbstractObject in the polymorphic hierarchy, has to be a subclass of polymorphic object

See also

EnablePolymorphicObject for creating a concrete subclass of PolymorphicObject.

The documentation for this class was generated from the following file:

- ginkgo/core/base/polymorphic_object.hpp (3f08cf0a)

24.33 gko::EnableCreateMethod< ConcreteType > Class Template Reference

This mixin implements a static `create()` method on `ConcreteType` that dynamically allocates the memory, uses the passed-in arguments to construct the object, and returns an std::unique_ptr to such an object.

`#include <ginkgo/core/base/polymorphic_object.hpp>`

24.33.1 Detailed Description

template<typename ConcreteType>
class gko::EnableCreateMethod< ConcreteType >

This mixin implements a static `create()` method on `ConcreteType` that dynamically allocates the memory, uses the passed-in arguments to construct the object, and returns an std::unique_ptr to such an object.

Template Parameters

ConcreteObject	the concrete type for which `create()` is being implemented [CRTP parameter]

The documentation for this class was generated from the following file:

- ginkgo/core/base/polymorphic_object.hpp (3f08cf0a)

24.34 gko::EnableDefaultFactory< ConcreteFactory, ProductType, ParametersType, PolymorphicBase > Class Template Reference

This mixin provides a default implementation of a concrete factory.

`#include <ginkgo/core/base/abstract_factory.hpp>`

Public Member Functions

- const parameters_type & get_parameters () const noexcept
  Returns the parameters of the factory.

Static Public Member Functions

- static parameters_type create ()
  Creates a new ParametersType object which can be used to instantiate a new ConcreteFactory.

24.34.1 Detailed Description

template<typename ConcreteFactory, typename ProductType, typename ParametersType, typename PolymorphicBase>
class gko::EnableDefaultFactory< ConcreteFactory, ProductType, ParametersType, PolymorphicBase >

This mixin provides a default implementation of a concrete factory.

It implements all the methods of AbstractFactory and PolymorphicObject. Its implementation of the generate↩_impl() method delegates the creation of the product by calling the `ProductType::ProductType(const ConcreteFactory *, const components_type &)` constructor. The factory also supports parameters by using the `ParametersType` structure, which is defined by the user.

For a simple example, see IntFactory in `core/test/base/abstract_factory.cpp`.

Template Parameters

ConcreteFactory	the concrete factory which is being implemented [CRTP parameter]
ProductType	the concrete type of products which this factory produces, has to be a subclass of PolymorphicBase::abstract_product_type
ParametersType	a type representing the parameters of the factory, has to inherit from the enable_parameters_type mixin
PolymorphicBase	parent of ConcreteFactory in the polymorphic hierarchy, has to be a subclass of AbstractFactory

24.34.2 Member Function Documentation

24.34.2.1 create()

```
template<typename ConcreteFactory , typename ProductType , typename ParametersType , typename
PolymorphicBase >
static parameters_type gko::EnableDefaultFactory< ConcreteFactory, ProductType, Parameters↩
Type, PolymorphicBase >::create ( ) [inline], [static]
```

Creates a new ParametersType object which can be used to instantiate a new ConcreteFactory.

This method does not construct the factory directly, but returns a new parameters_type object, which can be used to set the parameters of the factory. Once the parameters have been set, the parameters_type::on() method can be used to obtain an instance of the factory with those parameters.

Returns

a default parameters_type object

```
{ return {}; }
```

24.34.2.2 get_parameters()

```
template<typename ConcreteFactory , typename ProductType , typename ParametersType , typename
PolymorphicBase >
const parameters_type& gko::EnableDefaultFactory< ConcreteFactory, ProductType, Parameters←
Type, PolymorphicBase >::get_parameters ( ) const [inline], [noexcept]
```

Returns the parameters of the factory.

Returns

the parameters of the factory

```
    {
        return parameters_;
    };
```

The documentation for this class was generated from the following file:

- ginkgo/core/base/abstract_factory.hpp (8045ac75)

24.35 gko::EnableLinOp< ConcreteLinOp, PolymorphicBase > Class Template Reference

The EnableLinOp mixin can be used to provide sensible default implementations of the majority of the LinOp and PolymorphicObject interface.

```
#include <ginkgo/core/base/lin_op.hpp>
```

Additional Inherited Members

24.35.1 Detailed Description

template<typename ConcreteLinOp, typename PolymorphicBase = LinOp>
class gko::EnableLinOp< ConcreteLinOp, PolymorphicBase >

The EnableLinOp mixin can be used to provide sensible default implementations of the majority of the LinOp and PolymorphicObject interface.

The goal of the mixin is to facilitate the development of new LinOp, by enabling the implementers to focus on the important parts of their operator, while the library takes care of generating the trivial utility functions. The mixin will provide default implementations for the entire PolymorphicObject interface, including a default implementation of `copy_from` between objects of the new LinOp type. It will also hide the default LinOp::apply() methods with versions that preserve the static type of the object.

Implementers of new LinOps are required to specify only the following aspects:

1. Creation of the LinOp: This can be facilitated via either EnableCreateMethod mixin (used mostly for matrix formats), or GKO_ENABLE_LIN_OP_FACTORY macro (used for operators created from other operators, like preconditioners and solvers).
2. Application of the LinOp: Implementers have to override the two overloads of the LinOp::apply_impl() virtual methods.

Template Parameters

ConcreteLinOp	the concrete LinOp which is being implemented [CRTP parameter]
PolymorphicBase	parent of ConcreteLinOp in the polymorphic hierarchy, has to be a subclass of LinOp

The documentation for this class was generated from the following file:

- ginkgo/core/base/lin_op.hpp (fb72cdf1)

24.36 gko::log::EnableLogging< ConcreteLoggable, PolymorphicBase > Class Template Reference

EnableLogging is a mixin which should be inherited by any class which wants to enable logging.

`#include <ginkgo/core/log/logger.hpp>`

Public Member Functions

- void add_logger (std::shared_ptr< const Logger > logger) override
  Adds a new logger to the list of subscribed loggers.
- void remove_logger (const Logger *logger) override
  Removes a logger from the list of subscribed loggers.

24.36.1 Detailed Description

template<typename ConcreteLoggable, typename PolymorphicBase = Loggable>
class gko::log::EnableLogging< ConcreteLoggable, PolymorphicBase >

EnableLogging is a mixin which should be inherited by any class which wants to enable logging.

All the received events are passed to the loggers this class contains.

Template Parameters

ConcreteLoggable	the object being logged [CRTP parameter]
PolymorphicBase	the polymorphic base of this class. By default it is Loggable. Change it if you want to use a new superclass of `Loggable` as polymorphic base of this class.

24.36.2 Member Function Documentation

24.36.2.1 add_logger()

```
template<typename ConcreteLoggable, typename PolymorphicBase = Loggable>
void gko::log::EnableLogging< ConcreteLoggable, PolymorphicBase >::add_logger (
            std::shared_ptr< const Logger > logger ) [inline], [override], [virtual]
```

Adds a new logger to the list of subscribed loggers.

Parameters

logger	the logger to add

Implements gko::log::Loggable.

```
{
    loggers_.push_back(logger);
}
```

24.36.2.2 remove_logger()

```
template<typename ConcreteLoggable, typename PolymorphicBase = Loggable>
void gko::log::EnableLogging< ConcreteLoggable, PolymorphicBase >::remove_logger (
            const Logger * logger ) [inline], [override], [virtual]
```

Removes a logger from the list of subscribed loggers.

Parameters

logger	the logger to remove

Note

The comparison is done using the logger's object unique identity. Thus, two loggers constructed in the same way are not considered equal.

Implements gko::log::Loggable.

```
{
    auto idx = find_if(begin(loggers_), end(loggers_),
                       [&logger](std::shared_ptr<const Logger> l) {
                           return lend(l) == logger;
                       });
    if (idx != end(loggers_)) {
        loggers_.erase(idx);
    } else {
        throw OutOfBoundsError(__FILE__, __LINE__, loggers_.size(),
                               loggers_.size());
    }
}
```

The documentation for this class was generated from the following file:

- ginkgo/core/log/logger.hpp (0d7578c9)

24.37 gko::EnablePolymorphicAssignment< ConcreteType, ResultType > Class Template Reference

This mixin is used to enable a default PolymorphicObject::copy_from() implementation for objects that have implemented conversions between them.

```
#include <ginkgo/core/base/polymorphic_object.hpp>
```

Public Member Functions

- void convert_to (result_type ∗result) const override

  Converts the implementer to an object of type result_type.
- void move_to (result_type ∗result) override

  Converts the implementer to an object of type result_type by moving data from this object.

24.37.1 Detailed Description

template<typename ConcreteType, typename ResultType = ConcreteType>
class gko::EnablePolymorphicAssignment< ConcreteType, ResultType >

This mixin is used to enable a default PolymorphicObject::copy_from() implementation for objects that have implemented conversions between them.

The requirement is that there is either a conversion constructor from `ConcreteType` in `ResultType`, or a conversion operator to `ResultType` in `ConcreteType`.

Template Parameters

ConcreteType	the concrete type from which the copy_from is being enabled [CRTP parameter]
ResultType	the type to which copy_from is being enabled

24.37.2 Member Function Documentation

24.37.2.1 convert_to()

```
template<typename ConcreteType, typename ResultType = ConcreteType>
void gko::EnablePolymorphicAssignment< ConcreteType, ResultType >::convert_to (
            result_type * result ) const  [inline], [override], [virtual]
```

Converts the implementer to an object of type result_type.

Parameters

result	the object used to store the result of the conversion

Implements gko::ConvertibleTo< ResultType >.

```
616 { *result = *self(); }
```

24.37.2.2 move_to()

```
template<typename ConcreteType, typename ResultType = ConcreteType>
void gko::EnablePolymorphicAssignment< ConcreteType, ResultType >::move_to (
            result_type * result ) [inline], [override], [virtual]
```

Converts the implementer to an object of type result_type by moving data from this object.

This method is used when the implementer is a temporary object, and move semantics can be used.

Parameters

result	the object used to emplace the result of the conversion

Note

ConvertibleTo::move_to can be implemented by simply calling ConvertibleTo::convert_to. However, this operation can often be optimized by exploiting the fact that implementer's data can be moved to the result.

Implements gko::ConvertibleTo< ResultType >.

```
618 { *result = std::move(*self()); }
```

The documentation for this class was generated from the following file:

- ginkgo/core/base/polymorphic_object.hpp (3f08cf0a)

24.38 gko::EnablePolymorphicObject< ConcreteObject, PolymorphicBase > Class Template Reference

This mixin inherits from (a subclass of) PolymorphicObject and provides a base implementation of a new concrete polymorphic object.

```
#include <ginkgo/core/base/polymorphic_object.hpp>
```

24.38.1 Detailed Description

template<typename ConcreteObject, typename PolymorphicBase = PolymorphicObject>
class gko::EnablePolymorphicObject< ConcreteObject, PolymorphicBase >

This mixin inherits from (a subclass of) PolymorphicObject and provides a base implementation of a new concrete polymorphic object.

The mixin changes parameter and return types of appropriate public methods of PolymorphicObject in the same way EnableAbstractPolymorphicObject does. In addition, it also provides default implementations of PolymorphicObject's vritual methods by using the *executor default constructor* and the assignment operator of ConcreteObject. Consequently, the following is a minimal example of PolymorphicObject:

```
{c++}
struct MyObject : EnablePolymorphicObject<MyObject> {
    MyObject(std::shared_ptr<const Executor> exec)
        : EnablePolymorphicObject<MyObject>(std::move(exec))
    {}
};
```

In a way, this mixin can be viewed as an extension of default constructor/destructor/assignment operators.

Note

This mixin does not enable copying the polymorphic object to the object of the same type (i.e. it does not implement the ConvertibleTo<ConcreteObject> interface). To enable a default implementation of this interface see the EnablePolymorphicAssignment mixin.

Template Parameters

ConcreteObject	the concrete type which is being implemented [CRTP parameter]
PolymorphicBase	parent of ConcreteObject in the polymorphic hierarchy, has to be a subclass of polymorphic object

The documentation for this class was generated from the following file:

- ginkgo/core/base/polymorphic_object.hpp (3f08cf0a)

24.39 gko::Error Class Reference

The Error class is used to report exceptional behaviour in library functions.

`#include <ginkgo/core/base/exception.hpp>`

Public Member Functions

- Error (const std::string &file, int line, const std::string &what)
  Initializes an error.
- virtual const char ∗ what () const noexcept override
  Returns a human-readable string with a more detailed description of the error.

24.39.1 Detailed Description

The Error class is used to report exceptional behaviour in library functions.

Ginkgo uses C++ exception mechanism to this end, and the Error class represents a base class for all types of errors. The exact list of errors which could occur during the execution of a certain library routine is provided in the documentation of that routine, along with a short description of the situation when that error can occur. During runtime, these errors can be detected by using standard C++ try-catch blocks, and a human-readable error description can be obtained by calling the Error::what() method.

As an example, trying to compute a matrix-vector product with arguments of incompatible size will result in a DimensionMismatch error, which is demonstrated in the following program.

```
#include <ginkgo.h>
#include <iostream>

using namespace gko;

int main()
{
    auto omp = create<OmpExecutor>();
    auto A = randn_fill<matrix::Csr<float>>(5, 5, 0f, 1f, omp);
    auto x = fill<matrix::Dense<float>>(6, 1, 1f, omp);
    try {
        auto y = apply(A.get(), x.get());
    } catch(Error e) {
        // an error occured, write the message to screen and exit
        std::cout << e.what() << std::endl;
        return -1;
    }
    return 0;
}
```

24.39.2 Constructor & Destructor Documentation

24.39.2.1 Error()

```
gko::Error::Error (
              const std::string & file,
              int line,
              const std::string & what )  [inline]
```

Initializes an error.

Parameters

file	The name of the offending source file
line	The source code line number where the error occurred
what	The error message

```
        : what_(file + ":" + std::to_string(line) + ": " + what)
    {}
```

The documentation for this class was generated from the following file:

- ginkgo/core/base/exception.hpp (8fbad33a)

24.40 gko::Executor Class Reference

The first step in using the Ginkgo library consists of creating an executor.

`#include <ginkgo/core/base/executor.hpp>`

Public Member Functions

- virtual void run (const Operation &op) const =0

    Runs the specified Operation using this Executor.
- template<typename ClosureOmp , typename ClosureCuda >
  void run (const ClosureOmp &op_omp, const ClosureCuda &op_cuda) const

    Runs one of the passed in functors, depending on the Executor type.
- template<typename T >
  T ∗ alloc (size_type num_elems) const

    Allocates memory in this Executor.
- void free (void ∗ptr) const noexcept

    Frees memory previously allocated with Executor::alloc().
- template<typename T >
  void copy_from (const Executor ∗src_exec, size_type num_elems, const T ∗src_ptr, T ∗dest_ptr) const

    Copies data from another Executor.
- virtual std::shared_ptr< Executor > get_master () noexcept=0

    Returns the master OmpExecutor of this Executor.
- virtual std::shared_ptr< const Executor > get_master () const noexcept=0

    Returns the master OmpExecutor of this Executor.
- virtual void synchronize () const =0

    Synchronize the operations launched on the executor with its master.

24.40.1 Detailed Description

The first step in using the Ginkgo library consists of creating an executor.

Executors are used to specify the location for the data of linear algebra objects, and to determine where the operations will be executed. Ginkgo currently supports three different executor types:

- OmpExecutor specifies that the data should be stored and the associated operations executed on an OpenMP-supporting device (e.g. host CPU);
- CudaExecutor specifies that the data should be stored and the operations executed on the NVIDIA GPU accelerator;
- ReferenceExecutor executes a non-optimized reference implementation, which can be used to debug the library.

The following code snippet demonstrates the simplest possible use of the Ginkgo library:

```
auto omp = gko::create<gko::OmpExecutor>();
auto A = gko::read_from_mtx<gko::matrix::Csr<float>>("A.mtx", omp);
```

First, we create a OMP executor, which will be used in the next line to specify where we want the data for the matrix A to be stored. The second line will read a matrix from the matrix market file 'A.mtx', and store the data on the CPU in CSR format (gko::matrix::Csr is a Ginkgo matrix class which stores its data in CSR format). At this point, matrix A is bound to the CPU, and any routines called on it will be performed on the CPU. This approach is usually desired in sparse linear algebra, as the cost of individual operations is several orders of magnitude lower than the cost of copying the matrix to the GPU.

If matrix A is going to be reused multiple times, it could be beneficial to copy it over to the accelerator, and perform the operations there, as demonstrated by the next code snippet:

```
auto cuda = gko::create<gko::CudaExecutor>(0, omp);
auto dA = gko::copy_to<gko::matrix::Csr<float>>(A.get(), cuda);
```

The first line of the snippet creates a new CUDA executor. Since there may be multiple NVIDIA GPUs present on the system, the first parameter instructs the library to use the first device (i.e. the one with device ID zero, as in cudaSetDevice() routine from the CUDA runtime API). In addition, since GPUs are not stand-alone processors, it is required to pass a "master" OmpExecutor which will be used to schedule the requested CUDA kernels on the accelerator.

The second command creates a copy of the matrix A on the GPU. Notice the use of the get() method. As Ginkgo aims to provide automatic memory management of its objects, the result of calling gko::read_from_mtx() is a smart pointer (std::unique_ptr) to the created object. On the other hand, as the library will not hold a reference to A once the copy is completed, the input parameter for gko::copy_to() is a plain pointer. Thus, the get() method is used to convert from a std::unique_ptr to a plain pointer, as expected by gko::copy_to().

As a side note, the gko::copy_to routine is far more powerful than just copying data between different devices. It can also be used to convert data between different formats. For example, if the above code used gko::matrix::Ell as the template parameter, dA would be stored on the GPU, in ELLPACK format.

Finally, if all the processing of the matrix is supposed to be done on the GPU, and a CPU copy of the matrix is not required, we could have read the matrix to the GPU directly:

```
auto omp = gko::create<gko::OmpExecutor>();
auto cuda = gko::create<gko::CudaExecutor>(0, omp);
auto dA = gko::read_from_mtx<gko::matrix::Csr<float>>("A.mtx", cuda);
```

Notice that even though reading the matrix directly from a file to the accelerator is not supported, the library is designed to abstract away the intermediate step of reading the matrix to the CPU memory. This is a general design approach taken by the library: in case an operation is not supported by the device, the data will be copied to the CPU, the operation performed there, and finally the results copied back to the device. This approach makes using the library more concise, as explicit copies are not required by the user. Nevertheless, this feature should be taken into account when considering performance implications of using such operations.

24.40.2 Member Function Documentation

24.40.2.1 alloc()

```
template<typename T >
T* gko::Executor::alloc (
            size_type num_elems ) const  [inline]
```

Allocates memory in this Executor.

Template Parameters

T	datatype to allocate

Parameters

num_elems	number of elements of type T to allocate

Exceptions

AllocationError	if the allocation failed

Returns

pointer to allocated memory

```
{
    this->template log<log::Logger::allocation_started>(
        this, num_elems * sizeof(T));
    T *allocated = static_cast<T *>(this->raw_alloc(num_elems * sizeof(T)));
    this->template log<log::Logger::allocation_completed>(
        this, num_elems * sizeof(T), reinterpret_cast<uintptr>(allocated));
    return allocated;
}
```

24.40.2.2 copy_from()

```
template<typename T >
void gko::Executor::copy_from (
            const Executor * src_exec,
            size_type num_elems,
            const T * src_ptr,
            T * dest_ptr ) const  [inline]
```

Copies data from another Executor.

Template Parameters

T	datatype to copy

Parameters

src_exec	Executor from which the memory will be copied
num_elems	number of elements of type T to copy
src_ptr	pointer to a block of memory containing the data to be copied
dest_ptr	pointer to an allocated block of memory where the data will be copied to

```
{
```

```
    this->template log<log::Logger::copy_started>(
        src_exec, this, reinterpret_cast<uintptr>(src_ptr),
        reinterpret_cast<uintptr>(dest_ptr), num_elems * sizeof(T));
    this->raw_copy_from(src_exec, num_elems * sizeof(T), src_ptr, dest_ptr);
    this->template log<log::Logger::copy_completed>(
        src_exec, this, reinterpret_cast<uintptr>(src_ptr),
        reinterpret_cast<uintptr>(dest_ptr), num_elems * sizeof(T));
}
```

24.40.2.3 free()

```
void gko::Executor::free (
        void * ptr ) const [inline], [noexcept]
```

Frees memory previously allocated with Executor::alloc().

If `ptr` is a `nullptr`, the function has no effect.

Parameters

ptr	pointer to the allocated memory block

```
{
    this->template log<log::Logger::free_started>(
        this, reinterpret_cast<uintptr>(ptr));
    this->raw_free(ptr);
    this->template log<log::Logger::free_completed>(
        this, reinterpret_cast<uintptr>(ptr));
}
```

24.40.2.4 get_master() [1/2]

`virtual std::shared_ptr<Executor> gko::Executor::get_master ( ) [pure virtual], [noexcept]`

Returns the master OmpExecutor of this Executor.

Returns

the master OmpExecutor of this Executor.

Implemented in gko::CudaExecutor, and gko::OmpExecutor.

24.40.2.5 get_master() [2/2]

`virtual std::shared_ptr<const Executor> gko::Executor::get_master ( ) const [pure virtual], [noexcept]`

Returns the master OmpExecutor of this Executor.

Returns

the master OmpExecutor of this Executor.

Implemented in gko::CudaExecutor, and gko::OmpExecutor.

24.40.2.6 run() [1/2]

```
virtual void gko::Executor::run (
            const Operation & op ) const [pure virtual]
```

Runs the specified Operation using this Executor.

Parameters

op	the operation to run

Implemented in gko::CudaExecutor, and gko::ReferenceExecutor.

24.40.2.7 run() [2/2]

```
template<typename ClosureOmp , typename ClosureCuda >
void gko::Executor::run (
            const ClosureOmp & op_omp,
            const ClosureCuda & op_cuda ) const [inline]
```

Runs one of the passed in functors, depending on the Executor type.

Template Parameters

ClosureOmp	type of op_omp
ClosureCuda	type of op_cuda

Parameters

op_omp	functor to run in case of a OmpExecutor or ReferenceExecutor
op_cuda	functor to run in case of a CudaExecutor

```
{
    LambdaOperation<ClosureOmp, ClosureCuda> op(op_omp, op_cuda);
    this->run(op);
}
```

The documentation for this class was generated from the following file:

- ginkgo/core/base/executor.hpp (f1a4eb68)

24.41 gko::log::executor_data Struct Reference

Struct representing Executor related data.

`#include <ginkgo/core/log/record.hpp>`

24.41.1 Detailed Description

Struct representing Executor related data.

