

Ginkgo

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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.

1.0.0.1 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

2.0.1 Building

Use the standard cmake build procedure:

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

Use `cmake --build .` in some systems like MinGW or Microsoft Visual Studio which do not use `make`.

For Microsoft Visual Studio, use `cmake --build . --config <build_type>` to decide the build type. The possible options are `Debug`, `Release`, `RelWithDebInfo` and `MinSizeRel`.

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 `OFF`.
- `-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 `ON` if the selected C++ compiler supports OpenMP, `OFF` otherwise.
- `-DGINKGO_BUILD_CUDA={ON, OFF}` builds optimized cuda versions of the kernels (requires CUDA), default is `ON` if a CUDA compiler could be detected, `OFF` otherwise.
- `-DGINKGO_BUILD_DPCPP={ON, OFF}` builds optimized DPC++ versions of the kernels (requires C \leftrightarrow MAKE_CXX_COMPILER to be set to the dpcpp compiler). The default is `ON` if `CMAKE_CXX_COMPILER` is a DPC++ compiler, `OFF` otherwise.
- `-DGINKGO_BUILD_HIP={ON, OFF}` builds optimized HIP versions of the kernels (requires HIP), default is `ON` if an installation of HIP could be detected, `OFF` otherwise.

- `-DGINKGO_HIP_AMDGPU="gpuarch1;gpuarch2"` the `amdgpu_target(s)` variable passed to `hipcc` for the `hcc` HIP backend. The default is `none` (auto).
- `-DGINKGO_BUILD_HWLOC={ON, OFF}` builds Ginkgo with `HWLOC`. If system `HWLOC` is not found, Ginkgo will try to build it. Default is `ON`.
- `-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>`. The default is `OFF`.
- `-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>`. The default is `OFF`.
- `-DGINKGO_CHECK_CIRCULAR_DEPS={ON, OFF}` enables compile-time checks for circular dependencies between different Ginkgo libraries and self-sufficient headers. Should only be used for development purposes. The default is `OFF`.
- `-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), `LSAN` (LeakSanitizer), `TSAN` (ThreadSanitizer) and `UBSAN` (undefined behavior sanitizer) 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, Ampere
 - CODE, CODE (COMPUTE), (COMPUTE)

Auto will automatically detect the present CUDA-enabled GPU architectures in the system. Kepler, Maxwell, Pascal, Volta and Ampere 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.

- `-DGINKGO_WINDOWS_SHARED_LIBRARY_RELPATH=<path>` where `<path>` is a relative path built with `PROJECT_BINARY_DIR`. Users must add the absolute path (`PROJECT_BINARY_DIR/GINKGO_WINDOWS_SHARED_LIBRARY_RELPATH`) into the environment variable `PATH` when building shared libraries and executable program, default is `windows_shared_library`.
- `-DGINKGO_CHECK_PATH={ON, OFF}` checks if the environment variable `PATH` is valid. It is checked only when building shared libraries and executable program, default is `ON`.

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 -DGINKGO_BUILD_HIP=ON
cmake --build Debug
```

NOTE: Ginkgo is known to work with the Unix Makefiles, Ninja, MinGW Makefiles and Visual Studio 16 2019 based generators. Other CMake generators are untested.

2.0.2 Building Ginkgo in Windows

Depending on the configuration settings, some manual work might be required:

- Build Ginkgo as shared library: Add `PROJECT_BINARY_DIR/GINKGO_WINDOWS_SHARED_LIBRARY_RELPATH` into the environment variable `PATH`. `GINKGO_WINDOWS_SHARED_LIBRARY_RELPATH` is `windows_shared_library` by default. More Details are available in the Installation page.

- cmd: `set PATH="<PROJECT_BINARY_DIR/GINKGO_WINDOWS_SHARED_LIBRARY_RELPATH>;%PATH%"`

- powershell:

```
env
```

```
ATH="<PROJECT_BINARY_DIR/GINKGO_WINDOWS_SHARED_LIBRARY_RELPATH>;%PATH%"
```

```
env:PATH"
```

CMake will give the following error message if the path is not correct.

```
Did not find this build in the environment variable PATH. Please add <path> into the environment variable PATH.
```

where `<path>` is the needed `<PROJECT_BINARY_DIR/GINKGO_WINDOWS_SHARED_LIBRARY_RELPATH>`.

- Build Ginkgo with Debug mode: Some Debug build specific issues can appear depending on the machine and environment. The known issues are the following:
 1. bigobj issue: encountering too many sections needs the compilation flags `\bigobj` or `-Wa,-mbig-obj`
 2. ld issue: encountering `ld: error: export ordinal too large` needs the compilation flag `-O1`

The following are the details for different environments:

- Microsoft Visual Studio:

1. bigobj issue

- * `cmake -DCMAKE_CXX_FLAGS=\bigobj <other parameters> <source_↵ folder>` which might overwrite the default settings.
 - * add `\bigobj` into the environment variable `CXXFLAGS` (only available in the first cmake configuration)
 - `cmd: set CXXFLAGS=\bigobj`
 - `powershell: $env:CXXFLAGS=\bigobj`
 - 2. `ld` issue (*Microsoft Visual Studio* does not have this issue)
- *Cygwin*:
1. `bigobj` issue
 - * add `-Wa, -mbig-obj -O1` into the environment variable `CXXFLAGS` (only available in the first cmake configuration)
 - `export CXXFLAGS="-Wa, -mbig-obj -O1"`
 - * `cmake -DCMAKE_CXX_FLAGS=-Wa, -mbig-obj <other parameters> <source_↵ _folder>`, which might overwrite the default settings.
 2. `ld` issue (If building Ginkgo as static library, this is not needed)
 - * `cmake -DGINKGO_COMPILER_FLAGS="-Wpedantic -O1" <other parameters> <source_folder>` (`GINKGO_COMPILER_FLAGS` is `-Wpedantic` by default)
 - * add `-O1` in the environment variable `CXX_FLAGS` or `CMAKE_CXX_FLAGS`
- *MinGW*:
1. `bigobj` issue
 - * add `-Wa, -mbig-obj -O1` into the environment variable `CXXFLAGS` (only available in the first cmake configuration)
 - `cmd: set CXXFLAGS="-Wa, -mbig-obj"`
 - `powershell: $env:CXXFLAGS="-Wa, -mbig-obj"`
 - * `cmake -DCMAKE_CXX_FLAGS=-Wa, -mbig-obj <other parameters> <source_↵ _folder>`, which might overwrite the default settings.
 2. `ld` issue (If building Ginkgo as static library, this is not needed)
 - * `cmake -DGINKGO_COMPILER_FLAGS="-Wpedantic -O1" <other parameters> <source_folder>` (`GINKGO_COMPILER_FLAGS` is `-Wpedantic` by default)
 - * add `-O1` in the environment variable `CXX_FLAGS` or `CMAKE_CXX_FLAGS`
- Build Ginkgo in *MinGW*: If encountering the issue `cclplus.exe: out of memory allocating 65536 bytes`, please follow the workaround in [reference](#), or trying to compile ginkgo again might work.

2.0.3 Building Ginkgo with HIP support

Ginkgo provides a [HIP](#) backend. This allows to compile optimized versions of the kernels for either AMD or NV↵ IDIA GPUs. The CMake configuration step will try to auto-detect the presence of HIP either at `/opt/rocm/hip` or at the path specified by `HIP_PATH` as a CMake parameter (`-DHIP_PATH=`) or environment variable (`export HIP_PATH=`), unless `-DGINKGO_BUILD_HIP=ON/OFF` is set explicitly.

2.0.3.1 HIP dependencies for Ginkgo

Ginkgo's HIP backend adds a dependency to the following packages:

- HIP,
- hipBLAS,
- hipSPARSE,
- rocRAND,
- rocThrust.

2.0.3.2 Changing the paths to search for HIP and other packages

All HIP installation paths can be configured through the use of environment variables or CMake variables. This way of configuring the paths is currently imposed by the HIP tool suite. The variables are the following:

- CMake `-DHIP_PATH=` or environment `export HIP_PATH=`: sets the HIP installation path. The default value is `/opt/rocm/hip`.
- CMake `-DHIPBLAS_PATH=` or environment `export HIPBLAS_PATH=`: sets the hipBLAS installation path. The default value is `/opt/rocm/hipblas`.
- CMake `-DHIPSPARSE_PATH=` or environment `export HIPSPARSE_PATH=`: sets the hipSPARSE installation path. The default value is `/opt/rocm/hipsparse`.
- CMake `-DHCC_PATH=` or environment `export HCC_PATH=`: sets the HCC installation path, for AMD backends. The default value is `/opt/rocm/hcc`.
- environment `export CUDA_PATH=`: where `hipcc` can find CUDA if it is not in the default `/usr/local/cuda` path.

2.0.3.3 HIP platform detection of AMD and NVIDIA

By default, Ginkgo uses the output of `/opt/rocm/hip/bin/hipconfig --platform` to select the back-end. The accepted values are either `hcc` (AMD) or `nvcc` (NVIDIA). When on an AMD or NVIDIA system, this should output the correct platform by default. When on a system without GPUs, this should output `hcc` by default. To change this value, export the environment variable `HIP_PLATFORM` like so:

```
export HIP_PLATFORM=nvcc
```

When using `HIP_PLATFORM=hcc`, note that two HIP compilers can be set, the old `hcc` or since ROCm 3.5, `clang`. On newer installations, `clang` should be set by default, but if encountering any problem try to manually set the HIP compiler to `clang`:

```
export HIP_COMPILER=clang
```

2.0.3.4 Setting platform specific compilation flags

Platform specific compilation flags can be given through the following CMake variables:

- `-DGINKGO_HIP_COMPILER_FLAGS=`: compilation flags given to all platforms.
- `-DGINKGO_HIP_HCC_COMPILER_FLAGS=`: compilation flags given to AMD platforms.
- `-DGINKGO_HIP_NVCC_COMPILER_FLAGS=`: compilation flags given to NVIDIA platforms.
- `-DGINKGO_HIP_CLANG_COMPILER_FLAGS=`: compilation flags given to AMD clang compiler.

2.0.4 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 CUDA 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.
- GINKGO_BUILD_HWLOC=ON: [hwloc](#) to detect and control cores and devices.

Usually, Ginkgo uses the internal version of each package. For each of the packages `GTEST`, `GFLAGS`, `RAPIDJSON` 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`. `HWLOC` works the opposite way, Ginkgo always looks for the system's `hwloc` first.

Note that, if the external packages were not installed to the default location, the CMake option `-DCMAKE_INSTALL_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>_{LIBRARIES|INCLUDE_DIRS}` variables.

2.0.5 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

3.0.1 Running the unit tests

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

3.0.1.1 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`.

3.0.1.2 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 an extensive benchmark suite for checking its performance on all Ginkgo supported systems. The purpose of Ginkgo's benchmarking suite is to allow easy and complete reproduction of Ginkgo's performance, and to facilitate performance debugging as well. Most results published in Ginkgo papers are generated thanks to this benchmarking suite and are accessible online under the [ginkgo-data repository](#). These results can also be used for performance comparison in order to ensure that you get similar performance as what is published on this repository.

To compile the benchmarks, the flag `-GINKGO_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 purpose of this file is to explain in detail the capacities of this benchmarking suite as well as how to properly setup everything.

Here is a short description of the content of this file:

1. Ginkgo setup and best practice guidelines
2. Installing and using the `ssget` tool to fetch the [SuiteSparse matrices](#).
3. Benchmarking overview and how to run them in a simple way.
4. How to publish the benchmark results online and use the [Ginkgo Performance Explorer \(GPE\)](#) for performance analysis (optional).
5. Using the benchmark suite for performance debugging thanks to the loggers.
6. All available benchmark customization options.

4.0.1 1: Ginkgo setup and best practice guidelines

Before benchmarking Ginkgo, make sure that you follow the general guidelines in order to ensure best performance.

1. The code should be compiled in `Release` mode.
2. Make sure the machine has no competing jobs. On a Linux machine multiple commands can be used, `last` shows the currently opened sessions, `top` or `htop` allows to show the current machine load, and if considering using specific GPUs, `nvidia-smi` or `rocm-smi` can be used to check their load.
3. By default, Ginkgo's benchmarks will always do at least one warm-up run. For better accuracy, every benchmark is also averaged over 10 runs, except for the solver benchmark which are usually fairly long. These parameters can be tuned at the command line to either shorten benchmarking time or improve benchmarking accuracy.

In addition, the following specific options can be considered:

1. When specifically using the adaptive block jacobi preconditioner, enable the `GINKGO_JACOBI_FULL_OPTIMIZATIONS` CMake flag. Be careful that this will use much more memory and time for the compilation due to compiler performance issues with register optimizations, in particular.
2. The current benchmarking setup also allows to benchmark only the overhead by using as either (or for all) preconditioner/spmv/solver, the special overhead LinOp. If your purpose is to check Ginkgo's overhead, make sure to try this mode.

4.0.2 2: Using `ssget` to fetch the matrices

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. This is done thanks to the [ssget command-line utility](#).

To install `ssget`, access the repository and copy the file `ssget` into a directory present in your `PATH` variable as per the tool's `README.md` instructions. The tool can be installed either in a global system path or a local directory such as `$HOME/.local/bin`. After installing the tool, it is important to review the `ssget` script and configure as needed the variable `ARCHIVE_LOCATION` on line 39. This is where the matrices will be stored into.

The Ginkgo benchmark can be set to run on only a portion of the SuiteSparse matrix collection as we will see in the following section. 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 as 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.

Before proceeding, it can be useful in order to save time to download the matrices as preparation. This can be done by using the `ssget -f -i i` command where `i` is the ID of the matrix to be downloaded. The following loop allows to download the full SuiteSparse matrix collection:

```
for i in $(seq 0 $(ssget -n)); do
    ssget -f -i ${i}
done
```

Note that `ssget` can also be used to query properties of the matrix and filter the matrices which are downloaded. For example, the following will download only positive definite matrices with less than 500M non zero elements and 10M columns. Please refer to the [ssget documentation](#) for more information.

```
for i in $(seq 0 $(ssget -n)); do
    posdef=$(ssget -p posdef -i ${i})
    cols=$(ssget -p cols -i ${i})
    nnz=$(ssget -p nonzeros -i ${i})
    if [ "$posdef" -eq 1 -a "$cols" -lt 10000000 -a "$nnz" -lt 500000000 ]; then
        ssget -f -i ${i}
    fi
done
```

4.0.3 3: Benchmarking overview

The benchmark suite is invoked using the `make benchmark` command in the build directory. Under the hood, this command simply calls the script `benchmark/run_all_benchmarks.sh` so it is possible to manually launch this script as well. 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:

```
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).

The benchmark suite can take a number of configuration parameters. Benchmarks can be run only for sparse matrix vector products (`spmv`), for full solvers (with or without preconditioners), or for preconditioners only when supported. The benchmark suite also allows to target a sub-part of the SuiteSparse matrix collection. For details, see the available benchmark options. Here are the most important options:

- `BENCHMARK={spmv, solver, preconditioner}` - allows to select the type of benchmark to be ran.
- `EXECUTOR={reference, cuda, hip, omp, dpcpp}` - select the executor and platform the benchmarks should be ran on.
- `SYSTEM_NAME=<name>` - a name which will be used to designate this platform (e.g. V100, RadeonVII, ...).
- `SEGMENTS=<N>` - Split the benchmarked matrix space into `<N>` segments. If specified, `SEGMENT_ID` also has to be set.
- `SEGMENT_ID=<I>` - used in combination with the `SEGMENTS` variable. `<I>` should be an integer between 1 and `<N>`, the number of `SEGMENTS`. If specified, only the `<I>`-th segment of the benchmark suite will be run.
- `BENCHMARK_PRECISION` - defines the precision the benchmarks are run in. Supported values are: "double" (default), "single", "dcomplex" and "scomplex"
- `MATRIX_LIST_FILE=/path/to/matrix_list.file` - allows to list SuiteSparse matrix id or name to benchmark. As an example, a matrix list file containing the following will ensure that benchmarks are ran for only those three matrices:

```
``` 1903 Freescale/circuit5M thermal2 ```
```

#### 4.0.4 4: Publishing the results on Github and analyze the results with the GPE (optional)

The previous experiments generated json files for each matrices, each containing timing, iteration count, achieved precision, ... depending on the type of benchmark run. These files are available in the directory `${ginkgo_build_dir}/benchmark/results/`. These files can be analyzed and processed through any tool (e.g. python). In this section, we describe how to generate the plots by using Ginkgo's `GPE` tool. First, we need to publish the experiments into a Github repository which will be then linked as source input to the GPE. For this, we can simply fork the ginkgo-data repository. To do so, we can go to the github repository and use the forking interface: <https://github.com/ginkgo-project/ginkgo-data/>

Once it's done, we want to clone the repository locally, put all results online and access the GPE for plotting the results. Here are the detailed steps:

```
git clone https://github.com/<username>/ginkgo-data.git $HOME/ginkgo_benchmark/ginkgo-data
send the benchmarked data to the ginkgo-data repository
If needed, remove the old data so that no previous data is left.
rm -r ${HOME}/ginkgo_benchmark/ginkgo-data/data/${SYSTEM_NAME}
rsync -rtv ${ginkgo_build_dir}/benchmark/results/ $HOME/ginkgo_benchmark/ginkgo-data/data/
cd ${HOME}/ginkgo_benchmark/ginkgo-data/data/
The following updates the main '.json' files with the list of data.
Ensure a python 3 installation is available.
./build-list . > list.json
./aggregate < list.json > aggregate.json
./represent . > represent.json
git config --local user.name "<Name>"
git config --local user.email "<email>"
git commit -am "Ginkgo benchmark ${BENCHMARK} of ${SYSTEM_NAME}..."
```

```
git push
```

Note that depending on what data is of interest, you may need to update the scripts `build-list` or `agregate` to change which files you want to agglomerate and summarize (depending on the system name), or which data you want to select (solver results, `spmv` results, ...).

For the generating the plots in the GPE, here are the steps to go through:

1. Access the GPE: <https://ginkgo-project.github.io/gpe/>
2. Update data root URL, from <https://raw.githubusercontent.com/ginkgo-project/ginkgo-data/master> to <https://raw.githubusercontent.com/<username>/ginkgo-data/<branch>/data>
3. Click on the arrow to load the data, select the `Result Summary` entry above.
4. Click on `select an example` to choose a plotting script. Multiple scripts are available by default in different branches. You can use the `jsonata` and `chartjs` languages to develop your own as well.
5. The results should be available in the tab "plot" on the right side. Other tabs allow to access the result of the processed data after invoking the processing script.

#### 4.0.5 5: Detailed performance analysis and debugging

Detailed performance analysis can be ran by passing the environment variable `DETAILED=1` to the benchmarking script. This detailed run is available for solvers and allows to log the internal residual after every iteration as well as log the time taken by all operations. These features are also available in the `performance-debugging` example which can be used instead and modified as needed to analyze Ginkgo's performance.

These features are implemented thanks to the loggers located in the file `${ginkgo_src_dir}/benchmark/utls/loggers`. Ginkgo possesses hooks at all important code location points which can be inspected thanks to the logger. In this fashion, it is easy to use these loggers also for tracking memory allocation sizes and other important library aspects.

#### 4.0.6 6: Available benchmark options

There are a set amount of options available for benchmarking. Most important options can be configured through the benchmarking script itself thanks to environment variables. Otherwise, some specific options are not available through the benchmarking scripts but can be directly configured when running the benchmarking program itself. For a list of all options, run for example `${ginkgo_build_dir}/benchmark/solver/solver --help`.

The supported environment variables are described in the following list:

- `BENCHMARK={spmv, solver, preconditioner}` - allows to select the type of benchmark to be ran. 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.
  - `preconditioner` - Runs the preconditioner benchmarks on artificially generated block-diagonal matrices.
- `EXECUTOR={reference, cuda, hip, omp, dpcpp}` - select the executor and platform the benchmarks should be ran on. Default is `cuda`.
- `SYSTEM_NAME=<name>` - a name which will be used to designate this platform (e.g. V100, RadeonVII, ...) and not overwrite previous results. Default is `unknown`.

- `SEGMENTS=<N>` - Split the benchmarked matrix space into `<N>` segments. 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>`, the number of `SEGMENTS`. If specified, only the `<I>`-th segment of the benchmark suite will be run. Default is 1.
- `MATRIX_LIST_FILE=/path/to/matrix_list.file` - allows to list SuiteSparse matrix id or name to benchmark. As an example, a matrix list file containing the following will ensure that benchmarks are ran for only those three matrices: `` 1903 Freescale/circuit5M thermal2 ``\*`DEVICE_ID`- the accelerator device ID to target for the benchmark. The default is 0. \*`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.
- `PRECONDS={jacobi, ic, ilu, paric, parict, parilu, parilut, ic-isai, ilu-isai, paric-isai, parilu-isai, parilut-isai}` - the preconditioners to use for either solver or preconditioner benchmarks. Multiple options can be passed to this variable. Default is none.
- `FORMATS={csr, coo, ell, hybrid, sellp, hybridxx, cusp_xx, hipsp_xx}` - the matrix formats to benchmark for the spmv phase of the benchmark. Run `${ginkgo_build_dir}/benchmark/spmv/spmv --help` for a full list. If needed, multiple options for hybrid with different optimization parameters are available. Depending on the libraries available at build time, vendor library formats (cuSPARSE with `cusp_` prefix or hipSPARSE with `hipsp_` prefix) can be used as well. Multiple options can be passed. The default is `csr, coo, ell, hybrid, sellp`.
- `SOLVERS={bicgstab, bicg, cg, cgs, fcg, gmres, cb_gmres_{keep, reduce1, reduce2, integer, iredirect, _trs, upper_trs}}`
  - the solvers which should be benchmarked. Multiple options can be passed. The default is `bicgstab, cg, cgs, fcg, gmres, idr`. Note that `lower/upper_trs` by default don't use a preconditioner, as they are by default exact direct solvers.
- `SOLVERS_PRECISION=<precision>` - the minimal residual reduction before which the solver should stop. The default is `1e-6`.
- `SOLVERS_MAX_ITERATION=<number>` - the maximum number of iterations with which a solver should be ran. The default is 10000.
- `SOLVERS_RHS={1, random, sinus}` - whether to use a vector of all ones, random values or  $b = A * (s / |s|)$  with  $s(idx) = \sin(idx)$  (for complex numbers,  $s(idx) = \sin(2*idx) + i * \sin(2*idx+1)$ ) as the right-hand side in solver benchmarks. Default is 1.
- `SOLVERS_INITIAL_GUESS={rhs, 0, random}` - the initial guess generation of the solvers. `rhs` uses the right-hand side, `0` uses a zero vector and `random` generates a random vector as the initial guess.
- `DETAILED={0, 1}` - selects whether detailed benchmarks should be ran for the solver benchmarks, can be either 0 (off) or 1 (on). The default is 0.
- `GPU_TIMER={true, false}` - If set to true, use the gpu timer, which is valid for cuda/hip executor, to measure the timing. Default is false.
- `SOLVERS_JACOBI_MAX_BS` - sets the maximum block size for the Jacobi preconditioner (if used, otherwise, it does nothing) in the solvers benchmark. The default is '32'.
- `SOLVERS_GMRES_RESTART` - the maximum dimension of the Krylov space to use in GMRES. The default is 100.





## Chapter 5

# Contributing guidelines

We are glad that you are interested in contributing to Ginkgo. Please have a look at our coding guidelines before proposing a pull request.

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## 5.2 Most important stuff (A TL;DR)

- `GINKGO_DEVEL_TOOLS` needs to be set to `on` to commit. This requires `clang-format` to be installed. See [Automatic code formatting](#) for more details. Once installed, you can run `make format` in your `build/` folder to automatically format your modified files. As `make format` unstages your files post-formatting, you must stage the files again once you have verified that `make format` has done the appropriate formatting, before committing the files.
- See [Our git workflow](#) to get a quick overview of our workflow.
- See [Creating, Reviewing and Merging Pull Requests](#) on how to create a Pull request.

## 5.3 Project structure

Ginkgo is divided into a `core` module with common functionalities independent of the architecture, and several kernel modules (`reference`, `omp`, `cuda`, `hip`, `dpcpp`) which contain low-level computational routines for each supported architecture.

### 5.3.1 Extended header files

Some header files from the core module have to be extended to include special functionality for specific architectures. An example of this is `core/base/math.hpp`, which has a GPU counterpart in `cuda/base/math.↔.hpp`. For such files you should always include the version from the module you are working on, and this file will internally include its `core` counterpart.

### 5.3.2 Using library classes

You can use and call functions of existing classes inside a kernel (that are defined and not just declared in a header file), however, you are not allowed to create new instances of a polymorphic class inside a kernel (or in general inside any kernel module like `cuda/hip/omp/reference`) as this creates circular dependencies between the `core` and the backend library. With this in mind, our CI contains a job which checks if such a circular dependency exists. These checks can be run manually using the `-DGINKGO_CHECK_CIRCULAR_DEPS=ON` option in the CMake configuration.

For example, when creating a new matrix class `AB` by combining existing classes `A` and `B`, the `AB::apply()` function composed of invocations to `A::apply()` and `B::apply()` can only be defined in the `core` module, it is not possible to create instances of `A` and `B` inside the `AB` kernel files. This is to avoid the aforementioned circular dependency issue. An example for such a class is the `Hybrid` matrix format, which uses the `apply()` of the `Ell` and `Coo` matrix formats. Nevertheless, it is possible to call the kernels themselves directly within the same executor. For example, `cuda::dense::add_scaled()` can be called from any other `cuda` kernel.

## 5.4 Git related

Ginkgo uses `git`, the distributed version control system to track code changes and coordinate work among its developers. A general guide to `git` can be found in [its extensive documentation](#).

### 5.4.1 Our git workflow

In Ginkgo, we prioritize keeping a clean history over accurate tracking of commits. `git rebase` is hence our command of choice to make sure that we have a nice and linear history, especially for pulling the latest changes from the `develop` branch. More importantly, rebasing upon `develop` is **required** before the commits of the PR are merged into the `develop` branch.

### 5.4.2 Writing good commit messages

With software sustainability and maintainability in mind, it is important to write commit messages that are short, clear and informative. Ideally, this would be the format to prefer:

```
Summary of the changes in a sentence, max 50 chars.
More detailed comments:
+ Changes that have been added.
- Changes that have been removed.
Related PR: https://github.com/ginkgo-project/ginkgo/pull/<PR-number>
```

You can refer to [this informative guide](#) for more details.

#### 5.4.2.1 Attributing credit

Git has a nice feature where it allows you to add a co-author for your commit, if you would like to attribute credits for the changes made in the commit. This can be done by:

```
Commit message.
Co-authored-by: Name <email@domain>
```

In the Ginkgo commit history, this is most common associated with suggested improvements from code reviews.

### 5.4.3 Creating, Reviewing and Merging Pull Requests

- The `develop` branch is the default branch to submit PR's to. From time to time, we merge the `develop` branch to the `master` branch and create tags on the `master` to create new releases of Ginkgo. Therefore, all pull requests must be merged into `develop`.
- Please have a look at the labels and make sure to add the relevant labels.
- You can mark the PR as a WIP if you are still working on it, `Ready for Review` when it is ready for others to review it.
- Assignees to the PR should be the ones responsible for merging that PR. Currently, it is only possible to assign members within the `ginkgo-project`.
- Each pull request requires at least two approvals before merging.
- PR's created from within the repository will automatically trigger two CI pipelines on pushing to the branch from the which the PR has been created. The Github Actions pipeline tests our framework on Mac OSX and on Windows platforms. Another comprehensive Linux based pipeline is run from a [mirror on gitlab](#) and contains additional checks like static analysis and test coverage.
- Once a PR has been approved and the build has passed, one of the reviewers can mark the PR as `READY TO MERGE`. At this point the creator/assignee of the PR *needs to* verify that the branch is up to date with `develop` and rebase it on `develop` if it is not.

## 5.5 Code style

### 5.5.1 Automatic code formatting

Ginkgo uses `ClangFormat` (executable is usually named `clang-format`) and a custom `.clang-format` configuration file (mostly based on ClangFormat's *Google* style) to automatically format your code. **Make sure you have ClangFormat set up and running properly** ( you should be able to run `make format` from Ginkgo's build directory) before committing anything that will end up in a pull request against `ginkgo-project/ginkgo` repository. In addition, you should **never** modify the `.clang-format` configuration file shipped with Ginkgo. E.g. if ClangFormat has trouble reading this file on your system, you should install a newer version of ClangFormat, and avoid commenting out parts of the configuration file.

ClangFormat is the primary tool that helps us achieve a uniform look of Ginkgo's codebase, while reducing the learning curve of potential contributors. However, ClangFormat configuration is not expressive enough to incorporate the entire coding style, so there are several additional rules that all contributed code should follow.

*Note:* To learn more about how ClangFormat will format your code, see existing files in Ginkgo, `.clang-format` configuration file shipped with Ginkgo, and ClangFormat's documentation.

### 5.5.2 Naming scheme

#### 5.5.2.1 Filenames

Filenames use `snake_case` and use the following extensions:

- C++ source files: `.cpp`
- C++ header files: `.hpp`

- CUDA source files: `.cu`
- CUDA header files: `.cuh`
- HIP source files: `.hip.cpp`
- HIP header files: `.hip.hpp`
- Common source files used by both CUDA and HIP: `.hpp.inc`
- CMake utility files: `.cmake`
- Shell scripts: `.sh`

*Note:* A C++ source/header file is considered a CUDA file if it contains CUDA code that is not guarded with `#if` guards that disable this code in non-CUDA compilers. I.e. if a file can be compiled by a general C++ compiler, it is not considered a CUDA file.

#### 5.5.2.2 Macros

Macros (both object-like and function-like macros) use `CAPITAL_CASE`. They have to start with `GKO_` to avoid name clashes (even if they are `#undef-ed` in the same file!).

#### 5.5.2.3 Variables

Variables use `snake_case`.

#### 5.5.2.4 Constants

Constants use `snake_case`.

#### 5.5.2.5 Functions

Functions use `snake_case`.

#### 5.5.2.6 Structures and classes

Structures and classes which do not experience polymorphic behavior (i.e. do not contain virtual methods, nor members which experience polymorphic behavior) use `snake_case`.

All other structures and classes use `CamelCase`.

#### 5.5.2.7 Members

All structure / class members use the same naming scheme as they would if they were not members:

- methods use the naming scheme for functions
- data members the naming scheme for variables or constants
- type members for classes / structures

Additionally, non-public data members end with an underscore (`_`).

### 5.5.2.8 Namespaces

Namespaces use `snake_case`.

### 5.5.2.9 Template parameters

- Type template parameters use `CamelCase`, for example `ValueType`.
- Non-type template parameters use `snake_case`, for example `subwarp_size`.

## 5.5.3 Whitespace

Spaces and tabs are handled by ClangFormat, but blank lines are only partially handled (the current configuration doesn't allow for more than 2 blank lines). Thus, contributors should be aware of the following rules for blank lines:

1. Top-level statements and statements directly within namespaces are separated with 2 blank lines. The first / last statement of a namespace is separated by two blank lines from the opening / closing brace of the namespace.

- (a) *exception*: if the first **or** the last statement in the namespace is another namespace, then no blank lines are required *example*: ````c++ namespace foo {`

```
struct x {
};

} // namespace foo

namespace bar {
namespace baz {

void f();

} // namespace baz
} // namespace bar
```
```

2. `_exception_`: in header files whose only purpose is to `_declare_` a bunch of functions (e.g. the `*_kernel.hpp` files) these declarations can be separated by only 1 blank line (note: standard rules apply for all other statements that might be present in that file)`
3. `_exception_`: "related" statement can have 1 blank line between them. "Related" is not a strictly defined adjective in this sense, but is in general one of:
 1. overload of a same function,
 2. function / class template and it's specializations,
 3. macro that modifies the meaning or adds functionality to the previous / following statement.

However, simply calling function `'f'` from function `'g'` does not imply that `'f'` and `'g'` are "related".

1. Statements within structures / classes are separated with 1 blank line. There are no blank lines between the first / last statement in the structure / class.

- (a) *exception*: there is no blank line between an access modifier (`private`, `protected`, `public`) and the following statement. *example*: ````c++ class foo { public: int get_x() const noexcept { return x_; } int &get_x() noexcept { return x_; } private: int x_; }; ````
- 2. Function bodies cannot have multiple consecutive blank lines, and a single blank line can only appear between two logical sections of the function.
- 3. Unit tests should follow the `AAA` pattern, and a single blank line must appear between consecutive "A" sections. No other blank lines are allowed in unit tests.
- 4. Enumeration definitions should have no blank lines between consecutive enumerators.

5.5.4 Include statement grouping

In general, all include statements should be present on the top of the file, ordered in the following groups, with two blank lines between each group:

1. Related header file (e.g. `core/foo/bar.hpp` included in `core/foo/bar.cpp`, or in the unit test `core/test/foo/bar.cpp`)
2. Standard library headers (e.g. `vector`)
3. Executor specific library headers (e.g. `omp.h`)
4. System third-party library headers (e.g. `papi.h`)
5. Local third-party library headers
6. Public Ginkgo headers
7. Private Ginkgo headers

Example: A file `core/base/my_file.cpp` might have an include list like this:

```
{c++}
#include <ginkgo/core/base/my_file.hpp>
#include <algorithm>
#include <vector>
#include <tuple>
#include <omp.h>
#include <papi.h>
#include "third_party/blas/cblas.hpp"
#include "third_party/lapack/lapack.hpp"
#include <ginkgo/core/base/executor.hpp>
#include <ginkgo/core/base/lin_op.hpp>
#include <ginkgo/core/base/types.hpp>
#include "core/base/my_file_kernels.hpp"
```

5.5.4.1 Main header

This section presents general rules used to define the main header attributed to the file. In the previous example, this would be `#include <ginkgo/core/base/my_file.hpp>`.

General rules:

1. Some fixed main header.
2. components:
 - with `_kernel` suffix looks for the header in the same folder.

- without `_kernel` suffix looks for the header in `core`.
3. `test/Utils`: looks for the header in `core`
 4. `core`: looks for the header in `ginkgo`
 5. `test` or `base`: looks for the header in `ginkgo/core`
 6. `others`: looks for the header in `core`

Note: Please see the detail in the `dev_tools/scripts/config`.

5.5.4.2 Some general comments.

1. Private headers of Ginkgo should not be included within the public Ginkgo header.
2. It is a good idea to keep the headers self-sufficient, See [Google Style guide for reasoning](#). When compiling with `GINKGO_CHECK_CIRCULAR_DEPS` enabled, this property is explicitly checked.
3. The recommendations of the `iwyu` (Include what you use) tool can be used to make sure that the headers are self-sufficient and that the compiled files (`.cu`, `.cpp`, `.hip.cpp`) include only what they use. A [CI pipeline](#) is available that runs with the `iwyu` tool. Please be aware that this tool can be incorrect in some cases.

5.5.4.3 Automatic header arrangement

1. `dev_tools/script/format_header.sh` will take care of the group/sorting of headers according to this guideline.
2. `make format_header` arranges the header of the modified files in the branch.
3. `make format_header_all` arranges the header of all files.

5.5.5 Other Code Formatting not handled by ClangFormat

5.5.5.1 Control flow constructs

Single line statements should be avoided in all cases. Use of brackets is mandatory for all control flow constructs (e.g. `if`, `for`, `while`, ...).

5.5.5.2 Variable declarations

C++ supports declaring / defining multiple variables using a single *type-specifier*. However, this is often very confusing as references and pointers exhibit strange behavior:

```
{c++}
template <typename T> using pointer = T *;
int *    x, y; // x is a pointer, y is not
pointer<int> x, y; // both x and y are pointers
```

For this reason, **always** declare each variable on a separate line, with its own *type-specifier*.

5.5.6 CMake coding style

5.5.6.1 Whitespaces

All alignment in CMake files should use four spaces.

5.5.6.2 Use of macros vs functions

Macros in CMake do not have a scope. This means that any variable set in this macro will be available to the whole project. In contrast, functions in CMake have local scope and therefore all set variables are local only. In general, wrap all piece of algorithms using temporary variables in a function and use macros to propagate variables to the whole project.

5.5.6.3 Naming style

All Ginkgo specific variables should be prefixed with a `GINKGO_` and all functions by `ginkgo_`.

5.6 Helper scripts

To facilitate easy development within Ginkgo and to encourage coders and scientists who do not want get bogged down by the details of the Ginkgo library, but rather focus on writing the algorithms and the kernels, Ginkgo provides the developers with a few helper scripts.

5.6.1 Create a new algorithm

A `create_new_algorithm.sh` script is available for developers to facilitate easy addition of new algorithms. The options it provides can be queried with `./create_new_algorithm.sh --help`

The main objective of this script is to add files and boiler plate code for the new algorithm using a model and an instance of that model. For example, models can be any one of `factorization`, `matrix`, `preconditioner` or `solver`. For example to create a new solver named `my_solver` similar to `gmres`, you would set the `ModelType` to `solver` and set the `ModelName` to `gmres`. This would duplicate the core algorithm and kernels of the `gmres` algorithm and replace the naming to `my_solver`. Additionally, all the kernels of the new `my_solver` are marked as `GKO_NOT_IMPLEMENTED`. For easy navigation and `.txt` file is created in the folder where the script is run, which lists all the TODO's. These TODO's can also be found in the corresponding files.