The documentation for this struct was generated from the following file:

- ginkgo/core/log/record.hpp (f0a50f96)

24.42 gko::executor_deleter< T > Class Template Reference

This is a deleter that uses an executor's `free` method to deallocate the data.

`#include <ginkgo/core/base/executor.hpp>`

Public Member Functions

- executor_deleter (std::shared_ptr< const Executor > exec)

  Creates a new deleter.
- void operator() (pointer ptr) const

  Deletes the object.

24.42.1 Detailed Description

template<typename T>
class gko::executor_deleter< T >

This is a deleter that uses an executor's `free` method to deallocate the data.

Template Parameters

T	the type of object being deleted

24.42.2 Constructor & Destructor Documentation

24.42.2.1 executor_deleter()

```
template<typename T >
gko::executor_deleter< T >::executor_deleter (
            std::shared_ptr< const Executor > exec )  [inline], [explicit]
```

Creates a new deleter.

Parameters

exec	the executor used to free the data

```
        : exec_{exec}
    {}
```

24.42.3 Member Function Documentation

24.42.3.1 operator()()

```
template<typename T >
void gko::executor_deleter< T >::operator() (
            pointer ptr ) const  [inline]
```

Deletes the object.

Parameters

ptr	pointer to the object being deleted

```
    {
        if (exec_) {
            exec_->free(ptr);
        }
    }
```

The documentation for this class was generated from the following file:

- ginkgo/core/base/executor.hpp (f1a4eb68)

24.43 gko::preconditioner::Ilu< LSolverType, USolverType, ReverseApply >::Factory Class Reference

Used to replace the `GKO_ENABLE_LIN_OP_FACTORY` macro to allow for more variety in arguments for the `generate` function.

`#include <ginkgo/core/preconditioner/ilu.hpp>`

Additional Inherited Members

24.43.1 Detailed Description

template<typename LSolverType = solver::LowerTrs<>, typename USolverType = solver::UpperTrs<>, bool ReverseApply = false>
class gko::preconditioner::Ilu< LSolverType, USolverType, ReverseApply >::Factory

Used to replace the `GKO_ENABLE_LIN_OP_FACTORY` macro to allow for more variety in arguments for the `generate` function.

The documentation for this class was generated from the following file:

- ginkgo/core/preconditioner/ilu.hpp (650e6db0)

24.44 gko::solver::Fcg< ValueType > Class Template Reference

FCG or the flexible conjugate gradient method is an iterative type Krylov subspace method which is suitable for symmetric positive definite methods.

```
#include <ginkgo/core/solver/fcg.hpp>
```

Public Member Functions

- std::shared_ptr< const LinOp > get_system_matrix () const
  Gets the system operator (matrix) of the linear system.
- std::shared_ptr< const LinOp > get_preconditioner () const override
  Returns the preconditioner operator used by the solver.

24.44.1 Detailed Description

template<typename ValueType = default_precision>
class gko::solver::Fcg< ValueType >

FCG or the flexible conjugate gradient method is an iterative type Krylov subspace method which is suitable for symmetric positive definite methods.

Though this method performs very well for symmetric positive definite matrices, it is in general not suitable for general matrices.

In contrast to the standard CG based on the Polack-Ribiere formula, the flexible CG uses the Fletcher-Reeves formula for creating the orthonormal vectors spanning the Krylov subspace. This increases the computational cost of every Krylov solver iteration but allows for non-constant preconditioners.

The implementation in Ginkgo makes use of the merged kernel to make the best use of data locality. The inner operations in one iteration of FCG are merged into 2 separate steps.

Template Parameters

ValueType	precision of matrix elements

24.44.2 Member Function Documentation

24.44.2.1 get_preconditioner()

```
template<typename ValueType = default_precision>
std::shared_ptr<const LinOp> gko::solver::Fcg< ValueType >::get_preconditioner ( ) const
[inline], [override], [virtual]
```

Returns the preconditioner operator used by the solver.

Returns

the preconditioner operator used by the solver

Implements gko::Preconditionable.

References gko::stop::combine(), gko::PolymorphicObject::get_executor(), GKO_CREATE_FACTORY_PARAM↩ETERS, GKO_ENABLE_BUILD_METHOD, GKO_ENABLE_LIN_OP_FACTORY, GKO_FACTORY_PARAMETER, and gko::transpose().

```
{
    return preconditioner_;
}
```

24.44.2.2 get_system_matrix()

```
template<typename ValueType = default_precision>
std::shared_ptr<const LinOp> gko::solver::Fcg< ValueType >::get_system_matrix ( ) const [inline]
```

Gets the system operator (matrix) of the linear system.

Returns

the system operator (matrix)

```
{
    return system_matrix_;
}
```

The documentation for this class was generated from the following file:

- ginkgo/core/solver/fcg.hpp (f1a4eb68)

24.45 gko::solver::Gmres< ValueType > Class Template Reference

GMRES or the generalized minimal residual method is an iterative type Krylov subspace method which is suitable for nonsymmetric linear systems.

```
#include <ginkgo/core/solver/gmres.hpp>
```

Public Member Functions

- std::shared_ptr< const LinOp > get_system_matrix () const
  Gets the system operator (matrix) of the linear system.
- std::shared_ptr< const LinOp > get_preconditioner () const override
  Returns the preconditioner operator used by the solver.
- size_type get_krylov_dim () const
  Returns the krylov dimension.

24.45.1 Detailed Description

template<typename ValueType = default_precision>
class gko::solver::Gmres< ValueType >

GMRES or the generalized minimal residual method is an iterative type Krylov subspace method which is suitable for nonsymmetric linear systems.

The implementation in Ginkgo makes use of the merged kernel to make the best use of data locality. The inner operations in one iteration of GMRES are merged into 2 separate steps.

Template Parameters

ValueType	precision of matrix elements

24.45.2 Member Function Documentation

24.45.2.1 get_krylov_dim()

```
template<typename ValueType = default_precision>
size_type gko::solver::Gmres< ValueType >::get_krylov_dim ( ) const [inline]
```

Returns the krylov dimension.

Returns

the krylov dimension

References gko::stop::combine(), gko::PolymorphicObject::get_executor(), GKO_CREATE_FACTORY_PARAM↩ETERS, GKO_ENABLE_BUILD_METHOD, GKO_ENABLE_LIN_OP_FACTORY, GKO_FACTORY_PARAMETER, and gko::transpose().

```
103 { return krylov_dim_; }
```

24.45.2.2 get_preconditioner()

```
template<typename ValueType = default_precision>
std::shared_ptr<const LinOp> gko::solver::Gmres< ValueType >::get_preconditioner ( ) const
[inline], [override], [virtual]
```

Returns the preconditioner operator used by the solver.

Returns

the preconditioner operator used by the solver

Implements gko::Preconditionable.

```
94     {
95         return preconditioner_;
96     }
```

24.45.2.3 get_system_matrix()

```
template<typename ValueType = default_precision>
std::shared_ptr<const LinOp> gko::solver::Gmres< ValueType >::get_system_matrix ( ) const
[inline]
```

Gets the system operator (matrix) of the linear system.

Returns

the system operator (matrix)

```
84     {
85         return system_matrix_;
86     }
```

The documentation for this class was generated from the following file:

- ginkgo/core/solver/gmres.hpp (f1a4eb68)

24.46 gko::matrix::Hybrid< ValueType, IndexType > Class Template Reference

HYBRID is a matrix format which splits the matrix into ELLPACK and COO format.

```
#include <ginkgo/core/matrix/hybrid.hpp>
```

Classes

- class automatic

  automatic is a stratgy_type which decides the number of stored elements per row of the ell part automatically.
- class column_limit

  column_limit is a strategy_type which decides the number of stored elements per row of the ell part by specifying the number of columns.
- class imbalance_bounded_limit

  imbalance_bounded_limit is a stratgy_type which decides the number of stored elements per row of the ell part.
- class imbalance_limit

  imbalance_limit is a strategy_type which decides the number of stored elements per row of the ell part according to the percent.
- class minimal_storage_limit

  minimal_storage_limit is a stratgy_type which decides the number of stored elements per row of the ell part.
- class strategy_type

  strategy_type is to decide how to set the hybrid config.

Public Member Functions

- void read (const mat_data &data) override

  Reads a matrix from a matrix_data structure.
- void write (mat_data &data) const override

  Writes a matrix to a matrix_data structure.
- value_type ∗ get_ell_values () noexcept

  Returns the values of the ell part.
- const value_type ∗ get_const_ell_values () const noexcept

  Returns the values of the ell part.
- index_type ∗ get_ell_col_idxs () noexcept

  Returns the column indexes of the ell part.
- const index_type ∗ get_const_ell_col_idxs () const noexcept

  Returns the column indexes of the ell part.
- size_type get_ell_num_stored_elements_per_row () const noexcept

  Returns the number of stored elements per row of ell part.
- size_type get_ell_stride () const noexcept

  Returns the stride of the ell part.
- size_type get_ell_num_stored_elements () const noexcept

  Returns the number of elements explicitly stored in the ell part.
- value_type & ell_val_at (size_type row, size_type idx) noexcept

  Returns the `idx`-th non-zero element of the `row`-th row in the ell part.
- value_type ell_val_at (size_type row, size_type idx) const noexcept

  Returns the `idx`-th non-zero element of the `row`-th row in the ell part.
- index_type & ell_col_at (size_type row, size_type idx) noexcept

  Returns the `idx`-th column index of the `row`-th row in the ell part.
- index_type ell_col_at (size_type row, size_type idx) const noexcept

Returns the idx-th column index of the row-th row in the ell part.
- const ell_type * get_ell () const noexcept

  Returns the matrix of the ell part.
- value_type * get_coo_values () noexcept

  Returns the values of the coo part.
- const value_type * get_const_coo_values () const noexcept

  Returns the values of the coo part.
- index_type * get_coo_col_idxs () noexcept

  Returns the column indexes of the coo part.
- const index_type * get_const_coo_col_idxs () const noexcept

  Returns the column indexes of the coo part.
- index_type * get_coo_row_idxs () noexcept

  Returns the row indexes of the coo part.
- const index_type * get_const_coo_row_idxs () const noexcept

  Returns the row indexes of the coo part.
- size_type get_coo_num_stored_elements () const noexcept

  Returns the number of elements explicitly stored in the coo part.
- const coo_type * get_coo () const noexcept

  Returns the matrix of the coo part.
- size_type get_num_stored_elements () const noexcept

  Returns the number of elements explicitly stored in the matrix.
- std::shared_ptr< strategy_type > get_strategy () const noexcept

  Returns the strategy.
- Hybrid & operator= (const Hybrid &other)

  Copies data from another Hybrid.

24.46.1 Detailed Description

template<typename ValueType = default_precision, typename IndexType = int32>
class gko::matrix::Hybrid< ValueType, IndexType >

HYBRID is a matrix format which splits the matrix into ELLPACK and COO format.

Achieve the excellent performance with a proper partition of ELLPACK and COO.

Template Parameters

ValueType	precision of matrix elements
IndexType	precision of matrix indexes

24.46.2 Member Function Documentation

24.46.2.1 ell_col_at() [1/2]

```
template<typename ValueType = default_precision, typename IndexType = int32>
index_type& gko::matrix::Hybrid< ValueType, IndexType >::ell_col_at (
```

```
size_type row,
size_type idx ) [inline], [noexcept]
```

Returns the `idx`-th column index of the `row`-th row in the ell part.

Parameters

row	the row of the requested element
idx	the idx-th stored element of the row

Note

the method has to be called on the same Executor the matrix is stored at (e.g. trying to call this method on a GPU matrix from the OMP results in a runtime error)

```
{
    return ell_->col_at(row, idx);
}
```

24.46.2.2 ell_col_at() [2/2]

```
template<typename ValueType = default_precision, typename IndexType = int32>
index_type gko::matrix::Hybrid< ValueType, IndexType >::ell_col_at (
            size_type row,
            size_type idx ) const [inline], [noexcept]
```

Returns the `idx`-th column index of the `row`-th row in the ell part.

Parameters

row	the row of the requested element
idx	the idx-th stored element of the row

Note

the method has to be called on the same Executor the matrix is stored at (e.g. trying to call this method on a GPU matrix from the OMP results in a runtime error)

```
{
    return ell_->col_at(row, idx);
}
```

24.46.2.3 ell_val_at() [1/2]

```
template<typename ValueType = default_precision, typename IndexType = int32>
value_type& gko::matrix::Hybrid< ValueType, IndexType >::ell_val_at (
            size_type row,
            size_type idx ) [inline], [noexcept]
```

Returns the `idx`-th non-zero element of the `row`-th row in the ell part.

Parameters

row	the row of the requested element
idx	the idx-th stored element of the row

Note

the method has to be called on the same Executor the matrix is stored at (e.g. trying to call this method on a GPU matrix from the OMP results in a runtime error)

```
{
    return ell_->val_at(row, idx);
}
```

24.46.2.4 ell_val_at() [2/2]

```
template<typename ValueType = default_precision, typename IndexType = int32>
value_type gko::matrix::Hybrid< ValueType, IndexType >::ell_val_at (
            size_type row,
            size_type idx ) const  [inline], [noexcept]
```

Returns the `idx`-th non-zero element of the `row`-th row in the ell part.

Parameters

row	the row of the requested element
idx	the idx-th stored element of the row

Note

the method has to be called on the same Executor the matrix is stored at (e.g. trying to call this method on a GPU matrix from the OMP results in a runtime error)

```
{
    return ell_->val_at(row, idx);
}
```

24.46.2.5 get_const_coo_col_idxs()

```
template<typename ValueType = default_precision, typename IndexType = int32>
const index_type* gko::matrix::Hybrid< ValueType, IndexType >::get_const_coo_col_idxs ( )
const  [inline], [noexcept]
```

Returns the column indexes of the coo part.

Returns

the column indexes of the coo part.

Note

This is the constant version of the function, which can be significantly more memory efficient than the non-constant version, so always prefer this version.

```
{
    return coo_->get_const_col_idxs();
}
```

24.46.2.6 get_const_coo_row_idxs()

```
template<typename ValueType = default_precision, typename IndexType = int32>
const index_type* gko::matrix::Hybrid< ValueType, IndexType >::get_const_coo_row_idxs ( )
const [inline], [noexcept]
```

Returns the row indexes of the coo part.

Returns

the row indexes of the coo part.

Note

This is the constant version of the function, which can be significantly more memory efficient than the non-constant version, so always prefer this version.

```
{
    return coo_->get_const_row_idxs();
}
```

24.46.2.7 get_const_coo_values()

```
template<typename ValueType = default_precision, typename IndexType = int32>
const value_type* gko::matrix::Hybrid< ValueType, IndexType >::get_const_coo_values ( ) const
[inline], [noexcept]
```

Returns the values of the coo part.

Returns

the values of the coo part.

Note

This is the constant version of the function, which can be significantly more memory efficient than the non-constant version, so always prefer this version.

```
{
    return coo_->get_const_values();
}
```

24.46.2.8 get_const_ell_col_idxs()

```
template<typename ValueType = default_precision, typename IndexType = int32>
const index_type* gko::matrix::Hybrid< ValueType, IndexType >::get_const_ell_col_idxs ( )
const [inline], [noexcept]
```

Returns the column indexes of the ell part.

Returns

the column indexes of the ell part

Note

This is the constant version of the function, which can be significantly more memory efficient than the non-constant version, so always prefer this version.

```
{
    return ell_->get_const_col_idxs();
}
```

24.46.2.9 get_const_ell_values()

```
template<typename ValueType = default_precision, typename IndexType = int32>
const value_type* gko::matrix::Hybrid< ValueType, IndexType >::get_const_ell_values ( ) const
[inline], [noexcept]
```

Returns the values of the ell part.

Returns

the values of the ell part

Note

This is the constant version of the function, which can be significantly more memory efficient than the non-constant version, so always prefer this version.

```
{
    return ell_->get_const_values();
}
```

24.46.2.10 get_coo()

```
template<typename ValueType = default_precision, typename IndexType = int32>
const coo_type* gko::matrix::Hybrid< ValueType, IndexType >::get_coo ( ) const  [inline],
[noexcept]
```

Returns the matrix of the coo part.

Returns

the matrix of the coo part

```
536 { return coo_.get(); }
```

24.46.2.11 get_coo_col_idxs()

```
template<typename ValueType = default_precision, typename IndexType = int32>
index_type* gko::matrix::Hybrid< ValueType, IndexType >::get_coo_col_idxs ( )  [inline], [noexcept]
```

Returns the column indexes of the coo part.

Returns

the column indexes of the coo part.

```
488 { return coo_->get_col_idxs(); }
```

24.46.2.12 get_coo_num_stored_elements()

```
template<typename ValueType = default_precision, typename IndexType = int32>
size_type gko::matrix::Hybrid< ValueType, IndexType >::get_coo_num_stored_elements ( ) const
[inline], [noexcept]
```

Returns the number of elements explicitly stored in the coo part.

Returns

the number of elements explicitly stored in the coo part

```
527     {
528         return coo_->get_num_stored_elements();
529     }
```

24.46.2.13 get_coo_row_idxs()

```
template<typename ValueType = default_precision, typename IndexType = int32>
index_type* gko::matrix::Hybrid< ValueType, IndexType >::get_coo_row_idxs ( ) [inline], [noexcept]
```

Returns the row indexes of the coo part.

Returns

the row indexes of the coo part.

```
507 { return coo_->get_row_idxs(); }
```

24.46.2.14 get_coo_values()

```
template<typename ValueType = default_precision, typename IndexType = int32>
value_type* gko::matrix::Hybrid< ValueType, IndexType >::get_coo_values ( ) [inline], [noexcept]
```

Returns the values of the coo part.

Returns

the values of the coo part.

```
469 { return coo_->get_values(); }
```

24.46.2.15 get_ell()

```
template<typename ValueType = default_precision, typename IndexType = int32>
const ell_type* gko::matrix::Hybrid< ValueType, IndexType >::get_ell ( ) const [inline],
[noexcept]
```

Returns the matrix of the ell part.

Returns

the matrix of the ell part

```
462 { return ell_.get(); }
```

24.46.2.16 get_ell_col_idxs()

```
template<typename ValueType = default_precision, typename IndexType = int32>
index_type* gko::matrix::Hybrid< ValueType, IndexType >::get_ell_col_idxs ( ) [inline], [noexcept]
```

Returns the column indexes of the ell part.

Returns

the column indexes of the ell part

```
{ return ell_->get_col_idxs(); }
```

24.46.2.17 get_ell_num_stored_elements()

```
template<typename ValueType = default_precision, typename IndexType = int32>
size_type gko::matrix::Hybrid< ValueType, IndexType >::get_ell_num_stored_elements ( ) const
[inline], [noexcept]
```

Returns the number of elements explicitly stored in the ell part.

Returns

the number of elements explicitly stored in the ell part

```
{
    return ell_->get_num_stored_elements();
}
```

24.46.2.18 get_ell_num_stored_elements_per_row()

```
template<typename ValueType = default_precision, typename IndexType = int32>
size_type gko::matrix::Hybrid< ValueType, IndexType >::get_ell_num_stored_elements_per_row ( )
const [inline], [noexcept]
```

Returns the number of stored elements per row of ell part.

Returns

the number of stored elements per row of ell part

```
{
    return ell_->get_num_stored_elements_per_row();
}
```

24.46.2.19 get_ell_stride()

template<typename ValueType = default_precision, typename IndexType = int32>
size_type gko::matrix::Hybrid< ValueType, IndexType >::get_ell_stride ( ) const [inline], [noexcept]

Returns the stride of the ell part.

Returns

the stride of the ell part

```
{ return ell_->get_stride(); }
```

24.46.2.20 get_ell_values()

template<typename ValueType = default_precision, typename IndexType = int32>
value_type* gko::matrix::Hybrid< ValueType, IndexType >::get_ell_values ( ) [inline], [noexcept]

Returns the values of the ell part.

Returns

the values of the ell part

```
{ return ell_->get_values(); }
```

24.46.2.21 get_num_stored_elements()

template<typename ValueType = default_precision, typename IndexType = int32>
size_type gko::matrix::Hybrid< ValueType, IndexType >::get_num_stored_elements ( ) const [inline], [noexcept]

Returns the number of elements explicitly stored in the matrix.

Returns

the number of elements explicitly stored in the matrix

```
    {
        return coo_->get_num_stored_elements() +
               ell_->get_num_stored_elements();
    }
```

24.46.2.22 get_strategy()

```
template<typename ValueType = default_precision, typename IndexType = int32>
std::shared_ptr<strategy_type> gko::matrix::Hybrid< ValueType, IndexType >::get_strategy ( )
const [inline], [noexcept]
```

Returns the strategy.

Returns

the strategy

```
{
    return strategy_;
}
```

24.46.2.23 operator=()

```
template<typename ValueType = default_precision, typename IndexType = int32>
Hybrid& gko::matrix::Hybrid< ValueType, IndexType >::operator= (
            const Hybrid< ValueType, IndexType > & other ) [inline]
```

Copies data from another Hybrid.

Parameters

other	the Hybrid to copy from

Returns

this

```
{
    if (&other == this) {
        return *this;
    }
    EnableLinOp<Hybrid<ValueType, IndexType>>::operator=(other);
    this->coo_->copy_from(other.get_coo());
    this->ell_->copy_from(other.get_ell());
    return *this;
}
```

24.46.2.24 read()

```
template<typename ValueType = default_precision, typename IndexType = int32>
void gko::matrix::Hybrid< ValueType, IndexType >::read (
            const mat_data & data ) [override], [virtual]
```

Reads a matrix from a matrix_data structure.

Parameters

data	the matrix_data structure

Implements gko::ReadableFromMatrixData< ValueType, IndexType >.

Referenced by gko::matrix::Hybrid< ValueType, IndexType >::automatic::compute_ell_num_stored_elements_↩ per_row().

24.46.2.25 write()

```
template<typename ValueType = default_precision, typename IndexType = int32>
void gko::matrix::Hybrid< ValueType, IndexType >::write (
            mat_data & data ) const [override], [virtual]
```

Writes a matrix to a matrix_data structure.

Parameters

data	the matrix_data structure

Implements gko::WritableToMatrixData< ValueType, IndexType >.

Referenced by gko::matrix::Hybrid< ValueType, IndexType >::automatic::compute_ell_num_stored_elements_↩ per_row().

The documentation for this class was generated from the following files:

- ginkgo/core/matrix/csr.hpp (ec6dbb34)
- ginkgo/core/matrix/hybrid.hpp (3e51a52b)

24.47 gko::matrix::Identity< ValueType > Class Template Reference

This class is a utility which efficiently implements the identity matrix (a linear operator which maps each vector to itself).

`#include <ginkgo/core/matrix/identity.hpp>`

Additional Inherited Members

24.47.1 Detailed Description

template<typename ValueType = default_precision>
class gko::matrix::Identity< ValueType >

This class is a utility which efficiently implements the identity matrix (a linear operator which maps each vector to itself).

Thus, objects of the Identity class always represent a square matrix, and don't require any storage for their values. The apply method is implemented as a simple copy (or a linear combination).

Note

This class is useful when composing it with other operators. For example, it can be used instead of a preconditioner in Krylov solvers, if one wants to run a "plain" solver, without using a preconditioner.

Template Parameters

ValueType	precision of matrix elements

The documentation for this class was generated from the following file:

- ginkgo/core/matrix/identity.hpp (8045ac75)

24.48 gko::matrix::IdentityFactory< ValueType > Class Template Reference

This factory is a utility which can be used to generate Identity operators.

```
#include <ginkgo/core/matrix/identity.hpp>
```

Static Public Member Functions

- static std::unique_ptr< IdentityFactory > create (std::shared_ptr< const Executor > exec)
  Creates a new Identity factory.

Additional Inherited Members

24.48.1 Detailed Description

template<typename ValueType = default_precision>
class gko::matrix::IdentityFactory< ValueType >

This factory is a utility which can be used to generate Identity operators.

The factory will generate the Identity matrix with the same dimension as the passed in operator. It will throw an exception if the operator is not square.

Template Parameters

ValueType	precision of matrix elements

24.48.2 Member Function Documentation

24.48.2.1 create()

```
template<typename ValueType = default_precision>
static std::unique_ptr<IdentityFactory> gko::matrix::IdentityFactory< ValueType >::create (
            std::shared_ptr< const Executor > exec )  [inline], [static]
```

Creates a new Identity factory.

Parameters

exec	the executor where the Identity operator will be stored

Returns

a unique pointer to the newly created factory

```
    {
        return std::unique_ptr<IdentityFactory>(
            new IdentityFactory(std::move(exec)));
    }
```

The documentation for this class was generated from the following file:

- ginkgo/core/matrix/identity.hpp (8045ac75)

24.49 gko::preconditioner::Ilu< LSolverType, USolverType, ReverseApply > Class Template Reference

The Incomplete LU (ILU) preconditioner solves the equation $LUx = b$ for a given lower triangular matrix L, an upper triangular matrix U and the right hand side b (can contain multiple right hand sides).

```
#include <ginkgo/core/preconditioner/ilu.hpp>
```

Classes

- class Factory

  Used to replace the `GKO_ENABLE_LIN_OP_FACTORY` macro to allow for more variety in arguments for the `generate` function.

Public Member Functions

- std::shared_ptr< const l_solver_type > get_l_solver () const

  Returns the solver which is used for the provided L matrix.
- std::shared_ptr< const u_solver_type > get_u_solver () const

  Returns the solver which is used for the provided U matrix.
- const parameters_type & get_parameters () const

  Returns the parameters used to build the initial object.

24.49.1 Detailed Description

template<typename LSolverType = solver::LowerTrs<>, typename USolverType = solver::UpperTrs<>, bool ReverseApply = false>
class gko::preconditioner::Ilu< LSolverType, USolverType, ReverseApply >

The Incomplete LU (ILU) preconditioner solves the equation $LUx = b$ for a given lower triangular matrix L, an upper triangular matrix U and the right hand side b (can contain multiple right hand sides).

It allows to set both the solver for L and the solver for U independently, while providing the defaults solver::LowerTrs and solver::UpperTrs, which are direct triangular solvers. For these solvers, a factory can be provided (with `with_l_solver_factory` and `with_u_solver_factory`) to have more control over their behavior. In particular, it is possible to use an iterative method for solving the triangular systems. The default parameters for an iterative triangluar solver are:

- reduction factor = 1e-4
- max iteration = <number of="" rows="" of="" the="" matrix="" given="" to="" the="" solver>=""> Solvers without such criteria can also be used, in which case none are set.

Note

This class is not thread safe (even a const object is not) because it uses an internal cache to accelerate multiple (sequential) applies. Using it in parallel can lead to segmentation faults, wrong results and other unwanted behavior.

Template Parameters

LSolverType	type of the solver used for the L matrix. Defaults to solver::LowerTrs
USolverType	type of the solver used for the U matrix Defaults to solver::UpperTrs
ReverseApply	default behavior (ReverseApply = false) is first to solve with L (Ly = b) and then with U (Ux = y). When set to true, it will solve first with U, and then with L.

24.49.2 Member Function Documentation

24.49.2.1 get_l_solver()

```
template<typename LSolverType = solver::LowerTrs<>, typename USolverType = solver::UpperTrs<>, bool ReverseApply = false>
std::shared_ptr<const l_solver_type> gko::preconditioner::Ilu< LSolverType, USolverType,
ReverseApply >::get_l_solver ( ) const  [inline]
```

Returns the solver which is used for the provided L matrix.

Returns

the solver which is used for the provided L matrix

```
{
    return l_solver_;
}
```

24.49.2.2 get_parameters()

```
template<typename LSolverType = solver::LowerTrs<>, typename USolverType = solver::Upper↩
Trs<>, bool ReverseApply = false>
const parameters_type& gko::preconditioner::Ilu< LSolverType, USolverType, ReverseApply >↩
::get_parameters ( ) const [inline]
```

Returns the parameters used to build the initial object.

Returns

the parameters used to build the initial object.

```
{ return parameters_; }
```

24.49.2.3 get_u_solver()

```
template<typename LSolverType = solver::LowerTrs<>, typename USolverType = solver::Upper↩
Trs<>, bool ReverseApply = false>
std::shared_ptr<const u_solver_type> gko::preconditioner::Ilu< LSolverType, USolverType,
ReverseApply >::get_u_solver ( ) const [inline]
```

Returns the solver which is used for the provided U matrix.

Returns

the solver which is used for the provided U matrix

```
    {
        return u_solver_;
    }
```

The documentation for this class was generated from the following file:

- ginkgo/core/preconditioner/ilu.hpp (650e6db0)

24.50 gko::matrix::Hybrid< ValueType, IndexType >::imbalance_bounded_limit Class Reference

imbalance_bounded_limit is a stratgy_type which decides the number of stored elements per row of the ell part.

```
#include <ginkgo/core/matrix/hybrid.hpp>
```

Public Member Functions

- imbalance_bounded_limit (float percent=0.8, float ratio=0.0001)

  Creates a imbalance_bounded_limit strategy.
- size_type compute_ell_num_stored_elements_per_row (Array< size_type > *row_nnz) const override

  Computes the number of stored elements per row of the ell part.

24.50.1 Detailed Description

template<typename ValueType = default_precision, typename IndexType = int32>
class gko::matrix::Hybrid< ValueType, IndexType >::imbalance_bounded_limit

imbalance_bounded_limit is a stratgy_type which decides the number of stored elements per row of the ell part.

It uses the imbalance_limit and adds the upper bound of the number of ell's cols by the number of rows.

24.50.2 Member Function Documentation

24.50.2.1 compute_ell_num_stored_elements_per_row()

```
template<typename ValueType = default_precision, typename IndexType = int32>
size_type gko::matrix::Hybrid< ValueType, IndexType >::imbalance_bounded_limit::compute_ell_↩
num_stored_elements_per_row (
            Array< size_type > * row_nnz ) const  [inline], [override], [virtual]
```

Computes the number of stored elements per row of the ell part.

Parameters

row_nnz	the number of nonzeros of each row

Returns

the number of stored elements per row of the ell part

Implements gko::matrix::Hybrid< ValueType, IndexType >::strategy_type.

References gko::Array< ValueType >::get_num_elems().

```
        {
            auto num_rows = row_nnz->get_num_elems();
            auto ell_cols =
                strategy_.compute_ell_num_stored_elements_per_row(row_nnz);
            return std::min(ell_cols,
                            static_cast<size_type>(num_rows * ratio_));
        }
```

The documentation for this class was generated from the following file:

- ginkgo/core/matrix/hybrid.hpp (3e51a52b)

24.51 gko::matrix::Hybrid< ValueType, IndexType >::imbalance_limit Class Reference

imbalance_limit is a strategy_type which decides the number of stored elements per row of the ell part according to the percent.

`#include <ginkgo/core/matrix/hybrid.hpp>`

Public Member Functions

- imbalance_limit (float percent=0.8)

  Creates a imbalance_limit strategy.
- size_type compute_ell_num_stored_elements_per_row (Array< size_type > ∗row_nnz) const override

  Computes the number of stored elements per row of the ell part.

24.51.1 Detailed Description

template<typename ValueType = default_precision, typename IndexType = int32>
class gko::matrix::Hybrid< ValueType, IndexType >::imbalance_limit

imbalance_limit is a strategy_type which decides the number of stored elements per row of the ell part according to the percent.

It sorts the number of nonzeros of each row and takes the value at the position `floor(percent * num_row)` as the number of stored elements per row of the ell part. Thus, at least `percent` rows of all are in the ell part.

24.51.2 Constructor & Destructor Documentation

24.51.2.1 imbalance_limit()

```
template<typename ValueType = default_precision, typename IndexType = int32>
gko::matrix::Hybrid< ValueType, IndexType >::imbalance_limit::imbalance_limit (
            float percent = 0.8 )  [inline], [explicit]
```

Creates a imbalance_limit strategy.

Parameters

percent	the row_nnz[floor(num_rows∗percent)] is the number of stored elements per row of the ell part

```
                                                : percent_(percent)
        {
            percent_ = std::min(percent_, 1.0f);
            percent_ = std::max(percent_, 0.0f);
        }
```

24.51.3 Member Function Documentation

24.51.3.1 compute_ell_num_stored_elements_per_row()

```
template<typename ValueType = default_precision, typename IndexType = int32>
size_type gko::matrix::Hybrid< ValueType, IndexType >::imbalance_limit::compute_ell_num_↩
stored_elements_per_row (
            Array< size_type > * row_nnz ) const  [inline], [override], [virtual]
```

Computes the number of stored elements per row of the ell part.

Parameters

row_nnz	the number of nonzeros of each row

Returns

the number of stored elements per row of the ell part

Implements gko::matrix::Hybrid< ValueType, IndexType >::strategy_type.

References gko::Array< ValueType >::get_data(), and gko::Array< ValueType >::get_num_elems().

```
        {
            auto row_nnz_val = row_nnz->get_data();
            auto num_rows = row_nnz->get_num_elems();
            std::sort(row_nnz_val, row_nnz_val + num_rows);
            if (percent_ < 1) {
                auto percent_pos = static_cast<size_type>(num_rows * percent_);
                return row_nnz_val[percent_pos];
            } else {
                return row_nnz_val[num_rows - 1];
            }
        }
```

The documentation for this class was generated from the following file:

- ginkgo/core/matrix/hybrid.hpp (3e51a52b)

24.52 gko::solver::Ir< ValueType > Class Template Reference

Iterative refinement (IR) is an iterative method that uses another coarse method to approximate the error of the current solution via the current residual.

```
#include <ginkgo/core/solver/ir.hpp>
```

Public Member Functions

- std::shared_ptr< const LinOp > get_system_matrix () const

  Returns the system operator (matrix) of the linear system.
- std::shared_ptr< const LinOp > get_solver () const

  Returns the solver operator used as the inner solver.

24.52.1 Detailed Description

template<typename ValueType = default_precision>
class gko::solver::Ir< ValueType >

Iterative refinement (IR) is an iterative method that uses another coarse method to approximate the error of the current solution via the current residual.

For any approximation of the solution `solution` to the system `Ax = b`, the residual is defined as: `residual = b - A solution`. The error in `solution`, `e = x - solution` (with `x` being the exact solution) can be obtained as the solution to the residual equation `Ae = residual`, since `A e = Ax - A solution = b - A solution = residual`. Then, the real solution is computed as `x = solution + e`. Instead of accurately solving the residual equation `Ae = residual`, the solution of the system `e` can be approximated to obtain the approximation `error` using a coarse method `solver`, which is used to update `solution`, and the entire process is repeated with the updated `solution`. This yields the iterative refinement method:

```
solution = initial_guess
while not converged:
    residual = b - A solution
    error = solver(A, residual)
    solution = solution + error
```

Assuming that `solver` has accuracy `c`, i.e., `| e - error | <= c | e |`, iterative refinement will converge with a convergence rate of `c`. Indeed, from `e - error = x - solution - error = x - solution*` (where `solution*` denotes the value stored in `solution` after the update) and `e = inv(A) residual = inv(A)b - inv(A) A solution = x - solution` it follows that | x - solution* | <= c | x - solution |.

Unless otherwise specified via the `solver` factory parameter, this implementation uses the identity operator (i.e. the solver that approximates the solution of a system Ax = b by setting x := b) as the default inner solver. Such a setting results in a relaxation method known as the Richardson iteration with parameter 1, which is guaranteed to converge for matrices whose spectrum is strictly contained within the unit disc around 1 (i.e., all its eigenvalues `lambda` have to satisfy the equation '|lambda - 1| < 1).

Template Parameters

ValueType	precision of matrix elements

24.52.2 Member Function Documentation

24.52.2.1 get_solver()

```
template<typename ValueType = default_precision>
std::shared_ptr<const LinOp> gko::solver::Ir< ValueType >::get_solver ( ) const  [inline]
```

Returns the solver operator used as the inner solver.

Returns

the solver operator used as the inner solver

References gko::stop::combine(), gko::PolymorphicObject::get_executor(), GKO_CREATE_FACTORY_PARAMETERS, GKO_ENABLE_BUILD_METHOD, GKO_ENABLE_LIN_OP_FACTORY, GKO_FACTORY_PARAMETER, and gko::transpose().

```
116 { return solver_; }
```

24.52.2.2 get_system_matrix()

```
template<typename ValueType = default_precision>
std::shared_ptr<const LinOp> gko::solver::Ir< ValueType >::get_system_matrix ( ) const [inline]
```

Returns the system operator (matrix) of the linear system.

Returns

the system operator (matrix)

```
106     {
107         return system_matrix_;
108     }
```

The documentation for this class was generated from the following file:

- ginkgo/core/solver/ir.hpp (4bde4271)

24.53 gko::stop::Iteration Class Reference

The Iteration class is a stopping criterion which stops the iteration process after a preset number of iterations.

```
#include <ginkgo/core/stop/iteration.hpp>
```

24.53.1 Detailed Description

The Iteration class is a stopping criterion which stops the iteration process after a preset number of iterations.

Note

to use this stopping criterion, it is required to update the iteration count for the ::check() method.

The documentation for this class was generated from the following file:

- ginkgo/core/stop/iteration.hpp (f1a4eb68)

24.54 gko::log::iteration_complete_data Struct Reference

Struct representing iteration complete related data.

`#include <ginkgo/core/log/record.hpp>`

24.54.1 Detailed Description

Struct representing iteration complete related data.

The documentation for this struct was generated from the following file:

- ginkgo/core/log/record.hpp (f0a50f96)

24.55 gko::preconditioner::Jacobi< ValueType, IndexType > Class Template Reference

A block-Jacobi preconditioner is a block-diagonal linear operator, obtained by inverting the diagonal blocks of the source operator.

`#include <ginkgo/core/preconditioner/jacobi.hpp>`

Public Member Functions

- size_type get_num_blocks () const noexcept

  Returns the number of blocks of the operator.
- const block_interleaved_storage_scheme< index_type > & get_storage_scheme () const noexcept

  Returns the storage scheme used for storing Jacobi blocks.
- const value_type ∗ get_blocks () const noexcept

  Returns the pointer to the memory used for storing the block data.
- const remove_complex< value_type > ∗ get_conditioning () const noexcept

  Returns an array of 1-norm condition numbers of the blocks.
- size_type get_num_stored_elements () const noexcept

  Returns the number of elements explicitly stored in the matrix.
- void convert_to (matrix::Dense< value_type > ∗result) const override

  Converts the implementer to an object of type result_type.
- void move_to (matrix::Dense< value_type > ∗result) override

  Converts the implementer to an object of type result_type by moving data from this object.
- void write (mat_data &data) const override

  Writes a matrix to a matrix_data structure.

24.55.1 Detailed Description

template< typename ValueType = default_precision, typename IndexType = int32>
class gko::preconditioner::Jacobi< ValueType, IndexType >

A block-Jacobi preconditioner is a block-diagonal linear operator, obtained by inverting the diagonal blocks of the source operator.

The Jacobi class implements the inversion of the diagonal blocks using Gauss-Jordan elimination with column pivoting, and stores the inverse explicitly in a customized format.

If the diagonal blocks of the matrix are not explicitly set by the user, the implementation will try to automatically detect the blocks by first finding the natural blocks of the matrix, and then applying the supervariable agglomeration procedure on them. However, if problem-specific knowledge regarding the block diagonal structure is available, it is usually beneficial to explicitly pass the starting rows of the diagonal blocks, as the block detection is merely a heuristic and cannot perfectly detect the diagonal block structure. The current implementation supports blocks of up to 32 rows / columns.

The implementation also includes an improved, adaptive version of the block-Jacobi preconditioner, which can store some of the blocks in lower precision and thus improve the performance of preconditioner application by reducing the amount of memory transfers. This variant can be enabled by setting the Jacobi::Factory's `storage_optimization` parameter. Refer to the documentation of the parameter for more details.

Template Parameters

ValueType	precision of matrix elements
IndexType	integral type used to store pointers to the start of each block

Note

The current implementation supports blocks of up to 32 rows / columns.
When using the adaptive variant, there may be a trade-off in terms of slightly longer preconditioner generation due to extra work required to detect the optimal precision of the blocks.

24.55.2 Member Function Documentation

24.55.2.1 convert_to()

```
template<typename ValueType = default_precision, typename IndexType = int32>
void gko::preconditioner::Jacobi< ValueType, IndexType >::convert_to (
            matrix::Dense< value_type > * result ) const  [override], [virtual]
```

Converts the implementer to an object of type result_type.

Parameters

result	the object used to store the result of the conversion

Implements gko::ConvertibleTo< matrix::Dense< ValueType > >.

24.55.2.2 get_blocks()

template<typename ValueType = default_precision, typename IndexType = int32>
const value_type* gko::preconditioner::Jacobi< ValueType, IndexType >::get_blocks ( ) const [inline], [noexcept]

Returns the pointer to the memory used for storing the block data.

Element (i, j) of block b is stored in position (get_block_pointers()[b] + i) * stride + j of the array.

Returns

the pointer to the memory used for storing the block data

```
{
    return blocks_.get_const_data();
}
```

24.55.2.3 get_conditioning()

template<typename ValueType = default_precision, typename IndexType = int32>
const remove_complex<value_type>* gko::preconditioner::Jacobi< ValueType, IndexType >::get_conditioning ( ) const [inline], [noexcept]

Returns an array of 1-norm condition numbers of the blocks.

Returns

an array of 1-norm condition numbers of the blocks

Note

This value is valid only if adaptive precision variant is used, and implementations of the standard non-adaptive variant are allowed to omit the calculation of condition numbers.

```
{
    return conditioning_.get_const_data();
}
```

24.55.2.4 get_num_blocks()

```
template<typename ValueType = default_precision, typename IndexType = int32>
size_type gko::preconditioner::Jacobi< ValueType, IndexType >::get_num_blocks ( ) const [inline],
[noexcept]
```

Returns the number of blocks of the operator.

Returns

the number of blocks of the operator

```
230 { return num_blocks_; }
```

24.55.2.5 get_num_stored_elements()

```
template<typename ValueType = default_precision, typename IndexType = int32>
size_type gko::preconditioner::Jacobi< ValueType, IndexType >::get_num_stored_elements ( )
const [inline], [noexcept]
```

Returns the number of elements explicitly stored in the matrix.

Returns

the number of elements explicitly stored in the matrix

References gko::preconditioner::block_interleaved_storage_scheme< IndexType >::block_offset, gko::Array< ValueType >::get_num_elems(), gko::get_significant_bit(), gko::get_superior_power(), GKO_CREATE_FACTORY_PARAMETERS, GKO_ENABLE_BUILD_METHOD, GKO_ENABLE_LIN_OP_FACTORY, GKO_FACTORY_PARAMETER, gko::preconditioner::block_interleaved_storage_scheme< IndexType >::group_offset, gko::lend(), gko::transpose(), and gko::write().

```
282     {
283         return blocks_.get_num_elems();
284     }
```

24.55.2.6 get_storage_scheme()

```
template<typename ValueType = default_precision, typename IndexType = int32>
const block_interleaved_storage_scheme<index_type>& gko::preconditioner::Jacobi< ValueType,
IndexType >::get_storage_scheme ( ) const [inline], [noexcept]
```

Returns the storage scheme used for storing Jacobi blocks.

Returns

the storage scheme used for storing Jacobi blocks

```
242     {
243         return storage_scheme_;
244     }
```

24.55.2.7 move_to()

```
template<typename ValueType = default_precision, typename IndexType = int32>
void gko::preconditioner::Jacobi< ValueType, IndexType >::move_to (
            matrix::Dense< value_type > * result ) [override], [virtual]
```

Converts the implementer to an object of type result_type by moving data from this object.

This method is used when the implementer is a temporary object, and move semantics can be used.

Parameters

result	the object used to emplace the result of the conversion

Note

ConvertibleTo::move_to can be implemented by simply calling ConvertibleTo::convert_to. However, this operation can often be optimized by exploiting the fact that implementer's data can be moved to the result.

Implements gko::ConvertibleTo< matrix::Dense< ValueType > >.

24.55.2.8 write()

```
template<typename ValueType = default_precision, typename IndexType = int32>
void gko::preconditioner::Jacobi< ValueType, IndexType >::write (
            mat_data & data ) const  [override], [virtual]
```

Writes a matrix to a matrix_data structure.

Parameters

data	the matrix_data structure

Implements gko::WritableToMatrixData< ValueType, IndexType >.

The documentation for this class was generated from the following file:

- ginkgo/core/preconditioner/jacobi.hpp (9c2e5ae6)

24.56 gko::KernelNotFound Class Reference

KernelNotFound is thrown if Ginkgo cannot find a kernel which satisfies the criteria imposed by the input arguments.

```
#include <ginkgo/core/base/exception.hpp>
```

Public Member Functions

- KernelNotFound (const std::string &file, int line, const std::string &func)
  Initializes a KernelNotFound error.

24.56.1 Detailed Description

KernelNotFound is thrown if Ginkgo cannot find a kernel which satisfies the criteria imposed by the input arguments.

24.56.2 Constructor & Destructor Documentation

24.56.2.1 KernelNotFound()

```
gko::KernelNotFound::KernelNotFound (
            const std::string & file,
            int line,
            const std::string & func ) [inline]
```

Initializes a KernelNotFound error.