5.6.2 Converting CUDA code to HIP code

We provide a `cuda2hip` script that converts `cuda` kernel code into `hip` kernel code. Internally, this script calls the `hipify script` provided by HIP, converting the CUDA syntax to HIP syntax. Additionally, it also automatically replaces the instances of CUDA with HIP as appropriate. Hence, this script can be called on a Ginkgo CUDA file. You can find this script in the `dev_tools/scripts/` folder.

5.7 Writing Tests

Ginkgo uses the `GTest` framework for the unit test framework within Ginkgo. Writing good tests are extremely important to verify the functionality of the new code and to make sure that none of the existing code has been broken.

5.7.1 Testing know-how

- GTest provides a `comprehensive documentation` of the functionality available within Gtest.
- Reduce code duplication with `Testing Fixtures`, `TEST_F`
- Write templated tests using `TYPED_TEST`.

5.7.2 Some general rules.

- Unit tests must follow the `KISS principle`.
- Unit tests must follow the `AAA` pattern, and a single blank line must appear between consecutive "A" sections.

5.7.3 Writing tests for kernels

- Reference kernels, kernels on the `ReferenceExecutor`, are meant to be single threaded reference implementations. Therefore, tests for reference kernels need to be performed with data that can be as small as possible. For example, matrices lesser than 5x5 are acceptable. This allows the reviewers to verify the results for exactness with tools such as MATLAB.
- OpenMP, CUDA, HIP and DPC++ kernels have to be tested against the reference kernels. Hence data for the tests of these kernels can be generated in the test files using helper functions or by using external files to be read through the standard input. In particular for CUDA, HIP and DPC++ the data size should be at least bigger than the architecture's warp size to ensure there is no corner case in the kernels.

5.8 Documentation style

Documentation uses standard Doxygen.

5.8.1 Developer targeted notes

Make use of `@internal` doxygen tag. This can be used for any comment which is not intended for users, but is useful to better understand a piece of code.

5.8.2 Whitespaces

5.8.2.1 After named tags such as `<tt>@param foo</tt>`

The documentation tags which use an additional name should be followed by two spaces in order to better distinguish the text from the doxygen tag. It is also possible to use a line break instead.

5.8.3 Documenting examples

There are two main steps:

1. First, you can just copy over the `doc/` folder (you can copy it from the example most relevant to you) and adapt your example names and such, then you can modify the actual documentation.
 - In `tooltip`: A short description of the example.
 - In `short-intro`: The name of the example.
 - In `results.dox`: Run the example and write the output you get.
 - In `kind`: The kind of the example. For different kinds see [the documentation](#). Examples can be of `basic`, `techniques`, `logging`, `stopping_criteria` or `preconditioners`. If your example does not fit any of these categories, feel free to create one.
 - In `intro.dox`: You write an explanation of your code with some introduction similar to what you see in an existing example most relevant to you.
 - In `builds-on`: You write the examples it builds on.
1. You also need to modify the `examples.hpp.in` file. You add the name of the example in the main section and in the section that you specified in the `doc/kind` file in the example documentation.

5.9 Other programming comments

5.9.1 C++ standard stream objects

These are global objects and are shared inside the same translation unit. Therefore, whenever its state or formatting is changed (e.g. using `std::hex` or floating point formatting) inside library code, make sure to restore the state before returning the control to the user. See this [stackoverflow question](#) for examples on how to do it correctly. This is extremely important for header files.

5.9.2 Warnings

By default, the `-DGINKGO_COMPILER_FLAGS` is set to `-Wpedantic` and hence pedantic warnings are emitted by default. Some of these warnings are false positives and a complete list of the resolved warnings and their solutions is listed in [Issue 174](#). Specifically, when macros are being used, we have the issue of having `extra ; warnings`, which is resolved by adding a `static_assert()`. The CI system additionally also has a step where it compiles for pedantic warnings to be errors.

5.9.3 Avoiding circular dependencies

To facilitate finding circular dependencies issues (see [Using library classes](#) for more details), a CI step `no-circular-deps` was created. For more details on its usage, see [this pipeline](#), where Ginkgo did not abide to this policy and [PR #278](#) which fixed this. Note that doing so is not enough to guarantee with 100% accuracy that no circular dependency is present. For an example of such a case, take a look at [this pipeline](#) where one of the compiler setups detected an incorrect dependency of the `cuda` module (due to `jacobi`) on the `core` module.

Chapter 6

Citing Ginkgo

The main Ginkgo paper describing Ginkgo's purpose, design and interface is available through the following reference:

```
@misc{anzt2020ginkgo,
  title={Ginkgo: A Modern Linear Operator Algebra Framework for High Performance Computing},
  author={Hartwig Anzt and Terry Cojean and Goran Flegar and Fritz Göbel and Thomas Grützmacher and Pratik Nayak and Tobias Ribizel and Yuhsiang Mike Tsai and Enrique S. Quintana-Ortí},
  year={2020},
  eprint={2006.16852},
  archivePrefix={arXiv},
  primaryClass={cs.MS}
}
```

Multiple topical papers exist on Ginkgo and its algorithms. The following papers can be used to cite specific aspects of the Ginkgo project.

6.0.1 The Ginkgo Software

The Ginkgo software itself was reviewed and has a paper published in the Journal of Open Source Software, which can be cited with the following reference:

```
@article{GinkgoJoss2020,
  doi = {10.21105/joss.02260},
  url = {https://doi.org/10.21105/joss.02260},
  year = {2020},
  publisher = {The Open Journal},
  volume = {5},
  number = {52},
  pages = {2260},
  author = {Hartwig Anzt and Terry Cojean and Yen-Chen Chen and Goran Flegar and Fritz Göbel and Thomas Grützmacher and Pratik Nayak and Tobias Ribizel and Yu-Hsiang Tsai},
  title = {Ginkgo: A high performance numerical linear algebra library},
  journal = {Journal of Open Source Software}
}
```

6.0.2 On Portability

```
@misc{tsai2020amdportability,
  title={Preparing Ginkgo for AMD GPUs -- A Testimonial on Porting CUDA Code to HIP},
  author={Yuhsiang M. Tsai and Terry Cojean and Tobias Ribizel and Hartwig Anzt},
  year={2020},
  eprint={2006.14290},
  archivePrefix={arXiv},
  primaryClass={cs.MS}
}
```

6.0.3 On Software Sustainability

```
@inproceedings{anzt2019pasccb,
  author = {Anzt, Hartwig and Chen, Yen-Chen and Cojean, Terry and Dongarra, Jack and Flegar, Goran and Nayak, Pratik and Quintana-Ort\{'\i}, Enrique S. and Tsai, Yuhsiang M. and Wang, Weichung},
  title = {Towards Continuous Benchmarking: An Automated Performance Evaluation Framework for High Performance Software},
  year = {2019},
  isbn = {9781450367707},
  publisher = {Association for Computing Machinery},
  address = {New York, NY, USA},
  url = {https://doi.org/10.1145/3324989.3325719},
  doi = {10.1145/3324989.3325719},
  booktitle = {Proceedings of the Platform for Advanced Scientific Computing Conference},
  articleno = {9},
  numpages = {11},
  keywords = {interactive performance visualization, healthy software lifecycle, continuous integration, automated performance benchmarking},
  location = {Zurich, Switzerland},
  series = {PASC '19}
}
```

6.0.4 On SpMV or solvers performance

```
@InProceedings{tsai2020amdspmv,
  author="Tsai, Yuhsiang M.
  and Cojean, Terry
  and Anzt, Hartwig",
  editor="Sadayappan, Ponnuswamy
  and Chamberlain, Bradford L.
  and Juckeland, Guido
  and Ltaief, Hatem",
  title="Sparse Linear Algebra on AMD and&nbsp;NVIDIA GPUs -- The Race Is On",
  booktitle="High Performance Computing",
  year="2020",
  publisher="Springer International Publishing",
  address="Cham",
  pages="309--327",
  abstract="Efficiently processing sparse matrices is a central and performance-critical part of many scientific simulation codes. Recognizing the adoption of manycore accelerators in HPC, we evaluate in this paper the performance of the currently best sparse matrix-vector product (SpMV) implementations on high-end GPUs from AMD and NVIDIA. Specifically, we optimize SpMV kernels for the CSR, COO, ELL, and HYB format taking the hardware characteristics of the latest GPU technologies into account. We compare for 2,800 test matrices the performance of our kernels against AMD's hipSPARSE library and NVIDIA's cuSPARSE library, and ultimately assess how the GPU technologies from AMD and NVIDIA compare in terms of SpMV performance.",
  isbn="978-3-030-50743-5"
}

@article{anzt2020spmv,
  author = {Anzt, Hartwig and Cojean, Terry and Yen-Chen, Chen and Dongarra, Jack and Flegar, Goran and Nayak, Pratik and Tomov, Stanimire and Tsai, Yuhsiang M. and Wang, Weichung},
  title = {Load-Balancing Sparse Matrix Vector Product Kernels on GPUs},
  year = {2020},
  issue_date = {March 2020},
  publisher = {Association for Computing Machinery},
  address = {New York, NY, USA},
  volume = {7},
  number = {1},
  issn = {2329-4949},
  url = {https://doi.org/10.1145/3380930},
  doi = {10.1145/3380930},
  journal = {ACM Trans. Parallel Comput.},
  month = mar,
  articleno = {2},
  numpages = {26},
  keywords = {irregular matrices, GPUs, Sparse Matrix Vector Product (SpMV)}
}

@misc{tsai2020evaluating,
  title={Evaluating the Performance of NVIDIA's A100 Ampere GPU for Sparse Linear Algebra Computations},
  author={Yuhsiang Mike Tsai and Terry Cojean and Hartwig Anzt},
  year={2020},
  eprint={2008.08478},
  archivePrefix={arXiv},
  primaryClass={cs.MS}
}
```

Chapter 7

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.

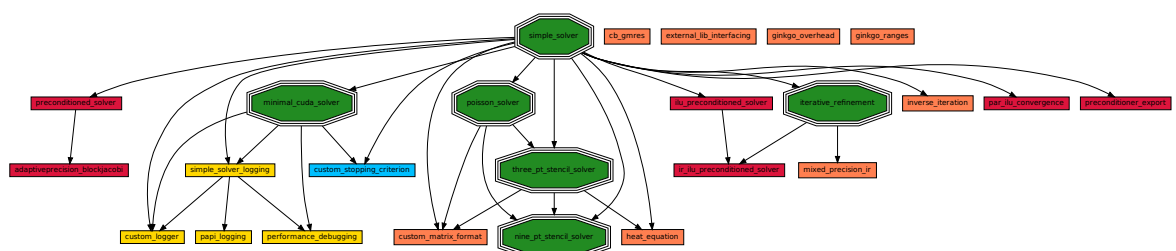
An example for building the examples and using Ginkgo as an external library without CMake can be found in the script provided for each example, which should be called with the form: `./build.sh PATH_TO_GINKGO_BUILD_DIR`

By default, Ginkgo is compiled with at least `-DGINKGO_BUILD_REFERENCE=ON`. Ginkgo also tries to detect your environment setup (presence of CUDA, ...) to enable the relevant accelerator modules. If you want to target a specific GPU, make sure that Ginkgo is compiled with the accelerator specific module enabled, such as:

1. `-DGINKGO_BUILD_CUDA=ON` option for NVIDIA GPUs.
2. `-DGINKGO_BUILD_HIP=ON` option for AMD or NVIDIA GPUs.
3. `-DGINKGO_BUILD_DPCPP=ON` option for Intel GPUs (and possibly any other platform).

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 NVIDIA 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 ilu-preconditioned-solver program | Using an ILU preconditioner to solve a linear system. |
| The performance-debugging program | Using Loggers to debug the performance within Ginkgo. |
| 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 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

| | |
|--|--|
| Solving a simple linear system with choice of executors. | The simple-solver program |
| Debug the performance of a solver using loggers. | The performance-debugging program |
| Using the CUDA executor | The minimal-cuda-solver program |
| Using preconditioners | The preconditioned-solver program ,
The ilu-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 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 ilu-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 |

Basic 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 8

The adaptiveprecision-blockjacobi program

The preconditioned solver example..

This example depends on preconditioned-solver.

This example shows how to use the adaptive precision block-Jacobi preconditioner.

In this example, we first read in a matrix from file, then generate a right-hand side and an initial guess. The preconditioned CG solver is enhanced with a block-Jacobi preconditioner that optimizes the storage format for the distinct inverted diagonal blocks to the numerical requirements. The example features the iteration count and runtime of the CG solver.

The commented program

```
#include <ginkgo/ginkgo.hpp>
#include <fstream>
#include <iomanip>
#include <iostream>
#include <map>
#include <string>
int main(int argc, char *argv[])
{
```

Some shortcuts

```
using ValueType = double;
using RealValueType = gko::remove_complex<ValueType>;
using IndexType = int;
using vec = gko::matrix::Dense<ValueType>;
using real_vec = gko::matrix::Dense<RealValueType>;
using mtx = gko::matrix::Csr<ValueType, IndexType>;
using cg = gko::solver::Cg<ValueType>;
using bj = gko::preconditioner::Jacobi<ValueType, IndexType>;
```

Print version information

```
std::cout << gko::version_info::get() << std::endl;
if (argc == 2 && (std::string(argv[1]) == "--help")) {
    std::cerr << "Usage: " << argv[0] << " [executor]" << std::endl;
    std::exit(-1);
}
const auto executor_string = argc >= 2 ? argv[1] : "reference";
```

Figure out where to run the code

```
std::map<std::string, std::function<std::shared_ptr<gko::Executor>()>>
exec_map{
    {"omp", [] { return gko::OmpExecutor::create(); }},
```

```

{"cuda",
 [] {
     return gko::CudaExecutor::create(0, gko::OmpExecutor::create(),
                                     true);
 }},
{"hip",
 [] {
     return gko::HipExecutor::create(0, gko::OmpExecutor::create(),
                                     true);
 }},
{"dpcpp",
 [] {
     return gko::DpcppExecutor::create(0,
                                       gko::OmpExecutor::create());
 }},
{"reference", [] { return gko::ReferenceExecutor::create(); }}};

```

executor where Ginkgo will perform the computation

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

Read data

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

Create RHS and initial guess as 1

```

gko::size_type size = A->get_size()[0];
auto host_x = vec::create(exec->get_master(), gko::dim<2>(size, 1));
for (auto i = 0; i < size; i++) {
    host_x->at(i, 0) = 1.;
}
auto x = vec::create(exec);
auto b = vec::create(exec);
x->copy_from(host_x.get());
b->copy_from(host_x.get());

```

Calculate initial residual by overwriting b

```

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

```

copy b again

```

b->copy_from(host_x.get());
const RealValueType reduction_factor = 1e-7;
auto iter_stop =
    gko::stop::Iteration::build().with_max_iters(10000u).on(exec);
auto tol_stop = gko::stop::ResidualNorm<ValueType>::build()
    .with_reduction_factor(reduction_factor)
    .on(exec);
std::shared_ptr<const gko::log::Convergence<ValueType>> logger =
    gko::log::Convergence<ValueType>::create(exec);
iter_stop->add_logger(logger);
tol_stop->add_logger(logger);

```

Create solver factory

```

auto solver_gen =
    cg::build()
    .with_criteria(gko::share(iter_stop), gko::share(tol_stop))

```

Add preconditioner, these 2 lines are the only difference from the simple solver example

```

.with_preconditioner(bj::build()
    .with_max_block_size(16u)
    .with_storage_optimization(
        gko::precision_reduction::autodetect())
    .on(exec))
.on(exec);

```

Create solver

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

Solve system

```

exec->synchronize();
std::chrono::nanoseconds time(0);
auto tic = std::chrono::steady_clock::now();
solver->apply(lend(b), lend(x));
auto toc = std::chrono::steady_clock::now();
time += std::chrono::duration_cast<std::chrono::nanoseconds>(toc - tic);

```

Calculate residual

```
auto res = gko::initialize<real_vec>({0.0}, exec);
A->apply(lend(one), lend(x), lend(neg_one), lend(b));
b->compute_norm2(lend(res));
std::cout << "Initial residual norm sqrt(r^T r):\n";
write(std::cout, lend(initres));
std::cout << "Final residual norm sqrt(r^T r):\n";
write(std::cout, lend(res));
```

Print solver statistics

```
std::cout << "CG iteration count:      " << logger->get_num_iterations()
           << std::endl;
std::cout << "CG execution time [ms]: "
           << static_cast<double>(time.count()) / 1000000.0 << std::endl;
}
```

Results

This is the expected output:

```
Initial residual norm sqrt(r^T r):
%%MatrixMarket matrix array real general
1 1
194.679
Final residual norm sqrt(r^T r):
%%MatrixMarket matrix array real general
1 1
5.69384e-06
CG iteration count:      5
CG execution time [ms]: 0.080041
```

Comments about programming and debugging

The plain program

```
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```

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```
*****<GINKGO LICENSE>*****/
#include <ginkgo/ginkgo.hpp>
#include <fstream>
#include <iomanip>
#include <iostream>
#include <map>
#include <string>
int main(int argc, char *argv[])
{
    using ValueType = double;
```

```

using RealValueType = gko::remove_complex<ValueType>;
using IndexType = int;
using vec = gko::matrix::Dense<ValueType>;
using real_vec = gko::matrix::Dense<RealValueType>;
using mtx = gko::matrix::Csr<ValueType, IndexType>;
using cg = gko::solver::Cg<ValueType>;
using bj = gko::preconditioner::Jacobi<ValueType, IndexType>;
std::cout << gko::version_info::get() << std::endl;
if (argc == 2 && (std::string(argv[1]) == "--help")) {
    std::cerr << "Usage: " << argv[0] << " [executor]" << std::endl;
    std::exit(-1);
}
const auto executor_string = argc >= 2 ? argv[1] : "reference";
std::map<std::string, std::function<std::shared_ptr<gko::Executor>()>>
    exec_map{
        {"omp", [] { return gko::OmpExecutor::create(); }},
        {"cuda",
         [] {
             return gko::CudaExecutor::create(0, gko::OmpExecutor::create(),
                                              true);
         }},
        {"hip",
         [] {
             return gko::HipExecutor::create(0, gko::OmpExecutor::create(),
                                              true);
         }},
        {"dpcpp",
         [] {
             return gko::DpcppExecutor::create(0,
                                              gko::OmpExecutor::create());
         }},
        {"reference", [] { return gko::ReferenceExecutor::create(); }
    };
const auto exec = exec_map.at(executor_string)(); // throws if not valid
auto A = share(gko::read<mtx>(std::ifstream("data/A.mtx"), exec));
gko::size_type size = A->get_size()[0];
auto host_x = vec::create(exec->get_master(), gko::dim<2>(size, 1));
for (auto i = 0; i < size; i++) {
    host_x->at(i, 0) = 1.;
}
auto x = vec::create(exec);
auto b = vec::create(exec);
x->copy_from(host_x.get());
b->copy_from(host_x.get());
auto one = gko::initialize<vec>({1.0}, exec);
auto neg_one = gko::initialize<vec>({-1.0}, exec);
auto initres = gko::initialize<real_vec>({0.0}, exec);
A->apply(lend(one), lend(x), lend(neg_one), lend(b));
b->compute_norm2(lend(initres));
b->copy_from(host_x.get());
const RealValueType reduction_factor = 1e-7;
auto iter_stop =
    gko::stop::Iteration::build().with_max_iters(10000u).on(exec);
auto tol_stop = gko::stop::ResidualNorm<ValueType>::build()
    .with_reduction_factor(reduction_factor)
    .on(exec);
std::shared_ptr<const gko::log::Convergence<ValueType>> logger =
    gko::log::Convergence<ValueType>::create(exec);
iter_stop->add_logger(logger);
tol_stop->add_logger(logger);
auto solver_gen =
    cg::build()
        .with_criteria(gko::share(iter_stop), gko::share(tol_stop))
        .with_preconditioner(bj::build()
            .with_max_block_size(16u)
            .with_storage_optimization(
                gko::precision_reduction::autodetect())
            .on(exec))
        .on(exec);
auto solver = solver_gen->generate(A);
exec->synchronize();
std::chrono::nanoseconds time(0);
auto tic = std::chrono::steady_clock::now();
solver->apply(lend(b), lend(x));
auto toc = std::chrono::steady_clock::now();
time += std::chrono::duration_cast<std::chrono::nanoseconds>(toc - tic);
auto res = gko::initialize<real_vec>({0.0}, exec);
A->apply(lend(one), lend(x), lend(neg_one), lend(b));
b->compute_norm2(lend(res));
std::cout << "Initial residual norm sqrt(r^T r):\n";
write(std::cout, lend(initres));
std::cout << "Final residual norm sqrt(r^T r):\n";
write(std::cout, lend(res));
std::cout << "CG iteration count:      " << logger->get_num_iterations()
    << std::endl;
std::cout << "CG execution time [ms]: "
    << static_cast<double>(time.count()) / 1000000.0 << std::endl;
}

```

Chapter 9

The cb-gmres program

The CB-GMRES solver example..

Introduction

About the example

This example showcases the usage of the Ginkgo solver CB-GMRES (Compressed Basis GMRES). A small system is solved with two un-preconditioned CB-GMRES solvers:

1. without compressing the krylov basis; it uses double precision for both the matrix and the krylov basis, and
2. with a compression of the krylov basis; it uses double precision for the matrix and all arithmetic operations, while using single precision for the storage of the krylov basis

Both solves are timed and the residual norm of each solution is computed to show that both solutions are correct.

The commented program

This is the main ginkgo header file.

```
#include <ginkgo/ginkgo.hpp>
#include <chrono>
#include <cmath>
#include <fstream>
#include <iostream>
#include <map>
#include <string>
```

Helper function which measures the time of `solver->apply(b, x)` in seconds To get an accurate result, the solve is repeated multiple times (while ensuring the initial guess is always the same). The result of the solve will be written to `x`.

```
double measure_solve_time_in_s(const gko::Executor *exec, gko::LinOp *solver,
                              const gko::LinOp *b, gko::LinOp *x)
{
    constexpr int repeats{5};
    double duration{0};
```

Make a copy of `x`, so we can re-use the same initial guess multiple times

```
auto x_copy = clone(x);
for (int i = 0; i < repeats; ++i) {
```

No need to copy it in the first iteration

```
if (i != 0) {
    x_copy->copy_from(x);
}
```

Make sure all previous executor operations have finished before starting the time

```
exec->synchronize();
auto tic = std::chrono::steady_clock::now();
solver->apply(b, lend(x_copy));
```

Make sure all computations are done before stopping the time

```
exec->synchronize();
auto tac = std::chrono::steady_clock::now();
duration += std::chrono::duration<double>(tac - tic).count();
}
```

Copy the solution back to x, so the caller has the result

```
x->copy_from(lend(x_copy));
return duration / static_cast<double>(repeats);
}
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 now a natural extension of adding columns/rows are necessary.

```
using ValueType = double;
using RealValueType = gko::remove_complex<ValueType>;
using IndexType = int;
using vec = gko::matrix::Dense<ValueType>;
using real_vec = gko::matrix::Dense<RealValueType>;
```

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<ValueType, IndexType>;
```

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

```
using cb_gmres = gko::solver::CbGmres<ValueType>;
```

Print the ginkgo version information.

```
std::cout << gko::version_info::get() << std::endl;
if (argc == 2 && (std::string(argv[1]) == "--help")) {
    std::cerr << "Usage: " << argv[0] << " [executor] " << std::endl;
    std::exit(-1);
}
```

Map which generates the appropriate executor

```
const auto executor_string = argc >= 2 ? argv[1] : "reference";
std::map<std::string, std::function<std::shared_ptr<gko::Executor>()>>
    exec_map{
        {"omp", [] { return gko::OmpExecutor::create(); }},
        {"cuda",
         [] {
             return gko::CudaExecutor::create(0, gko::OmpExecutor::create(),
                                              true);
         }},
        {"hip",
         [] {
             return gko::HipExecutor::create(0, gko::OmpExecutor::create(),
                                              true);
         }},
        {"dpcpp",
         [] {
             return gko::DpcppExecutor::create(0,
                                              gko::OmpExecutor::create());
         }},
        {"reference", [] { return gko::ReferenceExecutor::create(); }}}
```

executor where Ginkgo will perform the computation

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

Note: this matrix is copied from "SOURCE_DIR/matrices" instead of from the local directory. For details, see "examples/cb-gmres/CMakeLists.txt"

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

Create a uniform right-hand side with a norm2 of 1 on the host (norm2(b) == 1), followed by copying it to the actual executor (to make sure it also works for GPUs)


```

const auto A_size = A->get_size();
auto b_host = vec::create(exec->get_master(), gko::dim<2>{A_size[0], 1});
for (gko::size_type i = 0; i < A_size[0]; ++i) {
    b_host->at(i, 0) =
        ValueType{1} / std::sqrt(static_cast<ValueType>(A_size[0]));
}
auto b_norm = gko::initialize<real_vec>({0.0}, exec);
b_host->compute_norm2(lend(b_norm));
auto b = clone(exec, lend(b_host));

```

As an initial guess, use the right-hand side

```

auto x_keep = clone(lend(b));
auto x_reduce = clone(x_keep);
const RealValueType reduction_factor{1e-6};

```

Generate two solver factories: `_keep` uses the same precision for the krylov basis as the matrix, and `_reduce` uses one precision below it. If `ValueType` is double, then `_reduce` uses float as the krylov basis storage type

```

auto solver_gen_keep =
    cb_gmres::build()
        .with_criteria(
            gko::stop::Iteration::build().with_max_iters(1000u).on(exec),
            gko::stop::RelativeResidualNorm<ValueType>::build()
                .with_tolerance(reduction_factor)
                .on(exec))
        .with_krylov_dim(100u)
        .with_storage_precision(
            gko::solver::cb_gmres::storage_precision::keep)
        .on(exec);
auto solver_gen_reduce =
    cb_gmres::build()
        .with_criteria(
            gko::stop::Iteration::build().with_max_iters(1000u).on(exec),
            gko::stop::RelativeResidualNorm<ValueType>::build()
                .with_tolerance(reduction_factor)
                .on(exec))
        .with_krylov_dim(100u)
        .with_storage_precision(
            gko::solver::cb_gmres::storage_precision::reduce1)
        .on(exec);

```

Generate the actual solver from the factory and the matrix.

```

auto solver_keep = solver_gen_keep->generate(A);
auto solver_reduce = solver_gen_reduce->generate(A);

```

Solve both system and measure the time for each.

```

auto time_keep = measure_solve_time_in_s(lend(exec), lend(solver_keep),
                                         lend(b), lend(x_keep));
auto time_reduce = measure_solve_time_in_s(lend(exec), lend(solver_reduce),
                                           lend(b), lend(x_reduce));

```

Make sure the output is in scientific notation for easier comparison

```
std::cout << std::scientific;
```

Note: The time might not be significantly different since the matrix is quite small

```

std::cout << "Solve time without compression: " << time_keep << " s\n"
          << "Solve time with compression:      " << time_reduce << " s\n";

```

To measure if your solution has actually converged, the error of the solution is measured. `one`, `neg_one` are objects that represent the numbers which allow for a uniform interface when computing on any device. To compute the residual, the (advanced) `apply` method is used.

```

auto one = gko::initialize<vec>({1.0}, exec);
auto neg_one = gko::initialize<vec>({-1.0}, exec);
auto res_norm_keep = gko::initialize<real_vec>({0.0}, exec);
auto res_norm_reduce = gko::initialize<real_vec>({0.0}, exec);
auto tmp = gko::clone(gko::lend(b));

```

`tmp = Ax - tmp`

```

A->apply(lend(one), lend(x_keep), lend(neg_one), lend(tmp));
tmp->compute_norm2(lend(res_norm_keep));
std::cout << "\nResidual norm without compression:\n";
write(std::cout, lend(res_norm_keep));
tmp->copy_from(lend(b));
A->apply(lend(one), lend(x_reduce), lend(neg_one), lend(tmp));
tmp->compute_norm2(lend(res_norm_reduce));
std::cout << "\nResidual norm with compression:\n";
write(std::cout, lend(res_norm_reduce));
}

```

Results

The following is the expected result:

```
Solve time without compression: 1.842690e-04 s
Solve time with compression:    1.589936e-04 s
Residual norm without compression:
%%MatrixMarket matrix array real general
1 1
2.430544e-07
Residual norm with compression:
%%MatrixMarket matrix array real general
1 1
3.437257e-07
```

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.
*****/
#include <ginkgo/ginkgo.hpp>
#include <chrono>
#include <cmath>
#include <fstream>
#include <iostream>
#include <map>
#include <string>
double measure_solve_time_in_s(const gko::Executor *exec, gko::LinOp *solver,
                               const gko::LinOp *b, gko::LinOp *x)
{
    constexpr int repeats{5};
    double duration{0};
    auto x_copy = clone(x);
    for (int i = 0; i < repeats; ++i) {
        if (i != 0) {
            x_copy->copy_from(x);
        }
        exec->synchronize();
        auto tic = std::chrono::steady_clock::now();
        solver->apply(b, lend(x_copy));
        exec->synchronize();
        auto tac = std::chrono::steady_clock::now();
        duration += std::chrono::duration<double>(tac - tic).count();
    }
    x->copy_from(lend(x_copy));
    return duration / static_cast<double>(repeats);
}
int main(int argc, char *argv[])
{
    using ValueType = double;

```

```

using RealValueType = gko::remove_complex<ValueType>;
using IndexType = int;
using vec = gko::matrix::Dense<ValueType>;
using real_vec = gko::matrix::Dense<RealValueType>;
using mtx = gko::matrix::Csr<ValueType, IndexType>;
using cb_gmres = gko::solver::CbGmres<ValueType>;
std::cout << gko::version_info::get() << std::endl;
if (argc == 2 && (std::string(argv[1]) == "--help")) {
    std::cerr << "Usage: " << argv[0] << " [executor] " << std::endl;
    std::exit(-1);
}
const auto executor_string = argc >= 2 ? argv[1] : "reference";
std::map<std::string, std::function<std::shared_ptr<gko::Executor>()>>
    exec_map{
        {"omp", [] { return gko::OmpExecutor::create(); }},
        {"cuda",
         [] {
             return gko::CudaExecutor::create(0, gko::OmpExecutor::create(),
                 true);
         }},
        {"hip",
         [] {
             return gko::HipExecutor::create(0, gko::OmpExecutor::create(),
                 true);
         }},
        {"dpcpp",
         [] {
             return gko::DpcppExecutor::create(0,
                 gko::OmpExecutor::create());
         }},
        {"reference", [] { return gko::ReferenceExecutor::create(); }}};
const auto exec = exec_map.at(executor_string)(); // throws if not valid
auto A = share(gko::read<mtx>(std::ifstream("data/A.mtx"), exec));
const auto A_size = A->get_size();
auto b_host = vec::create(exec->get_master(), gko::dim<2>{A_size[0], 1});
for (gko::size_type i = 0; i < A_size[0]; ++i) {
    b_host->at(i, 0) =
        ValueType{1} / std::sqrt(static_cast<ValueType>(A_size[0]));
}
auto b_norm = gko::initialize<real_vec>({0.0}, exec);
b_host->compute_norm2(lend(b_norm));
auto b = clone(exec, lend(b_host));
auto x_keep = clone(lend(b));
auto x_reduce = clone(x_keep);
const RealValueType reduction_factor{1e-6};
auto solver_gen_keep =
    cb_gmres::build()
        .with_criteria(
            gko::stop::Iteration::build().with_max_iters(1000u).on(exec),
            gko::stop::RelativeResidualNorm<ValueType>::build()
                .with_tolerance(reduction_factor)
                .on(exec))
        .with_krylov_dim(100u)
        .with_storage_precision(
            gko::solver::cb_gmres::storage_precision::keep)
        .on(exec);
auto solver_gen_reduce =
    cb_gmres::build()
        .with_criteria(
            gko::stop::Iteration::build().with_max_iters(1000u).on(exec),
            gko::stop::RelativeResidualNorm<ValueType>::build()
                .with_tolerance(reduction_factor)
                .on(exec))
        .with_krylov_dim(100u)
        .with_storage_precision(
            gko::solver::cb_gmres::storage_precision::reduce1)
        .on(exec);
auto solver_keep = solver_gen_keep->generate(A);
auto solver_reduce = solver_gen_reduce->generate(A);
auto time_keep = measure_solve_time_in_s(lend(exec), lend(solver_keep),
    lend(b), lend(x_keep));
auto time_reduce = measure_solve_time_in_s(lend(exec), lend(solver_reduce),
    lend(b), lend(x_reduce));

std::cout << std::scientific;
std::cout << "Solve time without compression: " << time_keep << " s\n"
    << "Solve time with compression: " << time_reduce << " s\n";
auto one = gko::initialize<vec>({1.0}, exec);
auto neg_one = gko::initialize<vec>({-1.0}, exec);
auto res_norm_keep = gko::initialize<real_vec>({0.0}, exec);
auto res_norm_reduce = gko::initialize<real_vec>({0.0}, exec);
auto tmp = gko::clone(gko::lend(b));
A->apply(lend(one), lend(x_keep), lend(neg_one), lend(tmp));
tmp->compute_norm2(lend(res_norm_keep));
std::cout << "\nResidual norm without compression:\n";
write(std::cout, lend(res_norm_keep));
tmp->copy_from(lend(b));
A->apply(lend(one), lend(x_reduce), lend(neg_one), lend(tmp));

```

```
tmp->compute_norm2(lend(res_norm_reduce));  
std::cout << "\nResidual norm with compression:\n";  
write(std::cout, lend(res_norm_reduce));  
}
```

Chapter 10

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 map header for storing the executor map.

```
#include <map>
```

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 returns the first element (position [0, 0]) from a given `gko::matrix::Dense` matrix / vector.

```
template <typename ValueType>
ValueType get_first_element(const gko::matrix::Dense<ValueType> *mtx)
{
```

Copy the matrix / vector to the host device before accessing the value in case it is stored in a GPU.

```
    return mtx->get_executor()->copy_val_to_host(mtx->get_const_values());
}
```

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

```
template <typename ValueType>
gko::remove_complex<ValueType> 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<gko::remove_complex<ValueType>>>(
            {0.0}, exec);
```

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

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

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

```
    return get_first_element(gko::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 {
    using RealValueType = gko::remove_complex<ValueType>;
```

Output the logger's data in a table format

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

Print a header for the table

```
std::cout << "Recurrent vs true vs implicit residual norm:"
<< std::endl;
std::cout << '|' << std::setw(10) << "Iteration" << '|' << std::setw(25)
<< "Recurrent Residual Norm" << '|' << std::setw(25)
<< "True Residual Norm" << '|' << std::setw(25)
<< "Implicit 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::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::setw(25)
<< implicit_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::setw(26) << '|' << std::setfill(' ') << std::endl;
}
using gko_dense = gko::matrix::Dense<ValueType>;
using gko_real_dense = gko::matrix::Dense<RealValueType>;
```

This overload is necessary to avoid interface breaks for Ginkgo 2.0

```
void on_iteration_complete(const gko::LinOp *solver,
                          const gko::size_type &iteration,
                          const gko::LinOp *residual,
                          const gko::LinOp *solution,
                          const gko::LinOp *residual_norm) const override
{
    this->on_iteration_complete(solver, iteration, residual, solution,
                              residual_norm, nullptr);
}
```

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 gko::LinOp *implicit_sq_residual_norm) const override
{
}
```

If the solver shares a residual norm, log its value

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

Add the norm to the `recurrent_norms` vector

```
recurrent_norms.push_back(get_first_element(gko::lend(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);
}
if (implicit_sq_residual_norm) {
    auto dense_norm =
        gko::as<gko_real_dense>(implicit_sq_residual_norm);
```

Add the norm to the `implicit_norms` vector

```
implicit_norms.push_back(
    std::sqrt(get_first_element(gko::lend(dense_norm))));
} else {
```

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

```
implicit_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<RealValueType> recurrent_norms{};
```

Vector which stores all the real residual norms

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

Vector which stores all the implicit residual norms

```
mutable std::vector<RealValueType> implicit_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 now a natural extension of adding columns/rows are necessary.