Parameters

file	The name of the offending source file
line	The source code line number where the error occurred
func	The name of the function where the error occurred

```
        : Error(file, line, func + ": unable to find an eligible kernel")
    {}
```

The documentation for this class was generated from the following file:

- ginkgo/core/base/exception.hpp (8fbad33a)

24.57 gko::log::linop_data Struct Reference

Struct representing LinOp related data.

```
#include <ginkgo/core/log/record.hpp>
```

24.57.1 Detailed Description

Struct representing LinOp related data.

The documentation for this struct was generated from the following file:

- ginkgo/core/log/record.hpp (f0a50f96)

24.58 gko::log::linop_factory_data Struct Reference

Struct representing LinOp factory related data.

```
#include <ginkgo/core/log/record.hpp>
```

24.58.1 Detailed Description

Struct representing LinOp factory related data.

The documentation for this struct was generated from the following file:

- ginkgo/core/log/record.hpp (f0a50f96)

24.59 gko::LinOpFactory Class Reference

A LinOpFactory represents a higher order mapping which transforms one linear operator into another.

```
#include <ginkgo/core/base/lin_op.hpp>
```

Additional Inherited Members

24.59.1 Detailed Description

A LinOpFactory represents a higher order mapping which transforms one linear operator into another.

In Ginkgo, every linear solver is viewed as a mapping. For example, given an s.p.d linear system $Ax = b$, the solution $x = A^{-1}b$ can be computed using the CG method. This algorithm can be represented in terms of linear operators and mappings between them as follows:

- A Cg::Factory is a higher order mapping which, given an input operator A, returns a new linear operator A^{-1} stored in "CG format"
- Storing the operator A^{-1} in "CG format" means that the data structure used to store the operator is just a simple pointer to the original matrix A. The application $x = A^{-1}b$ of such an operator can then be implemented by solving the linear system $Ax = b$ using the CG method. This is achieved in code by having a special class for each of those "formats" (e.g. the "Cg" class defines such a format for the CG solver).

Another example of a LinOpFactory is a preconditioner. A preconditioner for a linear operator A is a linear operator M^{-1}, which approximates A^{-1}. In addition, it is stored in a way such that both the data of M^{-1} is cheap to compute from A, and the operation $x = M^{-1}b$ can be computed quickly. These operators are useful to accelerate the convergence of Krylov solvers. Thus, a preconditioner also fits into the LinOpFactory framework:

- The factory maps a linear operator A into a preconditioner M^{-1} which is stored in suitable format (e.g. as a product of two factors in case of ILU preconditioners).
- The resulting linear operator implements the application operation $x = M^{-1}b$ depending on the format the preconditioner is stored in (e.g. as two triangular solves in case of ILU)

Example: using CG in Ginkgo

```
{c++}
// Suppose A is a matrix, b a rhs vector, and x an initial guess
// Create a CG which runs for at most 1000 iterations, and stops after
// reducing the residual norm by 6 orders of magnitude
auto cg_factory = solver::Cg<>::build()
    .with_max_iters(1000)
    .with_rel_residual_goal(1e-6)
    .on(cuda);
// create a linear operator which represents the solver
auto cg = cg_factory->generate(A);
// solve the system
cg->apply(gko::lend(b), gko::lend(x));
```

The documentation for this class was generated from the following file:

- ginkgo/core/base/lin_op.hpp (fb72cdf1)

24.60 gko::log::Loggable Class Reference

Loggable class is an interface which should be implemented by classes wanting to support logging.

`#include <ginkgo/core/log/logger.hpp>`

Public Member Functions

- virtual void add_logger (std::shared_ptr< const Logger > logger)=0

    Adds a new logger to the list of subscribed loggers.
- virtual void remove_logger (const Logger *logger)=0

    Removes a logger from the list of subscribed loggers.

24.60.1 Detailed Description

Loggable class is an interface which should be implemented by classes wanting to support logging.

For most cases, one can rely on the EnableLogging mixin which provides a default implementation of this interface.

24.60.2 Member Function Documentation

24.60.2.1 add_logger()

```
virtual void gko::log::Loggable::add_logger (
            std::shared_ptr< const Logger > logger )  [pure virtual]
```

Adds a new logger to the list of subscribed loggers.

Parameters

logger	the logger to add

Implemented in gko::log::EnableLogging< ConcreteLoggable, PolymorphicBase >, gko::log::EnableLogging< PolymorphicObject >, and gko::log::EnableLogging< Executor >.

24.60.2.2 remove_logger()

```
virtual void gko::log::Loggable::remove_logger (
            const Logger * logger )  [pure virtual]
```

Removes a logger from the list of subscribed loggers.

Parameters

logger	the logger to remove

Note

The comparison is done using the logger's object unique identity. Thus, two loggers constructed in the same way are not considered equal.

Implemented in gko::log::EnableLogging< ConcreteLoggable, PolymorphicBase >, gko::log::EnableLogging< PolymorphicObject >, and gko::log::EnableLogging< Executor >.

The documentation for this class was generated from the following file:

- ginkgo/core/log/logger.hpp (0d7578c9)

24.61 gko::log::Record::logged_data Struct Reference

Struct storing the actually logged data.

```
#include <ginkgo/core/log/record.hpp>
```

24.61.1 Detailed Description

Struct storing the actually logged data.

The documentation for this struct was generated from the following file:

- ginkgo/core/log/record.hpp (f0a50f96)

24.62 gko::solver::LowerTrs< ValueType, IndexType > Class Template Reference

LowerTrs is the triangular solver which solves the system L x = b, when L is a lower triangular matrix.

```
#include <ginkgo/core/solver/lower_trs.hpp>
```

Public Member Functions

- std::shared_ptr< const matrix::Csr< ValueType, IndexType > > get_system_matrix () const
  Gets the system operator (CSR matrix) of the linear system.
- std::shared_ptr< const LinOp > get_preconditioner () const override
  Returns the preconditioner operator used by the solver.

24.62.1 Detailed Description

template<typename ValueType = default_precision, typename IndexType = int32>
class gko::solver::LowerTrs< ValueType, IndexType >

LowerTrs is the triangular solver which solves the system L x = b, when L is a lower triangular matrix.

It works best when passing in a matrix in CSR format. If the matrix is not in CSR, then the generate step converts it into a CSR matrix. The generation fails if the matrix is not convertible to CSR.

Note

As the constructor uses the copy and convert functionality, it is not possible to create a empty solver or a solver with a matrix in any other format other than CSR, if none of the executor modules are being compiled with.

Template Parameters

ValueType	precision of matrix elements
IndexType	precision of matrix indices

24.62.2 Member Function Documentation

24.62.2.1 get_preconditioner()

```
template<typename ValueType = default_precision, typename IndexType = int32>
std::shared_ptr<const LinOp> gko::solver::LowerTrs< ValueType, IndexType >::get_preconditioner
( ) const [inline], [override], [virtual]
```

Returns the preconditioner operator used by the solver.

Returns

the preconditioner operator used by the solver

Implements gko::Preconditionable.

References gko::PolymorphicObject::get_executor(), GKO_CREATE_FACTORY_PARAMETERS, GKO_ENABLE_BUILD_METHOD, GKO_ENABLE_LIN_OP_FACTORY, GKO_FACTORY_PARAMETER, and gko::transpose().

```
{
    return preconditioner_;
}
```

24.62.2.2 get_system_matrix()

```
template<typename ValueType = default_precision, typename IndexType = int32>
std::shared_ptr<const matrix::Csr<ValueType, IndexType> > gko::solver::LowerTrs< ValueType,
IndexType >::get_system_matrix ( ) const [inline]
```

Gets the system operator (CSR matrix) of the linear system.

Returns

the system operator (CSR matrix)

```
{
    return system_matrix_;
}
```

The documentation for this class was generated from the following file:

- ginkgo/core/solver/lower_trs.hpp (050c7273)

24.63 gko::matrix_data< ValueType, IndexType > Struct Template Reference

This structure is used as an intermediate data type to store a sparse matrix.

```
#include <ginkgo/core/base/matrix_data.hpp>
```

Classes

- struct nonzero_type

  Type used to store nonzeros.

Public Member Functions

- matrix_data (dim< 2 > size_=dim< 2 >{}, ValueType value=zero< ValueType >())

    Initializes a matrix filled with the specified value.
- template<typename RandomDistribution , typename RandomEngine >
  matrix_data (dim< 2 > size_, RandomDistribution &&dist, RandomEngine &&engine)

    Initializes a matrix with random values from the specified distribution.
- matrix_data (std::initializer_list< std::initializer_list< ValueType >> values)

    List-initializes the structure from a matrix of values.
- matrix_data (dim< 2 > size_, std::initializer_list< detail::input_triple< ValueType, IndexType >> nonzeros↩ _)

    Initializes the structure from a list of nonzeros.
- matrix_data (dim< 2 > size_, const matrix_data &block)

    Initializes a matrix out of a matrix block via duplication.
- template<typename Accessor >
  matrix_data (const range< Accessor > &data)

    Initializes a matrix from a range.
- void ensure_row_major_order ()

    Sorts the nonzero vector so the values follow row-major order.

Static Public Member Functions

- static matrix_data diag (dim< 2 > size_, ValueType value)

    Initializes a diagonal matrix.
- static matrix_data diag (dim< 2 > size_, std::initializer_list< ValueType > nonzeros_)

    Initializes a diagonal matrix using a list of diagonal elements.
- static matrix_data diag (dim< 2 > size_, const matrix_data &block)

    Initializes a block-diagonal matrix.
- template<typename ForwardIterator >
  static matrix_data diag (ForwardIterator begin, ForwardIterator end)

    Initializes a block-diagonal matrix from a list of diagonal blocks.
- static matrix_data diag (std::initializer_list< matrix_data > blocks)

    Initializes a block-diagonal matrix from a list of diagonal blocks.
- template<typename RandomDistribution , typename RandomEngine >
  static matrix_data cond (size_type size, remove_complex< ValueType > condition_number, Random↩ Distribution &&dist, RandomEngine &&engine, size_type num_reflectors)

    Initializes a random dense matrix with a specific condition number.
- template<typename RandomDistribution , typename RandomEngine >
  static matrix_data cond (size_type size, remove_complex< ValueType > condition_number, Random↩ Distribution &&dist, RandomEngine &&engine)

    Initializes a random dense matrix with a specific condition number.

Public Attributes

- dim< 2 > size

    Size of the matrix.
- std::vector< nonzero_type > nonzeros

    A vector of tuples storing the non-zeros of the matrix.

24.63.1 Detailed Description

template<typename ValueType = default_precision, typename IndexType = int32>
struct gko::matrix_data< ValueType, IndexType >

This structure is used as an intermediate data type to store a sparse matrix.

The matrix is stored as a sequence of nonzero elements, where each element is a triple of the form (row_index, column_index, value).

Note

All Ginkgo functions returning such a structure will return the nonzeros sorted in row-major order.
All Ginkgo functions that take this structure as input expect that the nonzeros are sorted in row-major order.
This structure is not optimized for usual access patterns and it can only exist on the CPU. Thus, it should only be used for utility functions which do not have to be optimized for performance.

Template Parameters

ValueType	type of matrix values stored in the structure
IndexType	type of matrix indexes stored in the structure

24.63.2 Constructor & Destructor Documentation

24.63.2.1 matrix_data() [1/6]

```
template<typename ValueType = default_precision, typename IndexType = int32>
gko::matrix_data< ValueType, IndexType >::matrix_data (
            dim< 2 > size_ = dim<2>{},
            ValueType value = zero<ValueType>() )  [inline]
```

Initializes a matrix filled with the specified value.

Parameters

*size_*	dimensions of the matrix
value	value used to fill the elements of the matrix

```
                                     {}, ValueType value = zero<ValueType>())
        : size{size_}
    {
        if (value == zero<ValueType>()) {
            return;
        }
        for (size_type row = 0; row < size[0]; ++row) {
            for (size_type col = 0; col < size[1]; ++col) {
                nonzeros.emplace_back(row, col, value);
            }
        }
    }
```

24.63.2.2 matrix_data() [2/6]

```
template<typename ValueType = default_precision, typename IndexType = int32>
template<typename RandomDistribution , typename RandomEngine >
gko::matrix_data< ValueType, IndexType >::matrix_data (
            dim< 2 > size_,
            RandomDistribution && dist,
            RandomEngine && engine )  [inline]
```

Initializes a matrix with random values from the specified distribution.

Template Parameters

RandomDistribution	random distribution type
RandomEngine	random engine type

Parameters

*size_*	dimensions of the matrix
dist	random distribution of the elements of the matrix
engine	random engine used to generate random values

```
        : size{size_}
    {
        for (size_type row = 0; row < size[0]; ++row) {
            for (size_type col = 0; col < size[1]; ++col) {
                const auto value =
                    detail::get_rand_value<ValueType>(dist, engine);
                if (value != zero<ValueType>()) {
                    nonzeros.emplace_back(row, col, value);
                }
            }
        }
    }
```

24.63.2.3 matrix_data() [3/6]

```
template<typename ValueType = default_precision, typename IndexType = int32>
gko::matrix_data< ValueType, IndexType >::matrix_data (
            std::initializer_list< std::initializer_list< ValueType >> values )  [inline]
```

List-initializes the structure from a matrix of values.

Parameters

values	a 2D braced-init-list of matrix values.

```
        : size{values.size(), 0}
```

```
    {
        for (size_type row = 0; row < values.size(); ++row) {
            const auto row_data = begin(values)[row];
            size[1] = std::max(size[1], row_data.size());
            for (size_type col = 0; col < row_data.size(); ++col) {
                const auto &val = begin(row_data)[col];
                if (val != zero<ValueType>()) {
                    nonzeros.emplace_back(row, col, val);
                }
            }
        }
    }
```

24.63.2.4 matrix_data() [4/6]

```
template<typename ValueType = default_precision, typename IndexType = int32>
gko::matrix_data< ValueType, IndexType >::matrix_data (
            dim< 2 > size_,
            std::initializer_list< detail::input_triple< ValueType, IndexType >> nonzeros_ )
[inline]
```

Initializes the structure from a list of nonzeros.

Parameters

*size_*	dimensions of the matrix
*nonzeros_*	list of nonzero elements

```
        : size{size_}, nonzeros()
    {
        nonzeros.reserve(nonzeros_.size());
        for (const auto &elem : nonzeros_) {
            nonzeros.emplace_back(elem.row, elem.col, elem.val);
        }
    }
```

24.63.2.5 matrix_data() [5/6]

```
template<typename ValueType = default_precision, typename IndexType = int32>
gko::matrix_data< ValueType, IndexType >::matrix_data (
            dim< 2 > size_,
            const matrix_data< ValueType, IndexType > & block )  [inline]
```

Initializes a matrix out of a matrix block via duplication.

Parameters

size	size of the block-matrix (in blocks)
diag_block	matrix block used to fill the complete matrix

References gko::matrix_data< ValueType, IndexType >::size.

```
        : size{size_ * block.size}
    {
        nonzeros.reserve(size_[0] * size_[1] * block.nonzeros.size());
        for (size_type row = 0; row < size_[0]; ++row) {
            for (size_type col = 0; col < size_[1]; ++col) {
                for (const auto &elem : block.nonzeros) {
                    nonzeros.emplace_back(row * block.size[0] + elem.row,
                                          col * block.size[1] + elem.column,
                                          elem.value);
                }
            }
        }
        this->ensure_row_major_order();
    }
```

24.63.2.6 matrix_data() [6/6]

```
template<typename ValueType = default_precision, typename IndexType = int32>
template<typename Accessor >
gko::matrix_data< ValueType, IndexType >::matrix_data (
            const range< Accessor > & data )  [inline]
```

Initializes a matrix from a range.

Template Parameters

Accessor	accessor type of the input range

Parameters

data	range used to initialize the matrix

References gko::range< Accessor >::length().

```
        : size{data.length(0), data.length(1)}
    {
        for (gko::size_type row = 0; row < size[0]; ++row) {
            for (gko::size_type col = 0; col < size[1]; ++col) {
                if (data(row, col) != zero<ValueType>()) {
                    nonzeros.emplace_back(row, col, data(row, col));
                }
            }
        }
    }
```

24.63.3 Member Function Documentation

24.63.3.1 cond() [1/2]

```
template<typename ValueType = default_precision, typename IndexType = int32>
template<typename RandomDistribution , typename RandomEngine >
static matrix_data gko::matrix_data< ValueType, IndexType >::cond (
            size_type size,
            remove_complex< ValueType > condition_number,
            RandomDistribution && dist,
            RandomEngine && engine,
            size_type num_reflectors )  [inline], [static]
```

Initializes a random dense matrix with a specific condition number.

The matrix is generated by applying a series of random Hausholder reflectors to a diagonal matrix with diagonal entries uniformly distributed between `sqrt(condition_number)` and `1/sqrt(condition_number)`.

Template Parameters

RandomDistribution	the type of the random distribution
RandomEngine	the type of the random engine

Parameters

size	number of rows and columns of the matrix
condition_number	condition number of the matrix
dist	random distribution used to generate reflectors
engine	random engine used to generate reflectors
num_reflectors	number of reflectors to apply from each side

Returns

the dense matrix with the specified condition number

```
{
    using range = range<accessor::row_major<ValueType, 2>>;
    std::vector<ValueType> mtx_data(size * size, zero<ValueType>());
    std::vector<ValueType> ref_data(size);
    std::vector<ValueType> work(size);
    range matrix(mtx_data.data(), size, size, size);
    range reflector(ref_data.data(), size, 1u, 1u);

    initialize_diag_with_cond(condition_number, matrix);
    for (size_type i = 0; i < num_reflectors; ++i) {
        generate_random_reflector(dist, engine, reflector);
        reflect_domain(reflector, matrix, work.data());
        generate_random_reflector(dist, engine, reflector);
        reflect_range(reflector, matrix, work.data());
    }
    return matrix;
}
```

24.63.3.2 cond() [2/2]

```
template<typename ValueType = default_precision, typename IndexType = int32>
template<typename RandomDistribution , typename RandomEngine >
```

```
static matrix_data gko::matrix_data< ValueType, IndexType >::cond (
            size_type size,
            remove_complex< ValueType > condition_number,
            RandomDistribution && dist,
            RandomEngine && engine ) [inline], [static]
```

Initializes a random dense matrix with a specific condition number.

The matrix is generated by applying a series of random Hausholder reflectors to a diagonal matrix with diagonal entries uniformly distributed between `sqrt(condition_number)` and `1/sqrt(condition_number)`.

This version of the function applies `size - 1` reflectors to each side of the diagonal matrix.

Template Parameters

RandomDistribution	the type of the random distribution
RandomEngine	the type of the random engine

Parameters

size	number of rows and columns of the matrix
condition_number	condition number of the matrix
dist	random distribution used to generate reflectors
engine	random engine used to generate reflectors

Returns

the dense matrix with the specified condition number

```
{
    return cond(size, condition_number,
                std::forward<RandomDistribution>(dist),
                std::forward<RandomEngine>(engine), size - 1);
}
```

24.63.3.3 diag() [1/5]

```
template<typename ValueType = default_precision, typename IndexType = int32>
static matrix_data gko::matrix_data< ValueType, IndexType >::diag (
            dim< 2 > size_,
            ValueType value ) [inline], [static]
```

Initializes a diagonal matrix.

Parameters

*size_*	dimensions of the matrix
value	value used to fill the elements of the matrix

Returns

the diagonal matrix

References gko::matrix_data< ValueType, IndexType >::nonzeros.

```
{
    matrix_data res(size_);
    if (value != zero<ValueType>()) {
        const auto num_nnz = std::min(size_[0], size_[1]);
        res.nonzeros.reserve(num_nnz);
        for (size_type i = 0; i < num_nnz; ++i) {
            res.nonzeros.emplace_back(i, i, value);
        }
    }
    return res;
}
```

24.63.3.4 diag() [2/5]

```
template<typename ValueType = default_precision, typename IndexType = int32>
static matrix_data gko::matrix_data< ValueType, IndexType >::diag (
            dim< 2 > size_,
            std::initializer_list< ValueType > nonzeros_ )  [inline], [static]
```

Initializes a diagonal matrix using a list of diagonal elements.

Parameters

*size_*	dimensions of the matrix
*nonzeros_*	list of diagonal elements

Returns

the diagonal matrix

References gko::matrix_data< ValueType, IndexType >::nonzeros.

```
{
    matrix_data res(size_);
    res.nonzeros.reserve(nonzeros_.size());
    int pos = 0;
    for (auto value : nonzeros_) {
        res.nonzeros.emplace_back(pos, pos, value);
        ++pos;
    }
    return res;
}
```

24.63.3.5 diag() [3/5]

```
template<typename ValueType = default_precision, typename IndexType = int32>
static matrix_data gko::matrix_data< ValueType, IndexType >::diag (
            dim< 2 > size_,
            const matrix_data< ValueType, IndexType > & block )  [inline], [static]
```

Initializes a block-diagonal matrix.

Parameters

*size_*	the size of the matrix
diag_block	matrix used to fill diagonal blocks

Returns

the block-diagonal matrix

References gko::matrix_data< ValueType, IndexType >::nonzeros, and gko::matrix_data< ValueType, IndexType >::size.

```
{
    matrix_data res(size_ * block.size);
    const auto num_blocks = std::min(size_[0], size_[1]);
    res.nonzeros.reserve(num_blocks * block.nonzeros.size());
    for (size_type b = 0; b < num_blocks; ++b) {
        for (const auto &elem : block.nonzeros) {
            res.nonzeros.emplace_back(b * block.size[0] + elem.row,
                                      b * block.size[1] + elem.column,
                                      elem.value);
        }
    }
    return res;
}
```

24.63.3.6 diag() [4/5]

```
template<typename ValueType = default_precision, typename IndexType = int32>
template<typename ForwardIterator >
static matrix_data gko::matrix_data< ValueType, IndexType >::diag (
            ForwardIterator begin,
            ForwardIterator end )  [inline], [static]
```

Initializes a block-diagonal matrix from a list of diagonal blocks.

Template Parameters

ForwardIterator	type of list iterator

Parameters

begin	the first iterator of the list
end	the last iterator of the list

Returns

the block-diagonal matrix with diagonal blocks set to the blocks between begin (inclusive) and end (exclusive)

References gko::matrix_data< ValueType, IndexType >::nonzeros.

```
    {
        matrix_data res(std::accumulate(
            begin, end, dim<2>{}, [](dim<2> s, const matrix_data &d) {
                return dim<2>{s[0] + d.size[0], s[1] + d.size[1]};
            }));

        size_type row_offset{};
        size_type col_offset{};
        for (auto it = begin; it != end; ++it) {
            for (const auto &elem : it->nonzeros) {
                res.nonzeros.emplace_back(row_offset + elem.row,
                                          col_offset + elem.column, elem.value);
            }
            row_offset += it->size[0];
            col_offset += it->size[1];
        }

        return res;
    }
```

24.63.3.7 diag() [5/5]

```
template<typename ValueType = default_precision, typename IndexType = int32>
static matrix_data gko::matrix_data< ValueType, IndexType >::diag (
            std::initializer_list< matrix_data< ValueType, IndexType > > blocks )  [inline],
[static]
```

Initializes a block-diagonal matrix from a list of diagonal blocks.

Parameters

blocks	a list of blocks to initialize from

Returns

the block-diagonal matrix with diagonal blocks set to the blocks passed in blocks

```
    {
        return diag(begin(blocks), end(blocks));
    }
```

24.63.4 Member Data Documentation

24.63.4.1 nonzeros

```
template<typename ValueType = default_precision, typename IndexType = int32>
std::vector<nonzero_type> gko::matrix_data< ValueType, IndexType >::nonzeros
```

A vector of tuples storing the non-zeros of the matrix.

The first two elements of the tuple are the row index and the column index of a matrix element, and its third element is the value at that position.

Referenced by gko::matrix_data< ValueType, IndexType >::diag().

The documentation for this struct was generated from the following file:

- ginkgo/core/base/matrix_data.hpp (4bde4271)

24.64 gko::matrix::Hybrid< ValueType, IndexType >::minimal_storage_limit Class Reference

minimal_storage_limit is a stratgy_type which decides the number of stored elements per row of the ell part.

`#include <ginkgo/core/matrix/hybrid.hpp>`

Public Member Functions

- minimal_storage_limit ()
  Creates a minimal_storage_limit strategy.
- size_type compute_ell_num_stored_elements_per_row (Array< size_type > *row_nnz) const override
  Computes the number of stored elements per row of the ell part.

24.64.1 Detailed Description

template<typename ValueType = default_precision, typename IndexType = int32>
class gko::matrix::Hybrid< ValueType, IndexType >::minimal_storage_limit

minimal_storage_limit is a stratgy_type which decides the number of stored elements per row of the ell part.

It is determined by the size of ValueType and IndexType, the storage is the minimum among all partition.

24.64.2 Member Function Documentation

24.64.2.1 compute_ell_num_stored_elements_per_row()

```
template<typename ValueType = default_precision, typename IndexType = int32>
size_type gko::matrix::Hybrid< ValueType, IndexType >::minimal_storage_limit::compute_ell_↩
num_stored_elements_per_row (
            Array< size_type > * row_nnz ) const  [inline], [override], [virtual]
```

Computes the number of stored elements per row of the ell part.

Parameters

row_nnz	the number of nonzeros of each row

Returns

the number of stored elements per row of the ell part

Implements gko::matrix::Hybrid< ValueType, IndexType >::strategy_type.

```
        {
            return strategy_.compute_ell_num_stored_elements_per_row
    (row_nnz);
        }
```

The documentation for this class was generated from the following file:

- ginkgo/core/matrix/hybrid.hpp (3e51a52b)

24.65 gko::matrix_data< ValueType, IndexType >::nonzero_type Struct Reference

Type used to store nonzeros.

```
#include <ginkgo/core/base/matrix_data.hpp>
```

24.65.1 Detailed Description

template< typename ValueType = default_precision, typename IndexType = int32 >
struct gko::matrix_data< ValueType, IndexType >::nonzero_type

Type used to store nonzeros.

The documentation for this struct was generated from the following file:

- ginkgo/core/base/matrix_data.hpp (4bde4271)

24.66 gko::NotCompiled Class Reference

NotCompiled is thrown when attempting to call an operation which is a part of a module that was not compiled on the system.

```
#include <ginkgo/core/base/exception.hpp>
```

Public Member Functions

- NotCompiled (const std::string &file, int line, const std::string &func, const std::string &module)
  Initializes a NotCompiled error.

24.66.1 Detailed Description

NotCompiled is thrown when attempting to call an operation which is a part of a module that was not compiled on the system.

24.66.2 Constructor & Destructor Documentation

24.66.2.1 NotCompiled()

```
gko::NotCompiled::NotCompiled (
            const std::string & file,
            int line,
            const std::string & func,
            const std::string & module )  [inline]
```

Initializes a NotCompiled error.

Parameters

file	The name of the offending source file
line	The source code line number where the error occurred
func	The name of the function that has not been compiled
module	The name of the module which contains the function

```
        : Error(file, line,
                "feature " + func + " is part of the " + module +
                    " module, which is not compiled on this system")
    {}
```

The documentation for this class was generated from the following file:

- ginkgo/core/base/exception.hpp (8fbad33a)

24.67 gko::NotImplemented Class Reference

NotImplemented is thrown in case an operation has not yet been implemented (but will be implemented in the future).

`#include <ginkgo/core/base/exception.hpp>`

Public Member Functions

- NotImplemented (const std::string &file, int line, const std::string &func)
  Initializes a NotImplemented error.

24.67.1 Detailed Description

NotImplemented is thrown in case an operation has not yet been implemented (but will be implemented in the future).

24.67.2 Constructor & Destructor Documentation

24.67.2.1 NotImplemented()

```
gko::NotImplemented::NotImplemented (
            const std::string & file,
            int line,
            const std::string & func )   [inline]
```

Initializes a NotImplemented error.

Parameters

file	The name of the offending source file
line	The source code line number where the error occurred
func	The name of the not-yet implemented function

```
        : Error(file, line, func + " is not implemented")
    {}
```

The documentation for this class was generated from the following file:

- ginkgo/core/base/exception.hpp (8fbad33a)

24.68 gko::NotSupported Class Reference

NotSupported is thrown in case it is not possible to perform the requested operation on the given object type.

```
#include <ginkgo/core/base/exception.hpp>
```

Public Member Functions

- NotSupported (const std::string &file, int line, const std::string &func, const std::string &obj_type)
    Initializes a NotSupported error.

24.68.1 Detailed Description

NotSupported is thrown in case it is not possible to perform the requested operation on the given object type.

24.68.2 Constructor & Destructor Documentation

24.68.2.1 NotSupported()

```
gko::NotSupported::NotSupported (
            const std::string & file,
            int line,
            const std::string & func,
            const std::string & obj_type )  [inline]
```

Initializes a NotSupported error.

Parameters

file	The name of the offending source file
line	The source code line number where the error occurred
func	The name of the function where the error occured
obj_type	The object type on which the requested operation cannot be performed.

```
        : Error(file, line,
                "Operation " + func + " does not support parameters of type " +
                    obj_type)
    {}
```

The documentation for this class was generated from the following file:

- ginkgo/core/base/exception.hpp (8fbad33a)

24.69 gko::null_deleter< T > Class Template Reference

This is a deleter that does not delete the object.

```
#include <ginkgo/core/base/utils.hpp>
```

Public Member Functions

- void operator() (pointer) const noexcept
  Deletes the object.

24.69.1 Detailed Description

template<typename T>
class gko::null_deleter< T >

This is a deleter that does not delete the object.

It is useful where the object has been allocated elsewhere and will be deleted manually.

24.69.2 Member Function Documentation

24.69.2.1 operator()()

```
template<typename T >
void gko::null_deleter< T >::operator() (
            pointer ) const [inline], [noexcept]
```

Deletes the object.

Parameters

ptr	pointer to the object being deleted

```
334 {}
```

The documentation for this class was generated from the following file:

- ginkgo/core/base/utils.hpp (4bde4271)

24.70 gko::OmpExecutor Class Reference

This is the Executor subclass which represents the OpenMP device (typically CPU).

`#include <ginkgo/core/base/executor.hpp>`

Public Member Functions

- std::shared_ptr< Executor > get_master () noexcept override

    Returns the master OmpExecutor of this Executor.
- std::shared_ptr< const Executor > get_master () const noexcept override

    Returns the master OmpExecutor of this Executor.
- void synchronize () const override

    Synchronize the operations launched on the executor with its master.

Static Public Member Functions

- static std::shared_ptr< OmpExecutor > create ()

    Creates a new OmpExecutor.

24.70.1 Detailed Description

This is the Executor subclass which represents the OpenMP device (typically CPU).

24.70.2 Member Function Documentation

24.70.2.1 get_master() [1/2]

```
std::shared_ptr<Executor> gko::OmpExecutor::get_master ( )  [override], [virtual], [noexcept]
```

Returns the master OmpExecutor of this Executor.

Returns

the master OmpExecutor of this Executor.

Implements gko::Executor.

24.70.2.2 get_master() [2/2]

```
std::shared_ptr<const Executor> gko::OmpExecutor::get_master ( ) const  [override], [virtual],
[noexcept]
```

Returns the master OmpExecutor of this Executor.

Returns

the master OmpExecutor of this Executor.

Implements gko::Executor.

The documentation for this class was generated from the following file:

- ginkgo/core/base/executor.hpp (f1a4eb68)

24.71 gko::Operation Class Reference

Operations can be used to define functionalities whose implementations differ among devices.

```
#include <ginkgo/core/base/executor.hpp>
```

Public Member Functions

- virtual const char ∗ get_name () const noexcept

  Returns the operation's name.

24.71.1 Detailed Description

Operations can be used to define functionalities whose implementations differ among devices.

This is done by extending the Operation class and implementing the overloads of the Operation::run() method for all Executor types. When invoking the Executor::run() method with the Operation as input, the library will select the Operation::run() overload corresponding to the dynamic type of the Executor instance.

Consider an overload of `operator<<` for Executors, which prints some basic device information (e.g. device type and id) of the Executor to a C++ stream:

```
std::ostream& operator<<(std::ostream &os, const gko::Executor &exec);
```

One possible implementation would be to use RTTI to find the dynamic type of the Executor, However, using the Operation feature of Ginkgo, there is a more elegant approach which utilizes polymorphism. The first step is to define an Operation that will print the desired information for each Executor type.

```
class DeviceInfoPrinter : public gko::Operation {
public:
    explicit DeviceInfoPrinter(std::ostream &os) : os_(os) {}

    void run(const gko::OmpExecutor *) const override { os_ << "OMP"; }

    void run(const gko::CudaExecutor *exec) const override
    { os_ << "CUDA(" << exec->get_device_id() << ")"; }

    // This is optional, if not overloaded, defaults to OmpExecutor overload
    void run(const gko::ReferenceExecutor *) const override
    { os_ << "Reference CPU"; }

private:
    std::ostream &os_;
};
```

Using DeviceInfoPrinter, the implementation of `operator<<` is as simple as calling the run() method of the executor.

```
std::ostream& operator<<(std::ostream &os, const gko::Executor &exec)
{
    DeviceInfoPrinter printer(os);
    exec.run(printer);
    return os;
}
```

Now it is possible to write the following code:

```
auto omp = gko::OmpExecutor::create();
std::cout << *omp << std::endl
          << *gko::CudaExecutor::create(0, omp) << std::endl
          << *gko::ReferenceExecutor::create() << std::endl;
```

which produces the expected output:

```
OMP
CUDA(0)
Reference CPU
```

One might feel that this code is too complicated for such a simple task. Luckily, there is an overload of the Executor::run() method, which is designed to facilitate writing simple operations like this one. The method takes two closures as input: one which is run for OMP, and the other one for CUDA executors. Using this method, there is no need to implement an Operation subclass:

```
std::ostream& operator<<(std::ostream &os, const gko::Executor &exec)
{
    exec.run(
        [&]() { os << "OMP"; },  // OMP closure
        [&]() { os << "CUDA("    // CUDA closure
                   << static_cast<gko::CudaExecutor&>(exec)
                        .get_device_id()
                   << ")"; });
    return os;
}
```

Using this approach, however, it is impossible to distinguish between a OmpExecutor and ReferenceExecutor, as both of them call the OMP closure.

24.71.2 Member Function Documentation

24.71.2.1 get_name()

```
virtual const char* gko::Operation::get_name ( ) const  [virtual], [noexcept]
```

Returns the operation's name.

Returns

the operation's name

The documentation for this class was generated from the following file:

- ginkgo/core/base/executor.hpp (f1a4eb68)

24.72 gko::log::operation_data Struct Reference

Struct representing Operator related data.

```
#include <ginkgo/core/log/record.hpp>
```

24.72.1 Detailed Description

Struct representing Operator related data.

The documentation for this struct was generated from the following file:

- ginkgo/core/log/record.hpp (f0a50f96)

24.73 gko::OutOfBoundsError Class Reference

OutOfBoundsError is thrown if a memory access is detected to be out-of-bounds.

```
#include <ginkgo/core/base/exception.hpp>
```

Public Member Functions

- OutOfBoundsError (const std::string &file, int line, size_type index, size_type bound)
  Initializes an OutOfBoundsError.

24.73.1 Detailed Description

OutOfBoundsError is thrown if a memory access is detected to be out-of-bounds.

24.73.2 Constructor & Destructor Documentation

24.73.2.1 OutOfBoundsError()

```
gko::OutOfBoundsError::OutOfBoundsError (
            const std::string & file,
            int line,
            size_type index,
            size_type bound )  [inline]
```

Initializes an OutOfBoundsError.

Parameters

file	The name of the offending source file
line	The source code line number where the error occurred
index	The position that was accessed
bound	The first out-of-bound index

```
        : Error(file, line,
                "trying to access index " + std::to_string(index) +
                    " in a memory block of " + std::to_string(bound) +
                    " elements")
    {}
```

The documentation for this class was generated from the following file:

- ginkgo/core/base/exception.hpp (8fbad33a)

24.74 gko::factorization::ParIlu< ValueType, IndexType > Class Template Reference

ParILU is an incomplete LU factorization which is computed in parallel.

```
#include <ginkgo/core/factorization/par_ilu.hpp>
```

Additional Inherited Members

24.74.1 Detailed Description

template<typename ValueType = default_precision, typename IndexType = int32>
class gko::factorization::ParIlu< ValueType, IndexType >

ParILU is an incomplete LU factorization which is computed in parallel.

L is a lower unitriangular, while U is an upper triangular matrix, which approximate a given matrix A with $A \approx LU$. Here, L and U have the same sparsity pattern as A, which is also called ILU(0).

The ParILU algorithm generates the incomplete factors iteratively, using a fixed-point iteration of the form

$$F(L,U) = \begin{cases} \frac{1}{u_{jj}} \left(a_{ij} - \sum_{k=1}^{j-1} l_{ik} u_{kj}\right), & i > j \\ a_{ij} - \sum_{k=1}^{i-1} l_{ik} u_{kj}, & i \leq j \end{cases}$$

In general, the entries of L and U can be iterated in parallel and in asynchronous fashion, the algorithm asymptotically converges to the incomplete factors L and U fulfilling $(R = A - L \cdot U)\vert_{\mathcal{S}} = 0\vert_{\mathcal{S}}$ where $\mathcal{S}$ is the pre-defined sparsity pattern (in case of ILU(0) the sparsity pattern of the system matrix A). The number of ParILU sweeps needed for convergence depends on the parallelism level: For sequential execution, a single sweep is sufficient, for fine-grained parallelism, 3 sweeps are typically generating a good approximation.

The ParILU algorithm in Ginkgo follows the design of E. Chow and A. Patel, Fine-grained Parallel Incomplete LU Factorization, SIAM Journal on Scientific Computing, 37, C169-C193 (2015).

Template Parameters

ValueType	Type of the values of all matrices used in this class
IndexType	Type of the indices of all matrices used in this class

The documentation for this class was generated from the following file:

- ginkgo/core/factorization/par_ilu.hpp (50506722)

24.75 gko::Perturbation< ValueType > Class Template Reference

The Perturbation class can be used to construct a LinOp to represent the operation `(identity + scalar * basis * projector)`.

`#include <ginkgo/core/base/perturbation.hpp>`

Public Member Functions

- const std::shared_ptr< const LinOp > get_basis () const noexcept
  Returns the basis of the perturbation.
- const std::shared_ptr< const LinOp > get_projector () const noexcept
  Returns the projector of the perturbation.
- const std::shared_ptr< const LinOp > get_scalar () const noexcept
  Returns the scalar of the perturbation.

24.75.1 Detailed Description

template<typename ValueType = default_precision>
class gko::Perturbation< ValueType >

The Perturbation class can be used to construct a LinOp to represent the operation `(identity + scalar * basis * projector)`.

This operator adds a movement along a direction constructed by `basis` and `projector` on the LinOp. `projector` gives the coefficient of `basis` to decide the direction.

For example, the Householder matrix can be represented with the Perturbation operator as follows. If u is the Householder factor then we can generate the `Householder transformation`, H = (I - 2 u u∗). In this case, the parameters of Perturbation class are scalar = -2, basis = u, and projector = u∗.

Template Parameters

ValueType	precision of input and result vectors

Note

the apply operations of Perturbation class are not thread safe

24.75.2 Member Function Documentation

24.75.2.1 get_basis()

```
template<typename ValueType = default_precision>
const std::shared_ptr<const LinOp> gko::Perturbation< ValueType >::get_basis ( ) const [inline],
[noexcept]
```

Returns the basis of the perturbation.

Returns

the basis of the perturbation

```
{
    return basis_;
}
```

24.75.2.2 get_projector()

template<typename ValueType = default_precision>
const std::shared_ptr<const LinOp> gko::Perturbation< ValueType >::get_projector ( ) const
[inline], [noexcept]

Returns the projector of the perturbation.

Returns

the projector of the perturbation

```
{
    return projector_;
}
```

24.75.2.3 get_scalar()

template<typename ValueType = default_precision>
const std::shared_ptr<const LinOp> gko::Perturbation< ValueType >::get_scalar ( ) const [inline],
[noexcept]

Returns the scalar of the perturbation.

Returns

the scalar of the perturbation

References gko::lend(), and gko::one().

```
{
    return scalar_;
}
```

The documentation for this class was generated from the following file:

- ginkgo/core/base/perturbation.hpp (c923f483)

24.76 gko::log::polymorphic_object_data Struct Reference

Struct representing PolymorphicObject related data.

`#include <ginkgo/core/log/record.hpp>`

24.76.1 Detailed Description

Struct representing PolymorphicObject related data.

The documentation for this struct was generated from the following file:

- ginkgo/core/log/record.hpp (f0a50f96)

24.77 gko::PolymorphicObject Class Reference

A PolymorphicObject is the abstract base for all "heavy" objects in Ginkgo that behave polymorphically.

`#include <ginkgo/core/base/polymorphic_object.hpp>`

Public Member Functions

- std::unique_ptr< PolymorphicObject > create_default (std::shared_ptr< const Executor > exec) const
  Creates a new "default" object of the same dynamic type as this object.
- std::unique_ptr< PolymorphicObject > create_default () const
  Creates a new "default" object of the same dynamic type as this object.
- std::unique_ptr< PolymorphicObject > clone (std::shared_ptr< const Executor > exec) const
  Creates a clone of the object.
- std::unique_ptr< PolymorphicObject > clone () const
  Creates a clone of the object.
- PolymorphicObject * copy_from (const PolymorphicObject *other)
  Copies another object into this object.
- PolymorphicObject * copy_from (std::unique_ptr< PolymorphicObject > other)
  Moves another object into this object.
- PolymorphicObject * clear ()
  Transforms the object into its default state.
- std::shared_ptr< const Executor > get_executor () const noexcept
  Returns the Executor of the object.

24.77.1 Detailed Description

A PolymorphicObject is the abstract base for all "heavy" objects in Ginkgo that behave polymorphically.

It defines the basic utilities (copying moving, cloning, clearing the objects) for all such objects. It takes into account that these objects are dynamically allocated, managed by smart pointers, and used polymorphically. Additionally, it assumes their data can be allocated on different executors, and that they can be copied between those executors.

Note

Most of the public methods of this class should not be overridden directly, and are thus not virtual. Instead, there are equivalent protected methods (ending in <method_name>_impl) that should be overriden instead. This allows polymorphic objects to implement default behavior around virtual methods (parameter checking, type casting).

See also

EnablePolymorphicObject if you wish to implement a concrete polymorphic object and have sensible defaults generated automatically. EnableAbstractPolymorphicObject if you wish to implement a new abstract polymorphic object, and have the return types of the methods updated to your type (instead of having them return PolymorphicObject).

24.77.2 Member Function Documentation

24.77.2.1 clear()

```
PolymorphicObject* gko::PolymorphicObject::clear ( ) [inline]
```

Transforms the object into its default state.

Equivalent to `this->copy_from(this->create_default())`.

See also

clear_impl() when implementing this method

Returns

this

```
{ return this->clear_impl(); }
```

24.77.2.2 clone() [1/2]

```
std::unique_ptr<PolymorphicObject> gko::PolymorphicObject::clone (
        std::shared_ptr< const Executor > exec ) const [inline]
```

Creates a clone of the object.

This is the polymorphic equivalent of the *executor copy constructor* `decltype(*this)(exec, this)`.

Parameters

exec	the executor where the clone will be created

Returns

A clone of the LinOp.

References create_default().

```
{
    auto new_op = this->create_default(exec);
    new_op->copy_from(this);
    return new_op;
}
```

24.77.2.3 clone() [2/2]

```
std::unique_ptr<PolymorphicObject> gko::PolymorphicObject::clone ( ) const [inline]
```

Creates a clone of the object.

This is a shorthand for clone(std::shared_ptr<const Executor>) that uses the executor of this object to construct the new object.

Returns

A clone of the LinOp.

```
{
    return this->clone(exec_);
}
```

24.77.2.4 copy_from() [1/2]

```
PolymorphicObject* gko::PolymorphicObject::copy_from (
            const PolymorphicObject * other ) [inline]
```

Copies another object into this object.

This is the polymorphic equivalent of the copy assignment operator.

See also

copy_from_impl(const PolymorphicObject ∗)

Parameters

other	the object to copy

Returns

this

```
{
    this->template log<log::Logger::polymorphic_object_copy_started>(
        exec_.get(), other, this);
    auto copied = this->copy_from_impl(other);
    this->template log<log::Logger::polymorphic_object_copy_completed>(
        exec_.get(), other, this);
    return copied;
}
```

24.77.2.5 copy_from() [2/2]

```
PolymorphicObject* gko::PolymorphicObject::copy_from (
            std::unique_ptr< PolymorphicObject > other ) [inline]
```

Moves another object into this object.

This is the polymorphic equivalent of the move assignment operator.