```
using ValueType = double;
using RealValueType = gko::remove_complex<ValueType>;
using IndexType = int;
using vec = gko::matrix::Dense<ValueType>;
using real_vec = gko::matrix::Dense<RealValueType>;
```

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<ValueType, IndexType>;
```

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

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

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.

```
if (argc == 2 && (std::string(argv[1]) == "--help")) {
    std::cerr << "Usage: " << argv[0] << " [executor]" << std::endl;
    std::exit(-1);
}
const auto executor_string = argc >= 2 ? argv[1] : "reference";
```

Figure out where to run the code

```
std::map<std::string, std::function<std::shared_ptr<gko::Executor>()>>
exec_map{
    {"omp", [] { return gko::OmpExecutor::create(); }},
    {"cuda",
     [] {
         return gko::CudaExecutor::create(0, gko::OmpExecutor::create(),
                                           true);
     }},
    {"hip",
     [] {
         return gko::HipExecutor::create(0, gko::OmpExecutor::create(),
                                           true);
     }},
    {"dpcpp",
     [] {
         return gko::DpcppExecutor::create(0,
                                           gko::OmpExecutor::create());
     }},
    {"reference", [] { return gko::ReferenceExecutor::create(); }}}
```

executor where Ginkgo will perform the computation

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

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);
const RealValueType reduction_factor = 1e-7;
```

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::ResidualNorm<ValueType>::build()
    .with_reduction_factor(reduction_factor)
    .on(exec))
.on(exec);
```

Instantiate a ResidualLogger logger.

```
auto logger = std::make_shared<ResidualLogger<ValueType>>(
    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(gko::lend(b), gko::lend(x));
```

Print the solution to the command line.

```
std::cout << "Solution (x):\n";
write(std::cout, gko::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<real_vec>({0.0}, exec);
A->apply(gko::lend(one), gko::lend(x), gko::lend(neg_one), gko::lend(b));
b->compute_norm2(gko::lend(res));
std::cout << "Residual norm sqrt(r^T r):\n";
write(std::cout, gko::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 true vs implicit residual norm:

| Iteration | Recurrent Residual Norm | True Residual Norm | Implicit Residual Norm |
|-----------|-------------------------|--------------------|------------------------|
| 0 | 4.358899e+00 | 4.358899e+00 | 4.358899e+00 |
| 1 | 2.304548e+00 | 2.304548e+00 | 2.304548e+00 |
| 2 | 1.467706e+00 | 1.467706e+00 | 1.467706e+00 |
| 3 | 9.848751e-01 | 9.848751e-01 | 9.848751e-01 |
| 4 | 7.418330e-01 | 7.418330e-01 | 7.418330e-01 |
| 5 | 5.136231e-01 | 5.136231e-01 | 5.136231e-01 |
| 6 | 3.841650e-01 | 3.841650e-01 | 3.841650e-01 |
| 7 | 3.164394e-01 | 3.164394e-01 | 3.164394e-01 |
| 8 | 2.277088e-01 | 2.277088e-01 | 2.277088e-01 |
| 9 | 1.703121e-01 | 1.703121e-01 | 1.703121e-01 |
| 10 | 9.737220e-02 | 9.737220e-02 | 9.737220e-02 |
| 11 | 6.168306e-02 | 6.168306e-02 | 6.168306e-02 |
| 12 | 4.541231e-02 | 4.541231e-02 | 4.541231e-02 |
| 13 | 3.195304e-02 | 3.195304e-02 | 3.195304e-02 |
| 14 | 1.616058e-02 | 1.616058e-02 | 1.616058e-02 |
| 15 | 6.570152e-03 | 6.570152e-03 | 6.570152e-03 |
| 16 | 2.643669e-03 | 2.643669e-03 | 2.643669e-03 |
| 17 | 8.588089e-04 | 8.588089e-04 | 8.588089e-04 |
| 18 | 2.864613e-04 | 2.864613e-04 | 2.864613e-04 |
| 19 | 1.641952e-15 | 2.107881e-15 | 1.641952e-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 <map>
#include <iomanip>
#include <ios>
#include <iostream>
#include <string>
#include <vector>
template <typename ValueType>
ValueType get_first_element(const gko::matrix::Dense<ValueType> *mtx)
{
    return mtx->get_executor()->copy_val_to_host(mtx->get_const_values());
}
template <typename ValueType>
gko::remove_complex<ValueType> compute_norm(
    const gko::matrix::Dense<ValueType> *b)
```

```

{
    auto exec = b->get_executor();
    auto b_norm =
        gko::initialize<gko::matrix::Dense<gko::remove_complex<ValueType>>>(
            {0.0}, exec);
    b->compute_norm2(gko::lend(b_norm));
    return get_first_element(gko::lend(b_norm));
}

template <typename ValueType>
struct ResidualLogger : gko::log::Logger {
    using RealValueType = gko::remove_complex<ValueType>;
    void write() const
    {
        std::cout << "Recurrent vs true vs implicit residual norm:"
            << std::endl;
        std::cout << '|' << std::setw(10) << "Iteration" << '|' << std::setw(25)
            << "Recurrent Residual Norm" << '|' << std::setw(25)
            << "True Residual Norm" << '|' << std::setw(25)
            << "Implicit Residual Norm" << '|' << std::endl;
        std::cout << '|' << std::setfill('-') << std::setw(11) << '|'
            << std::setw(26) << '|' << 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::setw(25)
                << implicit_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::setw(26) << '|' << std::setfill(' ') << std::endl;
    }
    using gko_dense = gko::matrix::Dense<ValueType>;
    using gko_real_dense = gko::matrix::Dense<RealValueType>;
    void on_iteration_complete(const gko::LinOp *solver,
                             const gko::size_type &iteration,
                             const gko::LinOp *residual,
                             const gko::LinOp *solution,
                             const gko::LinOp *residual_norm) const override
    {
        this->on_iteration_complete(solver, iteration, residual, solution,
                                   residual_norm, nullptr);
    }
    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 gko::LinOp *implicit_sq_residual_norm) const override
    {
        if (residual_norm) {
            auto dense_norm = gko::as<gko_real_dense>(residual_norm);
            recurrent_norms.push_back(get_first_element(gko::lend(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);
        }
        if (implicit_sq_residual_norm) {
            auto dense_norm =
                gko::as<gko_real_dense>(implicit_sq_residual_norm);
            implicit_norms.push_back(
                std::sqrt(get_first_element(gko::lend(dense_norm))));
        } else {
            implicit_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<RealValueType> recurrent_norms{};
mutable std::vector<RealValueType> real_norms{};
mutable std::vector<RealValueType> implicit_norms{};
mutable std::vector<std::size_t> iterations{};
};
int main(int argc, char *argv[])
{
    using ValueType = double;
    using RealValueType = gko::remove_complex<ValueType>;
    using IndexType = int;
    using vec = gko::matrix::Dense<ValueType>;
    using real_vec = gko::matrix::Dense<RealValueType>;
    using mtx = gko::matrix::Csr<ValueType, IndexType>;
    using cg = gko::solver::Cg<ValueType>;
    std::cout << gko::version_info::get() << std::endl;
    if (argc == 2 && (std::string(argv[1]) == "--help")) {
        std::cerr << "Usage: " << argv[0] << " [executor]" << std::endl;
        std::exit(-1);
    }
    const auto executor_string = argc >= 2 ? argv[1] : "reference";
    std::map<std::string, std::function<std::shared_ptr<gko::Executor>()>>
    exec_map{
        {"omp", [] { return gko::OmpExecutor::create(); }},
        {"cuda",
         [] {
             return gko::CudaExecutor::create(0, gko::OmpExecutor::create(),
                                              true);
         }},
        {"hip",
         [] {
             return gko::HipExecutor::create(0, gko::OmpExecutor::create(),
                                              true);
         }},
        {"dpcpp",
         [] {
             return gko::DpcppExecutor::create(0,
                                              gko::OmpExecutor::create());
         }},
        {"reference", [] { return gko::ReferenceExecutor::create(); }}};
    const auto exec = exec_map.at(executor_string)(); // throws if not valid
    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);
    const RealValueType reduction_factor = 1e-7;
    auto solver_gen =
        cg::build()
            .with_criteria(
                gko::stop::Iteration::build().with_max_iters(20u).on(exec),
                gko::stop::ResidualNorm<ValueType>::build()
                    .with_reduction_factor(reduction_factor)
                    .on(exec))
            .on(exec);
    auto logger = std::make_shared<ResidualLogger<ValueType>>(
        exec, gko::lend(A), gko::lend(b));
    solver_gen->add_logger(logger);
    auto solver = solver_gen->generate(A);
    solver->apply(gko::lend(b), gko::lend(x));
    std::cout << "Solution (x):\n";
    write(std::cout, gko::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<real_vec>({0.0}, exec);
    A->apply(gko::lend(one), gko::lend(x), gko::lend(neg_one), gko::lend(b));
    b->compute_norm2(gko::lend(res));
    std::cout << "Residual norm sqrt(r^T r):\n";
    write(std::cout, gko::lend(res));
}

```


Chapter 11

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:

$$\begin{aligned} u &: [0, 1] \rightarrow R \\ u'' &= f \\ u(0) &= u_0 \\ u(1) &= u_1 \end{aligned}$$

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:

$$\begin{aligned} u(x+h) &= u(x) + u'(x)h + 1/2u''(x)h^2 + O(h^3) \\ u(x-h) &= u(x) - u'(x)h + 1/2u''(x)h^2 + O(h^3) \\ \hline -u(x-h) + 2u(x) - u(x+h) &= -f(x)h^2 + O(h^3) \end{aligned}$$

For an equidistant grid with K "inner" discretization points x_1, \dots, x_K , and step size $h = 1/(K+1)$, the formula produces a system of linear equations

$$\begin{aligned} 2u_1 - u_2 &= -f_1h^2 + u_0 \\ -u_{k-1} + 2u_k - u_{k+1} &= -f_kh^2, k = 2, \dots, K-1 \\ -u_{K-1} + 2u_K &= -f_Kh^2 + u_1 \end{aligned}$$

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 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.

```
template <typename ValueType>
void stencil_kernel(std::size_t size, const ValueType *coefs,
                  const ValueType *b, ValueType *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.

```
template <typename ValueType>
class StencilMatrix : public gko::EnableLinOp<StencilMatrix<ValueType>,
                  public gko::EnableCreateMethod<StencilMatrix<ValueType> {
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, ValueType left = -1.0,
                  ValueType center = 2.0, ValueType right = -1.0)
    : gko::EnableLinOp<StencilMatrix>(exec, gko::dim<2>(size)),
      coefficients(exec, {left, center, right})
    {}
protected:
    using vec = gko::matrix::Dense<ValueType>;
    using coef_type = gko::Array<ValueType>;
```

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 += coeffs[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.

```

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

```

Prints the solution u.

```
template <typename ValueType>
void print_solution(ValueType u0, ValueType u1,
                   const gko::matrix::Dense<ValueType> *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, typename ValueType>
double calculate_error(int discretization_points,
                      const gko::matrix::Dense<ValueType> *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 ValueType = double;
using RealValueType = gko::remove_complex<ValueType>;
using IndexType = int;
using vec = gko::matrix::Dense<ValueType>;
using mtx = gko::matrix::Csr<ValueType, IndexType>;
using cg = gko::solver::Cg<ValueType>;
```

Figure out where to run the code

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

const auto executor_string = argc >= 2 ? argv[1] : "reference";
const unsigned int discretization_points =
    argc >= 3 ? std::atoi(argv[2]) : 100u;
std::map<std::string, std::function<std::shared_ptr<gko::Executor>()>>
exec_map{
    {"omp", [] { return gko::OmpExecutor::create(); }},
    {"cuda",
     [] {
         return gko::CudaExecutor::create(0, gko::OmpExecutor::create(),
                                           true);
     }},
    {"hip",
     [] {
         return gko::HipExecutor::create(0, gko::OmpExecutor::create(),
                                           true);
     }},
    {"dpcpp",
     [] {
         return gko::DpcppExecutor::create(0,
                                           gko::OmpExecutor::create());
     }},
    {"reference", [] { return 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->get_master();
```

problem:

```
auto correct_u = [] (ValueType x) { return x * x * x; };
auto f = [] (ValueType x) { return ValueType{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;
}
const RealValueType reduction_factor{1e-7};

```

Generate solver and solve the system

```

cg::build()
    .with_criteria(gko::stop::Iteration::build()
        .with_max_iters(discretization_points)
        .on(exec),
        gko::stop::ResidualNorm<ValueType>::build()
        .with_reduction_factor(reduction_factor)
        .on(exec))
    .on(exec)

```

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

```

->generate(StencilMatrix<ValueType>::create(exec, discretization_points,
                                           -1, 2, -1))
->apply(lend(rhs), lend(u));
std::cout << "\nSolve complete."
          << "\nThe 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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```

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```

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(INCLUDING NEGLIGENCE OR OTHERWISE) ARISING IN ANY WAY OUT OF THE USE
OF THIS SOFTWARE, EVEN IF ADVISED OF THE POSSIBILITY OF SUCH DAMAGE.
*****/
#include <iostream>
#include <map>
#include <string>
#include <omp.h>
#include <ginkgo/ginkgo.hpp>
template <typename ValueType>
void stencil_kernel(std::size_t size, const ValueType *coefs,
                  const ValueType *b, ValueType *x);
template <typename ValueType>
class StencilMatrix : public gko::EnableLinOp<StencilMatrix<ValueType>,
                  public gko::EnableCreateMethod<StencilMatrix<ValueType> {

```

```

public:
    StencilMatrix(std::shared_ptr<const gko::Executor> exec,
                  gko::size_type size = 0, ValueType left = -1.0,
                  ValueType center = 2.0, ValueType right = -1.0)
        : gko::EnableLinOp<StencilMatrix>(exec, gko::dim<2>(size)),
          coefficients(exec, {left, center, right})
    {}
protected:
    using vec = gko::matrix::Dense<ValueType>;
    using coef_type = gko::Array<ValueType>;
    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;
};
template <typename ValueType, typename IndexType>
void generate_stencil_matrix(gko::matrix::Csr<ValueType, IndexType> *matrix)
{
    const auto discretization_points = matrix->get_size()[0];
    auto row_ptrs = matrix->get_row_ptrs();
    auto col_idx = matrix->get_col_idx();
    auto values = matrix->get_values();
    IndexType pos = 0;
    const ValueType 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_idx[pos] = i + ofs;
                ++pos;
            }
        }
        row_ptrs[i + 1] = pos;
    }
}
template <typename Closure, typename ValueType>
void generate_rhs(Closure f, ValueType u0, ValueType u1,
                  gko::matrix::Dense<ValueType> *rhs)
{
    const auto discretization_points = rhs->get_size()[0];

```

```

    auto values = rhs->get_values();
    const ValueType h = 1.0 / (discretization_points + 1);
    for (int i = 0; i < discretization_points; ++i) {
        const ValueType xi = ValueType(i + 1) * h;
        values[i] = -f(xi) * h * h;
    }
    values[0] += u0;
    values[discretization_points - 1] += u1;
}
template <typename ValueType>
void print_solution(ValueType u0, ValueType u1,
    const gko::matrix::Dense<ValueType> *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, typename ValueType>
double calculate_error(int discretization_points,
    const gko::matrix::Dense<ValueType> *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 ValueType = double;
    using RealValueType = gko::remove_complex<ValueType>;
    using IndexType = int;
    using vec = gko::matrix::Dense<ValueType>;
    using mtx = gko::matrix::Csr<ValueType, IndexType>;
    using cg = gko::solver::Cg<ValueType>;
    if (argc == 2 && (std::string(argv[1]) == "--help")) {
        std::cerr << "Usage: " << argv[0] << " [executor]" << std::endl;
        std::exit(-1);
    }
    const auto executor_string = argc >= 2 ? argv[1] : "reference";
    const unsigned int discretization_points =
        argc >= 3 ? std::atoi(argv[2]) : 100u;
    std::map<std::string, std::function<std::shared_ptr<gko::Executor>()>>
    exec_map{
        {"omp", [] { return gko::OmpExecutor::create(); }},
        {"cuda",
            [] {
                return gko::CudaExecutor::create(0, gko::OmpExecutor::create(),
                    true);
            }},
        {"hip",
            [] {
                return gko::HipExecutor::create(0, gko::OmpExecutor::create(),
                    true);
            }},
        {"dpcpp",
            [] {
                return gko::DpcppExecutor::create(0,
                    gko::OmpExecutor::create());
            }},
        {"reference", [] { return gko::ReferenceExecutor::create(); }}};
    const auto exec = exec_map.at(executor_string)(); // throws if not valid
    const auto app_exec = exec->get_master();
    auto correct_u = [] (ValueType x) { return x * x * x; };
    auto f = [] (ValueType x) { return ValueType{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;
    }
    const RealValueType reduction_factor{1e-7};
    cg::build()
        .with_criteria(gko::stop::Iteration::build()
            .with_max_iters(discretization_points)
            .on(exec),
            gko::stop::ResidualNorm<ValueType>::build()
            .with_reduction_factor(reduction_factor)

```

```
        .on(exec))
    .on(exec)
    ->generate(StencilMatrix<ValueType>::create(exec, discretization_points,
                                                -1, 2, -1))
    ->apply(lend(rhs), lend(u));
std::cout << "\nSolve complete."
    << "\nThe average relative error is "
    << calculate_error(discretization_points, lend(u), correct_u) /
        discretization_points
    << std::endl;
}
```

Chapter 12

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 <map>
#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_SCALAR(
            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 ValueType = double;
using RealValueType = gko::remove_complex<ValueType>;
using IndexType = int;
using mtx = gko::matrix::Csr<ValueType, IndexType>;
using vec = gko::matrix::Dense<ValueType>;
using real_vec = gko::matrix::Dense<RealValueType>;
using bicg = gko::solver::Bicgstab<ValueType>;

```

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<ValueType>::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<real_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

```

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

```

Figure out where to run the code

```

const auto executor_string = argc >= 2 ? argv[1] : "reference";

```

Figure out where to run the code

```

std::map<std::string, std::function<std::shared_ptr<gko::Executor>()>
    exec_map{
        {"omp", [] { return gko::OmpExecutor::create(); }},
        {"cuda",
         [] {
             return gko::CudaExecutor::create(0, gko::OmpExecutor::create(),
                                                true);
         }},
        {"hip",
         [] {
             return gko::HipExecutor::create(0, gko::OmpExecutor::create(),

```



```

        true);
    },
    {"dpcpp",
     [] {
         return gko::DpcppExecutor::create(0,
                                           gko::OmpExecutor::create());
     }},
    {"reference", [] { return gko::ReferenceExecutor::create(); } }];

```

executor where Ginkgo will perform the computation

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

Declare a user controlled 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 22516 completed with solver LinOp[gko::solver::Bicgstab<double>,0x7fe6a4003710] with
      residual LinOp[gko::matrix::Dense<double>,0x7fe6a40050b0], solution
      LinOp[gko::matrix::Dense<double>,0x7fe6a40048e0] and residual_norm LinOp[gko::LinOp const*,0]
LinOp[gko::matrix::Dense<double>,0x7fe6a40050b0][
5.17803e-164
-7.6865e-165
-2.06149e-164
-4.84737e-165
-3.36597e-164
2.22353e-164
1.47594e-165
-1.78592e-165
-6.17274e-166
-3.02681e-166
7.82009e-166
8.57102e-165
-1.28879e-164
-2.62076e-165
2.55329e-165
-5.95988e-166
-5.79273e-166
-5.20172e-166
-6.79458e-166
]
// Typing 'stop' stops the solver.
User input command 'stop' - The solver will stop
LinOp[gko::matrix::Dense<double>,0x7fe6a40048e0][
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
6.50306e-16

```

Comments about programming and debugging

The plain program

```

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OF THIS SOFTWARE, EVEN IF ADVISED OF THE POSSIBILITY OF SUCH DAMAGE.
*****/
#include <ginkgo/ginkgo.hpp>
#include <fstream>
#include <iostream>
#include <map>
#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_SCALAR(
            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 ValueType = double;
    using RealValueType = gko::remove_complex<ValueType>;
    using IndexType = int;
    using mtx = gko::matrix::Csr<ValueType, IndexType>;
    using vec = gko::matrix::Dense<ValueType>;
    using real_vec = gko::matrix::Dense<RealValueType>;
    using bicg = gko::solver::Bicgstab<ValueType>;
    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<ValueType>::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<real_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;
    if (argc == 2 && (std::string(argv[1]) == "--help")) {
        std::cerr << "Usage: " << argv[0] << " [executor]" << std::endl;
        std::exit(-1);
    }
    const auto executor_string = argc >= 2 ? argv[1] : "reference";
    std::map<std::string, std::function<std::shared_ptr<gko::Executor>()>>
    exec_map{
        {"omp", [] { return gko::OmpExecutor::create(); }},
        {"cuda",
         [] {
             return gko::CudaExecutor::create(0, gko::OmpExecutor::create(),
                                                true);
         }},
        {"hip",

```

```
    [] {
        return gko::HipExecutor::create(0, gko::OmpExecutor::create(),
                                         true);
    },
    {"dpcpp",
     [] {
         return gko::DpcppExecutor::create(0,
                                             gko::OmpExecutor::create());
     },
     {"reference", [] { return gko::ReferenceExecutor::create(); }}};
const auto exec = exec_map.at(executor_string()); // throws if not valid
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 13

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 or 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, so Gauss 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::ResidualNorm<>::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 deal.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 \mathbf{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 \mathbf{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 thing 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, let's 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 \mathbf{y} connecting the centers of the two cells. Note that as opposed to the introduction, we denote by \mathbf{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 \mathbf{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 \mathbf{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 independently 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::ResidualNorm<>::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 14

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 ValueType = double;
    using IndexType = int;
    using vec = gko::matrix::Dense<ValueType>;
    using mtx = gko::matrix::Csr<ValueType, IndexType>;
    using cg = gko::solver::Cg<ValueType>;
    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 "
        « static_cast<double>(time.count()) /
            static_cast<double>(std::nano::den)
        « " seconds." « std::endl
        « "\tAverage library overhead:      "
        « static_cast<double>(time.count()) /
            static_cast<double>(num_iters)
        « " [nanoseconds / iteration]" « std::endl;
    }

```

Results

This is the expected output:

```

Running 1000000 iterations of the CG solver took a total of 1.60337 seconds.
    Average library overhead:      1603.37 [nanoseconds / iteration]

```

Comments about programming and debugging

The plain program

```

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```

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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 ValueType = double;
    using IndexType = int;
    using vec = gko::matrix::Dense<ValueType>;
    using mtx = gko::matrix::Csr<ValueType, IndexType>;
    using cg = gko::solver::Cg<ValueType>;
    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 "
    << static_cast<double>(time.count()) /
        static_cast<double>(std::nano::den)
    << " seconds." << std::endl
    << "\tAverage library overhead:      "
    << static_cast<double>(time.count()) /
        static_cast<double>(num_iters)
    << " [nanoseconds / iteration]" << std::endl;
}

```


Chapter 15

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]\nLU = [";
```

```

    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[])
{
    using ValueType = double;
    using IndexType = int;

```

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

```

ValueType 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<ValueType, 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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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 <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[])
{
    using ValueType = double;
    using IndexType = int;
    std::cout << gko::version_info::get() << std::endl;
    ValueType data[] = {
        2., 4., 5., -1.0,
        4., 11., 12., -1.0,
        6., 24., 24., -1.0
    };
    auto A =
        gko::range<gko::accessor::row_major<ValueType, 2>>(data, 3u, 3u, 4u);
    factorize(A);
    print_lu(A);
}
```


Chapter 16

The heat-equation program

The heat equation example..

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

Introduction

This example solves a 2D heat conduction equation

$$u : [0, d]^2 \rightarrow \mathbb{R}$$
$$\partial_t u = \delta u + f$$

with Dirichlet boundary conditions and given initial condition and constant-in-time source function f .

The partial differential equation (PDE) is solved with a finite difference spatial discretization on an equidistant grid: For n grid points, and grid distance $h = 1/n$ we write

$$u_{i,j}' = \alpha \frac{u_{i-1,j} + u_{i+1,j} + u_{i,j-1} + u_{i,j+1} - 4u_{i,j}}{h^2} + f_{i,j}$$

We then build an implicit Euler integrator by discretizing with time step τ

$$\frac{u_{i,j}^{k+1} - u_{i,j}^k}{\tau} = \alpha \frac{u_{i-1,j}^{k+1} + u_{i+1,j}^{k+1} - u_{i,j-1}^{k+1} - u_{i,j+1}^{k+1} + 4u_{i,j}^{k+1}}{h^2} + f_{i,j}$$

and solve the resulting linear system for u^{k+1} using Ginkgo's CG solver preconditioned with an incomplete Cholesky factorization for each time step, occasionally writing the resulting grid values into a video file using OpenCV and a custom color mapping.

The intention of this example is to provide a mini-app showing matrix assembly, vector initialization, solver setup and the use of Ginkgo in a more complex setting.

About the example

The commented program

```
/ *****<DESCRIPTION>*****
This example solves a 2D heat conduction equation
    u : [0, d]^2 \rightarrow R\
    \partial_t u = \delta u + f
with Dirichlet boundary conditions and given initial condition and
constant-in-time source function f.
The partial differential equation (PDE) is solved with a finite difference
spatial discretization on an equidistant grid: For 'n' grid points,
and grid distance h = 1/n we write
    u_{i,j}' = \alpha (u_{i-1,j} + u_{i+1,j} + u_{i,j-1} + u_{i,j+1}
                    - 4 u_{i,j}) / h^2
                    + f_{i,j}
```

We then build an implicit Euler integrator by discretizing with time step \tau

```
(u_{i,j}^{k+1} - u_{i,j}^k) / \tau =
\alpha (u_{i-1,j}^{k+1} - u_{i+1,j}^{k+1}
      + u_{i,j-1}^{k+1} - u_{i,j+1}^{k+1} - 4 u_{i,j}^{k+1}) / h^2
+ f_{i,j}
```

and solve the resulting linear system for u_{\cdot}^{k+1} using Ginkgo's CG solver preconditioned with an incomplete Cholesky factorization for each time step, occasionally writing the resulting grid values into a video file using OpenCV and a custom color mapping. The intention of this example is to provide a mini-app showing matrix assembly, vector initialization, solver setup and the use of Ginkgo in a more complex setting.

```
*****<DESCRIPTION>***** /
#include <ginkgo/ginkgo.hpp>
#include <chrono>
#include <fstream>
#include <iostream>
#include <opencv2/core.hpp>
#include <opencv2/videoio.hpp>
```

This function implements a simple Ginkgo-themed clamped color mapping for values in the range [0,5].

```
void set_val(unsigned char *data, double value)
{
```

RGB values for the 6 colors used for values 0, 1, ..., 5 We will interpolate linearly between these values.

```
double col_r[] = {255, 221, 129, 201, 249, 255};
double col_g[] = {255, 220, 130, 161, 158, 204};
double col_b[] = {255, 220, 133, 93, 24, 8};
value = std::max(0.0, value);
auto i = std::max(0, std::min(4, int(value)));
auto d = std::max(0.0, std::min(1.0, value - i));
```

OpenCV uses BGR instead of RGB by default, revert indices

```
data[2] = static_cast<unsigned char>(col_r[i + 1] * d + col_r[i] * (1 - d));
data[1] = static_cast<unsigned char>(col_g[i + 1] * d + col_g[i] * (1 - d));
data[0] = static_cast<unsigned char>(col_b[i + 1] * d + col_b[i] * (1 - d));
}
```

Initialize video output with given dimension and FPS (frames per seconds)

```
std::pair<cv::VideoWriter, cv::Mat> build_output(int n, double fps)
{
    cv::Size videosize{n, n};
    auto output =
        std::make_pair(cv::VideoWriter{}, cv::Mat{videosize, CV_8UC3});
    auto fourcc = cv::VideoWriter::fourcc('a', 'v', 'c', 'l');
    output.first.open("heat.mp4", fourcc, fps, videosize);
    return output;
}
```

Write the current frame to video output using the above color mapping

```
void output_timestep(std::pair<cv::VideoWriter, cv::Mat> &output, int n,
                    const double *data)
{
    for (int i = 0; i < n; i++) {
        auto row = output.second.ptr(i);
        for (int j = 0; j < n; j++) {
            set_val(&row[3 * j], data[i * n + j]);
        }
        output.first.write(output.second);
    }
}
```

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

Problem parameters: simulation length

```
auto t0 = 5.0;
```

diffusion factor

```
auto diffusion = 0.0005;
```

scaling factor for heat source

```
auto source_scale = 2.5;
```

Simulation parameters: inner grid points per discretization direction

```
auto n = 256;
```

number of simulation steps per second

```
auto steps_per_sec = 500;
```

number of video frames per second

```
auto fps = 25;
```

number of grid points

```
auto n2 = n * n;
```

grid point distance (ignoring boundary points)

```
auto h = 1.0 / (n + 1);
auto h2 = h * h;
```

time step size for the simulation

```
auto tau = 1.0 / steps_per_sec;
```

create a CUDA executor with an associated OpenMP host executor

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

load heat source and initial state vectors

```
std::ifstream source_stream("data/source.mtx");
std::ifstream initial_stream("data/initial.mtx");
auto source = gko::read<vec>(source_stream, exec);
auto in_vector = gko::read<vec>(initial_stream, exec);
```

create output vector with initial guess for

```
auto out_vector = in_vector->clone();
```

create scalar for source update

```
auto tau_source_scalar = gko::initialize<vec>({source_scale * tau}, exec);
```

create stencil matrix as shared_ptr for solver

```
auto stencil_matrix = gko::share(mtx::create(exec));
```

assemble matrix

```
gko::matrix_data<> mtx_data{gko::dim<2>(n2, n2)};
for (int i = 0; i < n; i++) {
    for (int j = 0; j < n; j++) {
        auto c = i * n + j;
        auto c_val = diffusion * tau * 4.0 / h2 + 1.0;
        auto off_val = -diffusion * tau / h2;
```

for each grid point: insert 5 stencil points with Dirichlet boundary conditions, i.e. with zero boundary value

```
        if (i > 0) {
            mtx_data.nonzeros.emplace_back(c, c - n, off_val);
        }
        if (j > 0) {
            mtx_data.nonzeros.emplace_back(c, c - 1, off_val);
        }
        mtx_data.nonzeros.emplace_back(c, c, c_val);
        if (j < n - 1) {
            mtx_data.nonzeros.emplace_back(c, c + 1, off_val);
        }
        if (i < n - 1) {
            mtx_data.nonzeros.emplace_back(c, c + n, off_val);
```

```

    }
}
stencil_matrix->read(mtx_data);

```

prepare video output

```
auto output = build_output(n, fps);
```

build CG solver on stencil with incomplete Cholesky preconditioner stopping at 1e-10 relative accuracy

```

auto solver =
    gko::solver::Cg<>::build()
        .with_preconditioner(gko::preconditioner::Ic<>::build().on(exec))
        .with_criteria(gko::stop::RelativeResidualNorm<>::build()
            .with_tolerance(1e-10)
            .on(exec))
        .on(exec)
    ->generate(stencil_matrix);

```

time stamp of the last output frame (initialized to a sentinel value)

```
double last_t = -t0;
```

execute implicit Euler method: for each timestep, solve stencil system

```
for (double t = 0; t < t0; t += tau) {
```

if enough time has passed, output the next video frame

```

if (t - last_t > 1.0 / fps) {
    last_t = t;
    std::cout << t << std::endl;
    output_timestep(
        output, n,
        gko::make_temporary_clone(exec->get_master(), in_vector.get())
        ->get_const_values());
}

```

add heat source contribution

```
in_vector->add_scaled(gko::lend(tau_source_scalar), gko::lend(source));
```

execute Euler step

```
solver->apply(gko::lend(in_vector), gko::lend(out_vector));
```

swap input and output

```

    std::swap(in_vector, out_vector);
}

```

Results

The program will generate a video file named heat.mp4 and output the timestamp of each generated frame.

Comments about programming and debugging

The plain program

```

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```

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*****<GINKGO LICENSE>*****
 /*****<DESCRIPTION>*****
 This example solves a 2D heat conduction equation

$$u : [0, d]^2 \rightarrow \mathbb{R} \\ \partial_t u = \Delta u + f$$

with Dirichlet boundary conditions and given initial condition and constant-in-time source function f .

The partial differential equation (PDE) is solved with a finite difference spatial discretization on an equidistant grid: For n grid points, and grid distance $h = 1/n$ we write

$$u_{i,j}' = \frac{\alpha (u_{i-1,j} + u_{i+1,j} + u_{i,j-1} + u_{i,j+1} - 4 u_{i,j})}{h^2} + f_{i,j}$$

We then build an implicit Euler integrator by discretizing with time step τ

$$\frac{(u_{i,j}^{k+1} - u_{i,j}^k) / \tau}{\alpha (u_{i-1,j}^{k+1} - u_{i+1,j}^{k+1} + u_{i,j-1}^{k+1} - u_{i,j+1}^{k+1} - 4 u_{i,j}^{k+1}) / h^2} + f_{i,j}$$

and solve the resulting linear system for $u_{i,j}^{k+1}$ using Ginkgo's CG solver preconditioned with an incomplete Cholesky factorization for each time step, occasionally writing the resulting grid values into a video file using OpenCV and a custom color mapping.

The intention of this example is to provide a mini-app showing matrix assembly, vector initialization, solver setup and the use of Ginkgo in a more complex setting.

*****<DESCRIPTION>*****
 #include <ginkgo/ginkgo.hpp>
 #include <chrono>
 #include <fstream>
 #include <iostream>
 #include <opencv2/core.hpp>
 #include <opencv2/videoio.hpp>
 void set_val(unsigned char *data, double value)
 {
 double col_r[] = {255, 221, 129, 201, 249, 255};
 double col_g[] = {255, 220, 130, 161, 158, 204};
 double col_b[] = {255, 220, 133, 93, 24, 8};
 value = std::max(0.0, value);
 auto i = std::max(0, std::min(4, int(value)));
 auto d = std::max(0.0, std::min(1.0, value - i));
 data[2] = static_cast<unsigned char>(col_r[i + 1] * d + col_r[i] * (1 - d));
 data[1] = static_cast<unsigned char>(col_g[i + 1] * d + col_g[i] * (1 - d));
 data[0] = static_cast<unsigned char>(col_b[i + 1] * d + col_b[i] * (1 - d));
 }
 std::pair<cv::VideoWriter, cv::Mat> build_output(int n, double fps)
 {
 cv::Size videosize{n, n};
 auto output =
 std::make_pair(cv::VideoWriter{}, cv::Mat{videosize, CV_8UC3});
 auto fourcc = cv::VideoWriter::fourcc('a', 'v', 'c', 'l');
 output.first.open("heat.mp4", fourcc, fps, videosize);
 return output;
 }
 void output_timestep(std::pair<cv::VideoWriter, cv::Mat> &output, int n,
 const double *data)
 {
 for (int i = 0; i < n; i++) {
 auto row = output.second.ptr(i);
 for (int j = 0; j < n; j++) {
 set_val(&row[3 * j], data[i * n + j]);
 }
 }
 output.first.write(output.second);
 }
}

```

int main(int argc, char *argv[])
{
    using mtx = gko::matrix::Csr<>;
    using vec = gko::matrix::Dense<>;
    auto t0 = 5.0;
    auto diffusion = 0.0005;
    auto source_scale = 2.5;
    auto n = 256;
    auto steps_per_sec = 500;
    auto fps = 25;
    auto n2 = n * n;
    auto h = 1.0 / (n + 1);
    auto h2 = h * h;
    auto tau = 1.0 / steps_per_sec;
    auto exec = gko::CudaExecutor::create(0, gko::OmpExecutor::create());
    std::ifstream source_stream("data/source.mtx");
    std::ifstream initial_stream("data/initial.mtx");
    auto source = gko::read<vec>(source_stream, exec);
    auto in_vector = gko::read<vec>(initial_stream, exec);
    auto out_vector = in_vector->clone();
    auto tau_source_scalar = gko::initialize<vec>({source_scale * tau}, exec);
    auto stencil_matrix = gko::share(mtx::create(exec));
    gko::matrix_data<> mtx_data{gko::dim<2>(n2, n2)};
    for (int i = 0; i < n; i++) {
        for (int j = 0; j < n; j++) {
            auto c = i * n + j;
            auto c_val = diffusion * tau * 4.0 / h2 + 1.0;
            auto off_val = -diffusion * tau / h2;
            if (i > 0) {
                mtx_data.nonzeros.emplace_back(c, c - n, off_val);
            }
            if (j > 0) {
                mtx_data.nonzeros.emplace_back(c, c - 1, off_val);
            }
            mtx_data.nonzeros.emplace_back(c, c, c_val);
            if (j < n - 1) {
                mtx_data.nonzeros.emplace_back(c, c + 1, off_val);
            }
            if (i < n - 1) {
                mtx_data.nonzeros.emplace_back(c, c + n, off_val);
            }
        }
    }
    stencil_matrix->read(mtx_data);
    auto output = build_output(n, fps);
    auto solver =
        gko::solver::Cg<>::build()
            .with_preconditioner(gko::preconditioner::Ic<>::build().on(exec))
            .with_criteria(gko::stop::RelativeResidualNorm<>::build()
                .with_tolerance(1e-10)
                .on(exec))
            .on(exec)
            ->generate(stencil_matrix);
    double last_t = -t0;
    for (double t = 0; t < t0; t += tau) {
        if (t - last_t > 1.0 / fps) {
            last_t = t;
            std::cout << t << std::endl;
            output_timestep(
                output, n,
                gko::make_temporary_clone(exec->get_master(), in_vector.get())
                    ->get_const_values());
        }
        in_vector->add_scaled(gko::lend(tau_source_scalar), gko::lend(source));
        solver->apply(gko::lend(in_vector), gko::lend(out_vector));
        std::swap(in_vector, out_vector);
    }
}

```


Chapter 17

The ilu-preconditioned-solver program

The ILU-preconditioned solver example..

This example depends on simple-solver.

Introduction

About the example

This example shows how to use incomplete factors generated via the ParILU algorithm to generate an incomplete factorization (ILU) preconditioner, how to specify the sparse triangular solves in the ILU preconditioner application, and how to generate an ILU-preconditioned solver and apply it to a specific problem.

The commented program

```
#include <ginkgo/ginkgo.hpp>
#include <cstdlib>
#include <fstream>
#include <iostream>
#include <map>
#include <string>
int main(int argc, char *argv[])
{
```

Some shortcuts

```
using ValueType = double;
using RealValueType = gko::remove_complex<ValueType>;
using IndexType = int;
using vec = gko::matrix::Dense<ValueType>;
using real_vec = gko::matrix::Dense<RealValueType>;
using mtx = gko::matrix::Csr<ValueType, IndexType>;
using gmres = gko::solver::Gmres<ValueType>;
```

Print version information

```
std::cout << gko::version_info::get() << std::endl;
if (argc == 2 && (std::string(argv[1]) == "--help")) {
    std::cerr << "Usage: " << argv[0] << " [executor]" << std::endl;
    std::exit(-1);
}
const auto executor_string = argc >= 2 ? argv[1] : "reference";
```

Figure out where to run the code

```
std::map<std::string, std::function<std::shared_ptr<gko::Executor>()>>
    exec_map{
        {"omp", [] { return gko::OmpExecutor::create(); }},
```

```

{"cuda",
 [] {
     return gko::CudaExecutor::create(0, gko::OmpExecutor::create(),
                                     true);
 }},
{"hip",
 [] {
     return gko::HipExecutor::create(0, gko::OmpExecutor::create(),
                                     true);
 }},
{"dpcpp",
 [] {
     return gko::DpcppExecutor::create(0,
                                     gko::OmpExecutor::create());
 }},
{"reference", [] { return gko::ReferenceExecutor::create(); }});

```

executor where Ginkgo will perform the computation

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

Read data

```

auto A = gko::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 incomplete factors using ParILU

```

auto par_ilu_fact =
    gko::factorization::ParIlu<ValueType, IndexType>::build().on(exec);

```

Generate concrete factorization for input matrix

```
auto par_ilu = par_ilu_fact->generate(A);
```

Generate an ILU preconditioner factory by setting lower and upper triangular solver - in this case the exact triangular solves

```

auto ilu_pre_factory =
    gko::preconditioner::Ilu<gko::solver::LowerTrs<ValueType, IndexType>,
                           gko::solver::UpperTrs<ValueType, IndexType>,
                           false>::build()
        .on(exec);

```

Use incomplete factors to generate ILU preconditioner

```
auto ilu_preconditioner = ilu_pre_factory->generate(gko::share(par_ilu));
```

Use preconditioner inside GMRES solver factory Generating a solver factory tied to a specific preconditioner makes sense if there are several very similar systems to solve, and the same solver+preconditioner combination is expected to be effective.

```

const RealValueType reduction_factor{1e-7};
auto ilu_gmres_factory =
    gmres::build()
        .with_criteria(
            gko::stop::Iteration::build().with_max_iters(1000u).on(exec),
            gko::stop::ResidualNorm<ValueType>::build()
                .with_reduction_factor(reduction_factor)
                .on(exec))
        .with_generated_preconditioner(gko::share(ilu_preconditioner))
        .on(exec);

```

Generate preconditioned solver for a specific target system

```
auto ilu_gmres = ilu_gmres_factory->generate(A);
```

Solve system

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

Print solution

```

std::cout << "Solution (x):\n";
write(std::cout, gko::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<real_vec>({0.0}, exec);
A->apply(gko::lend(one), gko::lend(x), gko::lend(neg_one), gko::lend(b));
b->compute_norm2(gko::lend(res));
std::cout << "Residual norm sqrt(r^T r):\n";
write(std::cout, gko::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
1.46249e-08
```

Comments about programming and debugging

The plain program

```
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*****<GINKGO LICENSE>*****/
#include <ginkgo/ginkgo.hpp>
#include <cstdlib>
#include <fstream>
#include <iostream>
#include <map>
#include <string>
int main(int argc, char *argv[])
{
    using ValueType = double;
    using RealValueType = gko::remove_complex<ValueType>;
    using IndexType = int;
    using vec = gko::matrix::Dense<ValueType>;
    using real_vec = gko::matrix::Dense<RealValueType>;
    using mtx = gko::matrix::Csr<ValueType, IndexType>;
```

```

using gmres = gko::solver::Gmres<ValueType>;
std::cout << gko::version_info::get() << std::endl;
if (argc == 2 && (std::string(argv[1]) == "--help")) {
    std::cerr << "Usage: " << argv[0] << " [executor]" << std::endl;
    std::exit(-1);
}
const auto executor_string = argc >= 2 ? argv[1] : "reference";
std::map<std::string, std::function<std::shared_ptr<gko::Executor>()>>
    exec_map{
        {"omp", [] { return gko::OmpExecutor::create(); }},
        {"cuda",
         [] {
             return gko::CudaExecutor::create(0, gko::OmpExecutor::create(),
                                                true);
         }},
        {"hip",
         [] {
             return gko::HipExecutor::create(0, gko::OmpExecutor::create(),
                                                true);
         }},
        {"dpcpp",
         [] {
             return gko::DpcppExecutor::create(0,
                                                gko::OmpExecutor::create());
         }},
        {"reference", [] { return gko::ReferenceExecutor::create(); }}};
const auto exec = exec_map.at(executor_string)(); // throws if not valid
auto A = gko::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 par_ilu_fact =
    gko::factorization::ParIlu<ValueType, IndexType>::build().on(exec);
auto par_ilu = par_ilu_fact->generate(A);
auto ilu_pre_factory =
    gko::preconditioner::Ilu<gko::solver::LowerTrs<ValueType, IndexType>,
                             gko::solver::UpperTrs<ValueType, IndexType>,
                             false>::build()
        .on(exec);
auto ilu_preconditioner = ilu_pre_factory->generate(gko::share(par_ilu));
const RealValueType reduction_factor{1e-7};
auto ilu_gmres_factory =
    gmres::build()
        .with_criteria(
            gko::stop::Iteration::build().with_max_iters(1000u).on(exec),
            gko::stop::ResidualNorm<ValueType>::build()
                .with_reduction_factor(reduction_factor)
                .on(exec))
        .with_generated_preconditioner(gko::share(ilu_preconditioner))
        .on(exec);
auto ilu_gmres = ilu_gmres_factory->generate(A);
ilu_gmres->apply(gko::lend(b), gko::lend(x));
std::cout << "Solution (x):\n";
write(std::cout, gko::lend(x));
auto one = gko::initialize<vec>({1.0}, exec);
auto neg_one = gko::initialize<vec>({-1.0}, exec);
auto res = gko::initialize<real_vec>({0.0}, exec);
A->apply(gko::lend(one), gko::lend(x), gko::lend(neg_one), gko::lend(b));
b->compute_norm2(gko::lend(res));
std::cout << "Residual norm sqrt(r^T r):\n";
write(std::cout, gko::lend(res));
}

```

Chapter 18

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 <map>
#include <string>
int main(int argc, char *argv[])
{
```

Some shortcuts

```
using precision = std::complex<double>;
using real_precision = gko::remove_complex<precision>;
using vec = gko::matrix::Dense<precision>;
using real_vec = gko::matrix::Dense<real_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

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

const auto executor_string = argc >= 2 ? argv[1] : "reference";
std::map<std::string, std::function<std::shared_ptr<gko::Executor>()>>
    exec_map{
        {"omp", [] { return gko::OmpExecutor::create(); }},
        {"cuda",
         [] {
             return gko::CudaExecutor::create(0, gko::OmpExecutor::create(),
                                              true);
         }},
        {"hip",
         [] {
             return gko::HipExecutor::create(0, gko::OmpExecutor::create(),
                                              true);
         }},
        {"dpcpp",
         [] {
             return gko::DpcppExecutor::create(0,
                                              gko::OmpExecutor::create());
         }},
        {"reference", [] { return gko::ReferenceExecutor::create(); }}};
```

executor where Ginkgo will perform the computation

```
const auto exec = exec_map.at(executor_string)(); // throws if not valid
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::ResidualNorm<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 = gko::initialize<real_vec>({1.0}, exec);
auto inv_norm = clone(this_exec, norm);
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] =
    real_precision{1.0} / clone(this_exec, norm)->get_values()[0];
x->scale(lend(clone(exec, inv_norm)));

```

$g = x^A * A x$

```

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": +1.61736920e-14, "eigenvalue": (+2.03741410e+01,-1.17744356e-16), "residual":
  (+2.92231055e-01,+1.68883476e-18) },
{ "system_residual": +4.98014795e-15, "eigenvalue": (+1.94878474e+01,+1.25948378e-15), "residual":
  (+7.94370276e-02,-5.13395071e-18) },
{ "system_residual": +3.39296916e-15, "eigenvalue": (+1.93282121e+01,-1.19329332e-15), "residual":
  (+4.11149623e-02,+2.53837290e-18) },
{ "system_residual": +3.35953656e-15, "eigenvalue": (+1.92638912e+01,+3.28657016e-16), "residual":
  (+2.34717040e-02,-4.00445585e-19) },
{ "system_residual": +2.91474009e-15, "eigenvalue": (+1.92409166e+01,+3.65597737e-16), "residual":
  (+1.34709547e-02,-2.55962367e-19) },
{ "system_residual": +3.09863953e-15, "eigenvalue": (+1.92331106e+01,-1.07919176e-15), "residual":
  (+7.72060707e-03,+4.33212063e-19) },
{ "system_residual": +2.31198069e-15, "eigenvalue": (+1.92305014e+01,-2.89755360e-16), "residual":
  (+4.42106625e-03,+6.66143651e-20) },
{ "system_residual": +3.02771202e-15, "eigenvalue": (+1.92296339e+01,+8.04259901e-16), "residual":
  (+2.53081312e-03,-1.05848687e-19) },
{ "system_residual": +2.02954523e-15, "eigenvalue": (+1.92293461e+01,+7.81834016e-16), "residual":
  (+1.44862114e-03,-5.88985854e-20) },
{ "system_residual": +2.31762332e-15, "eigenvalue": (+1.92292506e+01,-1.11718775e-16), "residual":
  (+8.29183451e-04,+4.81741912e-21) },
{ "system_residual": +8.12541038e-15, "eigenvalue": (+1.92292190e+01,-6.55606254e-16), "residual":
  (+4.74636702e-04,+1.61823936e-20) },
{ "system_residual": +2.77259926e-15, "eigenvalue": (+1.92292085e+01,+4.30588140e-16), "residual":
  (+2.71701077e-04,-6.08403935e-21) },
{ "system_residual": +8.87888675e-14, "eigenvalue": (+1.92292051e+01,+9.67936313e-18), "residual":
  (+1.55539937e-04,-7.82937998e-23) },
{ "system_residual": +2.85077117e-15, "eigenvalue": (+1.92292039e+01,-4.52923128e-16), "residual":
  (+8.90457139e-05,+2.09737561e-21) },

```

```
{ "system_residual": +6.46865302e-14, "eigenvalue": (+1.92292035e+01,+1.58710681e-17), "residual":
  (+5.09805252e-05,-4.20774259e-23) },
{ "system_residual": +4.18913713e-15, "eigenvalue": (+1.92292034e+01,+1.06839590e-15), "residual":
  (+2.91887365e-05,-1.62175862e-21) },
{ "system_residual": +1.06421578e-11, "eigenvalue": (+1.92292034e+01,+3.26089685e-17), "residual":
  (+1.67126561e-05,-2.83413965e-23) },
{ "system_residual": +2.97434420e-13, "eigenvalue": (+1.92292034e+01,-7.85427712e-16), "residual":
  (+9.56961199e-06,+3.90876227e-22) },
{ "system_residual": +1.63230281e-11, "eigenvalue": (+1.92292033e+01,+3.69307000e-16), "residual":
  (+5.47975753e-06,-1.05241636e-22) },
{ "system_residual": +6.14939758e-14, "eigenvalue": (+1.92292033e+01,+1.36057865e-15), "residual":
  (+3.13794996e-06,-2.22028320e-22) },
```

Comments about programming and debugging

The plain program

```
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```

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```
*****<GINKGO LICENSE>*****/
#include <ginkgo/ginkgo.hpp>
#include <cmath>
#include <complex>
#include <fstream>
#include <iomanip>
#include <iostream>
#include <map>
#include <string>
int main(int argc, char *argv[])
{
    using precision = std::complex<double>;
    using real_precision = gko::remove_complex<precision>;
    using vec = gko::matrix::Dense<precision>;
    using real_vec = gko::matrix::Dense<real_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;
    if (argc == 2 && (std::string(argv[1]) == "--help")) {
        std::cerr << "Usage: " << argv[0] << " [executor]" << std::endl;
        std::exit(-1);
    }
    const auto executor_string = argc >= 2 ? argv[1] : "reference";
    std::map<std::string, std::function<std::shared_ptr<gko::Executor>()>
    exec_map{
        {"omp", [] { return gko::OmpExecutor::create(); }},
        {"cuda",
         [] {
             return gko::CudaExecutor::create(0, gko::OmpExecutor::create(),
                                              true);
         }},
    },
```



```

    {"hip",
    [] {
        return gko::HipExecutor::create(0, gko::OmpExecutor::create(),
                                         true);
    }},
    {"dpcpp",
    [] {
        return gko::DpcppExecutor::create(0,
                                           gko::OmpExecutor::create());
    }},
    {"reference", [] { return gko::ReferenceExecutor::create(); }});
const auto exec = exec_map.at(executor_string)(); // throws if not valid
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::ResidualNorm<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 = gko::initialize<real_vec>({1.0}, exec);
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] =
        real_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 19

The ir-ilu-preconditioned-solver program

The IR-ILU preconditioned solver example..

This example depends on ilu-preconditioned-solver, iterative-refinement.

Introduction

About the example

This example shows how to combine iterative refinement with the adaptive precision block-Jacobi preconditioner in order to approximately solve the triangular systems occurring in ILU preconditioning. Using an adaptive precision block-Jacobi preconditioner matrix as inner solver for the iterative refinement method is equivalent to doing adaptive precision block-Jacobi relaxation in the triangular solves. This example roughly approximates the triangular solves with five adaptive precision block-Jacobi sweeps with a maximum block size of 16.

This example is motivated by "Multiprecision block-Jacobi for Iterative Triangular Solves" (Göbel, Anzt, Cojean, Flegar, Quintana-Ortí, Euro-Par 2020). The theory and a detailed analysis can be found there.

The commented program

```
#include <ginkgo/ginkgo.hpp>
#include <cstdlib>
#include <fstream>
#include <iostream>
#include <map>
#include <string>
int main(int argc, char *argv[])
{
```

Some shortcuts

```
using ValueType = double;
using RealValueType = gko::remove_complex<ValueType>;
using IndexType = int;
using vec = gko::matrix::Dense<ValueType>;
using real_vec = gko::matrix::Dense<RealValueType>;
using mtx = gko::matrix::Csr<ValueType, IndexType>;
using gmres = gko::solver::Gmres<ValueType>;
using ir = gko::solver::Ir<ValueType>;
using bj = gko::preconditioner::Jacobi<ValueType, IndexType>;
```

Print version information

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

Figure out where to run the code

```

if (argc == 2 && (std::string(argv[1]) == "--help")) {
    std::cerr << "Usage: " << argv[0] << " [executor]" << std::endl;
    std::exit(-1);
}
const auto executor_string = argc >= 2 ? argv[1] : "reference";
const unsigned int sweeps = argc == 3 ? std::atoi(argv[2]) : 5u;
std::map<std::string, std::function<std::shared_ptr<gko::Executor>()>>
exec_map{
    {"omp", [] { return gko::OmpExecutor::create(); }},
    {"cuda",
     [] {
         return gko::CudaExecutor::create(0, gko::OmpExecutor::create(),
                                           true);
     }},
    {"hip",
     [] {
         return gko::HipExecutor::create(0, gko::OmpExecutor::create(),
                                           true);
     }},
    {"dpcpp",
     [] {
         return gko::DpcppExecutor::create(0,
                                           gko::OmpExecutor::create());
     }},
    {"reference", [] { return gko::ReferenceExecutor::create(); }}};

```

executor where Ginkgo will perform the computation

```

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

```

Read data

```

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

```

Create RHS and initial guess as 1

```

gko::size_type num_rows = A->get_size()[0];
auto host_x = vec::create(exec->get_master(), gko::dim<2>(num_rows, 1));
for (gko::size_type i = 0; i < num_rows; i++) {
    host_x->at(i, 0) = 1.;
}
auto x = vec::create(exec);
auto b = vec::create(exec);
x->copy_from(host_x.get());
b->copy_from(host_x.get());
auto clone_x = vec::create(exec);
clone_x->copy_from(lend(x));

```

Generate incomplete factors using ParILU

```

auto par_ilu_fact =
    gko::factorization::ParIlut<ValueType, IndexType>::build().on(exec);

```

Generate concrete factorization for input matrix

```

auto par_ilu = par_ilu_fact->generate(A);

```

Generate an iterative refinement factory to be used as a triangular solver in the preconditioner application. The generated method is equivalent to doing five block-Jacobi sweeps with a maximum block size of 16.

```

auto bj_factory =
    bj::build()
        .with_max_block_size(16u)
        .with_storage_optimization(gko::precision_reduction::autodetect())
        .on(exec);
auto trisolve_factory =
    ir::build()
        .with_solver(share(bj_factory))
        .with_criteria(
            gko::stop::Iteration::build().with_max_iters(sweeps).on(exec))
        .on(exec);

```

Generate an ILU preconditioner factory by setting lower and upper triangular solver - in this case the previously defined iterative refinement method.

```

auto ilu_pre_factory =
    gko::preconditioner::Ilut<ir, ir>::build()
        .with_l_solver_factory(gko::clone(trisolve_factory))
        .with_u_solver_factory(gko::clone(trisolve_factory))
        .on(exec);

```

Use incomplete factors to generate ILU preconditioner

```

auto ilu_preconditioner = ilu_pre_factory->generate(gko::share(par_ilu));

```

Create stopping criteria for Gmres

```
const RealValueType reduction_factor{1e-12};
auto iter_stop =
    gko::stop::Iteration::build().with_max_iters(1000u).on(exec);
auto tol_stop = gko::stop::ResidualNorm<ValueType>::build()
    .with_reduction_factor(reduction_factor)
    .on(exec);
std::shared_ptr<const gko::log::Convergence<ValueType>> logger =
    gko::log::Convergence<ValueType>::create(exec);
iter_stop->add_logger(logger);
tol_stop->add_logger(logger);
```

Use preconditioner inside GMRES solver factory Generating a solver factory tied to a specific preconditioner makes sense if there are several very similar systems to solve, and the same solver+preconditioner combination is expected to be effective.

```
auto ilu_gmres_factory =
    gmres::build()
        .with_criteria(gko::share(iter_stop), gko::share(tol_stop))
        .with_generated_preconditioner(gko::share(ilu_preconditioner))
        .on(exec);
```

Generate preconditioned solver for a specific target system

```
auto ilu_gmres = ilu_gmres_factory->generate(A);
```

Warmup run

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

Solve system 100 times and take the average time.

```
std::chrono::nanoseconds time(0);
for (int i = 0; i < 100; i++) {
    x->copy_from(lend(clone_x));
    auto tic = std::chrono::high_resolution_clock::now();
    ilu_gmres->apply(lend(b), lend(x));
    auto toc = std::chrono::high_resolution_clock::now();
    time += std::chrono::duration_cast<std::chrono::nanoseconds>(toc - tic);
}
std::cout << "Using " << sweeps << " block-Jacobi sweeps.\n";
```

Print solution

```
std::cout << "Solution (x):\n";
write(std::cout, gko::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<real_vec>({0.0}, exec);
A->apply(gko::lend(one), gko::lend(x), gko::lend(neg_one), gko::lend(b));
b->compute_norm2(gko::lend(res));
std::cout << "GMRES iteration count: " << logger->get_num_iterations()
    << "\n";
std::cout << "GMRES execution time [ms]: "
    << static_cast<double>(time.count()) / 1000000000.0 << "\n";
std::cout << "Residual norm sqrt(r^T r):\n";
write(std::cout, gko::lend(res));
}
```

Results

This is the expected output:

```
Using 5 block-Jacobi sweeps.
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
GMRES iteration count:      8
GMRES execution time [ms]: 0.377673
Residual norm sqrt(r^T r):
%%MatrixMarket matrix array real general
1 1
1.65303e-12

```

Comments about programming and debugging

The plain program

```

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```

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```

*****/
#include <ginkgo/ginkgo.hpp>
#include <cstdlib>
#include <fstream>
#include <iostream>
#include <map>
#include <string>
int main(int argc, char *argv[])
{
    using ValueType = double;
    using RealValueType = gko::remove_complex<ValueType>;
    using IndexType = int;
    using vec = gko::matrix::Dense<ValueType>;
    using real_vec = gko::matrix::Dense<RealValueType>;
    using mtx = gko::matrix::Csr<ValueType, IndexType>;
    using gmres = gko::solver::Gmres<ValueType>;
    using ir = gko::solver::Ir<ValueType>;
    using bj = gko::preconditioner::Jacobi<ValueType, IndexType>;
    std::cout << gko::version_info::get() << std::endl;
    if (argc == 2 && (std::string(argv[1]) == "--help")) {
        std::cerr << "Usage: " << argv[0] << " [executor]" << std::endl;
        std::exit(-1);
    }
    const auto executor_string = argc >= 2 ? argv[1] : "reference";
    const unsigned int sweeps = argc == 3 ? std::atoi(argv[2]) : 5u;
    std::map<std::string, std::function<std::shared_ptr<gko::Executor>()>
    exec_map{
        {"omp", [] { return gko::OmpExecutor::create(); }},
        {"cuda",
         [] {
             return gko::CudaExecutor::create(0, gko::OmpExecutor::create(),
                                              true);
         }},
    },

```

```

    {"hip",
    [] {
        return gko::HipExecutor::create(0, gko::OmpExecutor::create(),
                                         true);
    }},
    {"dpcpp",
    [] {
        return gko::DpcppExecutor::create(0,
                                           gko::OmpExecutor::create());
    }},
    {"reference", [] { return gko::ReferenceExecutor::create(); }}};
const auto exec = exec_map.at(executor_string()); // throws if not valid
auto A = gko::share(gko::read<mtx>(std::ifstream("data/A.mtx"), exec));
gko::size_type num_rows = A->get_size()[0];
auto host_x = vec::create(exec->get_master(), gko::dim<2>(num_rows, 1));
for (gko::size_type i = 0; i < num_rows; i++) {
    host_x->at(i, 0) = 1.;
}
auto x = vec::create(exec);
auto b = vec::create(exec);
x->copy_from(host_x.get());
b->copy_from(host_x.get());
auto clone_x = vec::create(exec);
clone_x->copy_from(lend(x));
auto par_ilu_fact =
    gko::factorization::ParIlu<ValueType, IndexType>::build().on(exec);
auto par_ilu = par_ilu_fact->generate(A);
auto bj_factory =
    bj::build()
        .with_max_block_size(16u)
        .with_storage_optimization(gko::precision_reduction::autodetect())
        .on(exec);
auto trisolve_factory =
    ir::build()
        .with_solver(share(bj_factory))
        .with_criteria(
            gko::stop::Iteration::build().with_max_iters(sweeps).on(exec))
        .on(exec);
auto ilu_pre_factory =
    gko::preconditioner::Ilu<ir, ir>::build()
        .with_l_solver_factory(gko::clone(trisolve_factory))
        .with_u_solver_factory(gko::clone(trisolve_factory))
        .on(exec);
auto ilu_preconditioner = ilu_pre_factory->generate(gko::share(par_ilu));
const RealValueType reduction_factor{1e-12};
auto iter_stop =
    gko::stop::Iteration::build().with_max_iters(1000u).on(exec);
auto tol_stop = gko::stop::ResidualNorm<ValueType>::build()
    .with_reduction_factor(reduction_factor)
    .on(exec);
std::shared_ptr<const gko::log::Convergence<ValueType>> logger =
    gko::log::Convergence<ValueType>::create(exec);
iter_stop->add_logger(logger);
tol_stop->add_logger(logger);
auto ilu_gmres_factory =
    gmres::build()
        .with_criteria(gko::share(iter_stop), gko::share(tol_stop))
        .with_generated_preconditioner(gko::share(ilu_preconditioner))
        .on(exec);
auto ilu_gmres = ilu_gmres_factory->generate(A);
ilu_gmres->apply(lend(b), lend(x));
std::chrono::nanoseconds time(0);
for (int i = 0; i < 100; i++) {
    x->copy_from(lend(clone_x));
    auto tic = std::chrono::high_resolution_clock::now();
    ilu_gmres->apply(lend(b), lend(x));
    auto toc = std::chrono::high_resolution_clock::now();
    time += std::chrono::duration_cast<std::chrono::nanoseconds>(toc - tic);
}
std::cout << "Using " << sweeps << " block-Jacobi sweeps.\n";
std::cout << "Solution (x):\n";
write(std::cout, gko::lend(x));
auto one = gko::initialize<vec>({1.0}, exec);
auto neg_one = gko::initialize<vec>({-1.0}, exec);
auto res = gko::initialize<real_vec>({0.0}, exec);
A->apply(gko::lend(one), gko::lend(x), gko::lend(neg_one), gko::lend(b));
b->compute_norm2(gko::lend(res));
std::cout << "GMRES iteration count: " << logger->get_num_iterations()
    << "\n";
std::cout << "GMRES execution time [ms]: "
    << static_cast<double>(time.count()) / 1000000000.0 << "\n";
std::cout << "Residual norm sqrt(r^T r):\n";
write(std::cout, gko::lend(res));
}

```



```

    }},
    {"hip",
     [] {
         return gko::HipExecutor::create(0, gko::OmpExecutor::create(),
                                         true);
     }},
    {"dpcpp",
     [] {
         return gko::DpcppExecutor::create(0,
                                           gko::OmpExecutor::create());
     }},
    {"reference", [] { return gko::ReferenceExecutor::create(); } }
};

```

executor where Ginkgo will perform the computation

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

Read data

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

Create RHS and initial guess as 1

```

gko::size_type size = A->get_size()[0];
auto host_x = gko::matrix::Dense<ValueType>::create(exec->get_master(),
                                                    gko::dim<2>(size, 1));

for (auto i = 0; i < size; i++) {
    host_x->at(i, 0) = 1.;
}

auto x = gko::matrix::Dense<ValueType>::create(exec);
auto b = gko::matrix::Dense<ValueType>::create(exec);
x->copy_from(host_x.get());
b->copy_from(host_x.get());

```

Calculate initial residual by overwriting b

```

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

```

copy b again

```

b->copy_from(host_x.get());
gko::size_type max_iters = 10000u;
RealValueType outer_reduction_factor{1e-12};
auto iter_stop =
    gko::stop::Iteration::build().with_max_iters(max_iters).on(exec);
auto tol_stop = gko::stop::ResidualNorm<ValueType>::build()
    .with_reduction_factor(outer_reduction_factor)
    .on(exec);

std::shared_ptr<const gko::log::Convergence<ValueType>> logger =
    gko::log::Convergence<ValueType>::create(exec);
iter_stop->add_logger(logger);
tol_stop->add_logger(logger);

```

Create solver factory

```

RealValueType inner_reduction_factor{1e-2};
auto solver_gen =
    ir::build()
        .with_solver(
            cg::build()
                .with_criteria(
                    gko::stop::ResidualNorm<ValueType>::build()
                        .with_reduction_factor(inner_reduction_factor)
                        .on(exec)
                    .on(exec)
                )
            .with_criteria(gko::share(iter_stop), gko::share(tol_stop))
            .on(exec);

```

Create solver

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

Solve system

```

exec->synchronize();
std::chrono::nanoseconds time(0);
auto tic = std::chrono::steady_clock::now();
solver->apply(lend(b), lend(x));
auto toc = std::chrono::steady_clock::now();
time += std::chrono::duration_cast<std::chrono::nanoseconds>(toc - tic);

```

Calculate residual

```
auto res = gko::initialize<real_vec>({0.0}, exec);
```

```
A->apply(lend(one), lend(x), lend(neg_one), lend(b));
b->compute_norm2(lend(res));
std::cout << "Initial residual norm sqrt(r^T r):\n";
write(std::cout, lend(initres));
std::cout << "Final residual norm sqrt(r^T r):\n";
write(std::cout, lend(res));
```

Print solver statistics

```
std::cout << "IR iteration count:      " << logger->get_num_iterations()
<< std::endl;
std::cout << "IR execution time [ms]: "
<< static_cast<double>(time.count()) / 1000000.0 << std::endl;
}
```

Results

This is the expected output:

```
Initial residual norm sqrt(r^T r):
%%MatrixMarket matrix array real general
1 1
194.679
Final residual norm sqrt(r^T r):
%%MatrixMarket matrix array real general
1 1
4.23821e-11
IR iteration count:      24
IR execution time [ms]: 0.794962
```

Comments about programming and debugging

The plain program

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DATA, OR PROFITS; OR BUSINESS INTERRUPTION) HOWEVER CAUSED AND ON ANY
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 <fstream>
#include <iomanip>
#include <iostream>
#include <map>
#include <string>
int main(int argc, char *argv[])
{
    using ValueType = double;
    using RealValueType = gko::remove_complex<ValueType>;
    using IndexType = int;
```

```

using vec = gko::matrix::Dense<ValueType>;
using real_vec = gko::matrix::Dense<RealValueType>;
using mtx = gko::matrix::Csr<ValueType, IndexType>;
using cg = gko::solver::Cg<ValueType>;
using ir = gko::solver::Ir<ValueType>;
std::cout << gko::version_info::get() << std::endl;
if (argc == 2 && (std::string(argv[1]) == "--help")) {
    std::cerr << "Usage: " << argv[0] << " [executor]" << std::endl;
    std::exit(-1);
}
const auto executor_string = argc >= 2 ? argv[1] : "reference";
std::map<std::string, std::function<std::shared_ptr<gko::Executor>()>>
    exec_map{
        {"omp", [] { return gko::OmpExecutor::create(); }},
        {"cuda",
         [] {
             return gko::CudaExecutor::create(0, gko::OmpExecutor::create(),
                                              true);
         }},
        {"hip",
         [] {
             return gko::HipExecutor::create(0, gko::OmpExecutor::create(),
                                              true);
         }},
        {"dpcpp",
         [] {
             return gko::DpcppExecutor::create(0,
                                              gko::OmpExecutor::create());
         }},
        {"reference", [] { return gko::ReferenceExecutor::create(); }}};
const auto exec = exec_map.at(executor_string)(); // throws if not valid
auto A = share(gko::read<mtx>(std::ifstream("data/A.mtx"), exec));
gko::size_type size = A->get_size()[0];
auto host_x = gko::matrix::Dense<ValueType>::create(exec->get_master(),
                                                    gko::dim<2>(size, 1));
for (auto i = 0; i < size; i++) {
    host_x->at(i, 0) = 1.;
}
auto x = gko::matrix::Dense<ValueType>::create(exec);
auto b = gko::matrix::Dense<ValueType>::create(exec);
x->copy_from(host_x.get());
b->copy_from(host_x.get());
auto one = gko::initialize<vec>({1.0}, exec);
auto neg_one = gko::initialize<vec>({-1.0}, exec);
auto initres = gko::initialize<real_vec>({0.0}, exec);
A->apply(lend(one), lend(x), lend(neg_one), lend(b));
b->compute_norm2(lend(initres));
b->copy_from(host_x.get());
gko::size_type max_iters = 10000u;
RealValueType outer_reduction_factor{1e-12};
auto iter_stop =
    gko::stop::Iteration::build().with_max_iters(max_iters).on(exec);
auto tol_stop = gko::stop::ResidualNorm<ValueType>::build()
    .with_reduction_factor(outer_reduction_factor)
    .on(exec);
std::shared_ptr<const gko::log::Convergence<ValueType>> logger =
    gko::log::Convergence<ValueType>::create(exec);
iter_stop->add_logger(logger);
tol_stop->add_logger(logger);
RealValueType inner_reduction_factor{1e-2};
auto solver_gen =
    ir::build()
        .with_solver(
            cg::build()
                .with_criteria(
                    gko::stop::ResidualNorm<ValueType>::build()
                        .with_reduction_factor(inner_reduction_factor)
                        .on(exec)
                )
            .on(exec)
        )
        .with_criteria(gko::share(iter_stop), gko::share(tol_stop))
        .on(exec);
auto solver = solver_gen->generate(A);
exec->synchronize();
std::chrono::nanoseconds time(0);
auto tic = std::chrono::steady_clock::now();
solver->apply(lend(b), lend(x));
auto toc = std::chrono::steady_clock::now();
time += std::chrono::duration_cast<std::chrono::nanoseconds>(toc - tic);
auto res = gko::initialize<real_vec>({0.0}, exec);
A->apply(lend(one), lend(x), lend(neg_one), lend(b));
b->compute_norm2(lend(res));
std::cout << "Initial residual norm sqrt(r^T r):\n";
write(std::cout, lend(initres));
std::cout << "Final residual norm sqrt(r^T r):\n";
write(std::cout, lend(res));
std::cout << "IR iteration count:      " << logger->get_num_iterations()
    << std::endl;

```

```
std::cout << "IR execution time [ms]: "  
          << static_cast<double>(time.count()) / 1000000.0 << std::endl;  
}
```


Chapter 21

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-cuda-solver
```

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(), true);
```

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::ResidualNorm<>::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(), true);
    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::ResidualNorm<>::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 22

The mixed-precision-ir program

The Mixed Precision Iterative Refinement (MPIR) solver example..

This example depends on iterative-refinement.

This example manually implements a Mixed Precision Iterative Refinement (MPIR) solver.

In this example, we first read in a matrix from file, then generate a right-hand side and an initial guess. An inaccurate CG solver in single precision is used as the inner solver to an iterative refinement (IR) in double precision method which solves a linear system.