See also

copy_from_impl(std::unique_ptr<PolymorphicObject>)

Parameters

other	the object to move from

Returns

this

```
{
    this->template log<log::Logger::polymorphic_object_copy_started>(
        exec_.get(), other.get(), this);
    auto copied = this->copy_from_impl(std::move(other));
    this->template log<log::Logger::polymorphic_object_copy_completed>(
        exec_.get(), other.get(), this);
    return copied;
}
```

24.77.2.6 create_default() [1/2]

```
std::unique_ptr<PolymorphicObject> gko::PolymorphicObject::create_default (
            std::shared_ptr< const Executor > exec ) const [inline]
```

Creates a new "default" object of the same dynamic type as this object.

This is the polymorphic equivalent of the *executor default constructor* `decltype(*this)(exec);`.

Parameters

exec	the executor where the object will be created

Returns

a polymorphic object of the same type as this

```
{
    this->template log<log::Logger::polymorphic_object_create_started>(
        exec_.get(), this);
    auto created = this->create_default_impl(std::move(exec));
```

```
        this->template log<log::Logger::polymorphic_object_create_completed>(
            exec_.get(), this, created.get());
        return created;
    }
```

24.77.2.7 create_default() [2/2]

```
std::unique_ptr<PolymorphicObject> gko::PolymorphicObject::create_default ( ) const  [inline]
```

Creates a new "default" object of the same dynamic type as this object.

This is a shorthand for create_default(std::shared_ptr<const Executor>) that uses the executor of this object to construct the new object.

Returns

a polymorphic object of the same type as this

Referenced by clone().

```
    {
        return this->create_default(exec_);
    }
```

24.77.2.8 get_executor()

```
std::shared_ptr<const Executor> gko::PolymorphicObject::get_executor ( ) const  [inline],
[noexcept]
```

Returns the Executor of the object.

Returns

Executor of the object

Referenced by gko::matrix::Dense< ValueType >::add_scaled(), gko::matrix::Coo< ValueType, IndexType >::apply2(), gko::matrix::Dense< ValueType >::compute_dot(), gko::matrix::Dense< ValueType >::compute_norm2(), gko::matrix::Dense< ValueType >::create_submatrix(), gko::solver::Gmres< ValueType >::get_krylov_dim(), gko::solver::Cgs< ValueType >::get_preconditioner(), gko::solver::Cg< ValueType >::get_preconditioner(), gko::solver::Fcg< ValueType >::get_preconditioner(), gko::solver::Bicgstab< ValueType >::get_preconditioner(), gko::solver::LowerTrs< ValueType, IndexType >::get_preconditioner(), gko::solver::UpperTrs< ValueType, IndexType >::get_preconditioner(), gko::solver::Ir< ValueType >::get_solver(), and gko::matrix::Dense< ValueType >::scale().

```
    {
        return exec_;
    }
```

The documentation for this class was generated from the following file:

- ginkgo/core/base/polymorphic_object.hpp (3f08cf0a)

24.78 gko::precision_reduction Class Reference

This class is used to encode storage precisions of low precision algorithms.

`#include <ginkgo/core/base/types.hpp>`

Public Types

- using storage_type = uint8

    The underlying datatype used to store the encoding.

Public Member Functions

- constexpr precision_reduction () noexcept

    Creates a default precision_reduction encoding.
- constexpr precision_reduction (storage_type preserving, storage_type nonpreserving) noexcept

    Creates a precision_reduction encoding with the specified number of conversions.
- constexpr operator storage_type () const noexcept

    Extracts the raw data of the encoding.
- constexpr storage_type get_preserving () const noexcept

    Returns the number of preserving conversions in the encoding.
- constexpr storage_type get_nonpreserving () const noexcept

    Returns the number of non-preserving conversions in the encoding.

Static Public Member Functions

- static constexpr precision_reduction autodetect () noexcept

    Returns a special encoding which instructs the algorithm to automatically detect the best precision.
- static constexpr precision_reduction common (precision_reduction x, precision_reduction y) noexcept

    Returns the common encoding of input encodings.

24.78.1 Detailed Description

This class is used to encode storage precisions of low precision algorithms.

Some algorithms in Ginkgo can improve their performance by storing parts of the data in lower precision, while doing computation in full precision. This class is used to encode the precisions used to store the data. From the user's perspective, some algorithms can provide a parameter for fine-tuning the storage precision. Commonly, the special value returned by precision_reduction::autodetect() should be used to allow the algorithm to automatically choose an appropriate value, though manually selected values can be used for fine-tuning.

In general, a lower precision floating point value can be obtained by either dropping some of the insignificant bits of the significand (keeping the same number of exponent bits, and thus preserving the range of representable values) or using one of the hardware or software supported conversions between IEEE formats, such as double to float or float to half (reducing both the number of exponent, as well as significand bits, and thus decreasing the range of representable values).

The precision_reduction class encodes the lower precision format relative to the base precision used and the algorithm in question. The encoding is done by specifying the amount of range non-preserving conversions and the amount of range preserving conversions that should be done on the base precision to obtain the lower precision format. For example, starting with a double precision value (11 exp, 52 sig. bits), the encoding specifying 1 non-preserving conversion and 1 preserving conversion would first use a hardware-supported non-preserving conversion to obtain a single precision value (8 exp, 23 sig. bits), followed by a preserving bit truncation to obtain a value with 8 exponent and 7 significand bits. Note that non-preserving conversion are always done first, as preserving conversions usually result in datatypes that are not supported by builtin conversions (thus, it is generally not possible to apply a non-preserving conversion to the result of a preserving conversion).

If the specified conversion is not supported by the algorithm, it will most likely fall back to using full precision for storing the data. Refer to the documentation of specific algorithms using this class for details about such special cases.

24.78.2 Constructor & Destructor Documentation

24.78.2.1 precision_reduction() [1/2]

```
constexpr gko::precision_reduction::precision_reduction ( )  [inline], [noexcept]
```

Creates a default precision_reduction encoding.

This encoding represents the case where no conversions are performed.

Referenced by common().

```
: data_{0x0} {}
```

24.78.2.2 precision_reduction() [2/2]

```
constexpr gko::precision_reduction::precision_reduction (
            storage_type preserving,
            storage_type nonpreserving )  [inline], [noexcept]
```

Creates a precision_reduction encoding with the specified number of conversions.

Parameters

preserving	the number of range preserving conversion
nonpreserving	the number of range non-preserving conversions

```
        : data_((GKO_ASSERT(preserving < (0x1 << preserving_bits) - 1),
                 GKO_ASSERT(nonpreserving < (0x1 << nonpreserving_bits) - 1),
                 (preserving << nonpreserving_bits) | nonpreserving))
    {}
```

24.78.3 Member Function Documentation

24.78.3.1 autodetect()

```
static constexpr precision_reduction gko::precision_reduction::autodetect ( )  [inline], [static],
[noexcept]
```

Returns a special encoding which instructs the algorithm to automatically detect the best precision.

Returns

a special encoding instructing the algorithm to automatically detect the best precision.

```
{
    return precision_reduction{preserving_mask | nonpreserving_mask};
}
```

24.78.3.2 common()

```
static constexpr precision_reduction gko::precision_reduction::common (
            precision_reduction x,
            precision_reduction y )  [inline], [static], [noexcept]
```

Returns the common encoding of input encodings.

The common encoding is defined as the encoding that does not have more preserving, nor non-preserving conversions than the input encodings.

Parameters

x	an encoding
y	an encoding

Returns

the common encoding of `x` and `y`

References precision_reduction().

```
{
    return precision_reduction(
        min(x.data_ & preserving_mask, y.data_ & preserving_mask) |
        min(x.data_ & nonpreserving_mask, y.data_ & nonpreserving_mask));
}
```

24.78.3.3 get_nonpreserving()

```
constexpr storage_type gko::precision_reduction::get_nonpreserving ( ) const [inline], [noexcept]
```

Returns the number of non-preserving conversions in the encoding.

Returns

the number of non-preserving conversions in the encoding.

```
{
    return data_ & nonpreserving_mask;
}
```

24.78.3.4 get_preserving()

```
constexpr storage_type gko::precision_reduction::get_preserving ( ) const [inline], [noexcept]
```

Returns the number of preserving conversions in the encoding.

Returns

the number of preserving conversions in the encoding.

```
{
    return (data_ & preserving_mask) >> nonpreserving_bits;
}
```

24.78.3.5 operator storage_type()

```
constexpr gko::precision_reduction::operator storage_type ( ) const [inline], [noexcept]
```

Extracts the raw data of the encoding.

Returns

the raw data of the encoding

```
{
    return data_;
}
```

The documentation for this class was generated from the following file:

- ginkgo/core/base/types.hpp (4bde4271)

24.79 gko::Preconditionable Class Reference

A LinOp implementing this interface can be preconditioned.

`#include <ginkgo/core/base/lin_op.hpp>`

Public Member Functions

- virtual std::shared_ptr< const LinOp > get_preconditioner () const =0
  Returns the preconditioner operator used by the Preconditionable.

24.79.1 Detailed Description

A LinOp implementing this interface can be preconditioned.

24.79.2 Member Function Documentation

24.79.2.1 get_preconditioner()

```
virtual std::shared_ptr<const LinOp> gko::Preconditionable::get_preconditioner ( ) const
[pure virtual]
```

Returns the preconditioner operator used by the Preconditionable.

Returns

the preconditioner operator used by the Preconditionable

Implemented in gko::solver::LowerTrs< ValueType, IndexType >, gko::solver::UpperTrs< ValueType, IndexType >, gko::solver::Bicgstab< ValueType >, gko::solver::Fcg< ValueType >, gko::solver::Cg< ValueType >, gko::solver::Gmres< ValueType >, and gko::solver::Cgs< ValueType >.

The documentation for this class was generated from the following file:

- ginkgo/core/base/lin_op.hpp (fb72cdf1)

24.80 gko::range< Accessor > Class Template Reference

A range is a multidimensional view of the memory.

`#include <ginkgo/core/base/range.hpp>`

Public Types

- using accessor = Accessor

    The type of the underlying accessor.

Public Member Functions

- template<typename... AccessorParams>
  constexpr range (AccessorParams &&... params)

    Creates a new range.
- template<typename... DimensionTypes>
  constexpr auto operator() (DimensionTypes &&... dimensions) const -> decltype(std::declval< accessor >()(std::forward< DimensionTypes >(dimensions)...))

    Returns a value (or a sub-range) with the specified indexes.
- template<typename OtherAccessor >
  const range & operator= (const range< OtherAccessor > &other) const
- const range & operator= (const range &other) const

    Assigns another range to this range.
- constexpr size_type length (size_type dimension) const

    Returns the length of the specified dimension of the range.
- constexpr const accessor ∗ operator-> () const noexcept

    Returns a pointer to the accessor.
- constexpr const accessor & get_accessor () const noexcept

    'Returns a reference to the accessor.

Static Public Attributes

- static constexpr size_type dimensionality = accessor::dimensionality

    The number of dimensions of the range.

24.80.1 Detailed Description

template<typename Accessor>
class gko::range< Accessor >

A range is a multidimensional view of the memory.

The range does not store any of its values by itself. Instead, it obtains the values through an accessor (e.g. accessor::row_major) which describes how the indexes of the range map to physical locations in memory.

There are several advantages of using ranges instead of plain memory pointers:

1. Code using ranges is easier to read and write, as there is no need for index linearizations.
2. Code using ranges is safer, as it is impossible to accidentally miscalculate an index or step out of bounds, since range accessors perform bounds checking in debug builds. For performance, this can be disabled in release builds by defining the `NDEBUG` flag.
3. Ranges enable generalized code, as algorithms can be written independent of the memory layout. This does not impede various optimizations based on memory layout, as it is always possible to specialize algorithms for ranges with specific memory layouts.
4. Ranges have various pointwise operations predefined, which reduces the amount of loops that need to be written.

Range operations

Ranges define a complete set of pointwise unary and binary operators which extend the basic arithmetic operators in C++, as well as a few pointwise operations and mathematical functions useful in ginkgo, and a couple of non-pointwise operations. Compound assignment (+=, *=, etc.) is not yet supported at this moment. Here is a complete list of operations:

- standard unary operations: +, -, !, ~
- standard binary operations: +, * (this is pointwise, not matrix multiplication), /, %, <, >, <=, >=, ==, !=, ||, &&, |, &, ^, <<, >>
- useful unary functions: `zero`, `one`, `abs`, `real`, `imag`, `conj`, `squared_norm`
- useful binary functions: `min`, `max`

All binary pointwise operations also work as expected if one of the operands is a scalar and the other is a range. The scalar operand will have the effect as if it was a range of the same size as the other operand, filled with the specified scalar.

Two "global" functions `transpose` and `mmul` are also supported. `transpose` transposes the first two dimensions of the range (i.e. `transpose(r)(i, j, ...) == r(j, i, ...)`). `mmul` performs a (batched) matrix multiply of the ranges - the first two dimensions represent the matrices, while the rest represent the batch. For example, given the ranges `r1` and `r2` of dimensions `(3, 2, 3)` and `(2, 4, 3)`, respectively, `mmul(r1, r2)` will return a range of dimensions `(3, 4, 3)`, obtained by multiplying the 3 frontal slices of the range, and stacking the result back vertically.

Compound operations

Multiple range operations can be combined into a single expression. For example, an "axpy" operation can be obtained using `y = alpha * x + y`, where `x` an `y` are ranges, and `alpha` is a scalar. Range operations are optimized for memory access, and the above code does not allocate additional storage for intermediate ranges `alpha * x` or `aplha * x + y`. In fact, the entire computation is done during the assignment, and the results of operations + and * only register the data, and the types of operations that will be computed once the results are needed.

It is possible to store and reuse these intermediate expressions. The following example will overwrite the range `x` with it's 4th power:

```
{c++}
auto square = x * x;  // this is range constructor, not range assignment!
x = square;  // overwrites x with x*x (this is range assignment)
x = square;  // overwrites new x (x*x) with (x*x)*(x*x) (as is this)
```

Caveats

__`mmul` is not a highly-optimized BLAS-3 version of the matrix multiplication.__ The current design of ranges and accessors prevents that, so if you need a high-perfromance matrix multiplication, you should use one of the libraries that provide that, or implement your own (you can use pointwise range operations to help simplify that). However, range design might get improved in the future to allow efficient implementations of BLAS-3 kernels.

Aliasing the result range in `mmul` and `transpose` is not allowed. Constructs like `A = transpose(A)`, `A = mmul(A, A)`, or `A = mmul(A, A) + C` lead to undefined behavior. However, aliasing input arguments is allowed: `C = mmul(A, A)`, and even `C = mmul(A, A) + C` is valid code (in the last example, only pointwise operations are aliased). `C = mmul(A, A + C)` is not valid though.

Examples

The range unit tests in core/test/base/range.cpp contain lots of simple 1-line examples of range operations. The accessor unit tests in core/test/base/range.cpp show how to use ranges with concrete accessors, and how to use range slices using `span`s as arguments to range function call operator. Finally, examples/range contains a complete example where ranges are used to implement a simple version of the right-looking LU factorization.

Template Parameters

Accessor	underlying accessor of the range

24.80.2 Constructor & Destructor Documentation

24.80.2.1 range()

```
template<typename Accessor>
template<typename... AccessorParams>
constexpr gko::range< Accessor >::range (
            AccessorParams &&... params )  [inline], [explicit]
```

Creates a new range.

Template Parameters

AccessorParam	types of parameters forwarded to the accessor constructor

Parameters

params	parameters forwarded to Accessor constructor.

```
        : accessor_{std::forward<AccessorParams>(params)...}
    {}
```

24.80.3 Member Function Documentation

24.80.3.1 get_accessor()

```
template<typename Accessor>
constexpr const accessor& gko::range< Accessor >::get_accessor ( ) const  [inline], [noexcept]
```

'Returns a reference to the accessor.

Returns

reference to the accessor

Referenced by gko::range< Accessor >::operator=().

```
    {
        return accessor_;
    }
```

24.80.3.2 length()

```
template<typename Accessor>
constexpr size_type gko::range< Accessor >::length (
            size_type dimension ) const  [inline]
```

Returns the length of the specified dimension of the range.

Parameters

dimension	the dimensions whose length is returned

Returns

the length of the `dimension`-th dimension of the range

Referenced by gko::matrix_data< ValueType, IndexType >::ensure_row_major_order(), and gko::matrix_data< ValueType, IndexType >::matrix_data().

```
    {
        return accessor_.length(dimension);
    }
```

24.80.3.3 operator()()

```
template<typename Accessor>
template<typename... DimensionTypes>
constexpr auto gko::range< Accessor >::operator() (
            DimensionTypes &&... dimensions ) const -> decltype(std::declval<accessor>()(
std::forward<DimensionTypes>(dimensions)...))   [inline]
```

Returns a value (or a sub-range) with the specified indexes.

Template Parameters

DimensionTypes	The types of indexes. Supported types depend on the underlying accessor, but are usually either integer types or spans. If at least one index is a span, the returned value will be a sub-range.

Parameters

dimensions	the indexes of the values.

Returns

a value on position `(dimensions...)`.

```
    {
```

```
        static_assert(sizeof...(dimensions) <= dimensionality,
                      "Too many dimensions in range call");
        return accessor_(std::forward<DimensionTypes>(dimensions)...);
    }
```

24.80.3.4 operator->()

```
template<typename Accessor>
constexpr const accessor* gko::range< Accessor >::operator-> ( ) const  [inline], [noexcept]
```

Returns a pointer to the accessor.

Can be used to access data and functions of a specific accessor.

Returns

pointer to the accessor

```
    {
        return &accessor_;
    }
```

24.80.3.5 operator=() [1/2]

```
template<typename Accessor>
template<typename OtherAccessor >
const range& gko::range< Accessor >::operator= (
            const range< OtherAccessor > & other ) const  [inline]
```

This is a version of the function which allows to copy between ranges of different accessors.

Template Parameters

OtherAccessor	accessor of the other range

```
    {
        GKO_ASSERT(detail::equal_dimensions(*this, other));
        accessor_.copy_from(other);
        return *this;
    }
```

24.80.3.6 operator=() [2/2]

```
template<typename Accessor>
const range& gko::range< Accessor >::operator= (
            const range< Accessor > & other ) const  [inline]
```

Assigns another range to this range.

The order of assignment is defined by the accessor of this range, thus the memory access will be optimized for the resulting range, and not for the other range. If the sizes of two ranges do not match, the result is undefined. Sizes of the ranges are checked at runtime in debug builds.

Note

Temporary accessors are allowed to define the implementation of the assignment as deleted, so do not expect `r1 * r2 = r2` to work.

Parameters

other	the range to copy the data from

References gko::range< Accessor >::get_accessor().

```
{
    GKO_ASSERT(detail::equal_dimensions(*this, other));
    accessor_.copy_from(other.get_accessor());
    return *this;
}
```

The documentation for this class was generated from the following file:

- ginkgo/core/base/range.hpp (f1a4eb68)

24.81 gko::ReadableFromMatrixData< ValueType, IndexType > Class Template Reference

A LinOp implementing this interface can read its data from a matrix_data structure.

```
#include <ginkgo/core/base/lin_op.hpp>
```

Public Member Functions

- virtual void read (const matrix_data< ValueType, IndexType > &data)=0

    Reads a matrix from a matrix_data structure.

24.81.1 Detailed Description

template< typename ValueType, typename IndexType >
class gko::ReadableFromMatrixData< ValueType, IndexType >

A LinOp implementing this interface can read its data from a matrix_data structure.

24.81.2 Member Function Documentation

24.81.2.1 read()

```
template<typename ValueType, typename IndexType>
virtual void gko::ReadableFromMatrixData< ValueType, IndexType >::read (
            const matrix_data< ValueType, IndexType > & data )  [pure virtual]
```

Reads a matrix from a matrix_data structure.

Parameters

data	the matrix_data structure

Implemented in gko::matrix::Hybrid< ValueType, IndexType >, gko::matrix::Csr< ValueType, IndexType >, gko::matrix::Coo< ValueType, IndexType >, gko::matrix::Ell< ValueType, IndexType >, and gko::matrix::Sellp< ValueType, IndexType >.

The documentation for this class was generated from the following file:

- ginkgo/core/base/lin_op.hpp (fb72cdf1)

24.82 gko::log::Record Class Reference

Record is a Logger which logs every event to an object.

`#include <ginkgo/core/log/record.hpp>`

Classes

- struct logged_data

    Struct storing the actually logged data.

Public Member Functions

- const logged_data & get () const noexcept

    Returns the logged data.
- logged_data & get () noexcept

Static Public Member Functions

- static std::unique_ptr< Record > create (std::shared_ptr< const Executor > exec, const mask_type &enabled_events=Logger::all_events_mask, size_type max_storage=1)

    Creates a Record logger.

24.82.1 Detailed Description

Record is a Logger which logs every event to an object.

The object can then be accessed at any time by asking the logger to return it.

Note

Please note that this logger can have significant memory and performance overhead. In particular, when logging events such as the `check` events, all parameters are cloned. If it is sufficient to clone one parameter, consider implementing a specific logger for this. In addition, it is advised to tune the history size in order to control memory overhead.

24.82.2 Member Function Documentation

24.82.2.1 create()

```
static std::unique_ptr<Record> gko::log::Record::create (
            std::shared_ptr< const Executor > exec,
            const mask_type & enabled_events = Logger::all_events_mask,
            size_type max_storage = 1 ) [inline], [static]
```

Creates a Record logger.

This dynamically allocates the memory, constructs the object and returns an std::unique_ptr to this object.

Parameters

exec	the executor
enabled_events	the events enabled for this logger. By default all events.
max_storage	the size of storage (i.e. history) wanted by the user. By default 0 is used, which means unlimited storage. It is advised to control this to reduce memory overhead of this logger.

Returns

an std::unique_ptr to the the constructed object

```
{
    return std::unique_ptr<Record>(
        new Record(exec, enabled_events, max_storage));
}
```

24.82.2.2 get() [1/2]

```
const logged_data& gko::log::Record::get ( ) const [inline], [noexcept]
```

Returns the logged data.

Returns

the logged data

```
{ return data_; }
```

24.82.2.3 get() [2/2]

```
logged_data& gko::log::Record::get ( ) [inline], [noexcept]
```

```
412 { return data_; }
```

The documentation for this class was generated from the following file:

- ginkgo/core/log/record.hpp (f0a50f96)

24.83 gko::ReferenceExecutor Class Reference

This is a specialization of the OmpExecutor, which runs the reference implementations of the kernels used for debugging purposes.

`#include <ginkgo/core/base/executor.hpp>`

Public Member Functions

- void run (const Operation &op) const override

  Runs the specified Operation using this Executor.

Additional Inherited Members

24.83.1 Detailed Description

This is a specialization of the OmpExecutor, which runs the reference implementations of the kernels used for debugging purposes.

24.83.2 Member Function Documentation

24.83.2.1 run()

```
void gko::ReferenceExecutor::run (
            const Operation & op ) const [inline], [override], [virtual]
```

Runs the specified Operation using this Executor.