The commented program

```
#include <ginkgo/ginkgo.hpp>
#include <fstream>
#include <iomanip>
#include <iostream>
#include <map>
#include <string>
int main(int argc, char *argv[])
{
```

Some shortcuts

```
using ValueType = double;
using RealValueType = gko::remove_complex<ValueType>;
using SolverType = float;
using RealSolverType = gko::remove_complex<SolverType>;
using IndexType = int;
using vec = gko::matrix::Dense<ValueType>;
using real_vec = gko::matrix::Dense<RealValueType>;
using solver_vec = gko::matrix::Dense<SolverType>;
using mtx = gko::matrix::Csr<ValueType, IndexType>;
using solver_mtx = gko::matrix::Csr<SolverType, IndexType>;
using cg = gko::solver::Cg<SolverType>;
gko::size_type max_outer_iters = 100u;
gko::size_type max_inner_iters = 100u;
RealValueType outer_reduction_factor{1e-12};
RealSolverType inner_reduction_factor{1e-2};
```

Print version information

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

Figure out where to run the code

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

```

}
const auto executor_string = argc >= 2 ? argv[1] : "reference";
std::map<std::string, std::function<std::shared_ptr<gko::Executor>()>>
    exec_map{
        {"omp", [] { return gko::OmpExecutor::create(); }},
        {"cuda",
         [] {
             return gko::CudaExecutor::create(0, gko::OmpExecutor::create(),
                                              true);
         }},
        {"hip",
         [] {
             return gko::HipExecutor::create(0, gko::OmpExecutor::create(),
                                              true);
         }},
        {"dpcpp",
         [] {
             return gko::DpcppExecutor::create(0,
                                              gko::OmpExecutor::create());
         }},
        {"reference", [] { return gko::ReferenceExecutor::create(); }
    }
};

```

executor where Ginkgo will perform the computation

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

Read data

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

Create RHS and initial guess as 1

```

gko::size_type size = A->get_size()[0];
auto host_x = vec::create(exec->get_master(), gko::dim<2>(size, 1));
for (auto i = 0; i < size; i++) {
    host_x->at(i, 0) = 1.;
}
auto x = vec::create(exec);
auto b = vec::create(exec);
x->copy_from(host_x.get());
b->copy_from(host_x.get());

```

Calculate initial residual by overwriting b

```

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

```

Build lower-precision system matrix and residual

```

auto solver_A = solver_mtx::create(exec);
auto inner_residual = solver_vec::create(exec);
auto outer_residual = vec::create(exec);
A->convert_to(lend(solver_A));
b->convert_to(lend(outer_residual));

```

restore b

```
b->copy_from(host_x.get());
```

Create inner solver

```

auto inner_solver =
    cg::build()
        .with_criteria(gko::stop::ResidualNorm<SolverType>::build()
            .with_reduction_factor(inner_reduction_factor)
            .on(exec),
            gko::stop::Iteration::build()
                .with_max_iters(max_inner_iters)
                .on(exec))
        .on(exec)
        ->generate(give(solver_A));

```

Solve system

```

exec->synchronize();
std::chrono::nanoseconds time(0);
auto res_vec = gko::initialize<real_vec>({0.0}, exec);
auto initres = exec->copy_val_to_host(initres_vec->get_const_values());
auto inner_solution = solver_vec::create(exec);
auto outer_delta = vec::create(exec);
auto tic = std::chrono::steady_clock::now();
int iter = -1;
while (true) {
    ++iter;

```

convert residual to inner precision

```
outer_residual->convert_to(lend(inner_residual));
outer_residual->compute_norm2(lend(res_vec));
auto res = exec->copy_val_to_host(res_vec->get_const_values());
```

break if we exceed the number of iterations or have converged

```
if (iter > max_outer_iters || res / initres < outer_reduction_factor) {
    break;
}
```

Use the inner solver to solve $A * \text{inner_solution} = \text{inner_residual}$ with residual as initial guess.

```
inner_solution->copy_from(lend(inner_residual));
inner_solver->apply(lend(inner_residual), lend(inner_solution));
```

convert inner solution to outer precision

```
inner_solution->convert_to(lend(outer_delta));
```

 $x = x + \text{inner_solution}$

```
x->add_scaled(lend(one), lend(outer_delta));
```

residual = $b - A * x$

```
outer_residual->copy_from(lend(b));
A->apply(lend(neg_one), lend(x), lend(one), lend(outer_residual));
}
auto toc = std::chrono::steady_clock::now();
time += std::chrono::duration_cast<std::chrono::nanoseconds>(toc - tic);
```

Calculate residual

```
A->apply(lend(one), lend(x), lend(neg_one), lend(b));
b->compute_norm2(lend(res_vec));
std::cout << "Initial residual norm sqrt(r^T r):\n";
write(std::cout, lend(initres_vec));
std::cout << "Final residual norm sqrt(r^T r):\n";
write(std::cout, lend(res_vec));
```

Print solver statistics

```
std::cout << "MPIR iteration count: " << iter << std::endl;
std::cout << "MPIR execution time [ms]: "
    << static_cast<double>(time.count()) / 1000000.0 << std::endl;
}
```

Results

This is the expected output:

```
Initial residual norm sqrt(r^T r):
%%MatrixMarket matrix array real general
1 1
194.679
Final residual norm sqrt(r^T r):
%%MatrixMarket matrix array real general
1 1
1.22728e-10
MPIR iteration count:      25
MPIR execution time [ms]: 0.846559
```

Comments about programming and debugging

The plain program

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```

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```
*****<GINKGO LICENSE>*****/
#include <ginkgo/ginkgo.hpp>
#include <fstream>
#include <iomanip>
#include <iostream>
#include <map>
#include <string>
int main(int argc, char *argv[])
{
    using ValueType = double;
    using RealValueType = gko::remove_complex<ValueType>;
    using SolverType = float;
    using RealSolverType = gko::remove_complex<SolverType>;
    using IndexType = int;
    using vec = gko::matrix::Dense<ValueType>;
    using real_vec = gko::matrix::Dense<RealValueType>;
    using solver_vec = gko::matrix::Dense<SolverType>;
    using mtx = gko::matrix::Csr<ValueType, IndexType>;
    using solver_mtx = gko::matrix::Csr<SolverType, IndexType>;
    using cg = gko::solver::Cg<SolverType>;
    gko::size_type max_outer_iters = 100u;
    gko::size_type max_inner_iters = 100u;
    RealValueType outer_reduction_factor{1e-12};
    RealSolverType inner_reduction_factor{1e-2};
    std::cout << gko::version_info::get() << std::endl;
    if (argc == 2 && (std::string(argv[1]) == "--help")) {
        std::cerr << "Usage: " << argv[0] << " [executor]" << std::endl;
        std::exit(-1);
    }
    const auto executor_string = argc >= 2 ? argv[1] : "reference";
    std::map<std::string, std::function<std::shared_ptr<gko::Executor>()>
    exec_map{
        {"omp", [] { return gko::OmpExecutor::create(); }},
        {"cuda",
         [] {
             return gko::CudaExecutor::create(0, gko::OmpExecutor::create(),
             true);
         }},
        {"hip",
         [] {
             return gko::HipExecutor::create(0, gko::OmpExecutor::create(),
             true);
         }},
        {"dpcpp",
         [] {
             return gko::DpcppExecutor::create(0,
             gko::OmpExecutor::create());
         }},
        {"reference", [] { return gko::ReferenceExecutor::create(); }
    };
    const auto exec = exec_map.at(executor_string)(); // throws if not valid
    auto A = share(gko::read<mtx>(std::ifstream("data/A.mtx"), exec));
    gko::size_type size = A->get_size()[0];
    auto host_x = vec::create(exec->get_master(), gko::dim<2>(size, 1));
    for (auto i = 0; i < size; i++) {
        host_x->at(i, 0) = 1.;
    }
    auto x = vec::create(exec);
    auto b = vec::create(exec);
    x->copy_from(host_x.get());
    b->copy_from(host_x.get());
    auto one = gko::initialize<vec>({1.0}, exec);
    auto neg_one = gko::initialize<vec>({-1.0}, exec);
    auto initres_vec = gko::initialize<real_vec>({0.0}, exec);
    A->apply(lend(one), lend(x), lend(neg_one), lend(b));
    b->compute_norm2(lend(initres_vec));
    auto solver_A = solver_mtx::create(exec);
    auto inner_residual = solver_vec::create(exec);
```

```

auto outer_residual = vec::create(exec);
A->convert_to(lend(solver_A));
b->convert_to(lend(outer_residual));
b->copy_from(host_x.get());
auto inner_solver =
    cg::build()
        .with_criteria(gko::stop::ResidualNorm<SolverType>::build()
            .with_reduction_factor(inner_reduction_factor)
            .on(exec),
            gko::stop::Iteration::build()
                .with_max_iters(max_inner_iters)
                .on(exec))
        .on(exec)
        ->generate(give(solver_A));
exec->synchronize();
std::chrono::nanoseconds time(0);
auto res_vec = gko::initialize<real_vec>({0.0}, exec);
auto initres = exec->copy_val_to_host(initres_vec->get_const_values());
auto inner_solution = solver_vec::create(exec);
auto outer_delta = vec::create(exec);
auto tic = std::chrono::steady_clock::now();
int iter = -1;
while (true) {
    ++iter;
    outer_residual->convert_to(lend(inner_residual));
    outer_residual->compute_norm2(lend(res_vec));
    auto res = exec->copy_val_to_host(res_vec->get_const_values());
    if (iter > max_outer_iters || res / initres < outer_reduction_factor) {
        break;
    }
    inner_solution->copy_from(lend(inner_residual));
    inner_solver->apply(lend(inner_residual), lend(inner_solution));
    inner_solution->convert_to(lend(outer_delta));
    x->add_scaled(lend(one), lend(outer_delta));
    outer_residual->copy_from(lend(b));
    A->apply(lend(neg_one), lend(x), lend(one), lend(outer_residual));
}
auto toc = std::chrono::steady_clock::now();
time += std::chrono::duration_cast<std::chrono::nanoseconds>(toc - tic);
A->apply(lend(one), lend(x), lend(neg_one), lend(b));
b->compute_norm2(lend(res_vec));
std::cout << "Initial residual norm sqrt(r^T r):\n";
write(std::cout, lend(initres_vec));
std::cout << "Final residual norm sqrt(r^T r):\n";
write(std::cout, lend(res_vec));
std::cout << "MPIR iteration count: " << iter << std::endl;
std::cout << "MPIR execution time [ms]: "
    << static_cast<double>(time.count()) / 1000000.0 << std::endl;
}

```


Chapter 23

The nine-pt-stencil-solver program

The 9-point stencil example..

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

Introduction

This example solves a 2D Poisson equation:

$$\begin{aligned} & \Omega = (0,1)^2 \setminus \Omega_b = [0,1]^2 \setminus \text{boundary} \\ & \partial\Omega = \Omega_b \\ & u : \Omega_b \rightarrow \mathbb{R} \setminus u = f \text{ in } \Omega \quad u = u_D \text{ in } \partial\Omega \end{aligned}$$

using a finite difference method on an equidistant grid with K discretization points (K can be controlled with a command line parameter). The discretization may be done by any order Taylor polynomial. For an equidistant grid with K "inner" discretization points $((x_1, y_1), \dots, (x_k, y_1), (x_1, y_2), \dots, (x_k, y_k, z_1))$ step size $(h = 1 / (K + 1))$ and a stencil $(\text{in } \mathbb{R}^{3 \times 3})$, the formula produces a system of linear equations

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

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

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

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

```
/ *****<DESCRIPTION>*****
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 \rightarrow \mathbb{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
\mathbb{R}^{3 \times 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 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.

```
*****<DESCRIPTION>***** /
```

```
#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
* 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.

```
template <typename ValueType, typename IndexType>
void generate_stencil_matrix(IndexType dp, IndexType *row_ptrs,
                           IndexType *col_idxxs, ValueType *values,
                           ValueType *coefs)
{
    IndexType pos = 0;
    const size_t dp_2 = dp * dp;
    row_ptrs[0] = pos;
    for (IndexType k = 0; k < dp; ++k) {
        for (IndexType i = 0; i < dp; ++i) {
            const size_t index = i + k * dp;
            for (IndexType j = -1; j <= 1; ++j) {
                for (IndexType l = -1; l <= 1; ++l) {
                    const IndexType offset = 1 + 1 + 3 * (j + 1);
                    if ((k + j) >= 0 && (k + j) < dp && (i + l) >= 0 &&
                        (i + l) < dp) {
                        values[pos] = coefs[offset];
                        col_idxxs[pos] = index + 1 + dp * j;
                        ++pos;
                    }
                }
            }
            row_ptrs[index + 1] = pos;
        }
    }
}
```



```
}
```

Generates the RHS vector given f and the boundary conditions.

```
template <typename Closure, typename ClosureT, typename ValueType,
          typename IndexType>
void generate_rhs(IndexType dp, Closure f, ClosureT u, ValueType *rhs,
                 ValueType *coefs)
{
    const size_t dp_2 = dp * dp;
    const ValueType h = 1.0 / (dp + 1.0);
    for (IndexType i = 0; i < dp; ++i) {
        const auto yi = ValueType(i + 1) * h;
        for (IndexType j = 0; j < dp; ++j) {
            const auto xi = ValueType(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 = ValueType(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 = ValueType(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 .

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

```
void solve_system(const std::string &executor_string,
                 unsigned int discretization_points, IndexType *row_ptrs,
                 IndexType *col_idx, ValueType *values, ValueType *rhs,
                 ValueType *u, gko::remove_complex<ValueType> reduction_factor)
{
```

Some shortcuts

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

Figure out where to run the code

```
std::map<std::string, std::function<std::shared_ptr<gko::Executor>()>>
exec_map{
    {"omp", [] { return gko::OmpExecutor::create(); }},
    {"cuda",
     [] {
         return gko::CudaExecutor::create(0, gko::OmpExecutor::create(),
                                           true);
     }},
    {"hip",
     [] {
         return gko::HipExecutor::create(0, gko::OmpExecutor::create(),
                                           true);
     }},
    {"dpcpp",
     [] {
         return gko::DpcppExecutor::create(0,
                                           gko::OmpExecutor::create());
     }},
    {"reference", [] { return 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->get_master();
```

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 SpMV's 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_idx),
    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::ResidualNorm<ValueType>::build()
            .with_reduction_factor(reduction_factor)
            .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[])
{
    using ValueType = double;
    using IndexType = int;

```

Print version information

```

std::cout << gko::version_info::get() << std::endl;
if (argc == 2 && std::string(argv[1]) == "--help") {
    std::cerr
        << "Usage: " << argv[0]
        << " [executor] [DISCRETIZATION_POINTS] [alpha] [beta] [gamma]"
        << std::endl;
    std::exit(-1);
}
const auto executor_string = argc >= 2 ? argv[1] : "reference";
const IndexType discretization_points =
    argc >= 3 ? std::atoi(argv[2]) : 100;
const ValueType alpha_c = argc >= 4 ? std::atof(argv[3]) : default_alpha;
const ValueType beta_c = argc >= 5 ? std::atof(argv[4]) : default_beta;
const ValueType gamma_c = argc >= 6 ? std::atof(argv[5]) : default_gamma;

```

clang-format off

```

std::array<ValueType, 9> coeffs{
    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 = [] (ValueType x, ValueType y) {
    return x * x * x + y * y * y;
};
auto f = [] (ValueType x, ValueType y) {
    return ValueType(6) * x + ValueType(6) * y;
};

```

matrix

```

std::vector<IndexType> row_ptrs(dp_2 + 1);
std::vector<IndexType> col_idxs((3 * dp - 2) * (3 * dp - 2));
std::vector<ValueType> values((3 * dp - 2) * (3 * dp - 2));

```

right hand side

```

std::vector<ValueType> rhs(dp_2);

```

solution

```

std::vector<ValueType> u(dp_2, 0.0);
generate_stencil_matrix(dp, row_ptrs.data(), col_idxs.data(), values.data(),
    coeffs.data());

```

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

```

generate_rhs(dp, f, correct_u, rhs.data(), coeffs.data());
const gko::remove_complex<ValueType> reduction_factor = 1e-7;
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(), reduction_factor);
auto stop_time = std::chrono::steady_clock::now();
auto runtime_duration =
    static_cast<double>(
        std::chrono::duration_cast<std::chrono::nanoseconds>(stop_time -
            start_time)
            .count()) *
    1e-6;

```

Uncomment to print the solution print_solution(dp, u.data());

```

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

```

Results

The expected output should be

The average relative error is 6.35715e-06
The runtime is 167.320520 ms

Comments about programming and debugging

The plain program

```
/******<GINKGO LICENSE>*****
Copyright (c) 2017-2021, the Ginkgo authors
All rights reserved.
```

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```
*****<GINKGO LICENSE>*****/
/******<DESCRIPTION>*****
This example solves a 2D Poisson equation:
```

$$\begin{aligned} \Omega &= (0,1)^2 \\ \Omega_b &= [0,1]^2 \quad (\text{with boundary}) \\ \partial \Omega &= \Omega_b \setminus \Omega \\ u &: \Omega_b \rightarrow \mathbb{R} \\ u'' &= f \text{ in } \Omega \\ u &= u_D \text{ on } \partial \Omega \end{aligned}$$

using a finite difference method on an equidistant grid with 'K' discretization points ('K' can be controlled with a command line parameter). The discretization 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 $\setminus R^{\{3 \times 3\}}$, the formula produces a system of linear equations

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

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

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

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.

```
*****<DESCRIPTION>*****/
```

```

#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
 * default_alpha = 8.0;
 * default_beta = -1.0;
 * default_gamma = -1.0;
 */
template <typename ValueType, typename IndexType>
void generate_stencil_matrix(IndexType dp, IndexType *row_ptrs,
                           IndexType *col_idxes, ValueType *values,
                           ValueType *coefs)
{
    IndexType pos = 0;
    const size_t dp_2 = dp * dp;
    row_ptrs[0] = pos;
    for (IndexType k = 0; k < dp; ++k) {
        for (IndexType i = 0; i < dp; ++i) {
            const size_t index = i + k * dp;
            for (IndexType j = -1; j <= 1; ++j) {
                for (IndexType l = -1; l <= 1; ++l) {
                    const IndexType offset = 1 + 1 + 3 * (j + 1);
                    if ((k + j) >= 0 && (k + j) < dp && (i + l) >= 0 &&
                        (i + l) < dp) {
                        values[pos] = coefs[offset];
                        col_idxes[pos] = index + 1 + dp * j;
                        ++pos;
                    }
                }
            }
            row_ptrs[index + 1] = pos;
        }
    }
}

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

template <typename ValueType, typename IndexType>
void print_solution(IndexType dp, const ValueType *u)
{
    for (IndexType i = 0; i < dp; ++i) {

```

```

        for (IndexType j = 0; j < dp; ++j) {
            std::cout << u[i * dp + j] << ' ';
        }
        std::cout << '\n';
    }
    std::cout << std::endl;
}

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

template <typename ValueType, typename IndexType>
void solve_system(const std::string &executor_string,
                 unsigned int discretization_points, IndexType *row_ptrs,
                 IndexType *col_idxs, ValueType *values, ValueType *rhs,
                 ValueType *u, gko::remove_complex<ValueType> reduction_factor)
{
    using vec = gko::matrix::Dense<ValueType>;
    using mtx = gko::matrix::Csr<ValueType, IndexType>;
    using cg = gko::solver::Cg<ValueType>;
    using bj = gko::preconditioner::Jacobi<ValueType, IndexType>;
    using val_array = gko::Array<ValueType>;
    using idx_array = gko::Array<IndexType>;
    const auto &dp = discretization_points;
    const gko::size_type dp_2 = dp * dp;
    std::map<std::string, std::function<std::shared_ptr<gko::Executor>()>>()>
    exec_map{
        {"omp", [] { return gko::OmpExecutor::create(); }},
        {"cuda",
         [] {
             return gko::CudaExecutor::create(0, gko::OmpExecutor::create(),
                                              true);
         }},
        {"hip",
         [] {
             return gko::HipExecutor::create(0, gko::OmpExecutor::create(),
                                              true);
         }},
        {"dpcpp",
         [] {
             return gko::DpcppExecutor::create(0,
                                              gko::OmpExecutor::create());
         }},
        {"reference", [] { return gko::ReferenceExecutor::create(); }}};
    const auto exec = exec_map.at(executor_string)(); // throws if not valid
    const auto app_exec = exec->get_master();
    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::ResidualNorm<ValueType>::build()
                .with_reduction_factor(reduction_factor)
                .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[])
{
    using ValueType = double;
    using IndexType = int;
    std::cout << gko::version_info::get() << std::endl;
    if (argc == 2 && std::string(argv[1]) == "--help") {
        std::cerr

```

```

        « "Usage: " « argv[0]
        « " [executor] [DISCRETIZATION_POINTS] [alpha] [beta] [gamma]"
        « std::endl;
    std::exit(-1);
}

const auto executor_string = argc >= 2 ? argv[1] : "reference";
const IndexType discretization_points =
    argc >= 3 ? std::atoi(argv[2]) : 100;
const ValueType alpha_c = argc >= 4 ? std::atof(argv[3]) : default_alpha;
const ValueType beta_c = argc >= 5 ? std::atof(argv[4]) : default_beta;
const ValueType gamma_c = argc >= 6 ? std::atof(argv[5]) : default_gamma;
std::array<ValueType, 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 = [] (ValueType x, ValueType y) {
    return x * x * x + y * y * y;
};
auto f = [] (ValueType x, ValueType y) {
    return ValueType(6) * x + ValueType(6) * y;
};
std::vector<IndexType> row_ptrs(dp_2 + 1);
std::vector<IndexType> col_idxs((3 * dp - 2) * (3 * dp - 2));
std::vector<ValueType> values((3 * dp - 2) * (3 * dp - 2));
std::vector<ValueType> rhs(dp_2);
std::vector<ValueType> 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());
const gko::remove_complex<ValueType> reduction_factor = 1e-7;
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(), reduction_factor);
auto stop_time = std::chrono::steady_clock::now();
auto runtime_duration =
    static_cast<double>(
        std::chrono::duration_cast<std::chrono::nanoseconds>(stop_time -
                                                                start_time)
        .count()) *
    1e-6;
std::cout « "The average relative error is "
    « calculate_error(dp, u.data(), correct_u) /
        static_cast<gko::remove_complex<ValueType>>(dp_2)
    « std::endl;
std::cout « "The runtime is " « std::to_string(runtime_duration) « " ms"
    « std::endl;
}

```


Chapter 24

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 <map>
#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 ValueType = double;
using RealValueType = gko::remove_complex<ValueType>;
using IndexType = int;
using vec = gko::matrix::Dense<ValueType>;
using real_vec = gko::matrix::Dense<RealValueType>;
using mtx = gko::matrix::Csr<ValueType, IndexType>;
using cg = gko::solver::Cg<ValueType>;

```

Print version information

```

std::cout << gko::version_info::get() << std::endl;
if (argc == 2 && (std::string(argv[1]) == "--help")) {
    std::cerr << "Usage: " << argv[0] << " [executor]" << std::endl;
    std::exit(-1);
}

```

Figure out where to run the code

```

const auto executor_string = argc >= 2 ? argv[1] : "reference";
std::map<std::string, std::function<std::shared_ptr<gko::Executor>()>>
    exec_map{
        {"omp", [] { return gko::OmpExecutor::create(); }},
        {"cuda",
            [] {
                return gko::CudaExecutor::create(0, gko::OmpExecutor::create(),
                    true);
            }},
        {"hip",
            [] {
                return gko::HipExecutor::create(0, gko::OmpExecutor::create(),
                    true);
            }},
        {"dpcpp",
            [] {
                return gko::DpcppExecutor::create(0,
                    gko::OmpExecutor::create());
            }},
        {"reference", [] { return gko::ReferenceExecutor::create(); }}};

```

executor where Ginkgo will perform the computation

```

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

```

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

```

const RealValueType reduction_factor{1e-7};
auto solver_gen =
    cg::build()
        .with_criteria(
            gko::stop::Iteration::build().with_max_iters(20u).on(exec),
            gko::stop::ResidualNorm<ValueType>::build()
                .with_reduction_factor(reduction_factor)
                .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<ValueType>::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<real_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 <map>
#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 ValueType = double;
    using RealValueType = gko::remove_complex<ValueType>;
    using IndexType = int;
    using vec = gko::matrix::Dense<ValueType>;
    using real_vec = gko::matrix::Dense<RealValueType>;
    using mtx = gko::matrix::Csr<ValueType, IndexType>;
    using cg = gko::solver::Cg<ValueType>;
    std::cout << gko::version_info::get() << std::endl;
    if (argc == 2 && (std::string(argv[1]) == "--help")) {
        std::cerr << "Usage: " << argv[0] << " [executor]" << std::endl;
        std::exit(-1);
    }
    const auto executor_string = argc >= 2 ? argv[1] : "reference";
    std::map<std::string, std::function<std::shared_ptr<gko::Executor>()>>
    exec_map{
        {"omp", [] { return gko::OmpExecutor::create(); }},
        {"cuda",
         [] {
             return gko::CudaExecutor::create(0, gko::OmpExecutor::create(),
                                              true);
         }},
        {"hip",
         [] {
             return gko::HipExecutor::create(0, gko::OmpExecutor::create(),
                                              true);
         }},
        {"dpcpp",
         [] {
             return gko::DpcppExecutor::create(0,
                                              gko::OmpExecutor::create());
         }},
        {"reference", [] { return gko::ReferenceExecutor::create(); }}};
    const auto exec = exec_map.at(executor_string)(); // throws if not valid
    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);
    const RealValueType reduction_factor{1e-7};
    auto solver_gen =
        cg::build()
            .with_criteria(
                gko::stop::Iteration::build().with_max_iters(20u).on(exec),
                gko::stop::ResidualNorm<ValueType>::build()
                    .with_reduction_factor(reduction_factor)
                    .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<ValueType>::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<real_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 25

The par-ilu-convergence program

The ParILU convergence example..

This example depends on simple-solver.

Introduction

About the example

This example can be used to inspect the convergence behavior of parallel incomplete factorizations. *

The commented program

```
#include <ginkgo/ginkgo.hpp>
#include <fstream>
#include <functional>
#include <iostream>
#include <map>
#include <memory>
#include <string>
const std::map<std::string, std::function<std::shared_ptr<gko::Executor>()>>
    executors{
    {"reference", [] { return gko::ReferenceExecutor::create(); }},
    {"omp", [] { return gko::OmpExecutor::create(); }},
    {"cuda",
    [] {
        return gko::CudaExecutor::create(0, gko::OmpExecutor::create());
    }},
    {"hip",
    [] {
        return gko::HipExecutor::create(0, gko::OmpExecutor::create());
    }},
    {"dpcpp", [] {
        return gko::DpcppExecutor::create(0, gko::OmpExecutor::create());
    }}};
template <typename Function>
auto try_generate(Function fun) -> decltype(fun())
{
    decltype(fun()) result;
    try {
        result = fun();
    } catch (const gko::Error &err) {
        std::cerr << "Error: " << err.what() << '\n';
        std::exit(-1);
    }
    return result;
}
template <typename ValueType, typename IndexType>
double compute_ilu_residual_norm(
```

```

const gko::matrix::Csr<ValueType, IndexType> *residual,
const gko::matrix::Csr<ValueType, IndexType> *mtx)
{
    gko::matrix_data<ValueType, IndexType> residual_data;
    gko::matrix_data<ValueType, IndexType> mtx_data;
    residual->write(residual_data);
    mtx->write(mtx_data);
    residual_data.ensure_row_major_order();
    mtx_data.ensure_row_major_order();
    auto it = mtx_data.nonzeros.begin();
    double residual_norm{};
    for (auto entry : residual_data.nonzeros) {
        auto ref_row = it->row;
        auto ref_col = it->column;
        if (entry.row == ref_row && entry.column == ref_col) {
            residual_norm += gko::squared_norm(entry.value);
            ++it;
        }
    }
    return std::sqrt(residual_norm);
}
int main(int argc, char *argv[])
{
    using ValueType = double;
    using IndexType = int;

```

print usage message

```

if (argc < 2 || executors.find(argv[1]) == executors.end()) {
    std::cerr << "Usage: executable"
                << " <reference|omp|cuda|hip|dpcpp> [<matrix-file>] "
                << "[<parilu|parilut|paric|parict> [<max-iterations>] "
                << "[<num-repetitions>] [<fill-in-limit>]\n";
    return -1;
}

```

generate executor based on first argument

```

auto exec = try_generate([&] { return executors.at(argv[1])(); });

```

set matrix and preconditioner name with default values

```

std::string matrix = argc < 3 ? "data/A.mtx" : argv[2];
std::string precondition = argc < 4 ? "parilu" : argv[3];
int max_iterations = argc < 5 ? 10 : std::stoi(argv[4]);
int num_repetitions = argc < 6 ? 10 : std::stoi(argv[5]);
double limit = argc < 7 ? 2 : std::stod(argv[6]);

```

load matrix file into Csr format

```

auto mtx = gko::share(try_generate([&] {
    std::ifstream mtx_stream{matrix};
    if (!mtx_stream) {
        throw GKO_STREAM_ERROR("Unable to open matrix file");
    }
    std::cerr << "Reading " << matrix << std::endl;
    return gko::read<gko::matrix::Csr<ValueType, IndexType>>(mtx_stream,
                                                                exec);
}));
std::shared_ptr<gko::LinOpFactory> factory;
std::function<void(int)> set_iterations;
if (precond == "parilu") {
    factory =
        gko::factorization::ParIlc<ValueType, IndexType>::build().on(exec);
    set_iterations = [&](int it) {
        gko::as<gko::factorization::ParIlc<ValueType, IndexType>::Factory>(
            factory)
            ->get_parameters()
            .iterations = it;
    };
} else if (precond == "paric") {
    factory =
        gko::factorization::ParIc<ValueType, IndexType>::build().on(exec);
    set_iterations = [&](int it) {
        gko::as<gko::factorization::ParIc<ValueType, IndexType>::Factory>(
            factory)
            ->get_parameters()
            .iterations = it;
    };
} else if (precond == "parilut") {
    factory = gko::factorization::ParIlut<ValueType, IndexType>::build()
        .with_fill_in_limit(limit)
        .on(exec);
    set_iterations = [&](int it) {
        gko::as<gko::factorization::ParIlut<ValueType, IndexType>::Factory>(
            factory)
            ->get_parameters()

```


Results

```
Usage: executable <reference|omp|cuda|hip|dpcpp> [<matrix-file>] [<parilu|parilut|paric|parict>]
      [<max-iterations>] [<num-repetitions>] [fill-in-limit]
```

[illegible]

The plain program

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(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 <fstream>
#include <functional>
#include <iostream>
#include <map>
#include <memory>
#include <string>
const std::map<std::string, std::function<std::shared_ptr<gko::Executor>()>
    executors{
        {"reference", [] { return gko::ReferenceExecutor::create(); }},
        {"omp", [] { return gko::OmpExecutor::create(); }},
        {"cuda",
         [] {
             return gko::CudaExecutor::create(0, gko::OmpExecutor::create());
         }},
        {"hip",
         [] {
             return gko::HipExecutor::create(0, gko::OmpExecutor::create());
         }},
        {"dpcpp", [] {
             return gko::DpcppExecutor::create(0, gko::OmpExecutor::create());
         }}};
template <typename Function>
auto try_generate(Function fun) -> decltype(fun())
{
    decltype(fun()) result;
    try {
        result = fun();
    } catch (const gko::Error &err) {
        std::cerr << "Error: " << err.what() << '\n';
        std::exit(-1);
    }
    return result;
}
template <typename ValueType, typename IndexType>
double compute_ilu_residual_norm(
    const gko::matrix::Csr<ValueType, IndexType> *residual,
    const gko::matrix::Csr<ValueType, IndexType> *mtx)
{
    gko::matrix_data<ValueType, IndexType> residual_data;
    gko::matrix_data<ValueType, IndexType> mtx_data;
    residual->write(residual_data);
    mtx->write(mtx_data);
    residual_data.ensure_row_major_order();
    mtx_data.ensure_row_major_order();
    auto it = mtx_data.nonzeros.begin();
    double residual_norm{};
    for (auto entry : residual_data.nonzeros) {
        auto ref_row = it->row;
        auto ref_col = it->column;
        if (entry.row == ref_row && entry.column == ref_col) {
            residual_norm += gko::squared_norm(entry.value);
            ++it;
        }
    }
    return std::sqrt(residual_norm);
}
int main(int argc, char *argv[])
{
    using ValueType = double;
```

```

using IndexType = int;
if (argc < 2 || executors.find(argv[1]) == executors.end()) {
    std::cerr << "Usage: executable"
                << " <reference|omp|cuda|hip|dpcpp> [<matrix-file>] "
                << "[<parilu|parilut|paric|parict>] [<max-iterations>] "
                << "[<num-repetitions>] [<fill-in-limit>]\n";
    return -1;
}
auto exec = try_generate([&] { return executors.at(argv[1])(); });
std::string matrix = argc < 3 ? "data/A.mtx" : argv[2];
std::string precondition = argc < 4 ? "parilu" : argv[3];
int max_iterations = argc < 5 ? 10 : std::stoi(argv[4]);
int num_repetitions = argc < 6 ? 10 : std::stoi(argv[5]);
double limit = argc < 7 ? 2 : std::stod(argv[6]);
auto mtx = gko::share(try_generate([&] {
    std::ifstream mtx_stream{matrix};
    if (!mtx_stream) {
        throw GKO_STREAM_ERROR("Unable to open matrix file");
    }
    std::cerr << "Reading " << matrix << std::endl;
    return gko::read<gko::matrix::Csr<ValueType, IndexType>>(mtx_stream,
                                                                exec);
})));
std::shared_ptr<gko::LinOpFactory> factory;
std::function<void(int)> set_iterations;
if (precondition == "parilu") {
    factory =
        gko::factorization::ParIlc<ValueType, IndexType>::build().on(exec);
    set_iterations = [&](int it) {
        gko::as<gko::factorization::ParIlc<ValueType, IndexType>::Factory>(
            factory)
            ->get_parameters()
            .iterations = it;
    };
} else if (precondition == "paric") {
    factory =
        gko::factorization::ParIc<ValueType, IndexType>::build().on(exec);
    set_iterations = [&](int it) {
        gko::as<gko::factorization::ParIc<ValueType, IndexType>::Factory>(
            factory)
            ->get_parameters()
            .iterations = it;
    };
} else if (precondition == "parilut") {
    factory = gko::factorization::ParIlut<ValueType, IndexType>::build()
        .with_fill_in_limit(limit)
        .on(exec);
    set_iterations = [&](int it) {
        gko::as<gko::factorization::ParIlut<ValueType, IndexType>::Factory>(
            factory)
            ->get_parameters()
            .iterations = it;
    };
} else if (precondition == "parict") {
    factory = gko::factorization::ParIct<ValueType, IndexType>::build()
        .with_fill_in_limit(limit)
        .on(exec);
    set_iterations = [&](int it) {
        gko::as<gko::factorization::ParIct<ValueType, IndexType>::Factory>(
            factory)
            ->get_parameters()
            .iterations = it;
    };
}
auto one = gko::initialize<gko::matrix::Dense<ValueType>>({1.0}, exec);
auto minus_one =
    gko::initialize<gko::matrix::Dense<ValueType>>({-1.0}, exec);
for (int it = 1; it <= max_iterations; ++it) {
    set_iterations(it);
    std::cout << it << " ";
    std::vector<long> times;
    std::vector<double> residuals;
    for (int rep = 0; rep < num_repetitions; ++rep) {
        auto tic = std::chrono::high_resolution_clock::now();
        auto result =
            gko::as<gko::Composition<ValueType>>(factory->generate(mtx));
        exec->synchronize();
        auto toc = std::chrono::high_resolution_clock::now();
        auto residual = gko::clone(exec, mtx);
        result->get_operators()[0]->apply(lend(one),
                                         lend(result->get_operators()[1]),
                                         lend(minus_one), lend(residual));
        times.push_back(
            std::chrono::duration_cast<std::chrono::nanoseconds>(toc - tic)
                .count());
        residuals.push_back(
            compute_ilu_residual_norm(lend(residual), lend(mtx)));
    }
}

```

```
    }  
    for (auto el : times) {  
        std::cout << el << ' ';  
    }  
    for (auto el : residuals) {  
        std::cout << el << ' ';  
    }  
    std::cout << '\n';  
}  
}
```

Chapter 26

The performance-debugging program

The simple solver with performance debugging example..

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

Introduction

About the example

This example runs a solver on a test problem and shows how to use loggers to debug performance and convergence rate.

The commented program

```
#include <ginkgo/ginkgo.hpp>
#include <algorithm>
#include <array>
#include <chrono>
#include <cstdlib>
#include <fstream>
#include <iomanip>
#include <iostream>
#include <map>
#include <ostream>
#include <sstream>
#include <string>
#include <unordered_map>
#include <utility>
#include <vector>
template <typename ValueType>
using vec = gko::matrix::Dense<ValueType>;
template <typename ValueType>
using real_vec = gko::matrix::Dense<gko::remove_complex<ValueType>>;
namespace utils {
```

creates a zero vector

```
template <typename ValueType>
std::unique_ptr<vec<ValueType>> create_vector(
    std::shared_ptr<const gko::Executor> exec, gko::size_type size,
    ValueType value)
{
    auto res = vec<ValueType>::create(exec);
    res->read(gko::matrix_data<ValueType>(gko::dim<2>{size, 1}, value));
    return res;
}
```

utilities for computing norms and residuals

```

template <typename ValueType>
ValueType get_first_element(const vec<ValueType> *norm)
{
    return norm->get_executor()->copy_val_to_host(norm->get_const_values());
}
template <typename ValueType>
gko::remove_complex<ValueType> compute_norm(const vec<ValueType> *b)
{
    auto exec = b->get_executor();
    auto b_norm = gko::initialize<real_vec<ValueType>>({0.0}, exec);
    b->compute_norm2(gko::lend(b_norm));
    return get_first_element(gko::lend(b_norm));
}
template <typename ValueType>
gko::remove_complex<ValueType> compute_residual_norm(
    const gko::LinOp *system_matrix, const vec<ValueType> *b,
    const vec<ValueType> *x)
{
    auto exec = system_matrix->get_executor();
    auto one = gko::initialize<vec<ValueType>>({1.0}, exec);
    auto neg_one = gko::initialize<vec<ValueType>>({-1.0}, exec);
    auto res = gko::clone(b);
    system_matrix->apply(gko::lend(one), gko::lend(x), gko::lend(neg_one),
        gko::lend(res));
    return compute_norm(gko::lend(res));
}
} // namespace utils
namespace loggers {

```

A logger that accumulates the time of all operations. For each operation type (allocations, free, copy, internal operations i.e. kernels), the timing is taken before and after. This can create significant overhead since to ensure proper timings, calls to `synchronize` are required.

```

struct OperationLogger : gko::log::Logger {
    void on_allocation_started(const gko::Executor *exec,
        const gko::size_type &) const override
    {
        this->start_operation(exec, "allocate");
    }
    void on_allocation_completed(const gko::Executor *exec,
        const gko::size_type &,
        const gko::uintptr &) const override
    {
        this->end_operation(exec, "allocate");
    }
    void on_free_started(const gko::Executor *exec,
        const gko::uintptr &) const override
    {
        this->start_operation(exec, "free");
    }
    void on_free_completed(const gko::Executor *exec,
        const gko::uintptr &) const override
    {
        this->end_operation(exec, "free");
    }
    void on_copy_started(const gko::Executor *from, const gko::Executor *to,
        const gko::uintptr &, const gko::uintptr &,
        const gko::size_type &) const override
    {
        from->synchronize();
        this->start_operation(to, "copy");
    }
    void on_copy_completed(const gko::Executor *from, const gko::Executor *to,
        const gko::uintptr &, const gko::uintptr &,
        const gko::size_type &) const override
    {
        from->synchronize();
        this->end_operation(to, "copy");
    }
    void on_operation_launched(const gko::Executor *exec,
        const gko::Operation *op) const override
    {
        this->start_operation(exec, op->get_name());
    }
    void on_operation_completed(const gko::Executor *exec,
        const gko::Operation *op) const override
    {
        this->end_operation(exec, op->get_name());
    }
    void write_data(std::ostream &ostream)
    {
        for (const auto &entry : total) {
            ostream << "\t" << entry.first.c_str() << ": "
                << std::chrono::duration_cast<std::chrono::nanoseconds>(
                    entry.second)
                    .count()

```

```

        « std::endl;
    }
}
OperationLogger(std::shared_ptr<const gko::Executor> exec)
    : gko::log::Logger(exec)
{}
private:

```

Helper which synchronizes and starts the time before every operation.

```

void start_operation(const gko::Executor *exec,
                    const std::string &name) const
{
    nested.emplace_back(0);
    exec->synchronize();
    start[name] = std::chrono::steady_clock::now();
}

```

Helper to compute the end time and store the operation's time at its end. Also time nested operations.

```

void end_operation(const gko::Executor *exec, const std::string &name) const
{
    exec->synchronize();
    const auto end = std::chrono::steady_clock::now();
    const auto diff = end - start[name];
}

```

make sure timings for nested operations are not counted twice

```

total[name] += diff - nested.back();
nested.pop_back();
if (nested.size() > 0) {
    nested.back() += diff;
}
}
mutable std::map<std::string, std::chrono::steady_clock::time_point> start;
mutable std::map<std::string, std::chrono::steady_clock::duration> total;

```

the position *i* of this vector holds the total time spend on child operations on nesting level *i*

```

mutable std::vector<std::chrono::steady_clock::duration> nested;
};

```

This logger tracks the persistently allocated data

```

struct StorageLogger : gko::log::Logger {

```

Store amount of bytes allocated on every allocation

```

void on_allocation_completed(const gko::Executor *,
                             const gko::size_type &num_bytes,
                             const gko::uintptr &location) const override
{
    storage[location] = num_bytes;
}

```

Reset the amount of bytes on every free

```

void on_free_completed(const gko::Executor *,
                       const gko::uintptr &location) const override
{
    storage[location] = 0;
}

```

Write the data after summing the total from all allocations

```

void write_data(std::ostream &ostream)
{
    gko::size_type total{};
    for (const auto &e : storage) {
        total += e.second;
    }
    ostream « "Storage: " « total « std::endl;
}
StorageLogger(std::shared_ptr<const gko::Executor> exec)
    : gko::log::Logger(exec)
{}
private:
    mutable std::unordered_map<gko::uintptr, gko::size_type> storage;
};

```

Logs true and recurrent residuals of the solver

```

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

```

Depending on the available information, store the norm or compute it from the residual. If the true residual norm could not be computed, store the value -1.0 .

```

void on_iteration_complete(const gko::LinOp *, const gko::size_type &,
                           const gko::LinOp *residual,
                           const gko::LinOp *solution,
                           const gko::LinOp *residual_norm) const override
{
    if (residual_norm) {
        rec_res_norms.push_back(utils::get_first_element(
            gko::as<real_vec<ValueType>>(residual_norm)));
    } else {
        rec_res_norms.push_back(
            utils::compute_norm(gko::as<vec<ValueType>>(residual)));
    }
    if (solution) {
        true_res_norms.push_back(utils::compute_residual_norm(
            matrix, b, gko::as<vec<ValueType>>(solution)));
    } else {
        true_res_norms.push_back(-1.0);
    }
}

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

void write_data(std::ostream &ostream)
{
    ostream << "Recurrent Residual Norms: " << std::endl;
    ostream << "[" << std::endl;
    for (const auto &entry : rec_res_norms) {
        ostream << "\t" << entry << std::endl;
    }
    ostream << "]" << std::endl;
    ostream << "True Residual Norms: " << std::endl;
    ostream << "[" << std::endl;
    for (const auto &entry : true_res_norms) {
        ostream << "\t" << entry << std::endl;
    }
    ostream << "]" << std::endl;
}

private:
    const gko::LinOp *matrix;
    const vec<ValueType> *b;
    mutable std::vector<gko::remove_complex<ValueType>> rec_res_norms;
    mutable std::vector<gko::remove_complex<ValueType>> true_res_norms;
};

} // namespace loggers
namespace {

```

Print usage help

```

void print_usage(const char *filename)
{
    std::cerr << "Usage: " << filename << " [executor] [matrix file]"
              << std::endl;
    std::cerr << "matrix file should be a file in matrix market format. "
              << "The file data/A.mtx is provided as an example."
              << std::endl;
    std::exit(-1);
}

template <typename ValueType>
void print_vector(const gko::matrix::Dense<ValueType> *vec)
{
    auto elements_to_print = std::min(gko::size_type(10), vec->get_size()[0]);
    std::cout << "[" << std::endl;
    for (int i = 0; i < elements_to_print; ++i) {
        std::cout << "\t" << vec->at(i) << std::endl;
    }
    std::cout << "]" << std::endl;
}

} // namespace

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

```

Parametrize the benchmark here Pick a value type

```

using ValueType = double;
using IndexType = int;

```

Pick a matrix format

```

using mtx = gko::matrix::Csr<ValueType, IndexType>;

```

Pick a solver

```

using solver = gko::solver::Cg<ValueType>;

```


Pick a preconditioner type

```
using preconditioner = gko::matrix::IdentityFactory<ValueType>;
```

Pick a residual norm reduction value

```
const gko::remove_complex<ValueType> reduction_factor = 1e-12;
```

Pick an output file name

```
const auto of_name = "log.txt";
```

Simple shortcut

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

Print version information

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

Figure out where to run the code

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

Figure out where to run the code

```
const auto executor_string = argc >= 2 ? argv[1] : "reference";
std::map<std::string, std::function<std::shared_ptr<gko::Executor>()>>
    exec_map{
    {"omp", [] { return gko::OmpExecutor::create(); }},
    {"cuda",
     [] {
         return gko::CudaExecutor::create(0, gko::OmpExecutor::create(),
                                           true);
     }},
    {"hip",
     [] {
         return gko::HipExecutor::create(0, gko::OmpExecutor::create(),
                                           true);
     }},
    {"dpcpp",
     [] {
         return gko::DpcppExecutor::create(0,
                                           gko::OmpExecutor::create());
     }},
    {"reference", [] { return gko::ReferenceExecutor::create(); }}};
```

executor where Ginkgo will perform the computation

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

Read the input matrix file directory

```
std::string input_mtx = "data/A.mtx";
if (argc == 3) {
    input_mtx = std::string(argv[2]);
}
```

Read data: A is read from disk Create a StorageLogger to track the size of A

```
auto storage_logger = std::make_shared<loggers::StorageLogger>(exec);
```

Add the logger to the executor

```
exec->add_logger(storage_logger);
```

Read the matrix A from file

```
auto A = gko::share(gko::read<mtx>(std::ifstream(input_mtx), exec));
```

Remove the storage logger

```
exec->remove_logger(gko::lend(storage_logger));
```

Pick a maximum iteration count

```
const auto max_iters = A->get_size()[0];
```

Generate b and x vectors

```
auto b = utils::create_vector<ValueType>(exec, A->get_size()[0], 1.0);
auto x = utils::create_vector<ValueType>(exec, A->get_size()[0], 0.0);
```

Declare the solver factory. The preconditioner's arguments should be adapted if needed.

```
auto solver_factory =
```

```

solver::build()
    .with_criteria(
        gko::stop::ResidualNorm<ValueType>::build()
            .with_reduction_factor(reduction_factor)
            .on(exec),
        gko::stop::Iteration::build().with_max_iters(max_iters).on(
            exec)
    ).with_preconditioner(preconditioner::create(exec))
    .on(exec);

```

Declare the output file for all our loggers

```
std::ofstream output_file(of_name);
```

Do a warmup run

```
{
```

Clone x to not overwrite the original one

```
auto x_clone = gko::clone(x);
```

Generate and call apply on a solver

```

solver_factory->generate(A)->apply(gko::lend(b), gko::lend(x_clone));
exec->synchronize();
}

```

Do a timed run

```
{
```

Clone x to not overwrite the original one

```
auto x_clone = gko::clone(x);
```

Synchronize ensures no operation are ongoing

```
exec->synchronize();
```

Time before generate

```
auto g_tic = std::chrono::steady_clock::now();
```

Generate a solver

```

auto generated_solver = solver_factory->generate(A);
exec->synchronize();

```

Time after generate

```
auto g_tac = std::chrono::steady_clock::now();
```

Compute the generation time

```

auto generate_time =
    std::chrono::duration_cast<std::chrono::nanoseconds>(g_tac - g_tic);

```

Write the generate time to the output file

```

output_file << "Generate time (ns): " << generate_time.count()
    << std::endl;

```

Similarly time the apply

```

exec->synchronize();
auto a_tic = std::chrono::steady_clock::now();
generated_solver->apply(gko::lend(b), gko::lend(x_clone));
exec->synchronize();
auto a_tac = std::chrono::steady_clock::now();
auto apply_time =
    std::chrono::duration_cast<std::chrono::nanoseconds>(a_tac - a_tic);
output_file << "Apply time (ns): " << apply_time.count() << std::endl;

```

Compute the residual norm

```

auto residual = utils::compute_residual_norm(gko::lend(A), gko::lend(b),
    gko::lend(x_clone));
output_file << "Residual_norm: " << residual << std::endl;
}

```

Log the internal operations using the OperationLogger without timing

```
{
```

Create an OperationLogger to analyze the generate step

```
auto gen_logger = std::make_shared<loggers::OperationLogger>(exec);
```

Add the generate logger to the executor

```
exec->add_logger(gen_logger);
```

Generate a solver

```
auto generated_solver = solver_factory->generate(A);
```

Remove the generate logger from the executor

```
exec->remove_logger(gko::lend(gen_logger));
```

Write the data to the output file

```
output_file << "Generate operations times (ns):" << std::endl;
gen_logger->write_data(output_file);
```

Create an OperationLogger to analyze the apply step

```
auto apply_logger = std::make_shared<loggers::OperationLogger>(exec);
exec->add_logger(apply_logger);
```

Create a ResidualLogger to log the recurrent residual

```
auto res_logger = std::make_shared<loggers::ResidualLogger<ValueType>>(
    exec, gko::lend(A), gko::lend(b));
generated_solver->add_logger(res_logger);
```

Solve the system

```
generated_solver->apply(gko::lend(b), gko::lend(x));
exec->remove_logger(gko::lend(apply_logger));
```

Write the data to the output file

```
output_file << "Apply operations times (ns):" << std::endl;
apply_logger->write_data(output_file);
res_logger->write_data(output_file);
}
```

Print solution

```
std::cout << "Solution, first ten entries: \n";
print_vector(gko::lend(x));
```

Print output file location

```
std::cout << "The performance and residual data can be found in " << of_name
    << std::endl;
}
```

Results

This is the expected standard output:

```
Solution, first ten entries:
[
  0.252218
  0.108645
  0.0662811
  0.0630433
  0.0384088
  0.0396536
  0.0402648
  0.0338935
  0.0193098
  0.0234653
];
The performance and residual data can be found in log.txt
```

Here is a sample output in the file log.txt:

```
Generate time (ns): 861
Apply time (ns): 108144
Residual_norm: 2.10788e-15
Generate operations times (ns):
Apply operations times (ns):
  allocate: 14991
  cg::initialize#8: 872
  cg::step_1#5: 7683
  cg::step_2#7: 7756
  copy: 7751
  csr::advanced_spmv#5: 21819
  csr::spmv#3: 20429
```

```

dense::compute_dot#3: 18043
dense::compute_norm2#2: 16726
free: 8857
residual_norm::residual_norm#9: 3614
Recurrent Residual Norms:
[
  4.3589
  2.30455
  1.46771
  0.984875
  0.741833
  0.513623
  0.384165
  0.316439
  0.227709
  0.170312
  0.0973722
  0.0616831
  0.0454123
  0.031953
  0.0161606
  0.00657015
  0.00264367
  0.000858809
  0.000286461
  1.64195e-15
];
True Residual Norms:
[
  4.3589
  2.30455
  1.46771
  0.984875
  0.741833
  0.513623
  0.384165
  0.316439
  0.227709
  0.170312
  0.0973722
  0.0616831
  0.0454123
  0.031953
  0.0161606
  0.00657015
  0.00264367
  0.000858809
  0.000286461
  2.10788e-15
];

```

Comments about programming and debugging

The plain program

```

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```

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```

#include <ginkgo/ginkgo.hpp>
#include <algorithm>
#include <array>
#include <chrono>
#include <cstdlib>
#include <fstream>
#include <iomanip>
#include <iostream>
#include <map>
#include <ostream>
#include <sstream>
#include <string>
#include <unordered_map>
#include <utility>
#include <vector>
template <typename ValueType>
using vec = gko::matrix::Dense<ValueType>;
template <typename ValueType>
using real_vec = gko::matrix::Dense<gko::remove_complex<ValueType>>;
namespace utils {
template <typename ValueType>
std::unique_ptr<vec<ValueType>> create_vector(
    std::shared_ptr<const gko::Executor> exec, gko::size_type size,
    ValueType value)
{
    auto res = vec<ValueType>::create(exec);
    res->read(gko::matrix_data<ValueType>(gko::dim<2>(size, 1), value));
    return res;
}
template <typename ValueType>
ValueType get_first_element(const vec<ValueType> *norm)
{
    return norm->get_executor()->copy_val_to_host(norm->get_const_values());
}
template <typename ValueType>
gko::remove_complex<ValueType> compute_norm(const vec<ValueType> *b)
{
    auto exec = b->get_executor();
    auto b_norm = gko::initialize<vec<ValueType>>({0.0}, exec);
    b->compute_norm2(gko::lend(b_norm));
    return get_first_element(gko::lend(b_norm));
}
template <typename ValueType>
gko::remove_complex<ValueType> compute_residual_norm(
    const gko::LinOp *system_matrix, const vec<ValueType> *b,
    const vec<ValueType> *x)
{
    auto exec = system_matrix->get_executor();
    auto one = gko::initialize<vec<ValueType>>({1.0}, exec);
    auto neg_one = gko::initialize<vec<ValueType>>({-1.0}, exec);
    auto res = gko::clone(b);
    system_matrix->apply(gko::lend(one), gko::lend(x), gko::lend(neg_one),
        gko::lend(res));
    return compute_norm(gko::lend(res));
}
} // namespace utils
namespace loggers {
struct OperationLogger : gko::log::Logger {
    void on_allocation_started(const gko::Executor *exec,
        const gko::size_type &) const override
    {
        this->start_operation(exec, "allocate");
    }
    void on_allocation_completed(const gko::Executor *exec,
        const gko::size_type &,
        const gko::uintptr &) const override
    {
        this->end_operation(exec, "allocate");
    }
    void on_free_started(const gko::Executor *exec,
        const gko::uintptr &) const override
    {
        this->start_operation(exec, "free");
    }
    void on_free_completed(const gko::Executor *exec,
        const gko::uintptr &) const override
    {
        this->end_operation(exec, "free");
    }
    void on_copy_started(const gko::Executor *from, const gko::Executor *to,
        const gko::uintptr &, const gko::uintptr &,
        const gko::size_type &) const override

```

```

    {
        from->synchronize();
        this->start_operation(to, "copy");
    }
    void on_copy_completed(const gko::Executor *from, const gko::Executor *to,
                          const gko::uintptr &, const gko::uintptr &,
                          const gko::size_type &) const override
    {
        from->synchronize();
        this->end_operation(to, "copy");
    }
    void on_operation_launched(const gko::Executor *exec,
                              const gko::Operation *op) const override
    {
        this->start_operation(exec, op->get_name());
    }
    void on_operation_completed(const gko::Executor *exec,
                               const gko::Operation *op) const override
    {
        this->end_operation(exec, op->get_name());
    }
    void write_data(std::ostream &ostream)
    {
        for (const auto &entry : total) {
            ostream << "\t" << entry.first.c_str() << ": "
                << std::chrono::duration_cast<std::chrono::nanoseconds>(
                    entry.second)
                    .count()
                << std::endl;
        }
    }
    OperationLogger(std::shared_ptr<const gko::Executor> exec)
        : gko::log::Logger(exec)
    {}
private:
    void start_operation(const gko::Executor *exec,
                       const std::string &name) const
    {
        nested.emplace_back(0);
        exec->synchronize();
        start[name] = std::chrono::steady_clock::now();
    }
    void end_operation(const gko::Executor *exec, const std::string &name) const
    {
        exec->synchronize();
        const auto end = std::chrono::steady_clock::now();
        const auto diff = end - start[name];
        total[name] += diff - nested.back();
        nested.pop_back();
        if (nested.size() > 0) {
            nested.back() += diff;
        }
    }
    mutable std::map<std::string, std::chrono::steady_clock::time_point> start;
    mutable std::map<std::string, std::chrono::steady_clock::duration> total;
    mutable std::vector<std::chrono::steady_clock::duration> nested;
};
struct StorageLogger : gko::log::Logger {
    void on_allocation_completed(const gko::Executor *,
                               const gko::size_type &num_bytes,
                               const gko::uintptr &location) const override
    {
        storage[location] = num_bytes;
    }
    void on_free_completed(const gko::Executor *,
                          const gko::uintptr &location) const override
    {
        storage[location] = 0;
    }
    void write_data(std::ostream &ostream)
    {
        gko::size_type total{};
        for (const auto &e : storage) {
            total += e.second;
        }
        ostream << "Storage: " << total << std::endl;
    }
    StorageLogger(std::shared_ptr<const gko::Executor> exec)
        : gko::log::Logger(exec)
    {}
private:
    mutable std::unordered_map<gko::uintptr, gko::size_type> storage;
};
template <typename ValueType>
struct ResidualLogger : gko::log::Logger {
    void on_iteration_complete(const gko::LinOp *, const gko::size_type &,
                              const gko::LinOp *residual,

```

```

        const gko::LinOp *solution,
        const gko::LinOp *residual_norm) const override
    {
        if (residual_norm) {
            rec_res_norms.push_back(utils::get_first_element(
                gko::as<real_vec<ValueType>>(residual_norm)));
        } else {
            rec_res_norms.push_back(
                utils::compute_norm(gko::as<vec<ValueType>>(residual)));
        }
        if (solution) {
            true_res_norms.push_back(utils::compute_residual_norm(
                matrix, b, gko::as<vec<ValueType>>(solution)));
        } else {
            true_res_norms.push_back(-1.0);
        }
    }
}
ResidualLogger(std::shared_ptr<const gko::Executor> exec,
    const gko::LinOp *matrix, const vec<ValueType> *b)
    : gko::log::Logger(exec, gko::log::Logger::iteration_complete_mask),
      matrix{matrix},
      b{b}
{}
void write_data(std::ostream &ostream)
{
    ostream << "Recurrent Residual Norms: " << std::endl;
    ostream << "[" << std::endl;
    for (const auto &entry : rec_res_norms) {
        ostream << "\t" << entry << std::endl;
    }
    ostream << "]" << std::endl;
    ostream << "True Residual Norms: " << std::endl;
    ostream << "[" << std::endl;
    for (const auto &entry : true_res_norms) {
        ostream << "\t" << entry << std::endl;
    }
    ostream << "]" << std::endl;
}
private:
    const gko::LinOp *matrix;
    const vec<ValueType> *b;
    mutable std::vector<gko::remove_complex<ValueType>> rec_res_norms;
    mutable std::vector<gko::remove_complex<ValueType>> true_res_norms;
};
} // namespace loggers
namespace {
void print_usage(const char *filename)
{
    std::cerr << "Usage: " << filename << " [executor] [matrix file]"
        << std::endl;
    std::cerr << "matrix file should be a file in matrix market format. "
        << "The file data/A.mtx is provided as an example."
        << std::endl;
    std::exit(-1);
}
template <typename ValueType>
void print_vector(const gko::matrix::Dense<ValueType> *vec)
{
    auto elements_to_print = std::min(gko::size_type(10), vec->get_size()[0]);
    std::cout << "[" << std::endl;
    for (int i = 0; i < elements_to_print; ++i) {
        std::cout << "\t" << vec->at(i) << std::endl;
    }
    std::cout << "]" << std::endl;
}
} // namespace
int main(int argc, char *argv[])
{
    using ValueType = double;
    using IndexType = int;
    using mtx = gko::matrix::Csr<ValueType, IndexType>;
    using solver = gko::solver::Cg<ValueType>;
    using preconditioner = gko::matrix::IdentityFactory<ValueType>;
    const gko::remove_complex<ValueType> reduction_factor = 1e-12;
    const auto of_name = "log.txt";
    using vec = gko::matrix::Dense<ValueType>;
    std::cout << gko::version_info::get() << std::endl;
    if (argc == 2 && (std::string(argv[1]) == "--help")) {
        std::cerr << "Usage: " << argv[0] << " [executor]" << std::endl;
        std::exit(-1);
    }
    const auto executor_string = argc >= 2 ? argv[1] : "reference";
    std::map<std::string, std::function<std::shared_ptr<gko::Executor>()>>
    exec_map{
        {"omp", [] { return gko::OmpExecutor::create(); }},
        {"cuda",
            [] {

```

```

        return gko::CudaExecutor::create(0, gko::OmpExecutor::create(),
                                          true);
    },
    {"hip",
     [] {
         return gko::HipExecutor::create(0, gko::OmpExecutor::create(),
                                          true);
     }},
    {"dpcpp",
     [] {
         return gko::DpcppExecutor::create(0,
                                           gko::OmpExecutor::create());
     }},
    {"reference", [] { return gko::ReferenceExecutor::create(); }}};
const auto exec = exec_map.at(executor_string()); // throws if not valid
std::string input_mtx = "data/A.mtx";
if (argc == 3) {
    input_mtx = std::string(argv[2]);
}
auto storage_logger = std::make_shared<loggers::StorageLogger>(exec);
exec->add_logger(storage_logger);
auto A = gko::share(gko::read<mtx>(std::ifstream(input_mtx), exec));
exec->remove_logger(gko::lend(storage_logger));
const auto max_iters = A->get_size()[0];
auto b = utils::create_vector<ValueType>(exec, A->get_size()[0], 1.0);
auto x = utils::create_vector<ValueType>(exec, A->get_size()[0], 0.0);
auto solver_factory =
    solver::build()
        .with_criteria(
            gko::stop::ResidualNorm<ValueType>::build()
                .with_reduction_factor(reduction_factor)
                .on(exec),
            gko::stop::Iteration::build().with_max_iters(max_iters).on(
                exec))
        .with_preconditioner(preconditioner::create(exec))
        .on(exec);
std::ofstream output_file(of_name);
{
    auto x_clone = gko::clone(x);
    solver_factory->generate(A)->apply(gko::lend(b), gko::lend(x_clone));
    exec->synchronize();
}
{
    auto x_clone = gko::clone(x);
    exec->synchronize();
    auto g_tic = std::chrono::steady_clock::now();
    auto generated_solver = solver_factory->generate(A);
    exec->synchronize();
    auto g_tac = std::chrono::steady_clock::now();
    auto generate_time =
        std::chrono::duration_cast<std::chrono::nanoseconds>(g_tac - g_tic);
    output_file << "Generate time (ns): " << generate_time.count()
                << std::endl;
    exec->synchronize();
    auto a_tic = std::chrono::steady_clock::now();
    generated_solver->apply(gko::lend(b), gko::lend(x_clone));
    exec->synchronize();
    auto a_tac = std::chrono::steady_clock::now();
    auto apply_time =
        std::chrono::duration_cast<std::chrono::nanoseconds>(a_tac - a_tic);
    output_file << "Apply time (ns): " << apply_time.count() << std::endl;
    auto residual = utils::compute_residual_norm(gko::lend(A), gko::lend(b),
                                                gko::lend(x_clone));
    output_file << "Residual_norm: " << residual << std::endl;
}
{
    auto gen_logger = std::make_shared<loggers::OperationLogger>(exec);
    exec->add_logger(gen_logger);
    auto generated_solver = solver_factory->generate(A);
    exec->remove_logger(gko::lend(gen_logger));
    output_file << "Generate operations times (ns):" << std::endl;
    gen_logger->write_data(output_file);
    auto apply_logger = std::make_shared<loggers::OperationLogger>(exec);
    exec->add_logger(apply_logger);
    auto res_logger = std::make_shared<loggers::ResidualLogger<ValueType>>(
        exec, gko::lend(A), gko::lend(b));
    generated_solver->add_logger(res_logger);
    generated_solver->apply(gko::lend(b), gko::lend(x));
    exec->remove_logger(gko::lend(apply_logger));
    output_file << "Apply operations times (ns):" << std::endl;
    apply_logger->write_data(output_file);
    res_logger->write_data(output_file);
}
std::cout << "Solution, first ten entries: \n";
print_vector(gko::lend(x));
std::cout << "The performance and residual data can be found in " << of_name
          << std::endl;

```


}

Chapter 27

The poisson-solver program

The poisson solver example..

This example depends on simple-solver.

Introduction

This example solves a 1D Poisson equation:

$$\begin{aligned} u &: [0, 1] \rightarrow R \\ u'' &= f \\ u(0) &= u_0 \\ u(1) &= u_1 \end{aligned}$$

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:

$$\begin{aligned} u(x+h) &= u(x) + u'(x)h + \frac{1}{2}u''(x)h^2 + O(h^3) \\ u(x-h) &= u(x) - u'(x)h + \frac{1}{2}u''(x)h^2 + O(h^3) \\ \hline -u(x-h) + 2u(x) - u(x+h) &= -f(x)h^2 + O(h^3) \end{aligned}$$

For an equidistant grid with K "inner" discretization points x_1, \dots, x_K , and step size $h = 1/(K+1)$, the formula produces a system of linear equations

$$\begin{aligned} 2u_1 - u_2 &= -f_1 h^2 + u_0 \\ -u_{k-1} + 2u_k - u_{k+1} &= -f_k h^2, k = 2, \dots, K-1 \\ -u_{K-1} + 2u_K &= -f_K h^2 + u_1 \end{aligned}$$

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) = x3`), 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.

```
template <typename ValueType, typename IndexType>
void generate_stencil_matrix(gko::matrix::Csr<ValueType, IndexType> *matrix)
{
    const auto discretization_points = matrix->get_size()[0];
    auto row_ptrs = matrix->get_row_ptrs();
    auto col_idxes = matrix->get_col_idxes();
    auto values = matrix->get_values();
    int pos = 0;
    const ValueType coeffs[] = {-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] = coeffs[ofs + 1];
                col_idxes[pos] = i + ofs;
                ++pos;
            }
        }
        row_ptrs[i + 1] = pos;
    }
}
```

Generates the RHS vector given f and the boundary conditions.

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

Prints the solution u .

```
template <typename Closure, typename ValueType>
void print_solution(ValueType u0, ValueType u1,
                   const gko::matrix::Dense<ValueType> *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, typename ValueType>
gko::remove_complex<ValueType> calculate_error(
    int discretization_points, const gko::matrix::Dense<ValueType> *u,
    Closure correct_u)
{
    const ValueType h = 1.0 / static_cast<ValueType>(discretization_points + 1);
    gko::remove_complex<ValueType> error = 0.0;
    for (int i = 0; i < discretization_points; ++i) {
        using std::abs;
        const auto xi = static_cast<ValueType>(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 ValueType = double;
using IndexType = int;
using vec = gko::matrix::Dense<ValueType>;
using mtx = gko::matrix::Csr<ValueType, IndexType>;
using cg = gko::solver::Cg<ValueType>;
using bj = gko::preconditioner::Jacobi<ValueType, IndexType>;
```

Print version information

```
std::cout << gko::version_info::get() << std::endl;
if (argc == 2 && (std::string(argv[1]) == "--help")) {
    std::cerr << "Usage: " << argv[0]
        << " [executor] [DISCRETIZATION_POINTS]" << std::endl;
    std::exit(-1);
}
```

Get number of discretization points

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

Figure out where to run the code

```
std::map<std::string, std::function<std::shared_ptr<gko::Executor>()>>
exec_map{
    {"omp", [] { return gko::OmpExecutor::create(); }},
    {"cuda",
     [] {
         return gko::CudaExecutor::create(0, gko::OmpExecutor::create(),
                                           true);
     }},
    {"hip",
     [] {
         return gko::HipExecutor::create(0, gko::OmpExecutor::create(),
                                           true);
     }},
    {"dpcpp",
     [] {
         return gko::DpcppExecutor::create(0,
                                           gko::OmpExecutor::create());
     }},
    {"reference", [] { return 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->get_master();
```

problem:

```
auto correct_u = [] (ValueType x) { return x * x * x; };
auto f = [] (ValueType x) { return ValueType(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;
}
const gko::remove_complex<ValueType> reduction_factor = 1e-7;
```

Generate solver and solve the system

```
cg::build()
    .with_criteria(gko::stop::Iteration::build()
        .with_max_iters(discretization_points)
        .on(exec),
        gko::stop::ResidualNorm<ValueType>::build()
        .with_reduction_factor(reduction_factor)
        .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));
```

Uncomment to print the solution print_solution<ValueType>(u0, u1, lend(u));

```
std::cout << "Solve complete.\n" << "The average relative error is "
    << calculate_error(discretization_points, lend(u), correct_u) /
        static_cast<gko::remove_complex<ValueType>>(
            discretization_points)
    << std::endl;
}
```

Results

This is the expected output:

```
Solve complete.
The average relative error is 2.52236e-11
```

Comments about programming and debugging

The plain program

```

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OF THIS SOFTWARE, EVEN IF ADVISED OF THE POSSIBILITY OF SUCH DAMAGE.
*****/
#include <ginkgo/ginkgo.hpp>
#include <iostream>
#include <map>
#include <string>
#include <vector>
template <typename ValueType, typename IndexType>
void generate_stencil_matrix(gko::matrix::Csr<ValueType, IndexType> *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 ValueType 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, typename ValueType>
void generate_rhs(Closure f, ValueType u0, ValueType u1,
                 gko::matrix::Dense<ValueType> *rhs)
{
    const auto discretization_points = rhs->get_size()[0];
    auto values = rhs->get_values();
    const ValueType h = 1.0 / static_cast<ValueType>(discretization_points + 1);
    for (gko::size_type i = 0; i < discretization_points; ++i) {
        const auto xi = static_cast<ValueType>(i + 1) * h;
        values[i] = -f(xi) * h * h;
    }
    values[0] += u0;
}

```

```

        values[discretization_points - 1] += u1;
    }
    template <typename Closure, typename ValueType>
    void print_solution(ValueType u0, ValueType u1,
        const gko::matrix::Dense<ValueType> *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, typename ValueType>
    gko::remove_complex<ValueType> calculate_error(
        int discretization_points, const gko::matrix::Dense<ValueType> *u,
        Closure correct_u)
    {
        const ValueType h = 1.0 / static_cast<ValueType>(discretization_points + 1);
        gko::remove_complex<ValueType> error = 0.0;
        for (int i = 0; i < discretization_points; ++i) {
            using std::abs;
            const auto xi = static_cast<ValueType>(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 ValueType = double;
        using IndexType = int;
        using vec = gko::matrix::Dense<ValueType>;
        using mtx = gko::matrix::Csr<ValueType, IndexType>;
        using cg = gko::solver::Cg<ValueType>;
        using bj = gko::preconditioner::Jacobi<ValueType, IndexType>;
        std::cout << gko::version_info::get() << std::endl;
        if (argc == 2 && (std::string(argv[1]) == "--help")) {
            std::cerr << "Usage: " << argv[0]
                << " [executor] [DISCRETIZATION_POINTS]" << std::endl;
            std::exit(-1);
        }
        const auto executor_string = argc >= 2 ? argv[1] : "reference";
        const unsigned int discretization_points =
            argc >= 3 ? std::atoi(argv[2]) : 100;
        std::map<std::string, std::function<std::shared_ptr<gko::Executor>()>>
            exec_map{
                {"omp", [] { return gko::OmpExecutor::create(); }},
                {"cuda",
                    [] {
                        return gko::CudaExecutor::create(0, gko::OmpExecutor::create(),
                            true);
                    }},
                {"hip",
                    [] {
                        return gko::HipExecutor::create(0, gko::OmpExecutor::create(),
                            true);
                    }},
                {"dpcpp",
                    [] {
                        return gko::DpcppExecutor::create(0,
                            gko::OmpExecutor::create());
                    }},
                {"reference", [] { return gko::ReferenceExecutor::create(); }}};
        const auto exec = exec_map.at(executor_string)(); // throws if not valid
        const auto app_exec = exec->get_master();
        auto correct_u = [] (ValueType x) { return x * x * x; };
        auto f = [] (ValueType x) { return ValueType(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;
        }
        const gko::remove_complex<ValueType> reduction_factor = 1e-7;
        cg::build()
            .with_criteria(gko::stop::Iteration::build()
                .with_max_iters(discretization_points)
                .on(exec),
                gko::stop::ResidualNorm<ValueType>::build()
                    .with_reduction_factor(reduction_factor)
                    .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));
std::cout << "Solve complete.\nThe average relative error is "
    << calculate_error(discretization_points, lend(u), correct_u) /
        static_cast<gko::remove_complex<ValueType>>(
            discretization_points)
    << std::endl;
}
```


The preconditioned-solver program

This example depends on simple-solver.

About the example

```
#include <ginkgo/ginkgo.hpp>
#include <fstream>
#include <iostream>
#include <map>
#include <string>
int main(int argc, char *argv[])
{
```

```
using ValueType = double;
using RealValueType = gko::remove_complex<ValueType>;
using IndexType = int;
using vec = gko::matrix::Dense<ValueType>;
using real_vec = gko::matrix::Dense<RealValueType>;
using mtx = gko::matrix::Csr<ValueType, IndexType>;
using cg = gko::solver::Cg<ValueType>;
using bj = gko::preconditioner::Jacobi<ValueType, IndexType>;
```

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

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

[illegible]

```

{"hip",
 [] {
     return gko::HipExecutor::create(0, gko::OmpExecutor::create(),
                                     true);
 }},
{"dpcpp",
 [] {
     return gko::DpcppExecutor::create(0,
                                       gko::OmpExecutor::create());
 }},
{"reference", [] { return gko::ReferenceExecutor::create(); } }];

```

executor where Ginkgo will perform the computation

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

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);
const RealValueType reduction_factor{1e-7};

```

Create solver factory

```

auto solver_gen =
    cg::build()
        .with_criteria(
            gko::stop::Iteration::build().with_max_iters(20u).on(exec),
            gko::stop::ResidualNorm<ValueType>::build()
                .with_reduction_factor(reduction_factor)
                .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<real_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
4.82005e-08

```

Comments about programming and debugging

The plain program

```

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*****/
#include <ginkgo/ginkgo.hpp>
#include <fstream>
#include <iostream>
#include <map>
#include <string>
int main(int argc, char *argv[])
{
    using ValueType = double;
    using RealValueType = gko::remove_complex<ValueType>;
    using IndexType = int;
    using vec = gko::matrix::Dense<ValueType>;
    using real_vec = gko::matrix::Dense<RealValueType>;
    using mtx = gko::matrix::Csr<ValueType, IndexType>;
    using cg = gko::solver::Cg<ValueType>;
    using bj = gko::preconditioner::Jacobi<ValueType, IndexType>;
    std::cout << gko::version_info::get() << std::endl;
    if (argc == 2 && (std::string(argv[1]) == "--help")) {
        std::cerr << "Usage: " << argv[0] << " [executor]" << std::endl;
        std::exit(-1);
    }
    const auto executor_string = argc >= 2 ? argv[1] : "reference";
    std::map<std::string, std::function<std::shared_ptr<gko::Executor>()>>
    exec_map{
        {"omp", [] { return gko::OmpExecutor::create(); }},
        {"cuda",
         [] {
             return gko::CudaExecutor::create(0, gko::OmpExecutor::create(),
                                              true);
         }},
        {"hip",
         [] {
             return gko::HipExecutor::create(0, gko::OmpExecutor::create(),
                                              true);
         }},
        {"dpcpp",
         [] {
             return gko::DpcppExecutor::create(0,
                                              gko::OmpExecutor::create());
         }},
        {"reference", [] { return gko::ReferenceExecutor::create(); }};
    const auto exec = exec_map.at(executor_string)(); // throws if not valid
    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);
    const RealValueType reduction_factor{1e-7};
    auto solver_gen =
        cg::build()
        .with_criteria(
            gko::stop::Iteration::build().with_max_iters(20u).on(exec),

```

```
        gko::stop::ResidualNorm<ValueType>::build()
            .with_reduction_factor(reduction_factor)
            .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<real_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 29

The preconditioner-export program

The preconditioner export example..

This example depends on simple-solver.

Introduction

About the example

This example shows how to explicitly generate and store preconditioners for a given matrix. It can also be used to inspect and debug the preconditioner generation.

The commented program