Parameters

op	the operation to run

Implements gko::Executor.

```
{
    this->template log<log::Logger::operation_launched>(this, &op);
    op.run(std::static_pointer_cast<const ReferenceExecutor>(
        this->shared_from_this()));
    this->template log<log::Logger::operation_completed>(this, &op);
}
```

The documentation for this class was generated from the following file:

- ginkgo/core/base/executor.hpp (f1a4eb68)

24.84 gko::stop::ResidualNormReduction< ValueType > Class Template Reference

The ResidualNormReduction class is a stopping criterion which stops the iteration process when the relative residual norm is below a certain threshold.

```
#include <ginkgo/core/stop/residual_norm_reduction.hpp>
```

24.84.1 Detailed Description

template<typename ValueType = default_precision>
class gko::stop::ResidualNormReduction< ValueType >

The ResidualNormReduction class is a stopping criterion which stops the iteration process when the relative residual norm is below a certain threshold.

For better performance, the checks are run thanks to kernels on the executor where the algorithm is executed.

Note

> To use this stopping criterion there are some dependencies. The constructor depends on `initial_residual` in order to compute the first relative residual norm. The check method depends on either the `residual_norm` or the `residual` being set. When any of those is not correctly provided, an exception ::gko::NotSupported() is thrown.

The documentation for this class was generated from the following file:

- ginkgo/core/stop/residual_norm_reduction.hpp (8045ac75)

24.85 gko::accessor::row_major< ValueType, Dimensionality > Class Template Reference

A row_major accessor is a bridge between a range and the row-major memory layout.

```
#include <ginkgo/core/base/range_accessors.hpp>
```

Public Types

- using value_type = ValueType

    Type of values returned by the accessor.
- using data_type = value_type *

    Type of underlying data storage.

Public Member Functions

- constexpr value_type & operator() (size_type row, size_type col) const

    Returns the data element at position (row, col)
- constexpr range< row_major > operator() (const span &rows, const span &cols) const

    Returns the sub-range spanning the range (rows, cols)
- constexpr size_type length (size_type dimension) const

    Returns the length in dimension `dimension`.
- template<typename OtherAccessor >
  void copy_from (const OtherAccessor &other) const

    Copies data from another accessor.

Public Attributes

- const data_type data

    Reference to the underlying data.
- const std::array< const size_type, dimensionality > lengths

    An array of dimension sizes.
- const size_type stride

    Distance between consecutive rows.

Static Public Attributes

- static constexpr size_type dimensionality = 2

    Number of dimensions of the accessor.

24.85.1 Detailed Description

template<typename ValueType, size_type Dimensionality>
class gko::accessor::row_major< ValueType, Dimensionality >

A row_major accessor is a bridge between a range and the row-major memory layout.

You should never try to explicitly create an instance of this accessor. Instead, supply it as a template parameter to a range, and pass the constructor parameters for this class to the range (it will forward it to this class).

Warning

The current implementation is incomplete, and only allows for 2-dimensional ranges.

Template Parameters

ValueType	type of values this accessor returns
Dimensionality	number of dimensions of this accessor (has to be 2)

24.85.2 Member Function Documentation

24.85.2.1 copy_from()

```
template<typename ValueType , size_type Dimensionality>
template<typename OtherAccessor >
void gko::accessor::row_major< ValueType, Dimensionality >::copy_from (
            const OtherAccessor & other ) const  [inline]
```

Copies data from another accessor.

Template Parameters

OtherAccessor	type of the other accessor

Parameters

other	other accessor

References gko::accessor::row_major< ValueType, Dimensionality >::lengths.

```
{
    for (size_type i = 0; i < lengths[0]; ++i) {
        for (size_type j = 0; j < lengths[1]; ++j) {
            (*this)(i, j) = other(i, j);
        }
    }
}
```

24.85.2.2 length()

```
template<typename ValueType , size_type Dimensionality>
constexpr size_type gko::accessor::row_major< ValueType, Dimensionality >::length (
            size_type dimension ) const  [inline]
```

Returns the length in dimension `dimension`.

Parameters

dimension	a dimension index

Returns

length in dimension `dimension`

References gko::accessor::row_major< ValueType, Dimensionality >::lengths.

```
{
    return dimension < 2 ? lengths[dimension] : 1;
}
```

24.85.2.3 operator()() [1/2]

```
template<typename ValueType , size_type Dimensionality>
constexpr value_type& gko::accessor::row_major< ValueType, Dimensionality >::operator() (
            size_type row,
            size_type col ) const [inline]
```

Returns the data element at position (row, col)

Parameters

row	row index
col	column index

Returns

data element at (row, col)

References gko::accessor::row_major< ValueType, Dimensionality >::data, gko::accessor::row_major< ValueType, Dimensionality >::lengths, and gko::accessor::row_major< ValueType, Dimensionality >::stride.

```
{
    return GKO_ASSERT(row < lengths[0]), GKO_ASSERT(col < lengths[1]),
           data[row * stride + col];
}
```

24.85.2.4 operator()() [2/2]

```
template<typename ValueType , size_type Dimensionality>
constexpr range<row_major> gko::accessor::row_major< ValueType, Dimensionality >::operator()
(
            const span & rows,
            const span & cols ) const [inline]
```

Returns the sub-range spanning the range (rows, cols)

Parameters

rows	row span
cols	column span

Returns

sub-range spanning the range (rows, cols)

References gko::span::begin, gko::accessor::row_major< ValueType, Dimensionality >::data, gko::span::end, gko::span::is_valid(), gko::accessor::row_major< ValueType, Dimensionality >::lengths, and gko::accessor::row_major< ValueType, Dimensionality >::stride.

```
    {
        return GKO_ASSERT(rows.is_valid()), GKO_ASSERT(cols.is_valid()),
               GKO_ASSERT(rows <= span{lengths[0]}),
               GKO_ASSERT(cols <= span{lengths[1]}),
               range<row_major>(data + rows.begin * stride + cols.begin,
                                rows.end - rows.begin, cols.end - cols.begin,
                                stride);
    }
```

The documentation for this class was generated from the following file:

- ginkgo/core/base/range_accessors.hpp (f1a4eb68)

24.86 gko::matrix::Sellp< ValueType, IndexType > Class Template Reference

SELL-P is a matrix format similar to ELL format.

```
#include <ginkgo/core/matrix/sellp.hpp>
```

Public Member Functions

- void read (const mat_data &data) override
  Reads a matrix from a matrix_data structure.
- void write (mat_data &data) const override
  Writes a matrix to a matrix_data structure.
- value_type * get_values () noexcept
  Returns the values of the matrix.
- const value_type * get_const_values () const noexcept
  Returns the values of the matrix.
- index_type * get_col_idxs () noexcept
  Returns the column indexes of the matrix.
- const index_type * get_const_col_idxs () const noexcept
  Returns the column indexes of the matrix.
- size_type * get_slice_lengths () noexcept
  Returns the lengths(columns) of slices.
- const size_type * get_const_slice_lengths () const noexcept
  Returns the lengths(columns) of slices.
- size_type * get_slice_sets () noexcept

Returns the offsets of slices.

- const size_type ∗ get_const_slice_sets () const noexcept

  Returns the offsets of slices.
- size_type get_slice_size () const noexcept

  Returns the size of a slice.
- size_type get_stride_factor () const noexcept

  Returns the stride factor(t) of SELL-P.
- size_type get_total_cols () const noexcept

  Returns the total column number.
- size_type get_num_stored_elements () const noexcept

  Returns the number of elements explicitly stored in the matrix.
- value_type & val_at (size_type row, size_type slice_set, size_type idx) noexcept

  Returns the `idx`-th non-zero element of the `row`-th row with `slice_set` slice set.
- value_type val_at (size_type row, size_type slice_set, size_type idx) const noexcept

  Returns the `idx`-th non-zero element of the `row`-th row with `slice_set` slice set.
- index_type & col_at (size_type row, size_type slice_set, size_type idx) noexcept

  Returns the `idx`-th column index of the `row`-th row with `slice_set` slice set.
- index_type col_at (size_type row, size_type slice_set, size_type idx) const noexcept

  Returns the `idx`-th column index of the `row`-th row with `slice_set` slice set.

24.86.1 Detailed Description

template<typename ValueType = default_precision, typename IndexType = int32>
class gko::matrix::Sellp< ValueType, IndexType >

SELL-P is a matrix format similar to ELL format.

The difference is that SELL-P format divides rows into smaller slices and store each slice with ELL format.

Template Parameters

ValueType	precision of matrix elements
IndexType	precision of matrix indexes

24.86.2 Member Function Documentation

24.86.2.1 col_at() [1/2]

```
template<typename ValueType = default_precision, typename IndexType = int32>
index_type& gko::matrix::Sellp< ValueType, IndexType >::col_at (
            size_type row,
            size_type slice_set,
            size_type idx ) [inline], [noexcept]
```

Returns the `idx`-th column index of the `row`-th row with `slice_set` slice set.

Parameters

row	the row of the requested element in the slice
slice_set	the slice set of the slice
idx	the idx-th stored element of the row in the slice

Note

the method has to be called on the same Executor the matrix is stored at (e.g. trying to call this method on a GPU matrix from the CPU results in a runtime error)

References gko::matrix::Sellp< ValueType, IndexType >::get_col_idxs().

```
{
    return this->get_col_idxs()[this->linearize_index(row, slice_set, idx)];
}
```

24.86.2.2 col_at() [2/2]

```
template<typename ValueType = default_precision, typename IndexType = int32>
index_type gko::matrix::Sellp< ValueType, IndexType >::col_at (
            size_type row,
            size_type slice_set,
            size_type idx ) const [inline], [noexcept]
```

Returns the `idx`-th column index of the `row`-th row with `slice_set` slice set.

Parameters

row	the row of the requested element in the slice
slice_set	the slice set of the slice
idx	the idx-th stored element of the row in the slice

Note

the method has to be called on the same Executor the matrix is stored at (e.g. trying to call this method on a GPU matrix from the CPU results in a runtime error)

References gko::ceildiv().

```
{
    return this
        ->get_const_col_idxs()[this->linearize_index(row, slice_set, idx)];
}
```

24.86.2.3 get_col_idxs()

```
template<typename ValueType = default_precision, typename IndexType = int32>
index_type* gko::matrix::Sellp< ValueType, IndexType >::get_col_idxs ( )  [inline], [noexcept]
```

Returns the column indexes of the matrix.

Returns

the column indexes of the matrix.

References gko::Array< ValueType >::get_data().

Referenced by gko::matrix::Sellp< ValueType, IndexType >::col_at().

```
{ return col_idxs_.get_data(); }
```

24.86.2.4 get_const_col_idxs()

```
template<typename ValueType = default_precision, typename IndexType = int32>
const index_type* gko::matrix::Sellp< ValueType, IndexType >::get_const_col_idxs ( ) const
[inline], [noexcept]
```

Returns the column indexes of the matrix.

Returns

the column indexes of the matrix.

Note

This is the constant version of the function, which can be significantly more memory efficient than the non-constant version, so always prefer this version.

References gko::Array< ValueType >::get_const_data().

```
{
    return col_idxs_.get_const_data();
}
```

24.86.2.5 get_const_slice_lengths()

```
template<typename ValueType = default_precision, typename IndexType = int32>
const size_type* gko::matrix::Sellp< ValueType, IndexType >::get_const_slice_lengths ( ) const
[inline], [noexcept]
```

Returns the lengths(columns) of slices.

Returns

the lengths(columns) of slices.

Note

This is the constant version of the function, which can be significantly more memory efficient than the non-constant version, so always prefer this version.

References gko::Array< ValueType >::get_const_data().

```
    {
        return slice_lengths_.get_const_data();
    }
```

24.86.2.6 get_const_slice_sets()

```
template<typename ValueType = default_precision, typename IndexType = int32>
const size_type* gko::matrix::Sellp< ValueType, IndexType >::get_const_slice_sets ( ) const
[inline], [noexcept]
```

Returns the offsets of slices.

Returns

the offsets of slices.

Note

This is the constant version of the function, which can be significantly more memory efficient than the non-constant version, so always prefer this version.

References gko::Array< ValueType >::get_const_data().

```
    {
        return slice_sets_.get_const_data();
    }
```

24.86.2.7 get_const_values()

```
template<typename ValueType = default_precision, typename IndexType = int32>
const value_type* gko::matrix::Sellp< ValueType, IndexType >::get_const_values ( ) const  [inline],
[noexcept]
```

Returns the values of the matrix.

Returns

the values of the matrix.

Note

This is the constant version of the function, which can be significantly more memory efficient than the non-constant version, so always prefer this version.

References gko::Array< ValueType >::get_const_data().

```
{
    return values_.get_const_data();
}
```

24.86.2.8 get_num_stored_elements()

```
template<typename ValueType = default_precision, typename IndexType = int32>
size_type gko::matrix::Sellp< ValueType, IndexType >::get_num_stored_elements ( ) const  [inline],
[noexcept]
```

Returns the number of elements explicitly stored in the matrix.

Returns

the number of elements explicitly stored in the matrix

References gko::Array< ValueType >::get_num_elems().

```
{
    return values_.get_num_elems();
}
```

24.86.2.9 get_slice_lengths()

```
template<typename ValueType = default_precision, typename IndexType = int32>
size_type* gko::matrix::Sellp< ValueType, IndexType >::get_slice_lengths ( )  [inline], [noexcept]
```

Returns the lengths(columns) of slices.

Returns

the lengths(columns) of slices.

References gko::Array< ValueType >::get_data().

```
{
    return slice_lengths_.get_data();
}
```

24.86.2.10 get_slice_sets()

```
template<typename ValueType = default_precision, typename IndexType = int32>
size_type* gko::matrix::Sellp< ValueType, IndexType >::get_slice_sets ( )  [inline], [noexcept]
```

Returns the offsets of slices.

Returns

the offsets of slices.

References gko::Array< ValueType >::get_data().

```
{ return slice_sets_.get_data(); }
```

24.86.2.11 get_slice_size()

```
template<typename ValueType = default_precision, typename IndexType = int32>
size_type gko::matrix::Sellp< ValueType, IndexType >::get_slice_size ( ) const  [inline],
[noexcept]
```

Returns the size of a slice.

Returns

the size of a slice.

```
{ return slice_size_; }
```

24.86.2.12 get_stride_factor()

```
template<typename ValueType = default_precision, typename IndexType = int32>
size_type gko::matrix::Sellp< ValueType, IndexType >::get_stride_factor ( ) const [inline],
[noexcept]
```

Returns the stride factor(t) of SELL-P.

Returns

the stride factor(t) of SELL-P.

```
190 { return stride_factor_; }
```

24.86.2.13 get_total_cols()

```
template<typename ValueType = default_precision, typename IndexType = int32>
size_type gko::matrix::Sellp< ValueType, IndexType >::get_total_cols ( ) const [inline],
[noexcept]
```

Returns the total column number.

Returns

the total column number.

```
197 { return total_cols_; }
```

24.86.2.14 get_values()

```
template<typename ValueType = default_precision, typename IndexType = int32>
value_type* gko::matrix::Sellp< ValueType, IndexType >::get_values ( ) [inline], [noexcept]
```

Returns the values of the matrix.

Returns

the values of the matrix.

References gko::Array< ValueType >::get_data().

```
104 { return values_.get_data(); }
```

24.86.2.15 read()

```
template<typename ValueType = default_precision, typename IndexType = int32>
void gko::matrix::Sellp< ValueType, IndexType >::read (
            const mat_data & data ) [override], [virtual]
```

Reads a matrix from a matrix_data structure.

Parameters

data	the matrix_data structure

Implements gko::ReadableFromMatrixData< ValueType, IndexType >.

24.86.2.16 val_at() [1/2]

```
template<typename ValueType = default_precision, typename IndexType = int32>
value_type& gko::matrix::Sellp< ValueType, IndexType >::val_at (
            size_type row,
            size_type slice_set,
            size_type idx ) [inline], [noexcept]
```

Returns the `idx`-th non-zero element of the `row`-th row with `slice_set` slice set.

Parameters

row	the row of the requested element in the slice
slice_set	the slice set of the slice
idx	the idx-th stored element of the row in the slice

Note

the method has to be called on the same Executor the matrix is stored at (e.g. trying to call this method on a GPU matrix from the CPU results in a runtime error)

References gko::Array< ValueType >::get_data().

```
223     {
224         return values_.get_data()[this->linearize_index(row, slice_set, idx)];
225     }
```

24.86.2.17 val_at() [2/2]

```
template<typename ValueType = default_precision, typename IndexType = int32>
value_type gko::matrix::Sellp< ValueType, IndexType >::val_at (
            size_type row,
            size_type slice_set,
            size_type idx ) const [inline], [noexcept]
```

Returns the `idx`-th non-zero element of the `row`-th row with `slice_set` slice set.

Parameters

row	the row of the requested element in the slice
slice_set	the slice set of the slice
idx	the idx-th stored element of the row in the slice

Note

the method has to be called on the same Executor the matrix is stored at (e.g. trying to call this method on a GPU matrix from the CPU results in a runtime error)

References gko::Array< ValueType >::get_const_data().

```
{
    return values_
        .get_const_data()[this->linearize_index(row, slice_set, idx)];
}
```

24.86.2.18 write()

```
template<typename ValueType = default_precision, typename IndexType = int32>
void gko::matrix::Sellp< ValueType, IndexType >::write (
            mat_data & data ) const  [override], [virtual]
```

Writes a matrix to a matrix_data structure.

Parameters

data	the matrix_data structure

Implements gko::WritableToMatrixData< ValueType, IndexType >.

The documentation for this class was generated from the following files:

- ginkgo/core/matrix/csr.hpp (ec6dbb34)
- ginkgo/core/matrix/sellp.hpp (8045ac75)

24.87 gko::span Struct Reference

A span is a lightweight structure used to create sub-ranges from other ranges.

```
#include <ginkgo/core/base/range.hpp>
```

Public Member Functions

- constexpr span (size_type point) noexcept

  Creates a span representing a point `point`.
- constexpr span (size_type begin, size_type end) noexcept

  Creates a span.
- constexpr bool is_valid () const

  Checks if a span is valid.

Public Attributes

- const size_type begin

  Beginning of the span.
- const size_type end

  End of the span.

24.87.1 Detailed Description

A span is a lightweight structure used to create sub-ranges from other ranges.

A `span s` represents a contiguous set of indexes in one dimension of the range, starting on index `s.begin` (inclusive) and ending at index `s.end` (exclusive). A span is only valid if its starting index is smaller than its ending index.

Spans can be compared using the `==` and `!=` operators. Two spans are identical if both their `begin` and `end` values are identical.

Spans also have two distinct partial orders defined on them:

1. `x < y` (`y > x`) if and only if `x.end < y.begin`
2. `x <= y` (`y >= x`) if and only if `x.end <= y.begin`

Note that the orders are in fact partial - there are spans `x` and `y` for which none of the following inequalities holds: `x < y`, `x > y`, `x == y`, `x <= y`, `x >= y`. An example are spans `span{0, 2}` and `span{1, 3}`.

In addition, `<=` is a distinct order from `<`, and not just an extension of the strict order to its weak equivalent. Thus, `x <= y` is not equivalent to `x < y || x == y`.

24.87.2 Constructor & Destructor Documentation

24.87.2.1 span() [1/2]

```
constexpr gko::span::span (
            size_type point ) [inline], [noexcept]
```

Creates a span representing a point `point`.

The `begin` of this span is set to `point`, and the `end` to `point + 1`.

Parameters

point	the point which the span represents

```
        : span{point, point + 1}
    {}
```

24.87.2.2 span() [2/2]

```
constexpr gko::span::span (
            size_type begin,
            size_type end )  [inline], [noexcept]
```

Creates a span.

Parameters

begin	the beginning of the span
end	the end of the span

References begin, and end.

```
92          : begin{begin}, end{end}
93      {}
```

24.87.3 Member Function Documentation

24.87.3.1 is_valid()

```
constexpr bool gko::span::is_valid ( ) const  [inline]
```

Checks if a span is valid.

Returns

true if and only if `this->begin < this->end`

References begin, and end.

Referenced by gko::accessor::row_major< ValueType, Dimensionality >::operator()().

```
100 { return begin < end; }
```

The documentation for this struct was generated from the following file:

- ginkgo/core/base/range.hpp (f1a4eb68)

24.88 gko::stopping_status Class Reference

This class is used to keep track of the stopping status of one vector.

`#include <ginkgo/core/stop/stopping_status.hpp>`

Public Member Functions

- bool has_stopped () const noexcept

    Check if any stopping criteria was fulfilled.
- bool has_converged () const noexcept

    Check if convergence was reached.
- bool is_finalized () const noexcept

    Check if the corresponding vector stores the finalized result.
- uint8 get_id () const noexcept

    Get the id of the stopping criterion which caused the stop.
- void reset () noexcept

    Clear all flags.
- void stop (uint8 id, bool set_finalized=true) noexcept

    Call if a stop occured due to a hard limit (and convergence was not reached).
- void converge (uint8 id, bool set_finalized=true) noexcept

    Call if convergence occured.
- void finalize () noexcept

    Set the result to be finalized (it needs to be stopped or converged first).

Friends

- bool operator== (const stopping_status &x, const stopping_status &y) noexcept

    Checks if two stopping statuses are equivalent.
- bool operator!= (const stopping_status &x, const stopping_status &y) noexcept

    Checks if two stopping statuses are different.

24.88.1 Detailed Description

This class is used to keep track of the stopping status of one vector.

24.88.2 Member Function Documentation

24.88.2.1 converge()

```
void gko::stopping_status::converge (
            uint8 id,
            bool set_finalized = true )  [inline], [noexcept]
```

Call if convergence occured.

Parameters

id	id of the stopping criteria.
set_finalized	Controls if the current version should count as finalized (set to true) or not (set to false).

References has_stopped().

```
{
    if (!this->has_stopped()) {
        data_ |= converged_mask_ | (id & id_mask_);
        if (set_finalized) {
            data_ |= finalized_mask_;
        }
    }
}
```

24.88.2.2 get_id()

`uint8 gko::stopping_status::get_id ( ) const [inline], [noexcept]`

Get the id of the stopping criterion which caused the stop.

Returns

Returns the id of the stopping criterion which caused the stop.

Referenced by has_stopped().

```
{
    return data_ & id_mask_;
}
```

24.88.2.3 has_converged()

`bool gko::stopping_status::has_converged ( ) const [inline], [noexcept]`

Check if convergence was reached.

Returns

Returns true if convergence was reached.

```
{
    return data_ & converged_mask_;
}
```

24.88.2.4 has_stopped()

```
bool gko::stopping_status::has_stopped ( ) const  [inline], [noexcept]
```

Check if any stopping criteria was fulfilled.