```
#include <ginkgo/ginkgo.hpp>
#include <fstream>
#include <functional>
#include <iostream>
#include <map>
#include <memory>
#include <string>
const std::map<std::string, std::function<std::shared_ptr<gko::Executor>()>>
    executors{{"reference", [] { return gko::ReferenceExecutor::create(); }},
              {"omp", [] { return gko::OmpExecutor::create(); }},
              {"cuda",
               [] {
                   return gko::CudaExecutor::create(
                       0, gko::ReferenceExecutor::create());
               }},
              {"hip",
               [] {
                   return gko::HipExecutor::create(
                       0, gko::ReferenceExecutor::create());
               }},
              {"dpcpp", [] {
                   return gko::DpcppExecutor::create(
                       0, gko::ReferenceExecutor::create());
               }}}};

void output(const gko::WritableToMatrixData<double, int> *mtx, std::string name)
{
    std::ofstream stream{name};
    std::cerr << "Writing " << name << std::endl;
    gko::write(stream, mtx, gko::layout_type::coordinate);
}

template <typename Function>
auto try_generate(Function fun) -> decltype(fun())
{
    decltype(fun()) result;
```

```

    try {
        result = fun();
    } catch (const gko::Error &err) {
        std::cerr << "Error: " << err.what() << '\n';
        std::exit(-1);
    }
    return result;
}
int main(int argc, char *argv[])
{

```

print usage message

```

if (argc < 2 || executors.find(argv[1]) == executors.end()) {
    std::cerr << "Usage: executable"
        << " <reference|omp|cuda|hip|dpcpp> [<matrix-file>] "
        << "[<jacobi|ilu|parilu|parilut|ilu-isai|parilu-isai|parilut-"
        << "isai> [<preconditioner args>]\n";
    std::cerr << "Jacobi parameters: [<max-block-size>] [<accuracy>] "
        << "[<storage-optimization:auto|0|1|2>]\n";
    std::cerr << "ParILU parameters: [<iteration-count>]\n";
    std::cerr
        << "ParILUT parameters: [<iteration-count>] [<fill-in-limit>]\n";
    std::cerr << "ILU-ISAI parameters: [<sparsity-power>]\n";
    std::cerr << "ParILU-ISAI parameters: [<iteration-count>] "
        << "[<sparsity-power>]\n";
    std::cerr << "ParILUT-ISAI parameters: [<iteration-count>] "
        << "[<fill-in-limit>] [<sparsity-power>]\n";
    return -1;
}

```

generate executor based on first argument

```

auto exec = try_generate([&] { return executors.at(argv[1])(); });

```

set matrix and preconditioner name with default values

```

std::string matrix = argc < 3 ? "data/A.mtx" : argv[2];
std::string preconditioner = argc < 4 ? "jacobi" : argv[3];

```

load matrix file into Csr format

```

auto mtx = gko::share(try_generate([&] {
    std::ifstream mtx_stream{matrix};
    if (!mtx_stream) {
        throw GKO_STREAM_ERROR("Unable to open matrix file");
    }
    std::cerr << "Reading " << matrix << std::endl;
    return gko::read<gko::matrix::Csr>(mtx_stream, exec);
}));

```

concatenate remaining arguments for filename

```

std::string output_suffix;
for (auto i = 4; i < argc; ++i) {
    output_suffix = output_suffix + "-" + argv[i];
}

```

handle different preconditioners

```

if (precond == "jacobi") {

```

jacobi: max_block_size, accuracy, storage_optimization

```

    auto factory = gko::preconditioner::Jacobi<>::build().on(exec);
    if (argc >= 5) {
        factory->get_parameters().max_block_size = std::stoi(argv[4]);
    }
    if (argc >= 6) {
        factory->get_parameters().accuracy = std::stod(argv[5]);
    }
    if (argc >= 7) {
        factory->get_parameters().storage_optimization =
            std::string{argv[6]} == "auto"
            ? gko::precision_reduction::autodetect()
            : gko::precision_reduction(0, std::stoi(argv[6]));
    }
    auto jacobi = try_generate([&] { return factory->generate(mtx); });
    output(jacobi.get(), matrix + ".jacobi" + output_suffix);
} else if (precond == "ilu") {

```

ilu: no parameters

```

    auto ilu = gko::as<gko::Composition>(try_generate([&] {
        return gko::factorization::Ilu<>::build().on(exec)->generate(mtx);
    }));
    output(gko::as<gko::matrix::Csr>(ilu->get_operators()[0].get()),
        matrix + ".ilu-1");

```

```

        output(gko::as<gko::matrix::Csr<>>(ilu->get_operators()[1].get()),
               matrix + ".ilu-u");
    } else if (precond == "parilu") {

```

parilu: iterations

```

    auto factory = gko::factorization::ParIlut<>::build().on(exec);
    if (argc >= 5) {
        factory->get_parameters().iterations = std::stoi(argv[4]);
    }
    auto ilu = gko::as<gko::Composition<>>(
        try_generate([&] { return factory->generate(mtx); }));
    output(gko::as<gko::matrix::Csr<>>(ilu->get_operators()[0].get()),
           matrix + ".parilu" + output_suffix + "-l");
    output(gko::as<gko::matrix::Csr<>>(ilu->get_operators()[1].get()),
           matrix + ".parilu" + output_suffix + "-u");
} else if (precond == "parilut") {

```

parilut: iterations, fill-in limit

```

    auto factory = gko::factorization::ParIlut<>::build().on(exec);
    if (argc >= 5) {
        factory->get_parameters().iterations = std::stoi(argv[4]);
    }
    if (argc >= 6) {
        factory->get_parameters().fill_in_limit = std::stod(argv[5]);
    }
    auto ilut = gko::as<gko::Composition<>>(
        try_generate([&] { return factory->generate(mtx); }));
    output(gko::as<gko::matrix::Csr<>>(ilut->get_operators()[0].get()),
           matrix + ".parilut" + output_suffix + "-l");
    output(gko::as<gko::matrix::Csr<>>(ilut->get_operators()[1].get()),
           matrix + ".parilut" + output_suffix + "-u");
} else if (precond == "ilu-isai") {

```

ilu-isai: sparsity power

```

    auto fact_factory =
        gko::share(gko::factorization::Ilu<>::build().on(exec));
    int sparsity_power = 1;
    if (argc >= 5) {
        sparsity_power = std::stoi(argv[4]);
    }
    auto factory =
        gko::preconditioner::Ilu<gko::preconditioner::LowerIsai<>,
            gko::preconditioner::UpperIsai<>>::build()
        .with_factorization_factory(fact_factory)
        .with_l_solver_factory(gko::preconditioner::LowerIsai<>::build()
            .with_sparsity_power(sparsity_power)
            .on(exec))
        .with_u_solver_factory(gko::preconditioner::UpperIsai<>::build()
            .with_sparsity_power(sparsity_power)
            .on(exec))
        .on(exec);
    auto ilu_isai = try_generate([&] { return factory->generate(mtx); });
    output(ilu_isai->get_l_solver()->get_approximate_inverse().get(),
           matrix + ".ilu-isai" + output_suffix + "-l");
    output(ilu_isai->get_u_solver()->get_approximate_inverse().get(),
           matrix + ".ilu-isai" + output_suffix + "-u");
} else if (precond == "parilu-isai") {

```

parilu-isai: iterations, sparsity power

```

    auto fact_factory =
        gko::share(gko::factorization::ParIlut<>::build().on(exec));
    int sparsity_power = 1;
    if (argc >= 5) {
        fact_factory->get_parameters().iterations = std::stoi(argv[4]);
    }
    if (argc >= 6) {
        sparsity_power = std::stoi(argv[5]);
    }
    auto factory =
        gko::preconditioner::Ilu<gko::preconditioner::LowerIsai<>,
            gko::preconditioner::UpperIsai<>>::build()
        .with_factorization_factory(fact_factory)
        .with_l_solver_factory(gko::preconditioner::LowerIsai<>::build()
            .with_sparsity_power(sparsity_power)
            .on(exec))
        .with_u_solver_factory(gko::preconditioner::UpperIsai<>::build()
            .with_sparsity_power(sparsity_power)
            .on(exec))
        .on(exec);
    auto ilu_isai = try_generate([&] { return factory->generate(mtx); });
    output(ilu_isai->get_l_solver()->get_approximate_inverse().get(),
           matrix + ".parilu-isai" + output_suffix + "-l");
    output(ilu_isai->get_u_solver()->get_approximate_inverse().get(),

```

```
        matrix + ".parilu-isai" + output_suffix + "-u");
} else if (precond == "parilut-isai") {
```

parilut-isai: iterations, fill-in limit, sparsity power

```
    auto fact_factory =
        gko::share(gko::factorization::ParIlut<>::build().on(exec));
    int sparsity_power = 1;
    if (argc >= 5) {
        fact_factory->get_parameters().iterations = std::stoi(argv[4]);
    }
    if (argc >= 6) {
        fact_factory->get_parameters().fill_in_limit = std::stod(argv[5]);
    }
    if (argc >= 7) {
        sparsity_power = std::stoi(argv[6]);
    }
    auto factory =
        gko::preconditioner::Ilu<gko::preconditioner::LowerIsai<>,
            gko::preconditioner::UpperIsai<>>::build()
        .with_factorization_factory(fact_factory)
        .with_l_solver_factory(gko::preconditioner::LowerIsai<>::build()
            .with_sparsity_power(sparsity_power)
            .on(exec))
        .with_u_solver_factory(gko::preconditioner::UpperIsai<>::build()
            .with_sparsity_power(sparsity_power)
            .on(exec))
        .on(exec);
    auto ilu_isai = try_generate([&] { return factory->generate(mtx); });
    output(ilu_isai->get_l_solver()->get_approximate_inverse().get(),
        matrix + ".parilut-isai" + output_suffix + "-l");
    output(ilu_isai->get_u_solver()->get_approximate_inverse().get(),
        matrix + ".parilut-isai" + output_suffix + "-u");
}
}
```

Results

This is the expected output:

```
Usage: ./preconditioner-export <reference|omp|cuda|hip|dpcpp> [<matrix-file>]
        [<jacobi|ilu|parilu|parilut|ilu-isai|parilu-isai|parilut-isai>] [<preconditioner args>]
Jacobi parameters: [<max-block-size>] [<accuracy>] [<storage-optimization:auto|0|1|2>]
ParILU parameters: [<iteration-count>]
ParILUT parameters: [<iteration-count>] [<fill-in-limit>]
ILU-ISAI parameters: [<sparsity-power>]
ParILU-ISAI parameters: [<iteration-count>] [<sparsity-power>]
ParILUT-ISAI parameters: [<iteration-count>] [<fill-in-limit>] [<sparsity-power>]
```

When specifying an executor:

```
Reading data/A.mtx
Writing data/A.mtx.jacobi
```

Comments about programming and debugging

The plain program

```
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```

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```

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(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 <fstream>
#include <functional>
#include <iostream>
#include <map>
#include <memory>
#include <string>
const std::map<std::string, std::function<std::shared_ptr<gko::Executor>()>>
    executors{{"reference", [] { return gko::ReferenceExecutor::create(); }},
              {"omp", [] { return gko::OmpExecutor::create(); }},
              {"cuda",
               [] {
                   return gko::CudaExecutor::create(
                       0, gko::ReferenceExecutor::create());
               }},
              {"hip",
               [] {
                   return gko::HipExecutor::create(
                       0, gko::ReferenceExecutor::create());
               }},
              {"dpcpp", [] {
                   return gko::DpcppExecutor::create(
                       0, gko::ReferenceExecutor::create());
               }}}};
void output(const gko::WritableToMatrixData<double, int> *mtx, std::string name)
{
    std::ofstream stream(name);
    std::cerr << "Writing " << name << std::endl;
    gko::write(stream, mtx, gko::layout_type::coordinate);
}
template <typename Function>
auto try_generate(Function fun) -> decltype(fun())
{
    decltype(fun()) result;
    try {
        result = fun();
    } catch (const gko::Error &err) {
        std::cerr << "Error: " << err.what() << '\n';
        std::exit(-1);
    }
    return result;
}
int main(int argc, char *argv[])
{
    if (argc < 2 || executors.find(argv[1]) == executors.end()) {
        std::cerr << "Usage: executable"
                  << " <reference|omp|cuda|hip|dpcpp> [<matrix-file>] "
                  << "[<jacobi|ilu|parilu|parilut|ilu-isai|parilu-isai|parilut-"
                  << "isai> [<preconditioner args>]\n";
        std::cerr << "Jacobi parameters: [<max-block-size>] [<accuracy>] "
                  << "[<storage-optimization:auto|0|1|2>]\n";
        std::cerr << "ParILU parameters: [<iteration-count>]\n";
        std::cerr
            << "ParILUT parameters: [<iteration-count>] [<fill-in-limit>]\n";
        std::cerr << "ILU-ISAI parameters: [<sparsity-power>]\n";
        std::cerr << "ParILU-ISAI parameters: [<iteration-count>] "
                  << "[<sparsity-power>]\n";
        std::cerr << "ParILUT-ISAI parameters: [<iteration-count>] "
                  << "[<fill-in-limit>] [<sparsity-power>]\n";
        return -1;
    }
    auto exec = try_generate([&] { return executors.at(argv[1])(); });
    std::string matrix = argc < 3 ? "data/A.mtx" : argv[2];
    std::string precondition = argc < 4 ? "jacobi" : argv[3];
    auto mtx = gko::share(try_generate([&] {
        std::ifstream mtx_stream(matrix);
        if (!mtx_stream) {
            throw GKO_STREAM_ERROR("Unable to open matrix file");
        }
        std::cerr << "Reading " << matrix << std::endl;
        return gko::read<gko::matrix::Csr>(mtx_stream, exec);
    }));
    std::string output_suffix;
    for (auto i = 4; i < argc; ++i) {
        output_suffix = output_suffix + "-" + argv[i];
    }
}

```

```

}
if (precond == "jacobi") {
    auto factory = gko::preconditioner::Jacobi<>::build().on(exec);
    if (argc >= 5) {
        factory->get_parameters().max_block_size = std::stoi(argv[4]);
    }
    if (argc >= 6) {
        factory->get_parameters().accuracy = std::stod(argv[5]);
    }
    if (argc >= 7) {
        factory->get_parameters().storage_optimization =
            std::string(argv[6]) == "auto"
            ? gko::precision_reduction::autodetect()
            : gko::precision_reduction(0, std::stoi(argv[6]));
    }
    auto jacobi = try_generate([&] { return factory->generate(mtx); });
    output(jacobi.get(), matrix + ".jacobi" + output_suffix);
} else if (precond == "ilu") {
    auto ilu = gko::as<gko::Composition<>(>(try_generate([&] {
        return gko::factorization::Ilu<>::build().on(exec)->generate(mtx);
    })));
    output(gko::as<gko::matrix::Csr<>(>(ilu->get_operators()[0].get()),
        matrix + ".ilu-l");
    output(gko::as<gko::matrix::Csr<>(>(ilu->get_operators()[1].get()),
        matrix + ".ilu-u");
} else if (precond == "parilu") {
    auto factory = gko::factorization::ParIlu<>::build().on(exec);
    if (argc >= 5) {
        factory->get_parameters().iterations = std::stoi(argv[4]);
    }
    auto ilu = gko::as<gko::Composition<>(>(
        try_generate([&] { return factory->generate(mtx); })));
    output(gko::as<gko::matrix::Csr<>(>(ilu->get_operators()[0].get()),
        matrix + ".parilu" + output_suffix + "-l");
    output(gko::as<gko::matrix::Csr<>(>(ilu->get_operators()[1].get()),
        matrix + ".parilu" + output_suffix + "-u");
} else if (precond == "parilut") {
    auto factory = gko::factorization::ParIlu<>::build().on(exec);
    if (argc >= 5) {
        factory->get_parameters().iterations = std::stoi(argv[4]);
    }
    if (argc >= 6) {
        factory->get_parameters().fill_in_limit = std::stod(argv[5]);
    }
    auto ilut = gko::as<gko::Composition<>(>(
        try_generate([&] { return factory->generate(mtx); })));
    output(gko::as<gko::matrix::Csr<>(>(ilut->get_operators()[0].get()),
        matrix + ".parilut" + output_suffix + "-l");
    output(gko::as<gko::matrix::Csr<>(>(ilut->get_operators()[1].get()),
        matrix + ".parilut" + output_suffix + "-u");
} else if (precond == "ilu-isai") {
    auto fact_factory =
        gko::share(gko::factorization::Ilu<>::build().on(exec));
    int sparsity_power = 1;
    if (argc >= 5) {
        sparsity_power = std::stoi(argv[4]);
    }
    auto factory =
        gko::preconditioner::Ilu<gko::preconditioner::LowerIsai<>,
            gko::preconditioner::UpperIsai<>::build()
            .with_factorization_factory(fact_factory)
            .with_l_solver_factory(gko::preconditioner::LowerIsai<>::build()
                .with_sparsity_power(sparsity_power)
                .on(exec))
            .with_u_solver_factory(gko::preconditioner::UpperIsai<>::build()
                .with_sparsity_power(sparsity_power)
                .on(exec))
            .on(exec);
    auto ilu_isai = try_generate([&] { return factory->generate(mtx); });
    output(ilu_isai->get_l_solver()->get_approximate_inverse().get(),
        matrix + ".ilu-isai" + output_suffix + "-l");
    output(ilu_isai->get_u_solver()->get_approximate_inverse().get(),
        matrix + ".ilu-isai" + output_suffix + "-u");
} else if (precond == "parilu-isai") {
    auto fact_factory =
        gko::share(gko::factorization::ParIlu<>::build().on(exec));
    int sparsity_power = 1;
    if (argc >= 5) {
        fact_factory->get_parameters().iterations = std::stoi(argv[4]);
    }
    if (argc >= 6) {
        sparsity_power = std::stoi(argv[5]);
    }
    auto factory =
        gko::preconditioner::Ilu<gko::preconditioner::LowerIsai<>,
            gko::preconditioner::UpperIsai<>::build()
            .with_factorization_factory(fact_factory)

```

```

        .with_l_solver_factory(gko::preconditioner::LowerIsai<>::build()
                               .with_sparsity_power(sparsity_power)
                               .on(exec))
        .with_u_solver_factory(gko::preconditioner::UpperIsai<>::build()
                               .with_sparsity_power(sparsity_power)
                               .on(exec))
        .on(exec);
    auto ilu_isai = try_generate([&] { return factory->generate(mtx); });
    output(ilu_isai->get_l_solver()->get_approximate_inverse().get(),
           matrix + ".parilu-isai" + output_suffix + "-l");
    output(ilu_isai->get_u_solver()->get_approximate_inverse().get(),
           matrix + ".parilu-isai" + output_suffix + "-u");
} else if (precond == "parilut-isai") {
    auto fact_factory =
        gko::share(gko::factorization::ParIlut<>::build().on(exec));
    int sparsity_power = 1;
    if (argc >= 5) {
        fact_factory->get_parameters().iterations = std::stoi(argv[4]);
    }
    if (argc >= 6) {
        fact_factory->get_parameters().fill_in_limit = std::stod(argv[5]);
    }
    if (argc >= 7) {
        sparsity_power = std::stoi(argv[6]);
    }
    auto factory =
        gko::preconditioner::Ilut<gko::preconditioner::LowerIsai<>,
                               gko::preconditioner::UpperIsai<>>::build()
        .with_factorization_factory(fact_factory)
        .with_l_solver_factory(gko::preconditioner::LowerIsai<>::build()
                               .with_sparsity_power(sparsity_power)
                               .on(exec))
        .with_u_solver_factory(gko::preconditioner::UpperIsai<>::build()
                               .with_sparsity_power(sparsity_power)
                               .on(exec))
        .on(exec);
    auto ilu_isai = try_generate([&] { return factory->generate(mtx); });
    output(ilu_isai->get_l_solver()->get_approximate_inverse().get(),
           matrix + ".parilut-isai" + output_suffix + "-l");
    output(ilu_isai->get_u_solver()->get_approximate_inverse().get(),
           matrix + ".parilut-isai" + output_suffix + "-u");
}
}

```


Chapter 30

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 STL map header for the executor selection

```
#include <map>
```

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 now a natural extension of adding columns/rows are necessary.

```
using ValueType = double;
using RealValueType = gko::remove_complex<ValueType>;
using IndexType = int;
using vec = gko::matrix::Dense<ValueType>;
using real_vec = gko::matrix::Dense<RealValueType>;
```

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<ValueType, IndexType>;
```

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

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

Print the ginkgo version information.

```
std::cout << gko::version_info::get() << std::endl;
if (argc == 2 && (std::string(argv[1]) == "--help")) {
    std::cerr << "Usage: " << argv[0] << " [executor] " << std::endl;
    std::exit(-1);
}
```

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.

```
const auto executor_string = argc >= 2 ? argv[1] : "reference";
std::map<std::string, std::function<std::shared_ptr<gko::Executor>()>>
exec_map{
    {"omp", [] { return gko::OmpExecutor::create(); }},
    {"cuda",
     [] {
         return gko::CudaExecutor::create(0, gko::OmpExecutor::create(),
                                           true);
     }},
    {"hip",
     [] {
         return gko::HipExecutor::create(0, gko::OmpExecutor::create(),
                                           true);
     }},
    {"dpcpp",
     [] {
         return gko::DpcppExecutor::create(0,
                                           gko::OmpExecutor::create());
     }},
    {"reference", [] { return gko::ReferenceExecutor::create(); }}}
```

executor where Ginkgo will perform the computation

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

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-7. 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.

```
const RealValueType reduction_factor{1e-7};
auto solver_gen =
    cg::build()
        .with_criteria(
            gko::stop::Iteration::build().with_max_iters(20u).on(exec),
            gko::stop::ResidualNorm<ValueType>::build()
                .with_reduction_factor(reduction_factor)
                .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<real_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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*****<GINKGO LICENSE>*****/
#include <ginkgo/ginkgo.hpp>
#include <fstream>
#include <iostream>
#include <map>
#include <string>
int main(int argc, char *argv[])
{
    using ValueType = double;
    using RealValueType = gko::remove_complex<ValueType>;
    using IndexType = int;
    using vec = gko::matrix::Dense<ValueType>;
    using real_vec = gko::matrix::Dense<RealValueType>;
    using mtx = gko::matrix::Csr<ValueType, IndexType>;
    using cg = gko::solver::Cg<ValueType>;
```

```

std::cout << gko::version_info::get() << std::endl;
if (argc == 2 && (std::string(argv[1]) == "--help")) {
    std::cerr << "Usage: " << argv[0] << " [executor] " << std::endl;
    std::exit(-1);
}
const auto executor_string = argc >= 2 ? argv[1] : "reference";
std::map<std::string, std::function<std::shared_ptr<gko::Executor>()>>
    exec_map{
        {"omp", [] { return gko::OmpExecutor::create(); }},
        {"cuda",
         [] {
             return gko::CudaExecutor::create(0, gko::OmpExecutor::create(),
                                              true);
         }},
        {"hip",
         [] {
             return gko::HipExecutor::create(0, gko::OmpExecutor::create(),
                                              true);
         }},
        {"dpcpp",
         [] {
             return gko::DpcppExecutor::create(0,
                                              gko::OmpExecutor::create());
         }},
        {"reference", [] { return gko::ReferenceExecutor::create(); }}};
const auto exec = exec_map.at(executor_string)(); // throws if not valid
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);
const RealValueType reduction_factor{1e-7};
auto solver_gen =
    cg::build()
        .with_criteria(
            gko::stop::Iteration::build().with_max_iters(20u).on(exec),
            gko::stop::ResidualNorm<ValueType>::build()
                .with_reduction_factor(reduction_factor)
                .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<real_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 31

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 <map>
#include <string>
namespace {
template <typename ValueType>
void print_vector(const std::string &name,
                 const gko::matrix::Dense<ValueType> *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 ValueType = double;
using RealValueType = gko::remove_complex<ValueType>;
using IndexType = int;
using vec = gko::matrix::Dense<ValueType>;
using real_vec = gko::matrix::Dense<RealValueType>;
using mtx = gko::matrix::Csr<ValueType, IndexType>;
using cg = gko::solver::Cg<ValueType>;
```

Print version information

```
std::cout << gko::version_info::get() << std::endl;
if (argc == 2 && (std::string(argv[1]) == "--help")) {
    std::cerr << "Usage: " << argv[0] << " [executor]" << std::endl;
    std::exit(-1);
}
```

Figure out where to run the code

```

const auto executor_string = argc >= 2 ? argv[1] : "reference";
std::map<std::string, std::function<std::shared_ptr<gko::Executor>()>>
    exec_map{
        {"omp", [] { return gko::OmpExecutor::create(); }},
        {"cuda",
         [] {
             return gko::CudaExecutor::create(0, gko::OmpExecutor::create(),
                                              true);
         }},
        {"hip",
         [] {
             return gko::HipExecutor::create(0, gko::OmpExecutor::create(),
                                              true);
         }},
        {"dpcpp",
         [] {
             return gko::DpcppExecutor::create(0,
                                              gko::OmpExecutor::create());
         }},
        {"reference", [] { return gko::ReferenceExecutor::create(); }}};

```

executor where Ginkgo will perform the computation

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

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<ValueType> stream_logger =
    gko::log::Stream<ValueType>::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 ResidualNorm criterion Factory Note that the logger will get automatically propagated to every criterion generated from this factory.

```

const RealValueType reduction_factor{1e-7};
using ResidualCriterionFactory =
    gko::stop::ResidualNorm<ValueType>::Factory;
std::shared_ptr<ResidualCriterionFactory> residual_criterion =
    ResidualCriterionFactory::create()
        .with_reduction_factor(reduction_factor)
        .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<ValueType>::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<vec>(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<real_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>,0x2142d60] with b
    LinOp[gko::matrix::Dense<double>,0x2142140] and x LinOp[gko::matrix::Dense<double>,0x2143450]
[LOG] >> allocation started on Executor[gko::ReferenceExecutor,0x21400d0] with Bytes[8]
[LOG] >> allocation completed on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2142280] with
    Bytes[8]
[LOG] >> allocation started on Executor[gko::ReferenceExecutor,0x21400d0] with Bytes[8]
[LOG] >> allocation completed on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2143410] with
    Bytes[8]
[LOG] >> allocation started on Executor[gko::ReferenceExecutor,0x21400d0] with Bytes[152]
[LOG] >> allocation completed on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x21480a0] with
    Bytes[152]
[LOG] >> allocation started on Executor[gko::ReferenceExecutor,0x21400d0] with Bytes[152]
[LOG] >> allocation completed on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x21482f0] with
    Bytes[152]
[LOG] >> allocation started on Executor[gko::ReferenceExecutor,0x21400d0] with Bytes[152]
[LOG] >> allocation completed on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x21484d0] with
    Bytes[152]
[LOG] >> allocation started on Executor[gko::ReferenceExecutor,0x21400d0] with Bytes[152]
[LOG] >> allocation completed on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x21486b0] with
    Bytes[152]
[LOG] >> allocation started on Executor[gko::ReferenceExecutor,0x21400d0] with Bytes[8]
[LOG] >> allocation completed on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2148010] with
    Bytes[8]
[LOG] >> allocation started on Executor[gko::ReferenceExecutor,0x21400d0] with Bytes[8]
[LOG] >> allocation completed on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2148a60] with
    Bytes[8]
[LOG] >> allocation started on Executor[gko::ReferenceExecutor,0x21400d0] with Bytes[8]
[LOG] >> allocation completed on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x21482b0] with
    Bytes[8]
[LOG] >> allocation started on Executor[gko::ReferenceExecutor,0x21400d0] with Bytes[8]
[LOG] >> allocation completed on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2148a40] with
    Bytes[8]
[LOG] >> allocation started on Executor[gko::ReferenceExecutor,0x21400d0] with Bytes[1]
[LOG] >> allocation completed on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2147c90] 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>*>,0x7ffd93d14ef0] started on
    Executor[gko::ReferenceExecutor,0x21400d0]
```

```

[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>*>,0x7ffd93d14ef0] completed on
Executor[gko::ReferenceExecutor,0x21400d0]
[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>*>,0x7ffd93d14aa0] started on
Executor[gko::ReferenceExecutor,0x21400d0]
[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>*>,0x7ffd93d14aa0] completed on
Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> allocation started on Executor[gko::ReferenceExecutor,0x21400d0] with Bytes[2]
[LOG] >> allocation completed on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2148ee0] with
Bytes[2]
[LOG] >> allocation started on Executor[gko::ReferenceExecutor,0x21400d0] with Bytes[8]
[LOG] >> allocation completed on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2148e50] with
Bytes[8]
[LOG] >> allocation started on Executor[gko::ReferenceExecutor,0x21400d0] with Bytes[8]
[LOG] >> allocation completed on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2147ce0] with
Bytes[8]
[LOG] >> Operation[gko::matrix::dense::compute_norm2_operation<gko::matrix::Dense<double> const*,
gko::matrix::Dense<double>*>,0x7ffd93d14a20] started on Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::matrix::dense::compute_norm2_operation<gko::matrix::Dense<double> const*,
gko::matrix::Dense<double>*>,0x7ffd93d14a20] completed on Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> copy started from Executor[gko::ReferenceExecutor,0x21400d0] to
Executor[gko::ReferenceExecutor,0x21400d0] from Location[0x21480a0] to Location[0x21482f0] with
Bytes[152]
[LOG] >> copy completed from Executor[gko::ReferenceExecutor,0x21400d0] to
Executor[gko::ReferenceExecutor,0x21400d0] from Location[0x21480a0] to Location[0x21482f0] 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>*>,0x7ffd93d14c50] started on
Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::matrix::dense::compute_dot_operation<gko::matrix::Dense<double> const*,
gko::matrix::Dense<double> const*, gko::matrix::Dense<double>*>,0x7ffd93d14c50] completed on
Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> iteration 0 completed with solver LinOp[gko::solver::Cg<double>,0x2142d60] with residual
LinOp[gko::matrix::Dense<double>,0x2147b30], solution LinOp[gko::matrix::Dense<double>,0x2143450] and
residual_norm LinOp[gko::LinOp const*,0]
[LOG] >> check started for stop::Criterion[gko::stop::ResidualNorm<double>,0x2148db0] 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>*>,0x7ffd93d14ad0] started on Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::matrix::dense::compute_norm2_operation<gko::matrix::Dense<double> const*,
gko::matrix::Dense<double>*>,0x7ffd93d14ad0] completed on Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::stop::residual_norm::residual_norm_operation<gko::matrix::Dense<double> const*&,
gko::matrix::Dense<double>*, double&, unsigned char&, bool&, gko::Array<gko::stopping_status>*&,
gko::Array<bool>*, bool*, bool*>,0x7ffd93d14b90] started on
Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::stop::residual_norm::residual_norm_operation<gko::matrix::Dense<double> const*&,
gko::matrix::Dense<double>*, double&, unsigned char&, bool&, gko::Array<gko::stopping_status>*&,
gko::Array<bool>*, bool*, bool*>,0x7ffd93d14b90] completed on
Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> check completed for stop::Criterion[gko::stop::ResidualNorm<double>,0x2148db0] 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,0x21400d0] with Bytes[152]
[LOG] >> allocation completed on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2149550] with
Bytes[152]
[LOG] >> copy started from Executor[gko::ReferenceExecutor,0x21400d0] to
Executor[gko::ReferenceExecutor,0x21400d0] from Location[0x21480a0] to Location[0x2149550] with
Bytes[152]
[LOG] >> copy completed from Executor[gko::ReferenceExecutor,0x21400d0] to
Executor[gko::ReferenceExecutor,0x21400d0] from Location[0x21480a0] to Location[0x2149550] with
Bytes[152]
[LOG] >> allocation started on Executor[gko::ReferenceExecutor,0x21400d0] with Bytes[152]
[LOG] >> allocation completed on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2149730] with
Bytes[152]
[LOG] >> copy started from Executor[gko::ReferenceExecutor,0x21400d0] to
Executor[gko::ReferenceExecutor,0x21400d0] from Location[0x2143e90] to Location[0x2149730] with
Bytes[152]
[LOG] >> copy completed from Executor[gko::ReferenceExecutor,0x21400d0] to
Executor[gko::ReferenceExecutor,0x21400d0] from Location[0x2143e90] to Location[0x2149730] with
Bytes[152]
[LOG] >> Operation[gko::solver::cg::step_1_operation<gko::matrix::Dense<double>*,
gko::matrix::Dense<double>*, gko::matrix::Dense<double>*, gko::matrix::Dense<double>*,
gko::Array<gko::stopping_status>*>,0x7ffd93d14ef0] started on
Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::solver::cg::step_1_operation<gko::matrix::Dense<double>*,
gko::matrix::Dense<double>*, gko::matrix::Dense<double>*, gko::matrix::Dense<double>*,
gko::Array<gko::stopping_status>*>,0x7ffd93d14ef0] completed on
Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::matrix::csr::spmv_operation<gko::matrix::Csr<double, int> const*,
gko::matrix::Dense<double> const*, gko::matrix::Dense<double>*>,0x7ffd93d14b80] started on
Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::matrix::csr::spmv_operation<gko::matrix::Csr<double, int> const*,