Returns

Returns true if any stopping criteria was fulfilled.

References get_id().

Referenced by converge(), finalize(), and stop().

```
{
    return get_id();
}
```

24.88.2.5 is_finalized()

```
bool gko::stopping_status::is_finalized ( ) const  [inline], [noexcept]
```

Check if the corresponding vector stores the finalized result.

Returns

Returns true if the corresponding vector stores the finalized result.

```
{
    return data_ & finalized_mask_;
}
```

24.88.2.6 stop()

```
void gko::stopping_status::stop (
            uint8 id,
            bool set_finalized = true )  [inline], [noexcept]
```

Call if a stop occured due to a hard limit (and convergence was not reached).

Parameters

id	id of the stopping criteria.
set_finalized	Controls if the current version should count as finalized (set to true) or not (set to false).

References has_stopped().

```
    {
        if (!this->has_stopped()) {
            data_ |= (id & id_mask_);
            if (set_finalized) {
                data_ |= finalized_mask_;
            }
        }
    }
```

24.88.3 Friends And Related Function Documentation

24.88.3.1 operator"!=

```
bool operator!= (
            const stopping_status & x,
            const stopping_status & y )  [friend]
```

Checks if two stopping statuses are different.

Parameters

x	a stopping status
y	a stopping status

Returns

true if and only if `! (x == y)`

```
{
    return x.data_ != y.data_;
}
```

24.88.3.2 operator==

```
bool operator== (
            const stopping_status & x,
            const stopping_status & y )  [friend]
```

Checks if two stopping statuses are equivalent.

Parameters

x	a stopping status
y	a stopping status

Returns

true if and only if both x and y have the same mask and converged and finalized state

```
{
    return x.data_ == y.data_;
}
```

The documentation for this class was generated from the following file:

- ginkgo/core/stop/stopping_status.hpp (f1a4eb68)

24.89 gko::matrix::Hybrid< ValueType, IndexType >::strategy_type Class Reference

strategy_type is to decide how to set the hybrid config.

`#include <ginkgo/core/matrix/hybrid.hpp>`

Public Member Functions

- strategy_type ()
  Creates a strategy_type.
- void compute_hybrid_config (const Array< size_type > &row_nnz, size_type *ell_num_stored_elements_↩ per_row, size_type *coo_nnz)
  Computes the config of the Hybrid matrix (ell_num_stored_elements_per_row and coo_nnz).
- size_type get_ell_num_stored_elements_per_row () const noexcept
  Returns the number of stored elements per row of the ell part.
- size_type get_coo_nnz () const noexcept
  Returns the number of nonzeros of the coo part.
- virtual size_type compute_ell_num_stored_elements_per_row (Array< size_type > *row_nnz) const =0
  Computes the number of stored elements per row of the ell part.

24.89.1 Detailed Description

template<typename ValueType = default_precision, typename IndexType = int32>
class gko::matrix::Hybrid< ValueType, IndexType >::strategy_type

strategy_type is to decide how to set the hybrid config.

It computes the number of stored elements per row of the ell part and then set the number of residual nonzeros as the number of nonzeros of the coo part.

The practical strategy method should inherit strategy_type and implement its `compute_ell_num_stored_↩ elements_per_row` function.

24.89.2 Member Function Documentation

24.89.2.1 compute_ell_num_stored_elements_per_row()

```
template<typename ValueType = default_precision, typename IndexType = int32>
virtual size_type gko::matrix::Hybrid< ValueType, IndexType >::strategy_type::compute_ell_↩
num_stored_elements_per_row (
            Array< size_type > * row_nnz ) const  [pure virtual]
```

Computes the number of stored elements per row of the ell part.

Parameters

row_nnz	the number of nonzeros of each row

Returns

the number of stored elements per row of the ell part

Implemented in gko::matrix::Hybrid< ValueType, IndexType >::automatic, gko::matrix::Hybrid< ValueType, IndexType >::minimal_storage_limit, gko::matrix::Hybrid< ValueType, IndexType >::imbalance_bounded_limit, gko::matrix::Hybrid< ValueType, IndexType >::imbalance_limit, and gko::matrix::Hybrid< ValueType, IndexType >::column_limit.

Referenced by gko::matrix::Hybrid< ValueType, IndexType >::strategy_type::compute_hybrid_config(), and gko::matrix::Hybrid< ValueType, IndexType >::strategy_type::get_coo_nnz().

24.89.2.2 compute_hybrid_config()

```
template<typename ValueType = default_precision, typename IndexType = int32>
void gko::matrix::Hybrid< ValueType, IndexType >::strategy_type::compute_hybrid_config (
            const Array< size_type > & row_nnz,
            size_type * ell_num_stored_elements_per_row,
            size_type * coo_nnz ) [inline]
```

Computes the config of the Hybrid matrix (ell_num_stored_elements_per_row and coo_nnz).

For now, it copies row_nnz to the reference executor and performs all operations on the reference executor.

Parameters

row_nnz	the number of nonzeros of each row
ell_num_stored_elements_per_row	the output number of stored elements per row of the ell part
coo_nnz	the output number of nonzeros of the coo part

References gko::matrix::Hybrid< ValueType, IndexType >::strategy_type::compute_ell_num_stored_elements_per_row(), gko::Array< ValueType >::get_executor(), and gko::Array< ValueType >::get_num_elems().

```
        {
            Array<size_type> ref_row_nnz(row_nnz.get_executor()->get_master(),
                                         row_nnz.get_num_elems());
            ref_row_nnz = row_nnz;
            ell_num_stored_elements_per_row_ =
                this->compute_ell_num_stored_elements_per_row(&
     ref_row_nnz);
            coo_nnz_ = this->compute_coo_nnz(ref_row_nnz);
            *ell_num_stored_elements_per_row = ell_num_stored_elements_per_row_;
            *coo_nnz = coo_nnz_;
        }
```

24.89.2.3 get_coo_nnz()

```
template<typename ValueType = default_precision, typename IndexType = int32>
size_type gko::matrix::Hybrid< ValueType, IndexType >::strategy_type::get_coo_nnz ( ) const
[inline], [noexcept]
```

Returns the number of nonzeros of the coo part.

Returns

the number of nonzeros of the coo part

References gko::matrix::Hybrid< ValueType, IndexType >::strategy_type::compute_ell_num_stored_elements_↩ per_row(), gko::Array< ValueType >::get_const_data(), and gko::Array< ValueType >::get_num_elems().

```
{ return coo_nnz_; }
```

24.89.2.4 get_ell_num_stored_elements_per_row()

```
template<typename ValueType = default_precision, typename IndexType = int32>
size_type gko::matrix::Hybrid< ValueType, IndexType >::strategy_type::get_ell_num_stored_↩
elements_per_row ( ) const  [inline], [noexcept]
```

Returns the number of stored elements per row of the ell part.

Returns

the number of stored elements per row of the ell part

```
        {
            return ell_num_stored_elements_per_row_;
        }
```

The documentation for this class was generated from the following file:

- ginkgo/core/matrix/hybrid.hpp (3e51a52b)

24.90 gko::log::Stream< ValueType > Class Template Reference

Stream is a Logger which logs every event to a stream.

```
#include <ginkgo/core/log/stream.hpp>
```

Static Public Member Functions

- static std::unique_ptr< Stream > create (std::shared_ptr< const Executor > exec, const Logger::mask_type &enabled_events=Logger::all_events_mask, std::ostream &os=std::cout, bool verbose=false)
    Creates a Stream logger.

24.90.1 Detailed Description

template< typename ValueType = default_precision >
class gko::log::Stream< ValueType >

Stream is a Logger which logs every event to a stream.

This can typically be used to log to a file or to the console.

Template Parameters

ValueType	the type of values stored in the class (i.e. ValueType template parameter of the concrete Loggable this class will log)

24.90.2 Member Function Documentation

24.90.2.1 create()

```
template<typename ValueType = default_precision>
static std::unique_ptr<Stream> gko::log::Stream< ValueType >::create (
            std::shared_ptr< const Executor > exec,
            const Logger::mask_type & enabled_events = Logger::all_events_mask,
            std::ostream & os = std::cout,
            bool verbose = false )  [inline], [static]
```

Creates a Stream logger.

This dynamically allocates the memory, constructs the object and returns an std::unique_ptr to this object.

Parameters

exec	the executor
enabled_events	the events enabled for this logger. By default all events.
os	the stream used for this logger
verbose	whether we want detailed information or not. This includes always printing residuals and other information which can give a large output.

Returns

an std::unique_ptr to the the constructed object

```
    {
        return std::unique_ptr<Stream>(
            new Stream(exec, enabled_events, os, verbose));
    }
```

The documentation for this class was generated from the following file:

- ginkgo/core/log/stream.hpp (f1a4eb68)

24.91 gko::StreamError Class Reference

StreamError is thrown if accessing a stream failed.

```
#include <ginkgo/core/base/exception.hpp>
```

Public Member Functions

- StreamError (const std::string &file, int line, const std::string &func, const std::string &message)
  Initializes a file access error.

24.91.1 Detailed Description

StreamError is thrown if accessing a stream failed.

24.91.2 Constructor & Destructor Documentation

24.91.2.1 StreamError()

```
gko::StreamError::StreamError (
            const std::string & file,
            int line,
            const std::string & func,
            const std::string & message )  [inline]
```

Initializes a file access error.

Parameters

file	The name of the offending source file
line	The source code line number where the error occurred
func	The name of the function that tried to access the file
message	The error message

```
        : Error(file, line, func + ": " + message)
    {}
```

The documentation for this class was generated from the following file:

- ginkgo/core/base/exception.hpp (8fbad33a)

24.92 gko::temporary_clone< T > Class Template Reference

A temporary_clone is a special smart pointer-like object that is designed to hold an object temporarily copied to another executor.

```
#include <ginkgo/core/base/utils.hpp>
```

Public Member Functions

- temporary_clone (std::shared_ptr< const Executor > exec, pointer ptr)

  Creates a temporary_clone.
- T ∗ get () const

  Returns the object held by temporary_clone.
- T ∗ operator-> () const

  Calls a method on the underlying object.

24.92.1 Detailed Description

template<typename T>
class gko::temporary_clone< T >

A temporary_clone is a special smart pointer-like object that is designed to hold an object temporarily copied to another executor.

After the temporary_clone goes out of scope, the stored object will be copied back to its original location. This class is optimized to avoid copies if the object is already on the correct executor, in which case it will just hold a reference to that object, without performing the copy.

Template Parameters

T	the type of object held in the temporary_clone

24.92.2 Constructor & Destructor Documentation

24.92.2.1 temporary_clone()

```
template<typename T >
gko::temporary_clone< T >::temporary_clone (
            std::shared_ptr< const Executor > exec,
            pointer ptr )  [inline], [explicit]
```

Creates a temporary_clone.

Parameters

exec	the executor where the clone will be created
ptr	a pointer to the object of which the clone will be created

References gko::clone().

```
    {
        if (ptr->get_executor() == exec) {
```

```
            // just use the object we already have
            handle_ = handle_type(ptr, [](pointer) {});
        } else {
            // clone the object to the new executor and make sure it's copied
            // back before we delete it
            handle_ = handle_type(gko::clone(std::move(exec), ptr).release(),
                                  copy_back_deleter<T>(ptr));
        }
    }
```

24.92.3 Member Function Documentation

24.92.3.1 get()

```
template<typename T >
T* gko::temporary_clone< T >::get ( ) const [inline]
```

Returns the object held by temporary_clone.

Returns

the object held by temporary_clone

```
{ return handle_.get(); }
```

24.92.3.2 operator->()

```
template<typename T >
T* gko::temporary_clone< T >::operator-> ( ) const [inline]
```

Calls a method on the underlying object.

Returns

the underlying object

```
{ return handle_.get(); }
```

The documentation for this class was generated from the following file:

- ginkgo/core/base/utils.hpp (4bde4271)

24.93 gko::stop::Time Class Reference

The Time class is a stopping criterion which stops the iteration process after a certain amout of time has passed.

```
#include <ginkgo/core/stop/time.hpp>
```

24.93.1 Detailed Description

The Time class is a stopping criterion which stops the iteration process after a certain amout of time has passed.

The documentation for this class was generated from the following file:

- ginkgo/core/stop/time.hpp (ea195fb4)

24.94 gko::Transposable Class Reference

Linear operators which support transposition should implement the Transposable interface.

`#include <ginkgo/core/base/lin_op.hpp>`

Public Member Functions

- virtual std::unique_ptr< LinOp > transpose () const =0

  Returns a LinOp representing the transpose of the Transposable object.
- virtual std::unique_ptr< LinOp > conj_transpose () const =0

  Returns a LinOp representing the conjugate transpose of the Transposable object.

24.94.1 Detailed Description

Linear operators which support transposition should implement the Transposable interface.

It provides two functionalities, the normal transpose and the conjugate transpose.

The normal transpose returns the transpose of the linear operator without changing any of its elements representing the operation, $B = A^T$.

The conjugate transpose returns the conjugate of each of the elements and additionally transposes the linear operator representing the operation, $B = A^H$.

Example: Transposing a Csr matrix:

```
{c++}
//Transposing an object of LinOp type.
//The object you want to transpose.
auto op = matrix::Csr::create(exec);
//Transpose the object by first converting it to a transposable type.
auto trans = op->transpose();
```

24.94.2 Member Function Documentation

24.94.2.1 conj_transpose()

```
virtual std::unique_ptr<LinOp> gko::Transposable::conj_transpose ( ) const [pure virtual]
```

Returns a LinOp representing the conjugate transpose of the Transposable object.

Returns

a pointer to the new conjugate transposed object

Implemented in gko::matrix::Csr< ValueType, IndexType >, and gko::matrix::Dense< ValueType >.

24.94.2.2 transpose()

```
virtual std::unique_ptr<LinOp> gko::Transposable::transpose ( ) const [pure virtual]
```

Returns a LinOp representing the transpose of the Transposable object.

Returns

a pointer to the new transposed object

Implemented in gko::matrix::Csr< ValueType, IndexType >, and gko::matrix::Dense< ValueType >.

The documentation for this class was generated from the following file:

- ginkgo/core/base/lin_op.hpp (fb72cdf1)

24.95 gko::stop::Criterion::Updater Class Reference

The Updater class serves for convenient argument passing to the Criterion's check function.

```
#include <ginkgo/core/stop/criterion.hpp>
```

Public Member Functions

- Updater (const Updater &)=delete

  Prevent copying and moving the object This is to enforce the use of argument passing and calling check at the same time.
- bool check (uint8 stoppingId, bool setFinalized, Array< stopping_status > ∗stop_status, bool ∗one_changed) const

  Calls the parent Criterion object's check method.

24.95.1 Detailed Description

The Updater class serves for convenient argument passing to the Criterion's check function.

The pattern used is a Builder, except Updater builds a function's arguments before calling the function itself, and does not build an object. This allows calling a Criterion's check in the form of: stop_criterion->update() .num_iterations(num_iterations) .residual_norm(residual_norm) .residual(residual) .solution(solution) .check(converged);

If there is a need for a new form of data to pass to the Criterion, it should be added here.

24.95.2 Member Function Documentation

24.95.2.1 check()

```
bool gko::stop::Criterion::Updater::check (
            uint8 stoppingId,
            bool setFinalized,
            Array< stopping_status > * stop_status,
            bool * one_changed ) const  [inline]
```

Calls the parent Criterion object's check method.

References gko::stop::Criterion::check(), and Updater().

```
      {
          auto converged = parent_->check(stoppingId, setFinalized,
                                          stop_status, one_changed, *this);
          return converged;
       }
```

The documentation for this class was generated from the following file:

- ginkgo/core/stop/criterion.hpp (f0a50f96)

24.96 gko::solver::UpperTrs< ValueType, IndexType > Class Template Reference

UpperTrs is the triangular solver which solves the system U x = b, when U is an upper triangular matrix.

```
#include <ginkgo/core/solver/upper_trs.hpp>
```

Public Member Functions

- std::shared_ptr< const matrix::Csr< ValueType, IndexType > > get_system_matrix () const

    Gets the system operator (CSR matrix) of the linear system.
- std::shared_ptr< const LinOp > get_preconditioner () const override

    Returns the preconditioner operator used by the solver.

24.96.1 Detailed Description

template<typename ValueType = default_precision, typename IndexType = int32>
class gko::solver::UpperTrs< ValueType, IndexType >

UpperTrs is the triangular solver which solves the system U x = b, when U is an upper triangular matrix.

It works best when passing in a matrix in CSR format. If the matrix is not in CSR, then the generate step converts it into a CSR matrix. The generation fails if the matrix is not convertible to CSR.

Note

As the constructor uses the copy and convert functionality, it is not possible to create a empty solver or a solver with a matrix in any other format other than CSR, if none of the executor modules are being compiled with.

Template Parameters

ValueType	precision of matrix elements
IndexType	precision of matrix indices

24.96.2 Member Function Documentation

24.96.2.1 get_preconditioner()

```
template<typename ValueType = default_precision, typename IndexType = int32>
std::shared_ptr<const LinOp> gko::solver::UpperTrs< ValueType, IndexType >::get_preconditioner
( ) const [inline], [override], [virtual]
```

Returns the preconditioner operator used by the solver.

Returns

the preconditioner operator used by the solver

Implements gko::Preconditionable.

References gko::PolymorphicObject::get_executor(), GKO_CREATE_FACTORY_PARAMETERS, GKO_ENABL↩ E_BUILD_METHOD, GKO_ENABLE_LIN_OP_FACTORY, GKO_FACTORY_PARAMETER, and gko::transpose().

```
{
    return preconditioner_;
}
```

24.96.2.2 get_system_matrix()

```
template<typename ValueType = default_precision, typename IndexType = int32>
std::shared_ptr<const matrix::Csr<ValueType, IndexType> > gko::solver::UpperTrs< ValueType,
IndexType >::get_system_matrix ( ) const [inline]
```

Gets the system operator (CSR matrix) of the linear system.

Returns

the system operator (CSR matrix)

```
{
    return system_matrix_;
}
```

The documentation for this class was generated from the following file:

- ginkgo/core/solver/upper_trs.hpp (0d32d72c)

24.97 gko::version Struct Reference

This structure is used to represent versions of various Ginkgo modules.

`#include <ginkgo/core/base/version.hpp>`

Public Attributes

- const uint64 major
  The major version number.
- const uint64 minor
  The minor version number.
- const uint64 patch
  The patch version number.
- const char ∗const tag
  Addition tag string that describes the version in more detail.

24.97.1 Detailed Description

This structure is used to represent versions of various Ginkgo modules.

Version structures can be compared using the usual relational operators.

24.97.2 Member Data Documentation

24.97.2.1 tag

```
const char* const gko::version::tag
```

Addition tag string that describes the version in more detail.

It does not participate in comparisons.

Referenced by gko::operator<<().

The documentation for this struct was generated from the following file:

- ginkgo/core/base/version.hpp (9c2e5ae6)

24.98 gko::version_info Class Reference

Ginkgo uses version numbers to label new features and to communicate backward compatibility guarantees:

```
#include <ginkgo/core/base/version.hpp>
```

Static Public Member Functions

- static const version_info & get ()

    Returns an instance of version_info.

Public Attributes

- version header_version

    Contains version information of the header files.
- version core_version

    Contains version information of the core library.
- version reference_version

    Contains version information of the reference module.
- version omp_version

    Contains version information of the OMP module.
- version cuda_version

    Contains version information of the CUDA module.

24.98.1 Detailed Description

Ginkgo uses version numbers to label new features and to communicate backward compatibility guarantees:

1. Versions with different major version number have incompatible interfaces (parts of the earlier interface may not be present anymore, and new interfaces can appear).
2. Versions with the same major number X, but different minor numbers Y1 and Y2 numbers keep the same interface as version X.0.0, but additions to the interface in X.0.0 present in X.Y1.0 may not be present in X.Y2.0 and vice versa.
3. Versions with the same major an minor version numbers, but different patch numbers have exactly the same interface, but the functionality may be different (something that is not implemented or has a bug in an earlier version may have this implemented or fixed in a later version).

This structure provides versions of different parts of Ginkgo: the headers, the core and the kernel modules (reference, OpenMP, CUDA). To obtain an instance of version_info filled with information about the current version of Ginkgo, call the version_info::get() static method.

24.98.2 Member Function Documentation

24.98.2.1 get()

```
static const version_info& gko::version_info::get ( )  [inline], [static]
```

Returns an instance of version_info.

Returns

an instance of version info

```
{
    static version_info info{};
    return info;
}
```

24.98.3 Member Data Documentation

24.98.3.1 core_version

```
version gko::version_info::core_version
```

Contains version information of the core library.

This is the version of the static/shared library called "ginkgo".

24.98.3.2 cuda_version

```
version gko::version_info::cuda_version
```

Contains version information of the CUDA module.

This is the version of the static/shared library called "ginkgo_cuda".

24.98.3.3 omp_version

```
version gko::version_info::omp_version
```

Contains version information of the OMP module.

This is the version of the static/shared library called "ginkgo_omp".

24.98.3.4 reference_version

```
version gko::version_info::reference_version
```

Contains version information of the reference module.

This is the version of the static/shared library called "ginkgo_reference".

The documentation for this class was generated from the following file:

- ginkgo/core/base/version.hpp (9c2e5ae6)

24.99 gko::WritableToMatrixData< ValueType, IndexType > Class Template Reference

A LinOp implementing this interface can write its data to a matrix_data structure.

```
#include <ginkgo/core/base/lin_op.hpp>
```

Public Member Functions

- virtual void write (matrix_data< ValueType, IndexType > &data) const =0
  Writes a matrix to a matrix_data structure.

24.99.1 Detailed Description

template<typename ValueType, typename IndexType>
class gko::WritableToMatrixData< ValueType, IndexType >

A LinOp implementing this interface can write its data to a matrix_data structure.

24.99.2 Member Function Documentation

24.99.2.1 write()

```
template<typename ValueType, typename IndexType>
virtual void gko::WritableToMatrixData< ValueType, IndexType >::write (
            matrix_data< ValueType, IndexType > & data ) const  [pure virtual]
```

Writes a matrix to a matrix_data structure.

Parameters

data	the matrix_data structure

Implemented in gko::matrix::Hybrid< ValueType, IndexType >, gko::matrix::Csr< ValueType, IndexType >, gko::preconditioner::Jacobi< ValueType, IndexType >, gko::matrix::Coo< ValueType, IndexType >, gko::matrix::Ell< ValueType, IndexType >, and gko::matrix::Sellp< ValueType, IndexType >.

The documentation for this class was generated from the following file:

- ginkgo/core/base/lin_op.hpp (fb72cdf1)

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