```

```

gko::matrix::Dense<double> const*, gko::matrix::Dense<double>*>,0x7ffd93d14b80] completed on
Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::matrix::dense::compute_dot_operation<gko::matrix::Dense<double> const*,
gko::matrix::Dense<double> const*, gko::matrix::Dense<double>*>,0x7ffd93d14c50] started on
Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::matrix::dense::compute_dot_operation<gko::matrix::Dense<double> const*,
gko::matrix::Dense<double> const*, gko::matrix::Dense<double>*>,0x7ffd93d14c50] completed on
Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::solver::cg::step_2_operation<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>*>,0x7ffd93d14ef0] started on
Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::solver::cg::step_2_operation<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>*>,0x7ffd93d14ef0] completed on
Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> copy started from Executor[gko::ReferenceExecutor,0x21400d0] to
Executor[gko::ReferenceExecutor,0x21400d0] from Location[0x21480a0] to Location[0x21482f0] with
Bytes[152]
[LOG] >> copy completed from Executor[gko::ReferenceExecutor,0x21400d0] to
Executor[gko::ReferenceExecutor,0x21400d0] from Location[0x21480a0] to Location[0x21482f0] 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>*>,0x7ffd93d14c50] started on
Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::matrix::dense::compute_dot_operation<gko::matrix::Dense<double> const*,
gko::matrix::Dense<double> const*, gko::matrix::Dense<double>*>,0x7ffd93d14c50] completed on
Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> iteration 1 completed with solver LinOp[gko::solver::Cg<double>,0x2142d60] with residual
LinOp[gko::matrix::Dense<double>,0x2147b30], solution LinOp[gko::matrix::Dense<double>,0x2143450] and
residual_norm LinOp[gko::LinOp const*,0]
[LOG] >> check started for stop::Criterion[gko::stop::ResidualNorm<double>,0x2148db0] at iteration 1 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>*>,0x7ffd93d14ad0] started on Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::matrix::dense::compute_norm2_operation<gko::matrix::Dense<double> const*,
gko::matrix::Dense<double>*>,0x7ffd93d14ad0] completed on Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::stop::residual_norm::residual_norm_operation<gko::matrix::Dense<double> const*&,
gko::matrix::Dense<double>*, double&, unsigned char&, bool&, gko::Array<gko::stopping_status>*&,
gko::Array<bool>*, bool*, bool*&>,0x7ffd93d14b90] started on
Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::stop::residual_norm::residual_norm_operation<gko::matrix::Dense<double> const*&,
gko::matrix::Dense<double>*, double&, unsigned char&, bool&, gko::Array<gko::stopping_status>*&,
gko::Array<bool>*, bool*, bool*&>,0x7ffd93d14b90] completed on
Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> check completed for stop::Criterion[gko::stop::ResidualNorm<double>,0x2148db0] at iteration 1 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,0x21400d0] with Bytes[152]
[LOG] >> allocation completed on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2149980] with
Bytes[152]
[LOG] >> copy started from Executor[gko::ReferenceExecutor,0x21400d0] to
Executor[gko::ReferenceExecutor,0x21400d0] from Location[0x21480a0] to Location[0x2149980] with
Bytes[152]
[LOG] >> copy completed from Executor[gko::ReferenceExecutor,0x21400d0] to
Executor[gko::ReferenceExecutor,0x21400d0] from Location[0x21480a0] to Location[0x2149980] with
Bytes[152]
[LOG] >> allocation started on Executor[gko::ReferenceExecutor,0x21400d0] with Bytes[152]
[LOG] >> allocation completed on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2149b80] with
Bytes[152]
[LOG] >> copy started from Executor[gko::ReferenceExecutor,0x21400d0] to
Executor[gko::ReferenceExecutor,0x21400d0] from Location[0x2143e90] to Location[0x2149b80] with
Bytes[152]
[LOG] >> copy completed from Executor[gko::ReferenceExecutor,0x21400d0] to
Executor[gko::ReferenceExecutor,0x21400d0] from Location[0x2143e90] to Location[0x2149b80] with
Bytes[152]
[LOG] >> free started on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2149730]
[LOG] >> free completed on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2149730]
[LOG] >> free started on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2149550]
[LOG] >> free completed on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2149550]
[LOG] >> Operation[gko::solver::cg::step_1_operation<gko::matrix::Dense<double>*>,
gko::matrix::Dense<double>*, gko::matrix::Dense<double>*, gko::matrix::Dense<double>*,
gko::Array<gko::stopping_status>*>,0x7ffd93d14ef0] started on
Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::solver::cg::step_1_operation<gko::matrix::Dense<double>*>,
gko::matrix::Dense<double>*, gko::matrix::Dense<double>*, gko::matrix::Dense<double>*,
gko::Array<gko::stopping_status>*>,0x7ffd93d14ef0] completed on
Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::matrix::csr::spmv_operation<gko::matrix::Csr<double, int> const*,
gko::matrix::Dense<double> const*, gko::matrix::Dense<double>*>,0x7ffd93d14b80] started on
Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::matrix::csr::spmv_operation<gko::matrix::Csr<double, int> const*,
gko::matrix::Dense<double> const*, gko::matrix::Dense<double>*>,0x7ffd93d14b80] completed on
Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::matrix::dense::compute_dot_operation<gko::matrix::Dense<double> const*,
gko::matrix::Dense<double> const*, gko::matrix::Dense<double>*>,0x7ffd93d14c50] started on

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    Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::matrix::dense::compute_dot_operation<gko::matrix::Dense<double> const*,
    gko::matrix::Dense<double> const*, gko::matrix::Dense<double>*>,0x7ffd93d14c50] completed on
    Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::solver::cg::step_2_operation<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>*>,0x7ffd93d14ef0] started on
    Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::solver::cg::step_2_operation<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>*>,0x7ffd93d14ef0] completed on
    Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> copy started from Executor[gko::ReferenceExecutor,0x21400d0] to
    Executor[gko::ReferenceExecutor,0x21400d0] from Location[0x21480a0] to Location[0x21482f0] with
    Bytes[152]
[LOG] >> copy completed from Executor[gko::ReferenceExecutor,0x21400d0] to
    Executor[gko::ReferenceExecutor,0x21400d0] from Location[0x21480a0] to Location[0x21482f0] 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>*>,0x7ffd93d14c50] started on
    Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::matrix::dense::compute_dot_operation<gko::matrix::Dense<double> const*,
    gko::matrix::Dense<double> const*, gko::matrix::Dense<double>*>,0x7ffd93d14c50] completed on
    Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> iteration 2 completed with solver LinOp[gko::solver::Cg<double>,0x2142d60] with residual
    LinOp[gko::matrix::Dense<double>,0x2147b30], solution LinOp[gko::matrix::Dense<double>,0x2143450] and
    residual_norm LinOp[gko::LinOp const*,0]
[LOG] >> check started for stop::Criterion[gko::stop::ResidualNorm<double>,0x2148db0] at iteration 2 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>*>,0x7ffd93d14ad0] started on Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::matrix::dense::compute_norm2_operation<gko::matrix::Dense<double> const*,
    gko::matrix::Dense<double>*>,0x7ffd93d14ad0] completed on Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::stop::residual_norm::residual_norm_operation<gko::matrix::Dense<double> const*&,
    gko::matrix::Dense<double>*, double&, unsigned char&, bool&, gko::Array<gko::stopping_status>*&,
    gko::Array<bool>*, bool*, bool*>,0x7ffd93d14b90] started on
    Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::stop::residual_norm::residual_norm_operation<gko::matrix::Dense<double> const*&,
    gko::matrix::Dense<double>*, double&, unsigned char&, bool&, gko::Array<gko::stopping_status>*&,
    gko::Array<bool>*, bool*, bool*>,0x7ffd93d14b90] completed on
    Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> check completed for stop::Criterion[gko::stop::ResidualNorm<double>,0x2148db0] at iteration 2 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,0x21400d0] with Bytes[152]
[LOG] >> allocation completed on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2149290] with
    Bytes[152]
[LOG] >> copy started from Executor[gko::ReferenceExecutor,0x21400d0] to
    Executor[gko::ReferenceExecutor,0x21400d0] from Location[0x21480a0] to Location[0x2149290] with
    Bytes[152]
[LOG] >> copy completed from Executor[gko::ReferenceExecutor,0x21400d0] to
    Executor[gko::ReferenceExecutor,0x21400d0] from Location[0x21480a0] to Location[0x2149290] with
    Bytes[152]
[LOG] >> allocation started on Executor[gko::ReferenceExecutor,0x21400d0] with Bytes[152]
[LOG] >> allocation completed on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2149690] with
    Bytes[152]
[LOG] >> copy started from Executor[gko::ReferenceExecutor,0x21400d0] to
    Executor[gko::ReferenceExecutor,0x21400d0] from Location[0x2143e90] to Location[0x2149690] with
    Bytes[152]
[LOG] >> copy completed from Executor[gko::ReferenceExecutor,0x21400d0] to
    Executor[gko::ReferenceExecutor,0x21400d0] from Location[0x2143e90] to Location[0x2149690] with
    Bytes[152]
[LOG] >> free started on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2149b80]
[LOG] >> free completed on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2149b80]
[LOG] >> free started on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2149980]
[LOG] >> free completed on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2149980]
[LOG] >> Operation[gko::solver::cg::step_1_operation<gko::matrix::Dense<double>*,
    gko::matrix::Dense<double>*, gko::matrix::Dense<double>*, gko::matrix::Dense<double>*,
    gko::Array<gko::stopping_status>*>,0x7ffd93d14ef0] started on
    Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::solver::cg::step_1_operation<gko::matrix::Dense<double>*,
    gko::matrix::Dense<double>*, gko::matrix::Dense<double>*, gko::matrix::Dense<double>*,
    gko::Array<gko::stopping_status>*>,0x7ffd93d14ef0] completed on
    Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::matrix::csr::spmv_operation<gko::matrix::Csr<double, int> const*,
    gko::matrix::Dense<double> const*, gko::matrix::Dense<double>*>,0x7ffd93d14b80] started on
    Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::matrix::csr::spmv_operation<gko::matrix::Csr<double, int> const*,
    gko::matrix::Dense<double> const*, gko::matrix::Dense<double>*>,0x7ffd93d14b80] completed on
    Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::matrix::dense::compute_dot_operation<gko::matrix::Dense<double> const*,
    gko::matrix::Dense<double> const*, gko::matrix::Dense<double>*>,0x7ffd93d14c50] started on
    Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::matrix::dense::compute_dot_operation<gko::matrix::Dense<double> const*,
    gko::matrix::Dense<double> const*, gko::matrix::Dense<double>*>,0x7ffd93d14c50] completed on
    Executor[gko::ReferenceExecutor,0x21400d0]

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[LOG] >> Operation[gko::solver::cg::step_2_operation<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>*],0x7ffd93d14ef0] started on
Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::solver::cg::step_2_operation<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>*],0x7ffd93d14ef0] completed on
Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> copy started from Executor[gko::ReferenceExecutor,0x21400d0] to
Executor[gko::ReferenceExecutor,0x21400d0] from Location[0x21480a0] to Location[0x21482f0] with
Bytes[152]
[LOG] >> copy completed from Executor[gko::ReferenceExecutor,0x21400d0] to
Executor[gko::ReferenceExecutor,0x21400d0] from Location[0x21480a0] to Location[0x21482f0] 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>*>],0x7ffd93d14c50] started on
Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::matrix::dense::compute_dot_operation<gko::matrix::Dense<double> const*,
gko::matrix::Dense<double> const*, gko::matrix::Dense<double>*>],0x7ffd93d14c50] completed on
Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> iteration 3 completed with solver LinOp[gko::solver::Cg<double>],0x2142d60] with residual
LinOp[gko::matrix::Dense<double>],0x2147b30], solution LinOp[gko::matrix::Dense<double>],0x2143450] and
residual_norm LinOp[gko::LinOp const*,0]
[LOG] >> check started for stop::Criterion[gko::stop::ResidualNorm<double>],0x2148db0] at iteration 3 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>*>],0x7ffd93d14ad0] started on Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::matrix::dense::compute_norm2_operation<gko::matrix::Dense<double> const*,
gko::matrix::Dense<double>*>],0x7ffd93d14ad0] completed on Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::stop::residual_norm::residual_norm_operation<gko::matrix::Dense<double> const*&,
gko::matrix::Dense<double>*, double&, unsigned char&, bool&, gko::Array<gko::stopping_status>*&,
gko::Array<bool>*, bool*, bool*>],0x7ffd93d14b90] started on
Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::stop::residual_norm::residual_norm_operation<gko::matrix::Dense<double> const*&,
gko::matrix::Dense<double>*, double&, unsigned char&, bool&, gko::Array<gko::stopping_status>*&,
gko::Array<bool>*, bool*, bool*>],0x7ffd93d14b90] completed on
Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> check completed for stop::Criterion[gko::stop::ResidualNorm<double>],0x2148db0] at iteration 3 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,0x21400d0] with Bytes[152]
[LOG] >> allocation completed on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2149890] with
Bytes[152]
[LOG] >> copy started from Executor[gko::ReferenceExecutor,0x21400d0] to
Executor[gko::ReferenceExecutor,0x21400d0] from Location[0x21480a0] to Location[0x2149890] with
Bytes[152]
[LOG] >> copy completed from Executor[gko::ReferenceExecutor,0x21400d0] to
Executor[gko::ReferenceExecutor,0x21400d0] from Location[0x21480a0] to Location[0x2149890] with
Bytes[152]
[LOG] >> allocation started on Executor[gko::ReferenceExecutor,0x21400d0] with Bytes[152]
[LOG] >> allocation completed on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2149ae0] with
Bytes[152]
[LOG] >> copy started from Executor[gko::ReferenceExecutor,0x21400d0] to
Executor[gko::ReferenceExecutor,0x21400d0] from Location[0x2143e90] to Location[0x2149ae0] with
Bytes[152]
[LOG] >> copy completed from Executor[gko::ReferenceExecutor,0x21400d0] to
Executor[gko::ReferenceExecutor,0x21400d0] from Location[0x2143e90] to Location[0x2149ae0] with
Bytes[152]
[LOG] >> free started on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2149690]
[LOG] >> free completed on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2149690]
[LOG] >> free started on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2149290]
[LOG] >> free completed on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2149290]
[LOG] >> Operation[gko::solver::cg::step_1_operation<gko::matrix::Dense<double>*,
gko::matrix::Dense<double>*, gko::matrix::Dense<double>*, gko::matrix::Dense<double>*,
gko::Array<gko::stopping_status>*],0x7ffd93d14ef0] started on
Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::solver::cg::step_1_operation<gko::matrix::Dense<double>*,
gko::matrix::Dense<double>*, gko::matrix::Dense<double>*, gko::matrix::Dense<double>*,
gko::Array<gko::stopping_status>*],0x7ffd93d14ef0] completed on
Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::matrix::csr::spmv_operation<gko::matrix::Csr<double, int> const*,
gko::matrix::Dense<double> const*, gko::matrix::Dense<double>*>],0x7ffd93d14b80] started on
Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::matrix::csr::spmv_operation<gko::matrix::Csr<double, int> const*,
gko::matrix::Dense<double> const*, gko::matrix::Dense<double>*>],0x7ffd93d14b80] completed on
Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::matrix::dense::compute_dot_operation<gko::matrix::Dense<double> const*,
gko::matrix::Dense<double> const*, gko::matrix::Dense<double>*>],0x7ffd93d14c50] started on
Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::matrix::dense::compute_dot_operation<gko::matrix::Dense<double> const*,
gko::matrix::Dense<double> const*, gko::matrix::Dense<double>*>],0x7ffd93d14c50] completed on
Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::solver::cg::step_2_operation<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>*],0x7ffd93d14ef0] started on

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    Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::solver::cg::step_2_operation<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>*>,0x7ffd93d14ef0] completed on
    Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> copy started from Executor[gko::ReferenceExecutor,0x21400d0] to
    Executor[gko::ReferenceExecutor,0x21400d0] from Location[0x21480a0] to Location[0x21482f0] with
    Bytes[152]
[LOG] >> copy completed from Executor[gko::ReferenceExecutor,0x21400d0] to
    Executor[gko::ReferenceExecutor,0x21400d0] from Location[0x21480a0] to Location[0x21482f0] 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>*>,0x7ffd93d14c50] started on
    Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::matrix::dense::compute_dot_operation<gko::matrix::Dense<double> const*,
    gko::matrix::Dense<double> const*, gko::matrix::Dense<double>*>,0x7ffd93d14c50] completed on
    Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> iteration 4 completed with solver LinOp[gko::solver::Cg<double>,0x2142d60] with residual
    LinOp[gko::matrix::Dense<double>,0x2147b30], solution LinOp[gko::matrix::Dense<double>,0x2143450] and
    residual_norm LinOp[gko::LinOp const*,0]
[LOG] >> check started for stop::Criterion[gko::stop::ResidualNorm<double>,0x2148db0] at iteration 4 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>*>,0x7ffd93d14ad0] started on Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::matrix::dense::compute_norm2_operation<gko::matrix::Dense<double> const*,
    gko::matrix::Dense<double>*>,0x7ffd93d14ad0] completed on Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::stop::residual_norm::residual_norm_operation<gko::matrix::Dense<double> const*&,
    gko::matrix::Dense<double>*, double&, unsigned char&, bool&, gko::Array<gko::stopping_status>*&,
    gko::Array<bool>**, bool*, bool*&>,0x7ffd93d14b90] started on
    Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::stop::residual_norm::residual_norm_operation<gko::matrix::Dense<double> const*&,
    gko::matrix::Dense<double>*, double&, unsigned char&, bool&, gko::Array<gko::stopping_status>*&,
    gko::Array<bool>**, bool*, bool*&>,0x7ffd93d14b90] completed on
    Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> check completed for stop::Criterion[gko::stop::ResidualNorm<double>,0x2148db0] at iteration 4 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,0x21400d0] with Bytes[152]
[LOG] >> allocation completed on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2149200] with
    Bytes[152]
[LOG] >> copy started from Executor[gko::ReferenceExecutor,0x21400d0] to
    Executor[gko::ReferenceExecutor,0x21400d0] from Location[0x21480a0] to Location[0x2149200] with
    Bytes[152]
[LOG] >> copy completed from Executor[gko::ReferenceExecutor,0x21400d0] to
    Executor[gko::ReferenceExecutor,0x21400d0] from Location[0x21480a0] to Location[0x2149200] with
    Bytes[152]
[LOG] >> allocation started on Executor[gko::ReferenceExecutor,0x21400d0] with Bytes[152]
[LOG] >> allocation completed on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2149310] with
    Bytes[152]
[LOG] >> copy started from Executor[gko::ReferenceExecutor,0x21400d0] to
    Executor[gko::ReferenceExecutor,0x21400d0] from Location[0x2143e90] to Location[0x2149310] with
    Bytes[152]
[LOG] >> copy completed from Executor[gko::ReferenceExecutor,0x21400d0] to
    Executor[gko::ReferenceExecutor,0x21400d0] from Location[0x2143e90] to Location[0x2149310] with
    Bytes[152]
[LOG] >> free started on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2149ae0]
[LOG] >> free completed on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2149ae0]
[LOG] >> free started on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2149890]
[LOG] >> free completed on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2149890]
[LOG] >> Operation[gko::solver::cg::step_1_operation<gko::matrix::Dense<double>*&,
    gko::matrix::Dense<double>*, gko::matrix::Dense<double>*, gko::matrix::Dense<double>*,
    gko::Array<gko::stopping_status>*>,0x7ffd93d14ef0] started on
    Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::solver::cg::step_1_operation<gko::matrix::Dense<double>*&,
    gko::matrix::Dense<double>*, gko::matrix::Dense<double>*, gko::matrix::Dense<double>*,
    gko::Array<gko::stopping_status>*>,0x7ffd93d14ef0] completed on
    Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::matrix::csr::spmv_operation<gko::matrix::Csr<double, int> const*,
    gko::matrix::Dense<double> const*, gko::matrix::Dense<double>*>,0x7ffd93d14b80] started on
    Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::matrix::csr::spmv_operation<gko::matrix::Csr<double, int> const*,
    gko::matrix::Dense<double> const*, gko::matrix::Dense<double>*>,0x7ffd93d14b80] completed on
    Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::matrix::dense::compute_dot_operation<gko::matrix::Dense<double> const*,
    gko::matrix::Dense<double> const*, gko::matrix::Dense<double>*>,0x7ffd93d14c50] started on
    Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::matrix::dense::compute_dot_operation<gko::matrix::Dense<double> const*,
    gko::matrix::Dense<double> const*, gko::matrix::Dense<double>*>,0x7ffd93d14c50] completed on
    Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::solver::cg::step_2_operation<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>*>,0x7ffd93d14ef0] started on
    Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::solver::cg::step_2_operation<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>*>,0x7ffd93d14ef0] completed on
    Executor[gko::ReferenceExecutor,0x21400d0]

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gko::Array<gko::stopping_status>*>,0x7ffd93d14ef0] completed on
Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> copy started from Executor[gko::ReferenceExecutor,0x21400d0] to
Executor[gko::ReferenceExecutor,0x21400d0] from Location[0x21480a0] to Location[0x21482f0] with
Bytes[152]
[LOG] >> copy completed from Executor[gko::ReferenceExecutor,0x21400d0] to
Executor[gko::ReferenceExecutor,0x21400d0] from Location[0x21480a0] to Location[0x21482f0] 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>*>,0x7ffd93d14c50] started on
Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::matrix::dense::compute_dot_operation<gko::matrix::Dense<double> const*,
gko::matrix::Dense<double> const*, gko::matrix::Dense<double>*>,0x7ffd93d14c50] completed on
Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> iteration 5 completed with solver LinOp[gko::solver::Cg<double>,0x2142d60] with residual
LinOp[gko::matrix::Dense<double>,0x2147b30], solution LinOp[gko::matrix::Dense<double>,0x2143450] and
residual_norm LinOp[gko::LinOp const*,0]
[LOG] >> check started for stop::Criterion[gko::stop::ResidualNorm<double>,0x2148db0] at iteration 5 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>*>,0x7ffd93d14ad0] started on Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::matrix::dense::compute_norm2_operation<gko::matrix::Dense<double> const*,
gko::matrix::Dense<double>*>,0x7ffd93d14ad0] completed on Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::stop::residual_norm::residual_norm_operation<gko::matrix::Dense<double> const*&,
gko::matrix::Dense<double>*, double&, unsigned char&, bool&, gko::Array<gko::stopping_status>*&,
gko::Array<bool>*, bool*, bool*>,0x7ffd93d14b90] started on
Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::stop::residual_norm::residual_norm_operation<gko::matrix::Dense<double> const*&,
gko::matrix::Dense<double>*, double&, unsigned char&, bool&, gko::Array<gko::stopping_status>*&,
gko::Array<bool>*, bool*, bool*>,0x7ffd93d14b90] completed on
Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> check completed for stop::Criterion[gko::stop::ResidualNorm<double>,0x2148db0] at iteration 5 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,0x21400d0] with Bytes[152]
[LOG] >> allocation completed on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2149890] with
Bytes[152]
[LOG] >> copy started from Executor[gko::ReferenceExecutor,0x21400d0] to
Executor[gko::ReferenceExecutor,0x21400d0] from Location[0x21480a0] to Location[0x2149890] with
Bytes[152]
[LOG] >> copy completed from Executor[gko::ReferenceExecutor,0x21400d0] to
Executor[gko::ReferenceExecutor,0x21400d0] from Location[0x21480a0] to Location[0x2149890] with
Bytes[152]
[LOG] >> allocation started on Executor[gko::ReferenceExecutor,0x21400d0] with Bytes[152]
[LOG] >> allocation completed on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2149cc0] with
Bytes[152]
[LOG] >> copy started from Executor[gko::ReferenceExecutor,0x21400d0] to
Executor[gko::ReferenceExecutor,0x21400d0] from Location[0x2143e90] to Location[0x2149cc0] with
Bytes[152]
[LOG] >> copy completed from Executor[gko::ReferenceExecutor,0x21400d0] to
Executor[gko::ReferenceExecutor,0x21400d0] from Location[0x2143e90] to Location[0x2149cc0] with
Bytes[152]
[LOG] >> free started on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2149310]
[LOG] >> free completed on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2149310]
[LOG] >> free started on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2149200]
[LOG] >> free completed on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2149200]
[LOG] >> Operation[gko::solver::cg::step_1_operation<gko::matrix::Dense<double>*,
gko::matrix::Dense<double>*, gko::matrix::Dense<double>*, gko::matrix::Dense<double>*,
gko::Array<gko::stopping_status>*>,0x7ffd93d14ef0] started on
Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::solver::cg::step_1_operation<gko::matrix::Dense<double>*,
gko::matrix::Dense<double>*, gko::matrix::Dense<double>*, gko::matrix::Dense<double>*,
gko::Array<gko::stopping_status>*>,0x7ffd93d14ef0] completed on
Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::matrix::csr::spmv_operation<gko::matrix::Csr<double, int> const*,
gko::matrix::Dense<double> const*, gko::matrix::Dense<double>*>,0x7ffd93d14b80] started on
Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::matrix::csr::spmv_operation<gko::matrix::Csr<double, int> const*,
gko::matrix::Dense<double> const*, gko::matrix::Dense<double>*>,0x7ffd93d14b80] completed on
Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::matrix::dense::compute_dot_operation<gko::matrix::Dense<double> const*,
gko::matrix::Dense<double> const*, gko::matrix::Dense<double>*>,0x7ffd93d14c50] started on
Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::matrix::dense::compute_dot_operation<gko::matrix::Dense<double> const*,
gko::matrix::Dense<double> const*, gko::matrix::Dense<double>*>,0x7ffd93d14c50] completed on
Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::solver::cg::step_2_operation<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>*>,0x7ffd93d14ef0] started on
Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::solver::cg::step_2_operation<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>*>,0x7ffd93d14ef0] completed on
Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> copy started from Executor[gko::ReferenceExecutor,0x21400d0] to
Executor[gko::ReferenceExecutor,0x21400d0] from Location[0x21480a0] to Location[0x21482f0] with

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Bytes[152]
[LOG] >> copy completed from Executor[gko::ReferenceExecutor,0x21400d0] to
Executor[gko::ReferenceExecutor,0x21400d0] from Location[0x21480a0] to Location[0x21482f0] 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>*>,0x7ffd93d14c50] started on
Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::matrix::dense::compute_dot_operation<gko::matrix::Dense<double> const*,
gko::matrix::Dense<double> const*, gko::matrix::Dense<double>*>,0x7ffd93d14c50] completed on
Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> iteration 6 completed with solver LinOp[gko::solver::Cg<double>,0x2142d60] with residual
LinOp[gko::matrix::Dense<double>,0x2147b30], solution LinOp[gko::matrix::Dense<double>,0x2143450] and
residual_norm LinOp[gko::LinOp const*,0]
[LOG] >> check started for stop::Criterion[gko::stop::ResidualNorm<double>,0x2148db0] at iteration 6 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>*>,0x7ffd93d14ad0] started on Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::matrix::dense::compute_norm2_operation<gko::matrix::Dense<double> const*,
gko::matrix::Dense<double>*>,0x7ffd93d14ad0] completed on Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::stop::residual_norm::residual_norm_operation<gko::matrix::Dense<double> const*&,
gko::matrix::Dense<double>*, double&, unsigned char&, bool&, gko::Array<gko::stopping_status>*&,
gko::Array<bool>*, bool*, bool*>,0x7ffd93d14b90] started on
Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::stop::residual_norm::residual_norm_operation<gko::matrix::Dense<double> const*&,
gko::matrix::Dense<double>*, double&, unsigned char&, bool&, gko::Array<gko::stopping_status>*&,
gko::Array<bool>*, bool*, bool*>,0x7ffd93d14b90] completed on
Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> check completed for stop::Criterion[gko::stop::ResidualNorm<double>,0x2148db0] at iteration 6 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,0x21400d0] with Bytes[152]
[LOG] >> allocation completed on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2149450] with
Bytes[152]
[LOG] >> copy started from Executor[gko::ReferenceExecutor,0x21400d0] to
Executor[gko::ReferenceExecutor,0x21400d0] from Location[0x21480a0] to Location[0x2149450] with
Bytes[152]
[LOG] >> copy completed from Executor[gko::ReferenceExecutor,0x21400d0] to
Executor[gko::ReferenceExecutor,0x21400d0] from Location[0x21480a0] to Location[0x2149450] with
Bytes[152]
[LOG] >> allocation started on Executor[gko::ReferenceExecutor,0x21400d0] with Bytes[152]
[LOG] >> allocation completed on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x21494f0] with
Bytes[152]
[LOG] >> copy started from Executor[gko::ReferenceExecutor,0x21400d0] to
Executor[gko::ReferenceExecutor,0x21400d0] from Location[0x2143e90] to Location[0x21494f0] with
Bytes[152]
[LOG] >> copy completed from Executor[gko::ReferenceExecutor,0x21400d0] to
Executor[gko::ReferenceExecutor,0x21400d0] from Location[0x2143e90] to Location[0x21494f0] with
Bytes[152]
[LOG] >> free started on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2149cc0]
[LOG] >> free completed on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2149cc0]
[LOG] >> free started on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2149890]
[LOG] >> free completed on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2149890]
[LOG] >> Operation[gko::solver::cg::step_1_operation<gko::matrix::Dense<double>*,
gko::matrix::Dense<double>*, gko::matrix::Dense<double>*, gko::matrix::Dense<double>*,
gko::Array<gko::stopping_status>*>,0x7ffd93d14ef0] started on
Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::solver::cg::step_1_operation<gko::matrix::Dense<double>*,
gko::matrix::Dense<double>*, gko::matrix::Dense<double>*, gko::matrix::Dense<double>*,
gko::Array<gko::stopping_status>*>,0x7ffd93d14ef0] completed on
Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::matrix::csr::spmv_operation<gko::matrix::Csr<double, int> const*,
gko::matrix::Dense<double> const*, gko::matrix::Dense<double>*>,0x7ffd93d14b80] started on
Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::matrix::csr::spmv_operation<gko::matrix::Csr<double, int> const*,
gko::matrix::Dense<double> const*, gko::matrix::Dense<double>*>,0x7ffd93d14b80] completed on
Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::matrix::dense::compute_dot_operation<gko::matrix::Dense<double> const*,
gko::matrix::Dense<double> const*, gko::matrix::Dense<double>*>,0x7ffd93d14c50] started on
Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::matrix::dense::compute_dot_operation<gko::matrix::Dense<double> const*,
gko::matrix::Dense<double> const*, gko::matrix::Dense<double>*>,0x7ffd93d14c50] completed on
Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::solver::cg::step_2_operation<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>*>,0x7ffd93d14ef0] started on
Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::solver::cg::step_2_operation<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>*>,0x7ffd93d14ef0] completed on
Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> copy started from Executor[gko::ReferenceExecutor,0x21400d0] to
Executor[gko::ReferenceExecutor,0x21400d0] from Location[0x21480a0] to Location[0x21482f0] with
Bytes[152]
[LOG] >> copy completed from Executor[gko::ReferenceExecutor,0x21400d0] to
Executor[gko::ReferenceExecutor,0x21400d0] from Location[0x21480a0] to Location[0x21482f0] with
Bytes[152]

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[LOG] >> Operation[gko::matrix::dense::compute_dot_operation<gko::matrix::Dense<double> const*,
gko::matrix::Dense<double> const*, gko::matrix::Dense<double>*>,0x7ffd93d14c50] started on
Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::matrix::dense::compute_dot_operation<gko::matrix::Dense<double> const*,
gko::matrix::Dense<double> const*, gko::matrix::Dense<double>*>,0x7ffd93d14c50] completed on
Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> iteration 7 completed with solver LinOp[gko::solver::Cg<double>,0x2142d60] with residual
LinOp[gko::matrix::Dense<double>,0x2147b30], solution LinOp[gko::matrix::Dense<double>,0x2143450] and
residual_norm LinOp[gko::LinOp const*,0]
[LOG] >> check started for stop::Criterion[gko::stop::ResidualNorm<double>,0x2148db0] at iteration 7 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>*>,0x7ffd93d14ad0] started on Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::matrix::dense::compute_norm2_operation<gko::matrix::Dense<double> const*,
gko::matrix::Dense<double>*>,0x7ffd93d14ad0] completed on Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::stop::residual_norm::residual_norm_operation<gko::matrix::Dense<double> const*&,
gko::matrix::Dense<double>*, double&, unsigned char&, bool&, gko::Array<gko::stopping_status>*&,
gko::Array<bool>*, bool*, bool*>,0x7ffd93d14b90] started on
Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::stop::residual_norm::residual_norm_operation<gko::matrix::Dense<double> const*&,
gko::matrix::Dense<double>*, double&, unsigned char&, bool&, gko::Array<gko::stopping_status>*&,
gko::Array<bool>*, bool*, bool*>,0x7ffd93d14b90] completed on
Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> check completed for stop::Criterion[gko::stop::ResidualNorm<double>,0x2148db0] at iteration 7 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,0x21400d0] with Bytes[152]
[LOG] >> allocation completed on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2149730] with
Bytes[152]
[LOG] >> copy started from Executor[gko::ReferenceExecutor,0x21400d0] to
Executor[gko::ReferenceExecutor,0x21400d0] from Location[0x21480a0] to Location[0x2149730] with
Bytes[152]
[LOG] >> copy completed from Executor[gko::ReferenceExecutor,0x21400d0] to
Executor[gko::ReferenceExecutor,0x21400d0] from Location[0x21480a0] to Location[0x2149730] with
Bytes[152]
[LOG] >> allocation started on Executor[gko::ReferenceExecutor,0x21400d0] with Bytes[152]
[LOG] >> allocation completed on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x21497d0] with
Bytes[152]
[LOG] >> copy started from Executor[gko::ReferenceExecutor,0x21400d0] to
Executor[gko::ReferenceExecutor,0x21400d0] from Location[0x2143e90] to Location[0x21497d0] with
Bytes[152]
[LOG] >> copy completed from Executor[gko::ReferenceExecutor,0x21400d0] to
Executor[gko::ReferenceExecutor,0x21400d0] from Location[0x2143e90] to Location[0x21497d0] with
Bytes[152]
[LOG] >> free started on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x21494f0]
[LOG] >> free completed on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x21494f0]
[LOG] >> free started on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2149450]
[LOG] >> free completed on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2149450]
[LOG] >> Operation[gko::solver::cg::step_1_operation<gko::matrix::Dense<double>*,
gko::matrix::Dense<double>*, gko::matrix::Dense<double>*, gko::matrix::Dense<double>*,
gko::Array<gko::stopping_status>*>,0x7ffd93d14ef0] started on
Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::solver::cg::step_1_operation<gko::matrix::Dense<double>*,
gko::matrix::Dense<double>*, gko::matrix::Dense<double>*, gko::matrix::Dense<double>*,
gko::Array<gko::stopping_status>*>,0x7ffd93d14ef0] completed on
Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::matrix::csr::spmv_operation<gko::matrix::Csr<double, int> const*,
gko::matrix::Dense<double> const*, gko::matrix::Dense<double>*>,0x7ffd93d14b80] started on
Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::matrix::csr::spmv_operation<gko::matrix::Csr<double, int> const*,
gko::matrix::Dense<double> const*, gko::matrix::Dense<double>*>,0x7ffd93d14b80] completed on
Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::matrix::dense::compute_dot_operation<gko::matrix::Dense<double> const*,
gko::matrix::Dense<double> const*, gko::matrix::Dense<double>*>,0x7ffd93d14c50] started on
Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::matrix::dense::compute_dot_operation<gko::matrix::Dense<double> const*,
gko::matrix::Dense<double> const*, gko::matrix::Dense<double>*>,0x7ffd93d14c50] completed on
Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::solver::cg::step_2_operation<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>*>,0x7ffd93d14ef0] started on
Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::solver::cg::step_2_operation<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>*>,0x7ffd93d14ef0] completed on
Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> copy started from Executor[gko::ReferenceExecutor,0x21400d0] to
Executor[gko::ReferenceExecutor,0x21400d0] from Location[0x21480a0] to Location[0x21482f0] with
Bytes[152]
[LOG] >> copy completed from Executor[gko::ReferenceExecutor,0x21400d0] to
Executor[gko::ReferenceExecutor,0x21400d0] from Location[0x21480a0] to Location[0x21482f0] 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>*>,0x7ffd93d14c50] started on
Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::matrix::dense::compute_dot_operation<gko::matrix::Dense<double> const*,

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gko::matrix::Dense<double> const*, gko::matrix::Dense<double>*>,0x7ffd93d14c50] completed on
Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> iteration 8 completed with solver LinOp[gko::solver::Cg<double>,0x2142d60] with residual
LinOp[gko::matrix::Dense<double>,0x2147b30], solution LinOp[gko::matrix::Dense<double>,0x2143450] and
residual_norm LinOp[gko::LinOp const*,0]
[LOG] >> check started for stop::Criterion[gko::stop::ResidualNorm<double>,0x2148db0] at iteration 8 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>*>,0x7ffd93d14ad0] started on Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::matrix::dense::compute_norm2_operation<gko::matrix::Dense<double> const*,
gko::matrix::Dense<double>*>,0x7ffd93d14ad0] completed on Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::residual_norm::residual_norm_operation<gko::matrix::Dense<double> const*&,
gko::matrix::Dense<double>*, double&, unsigned char&, bool&, gko::Array<gko::stopping_status>*&,
gko::Array<bool>*, bool*, bool*>,0x7ffd93d14b90] started on
Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::stop::residual_norm::residual_norm_operation<gko::matrix::Dense<double> const*&,
gko::matrix::Dense<double>*, double&, unsigned char&, bool&, gko::Array<gko::stopping_status>*&,
gko::Array<bool>*, bool*, bool*>,0x7ffd93d14b90] completed on
Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> check completed for stop::Criterion[gko::stop::ResidualNorm<double>,0x2148db0] at iteration 8 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,0x21400d0] with Bytes[152]
[LOG] >> allocation completed on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2149200] with
Bytes[152]
[LOG] >> copy started from Executor[gko::ReferenceExecutor,0x21400d0] to
Executor[gko::ReferenceExecutor,0x21400d0] from Location[0x21480a0] to Location[0x2149200] with
Bytes[152]
[LOG] >> copy completed from Executor[gko::ReferenceExecutor,0x21400d0] to
Executor[gko::ReferenceExecutor,0x21400d0] from Location[0x21480a0] to Location[0x2149200] with
Bytes[152]
[LOG] >> allocation started on Executor[gko::ReferenceExecutor,0x21400d0] with Bytes[152]
[LOG] >> allocation completed on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x21492a0] with
Bytes[152]
[LOG] >> copy started from Executor[gko::ReferenceExecutor,0x21400d0] to
Executor[gko::ReferenceExecutor,0x21400d0] from Location[0x2143e90] to Location[0x21492a0] with
Bytes[152]
[LOG] >> copy completed from Executor[gko::ReferenceExecutor,0x21400d0] to
Executor[gko::ReferenceExecutor,0x21400d0] from Location[0x2143e90] to Location[0x21492a0] with
Bytes[152]
[LOG] >> free started on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x21497d0]
[LOG] >> free completed on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x21497d0]
[LOG] >> free started on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2149730]
[LOG] >> free completed on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2149730]
[LOG] >> Operation[gko::solver::cg::step_1_operation<gko::matrix::Dense<double>*,
gko::matrix::Dense<double>*, gko::matrix::Dense<double>*, gko::matrix::Dense<double>*,
gko::Array<gko::stopping_status>*&,0x7ffd93d14ef0] started on
Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::solver::cg::step_1_operation<gko::matrix::Dense<double>*,
gko::matrix::Dense<double>*, gko::matrix::Dense<double>*, gko::matrix::Dense<double>*,
gko::Array<gko::stopping_status>*&,0x7ffd93d14ef0] completed on
Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::matrix::csr::spmv_operation<gko::matrix::Csr<double, int> const*,
gko::matrix::Dense<double> const*, gko::matrix::Dense<double>*>,0x7ffd93d14b80] started on
Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::matrix::csr::spmv_operation<gko::matrix::Csr<double, int> const*,
gko::matrix::Dense<double> const*, gko::matrix::Dense<double>*>,0x7ffd93d14b80] completed on
Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::matrix::dense::compute_dot_operation<gko::matrix::Dense<double> const*,
gko::matrix::Dense<double> const*, gko::matrix::Dense<double>*>,0x7ffd93d14c50] started on
Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::matrix::dense::compute_dot_operation<gko::matrix::Dense<double> const*,
gko::matrix::Dense<double> const*, gko::matrix::Dense<double>*>,0x7ffd93d14c50] completed on
Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::solver::cg::step_2_operation<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::matrix::Dense<double>*,
gko::Array<gko::stopping_status>*&,0x7ffd93d14ef0] started on
Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::solver::cg::step_2_operation<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::matrix::Dense<double>*,
gko::Array<gko::stopping_status>*&,0x7ffd93d14ef0] completed on
Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> copy started from Executor[gko::ReferenceExecutor,0x21400d0] to
Executor[gko::ReferenceExecutor,0x21400d0] from Location[0x21480a0] to Location[0x21482f0] with
Bytes[152]
[LOG] >> copy completed from Executor[gko::ReferenceExecutor,0x21400d0] to
Executor[gko::ReferenceExecutor,0x21400d0] from Location[0x21480a0] to Location[0x21482f0] 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>*>,0x7ffd93d14c50] started on
Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::matrix::dense::compute_dot_operation<gko::matrix::Dense<double> const*,
gko::matrix::Dense<double> const*, gko::matrix::Dense<double>*>,0x7ffd93d14c50] completed on
Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> iteration 9 completed with solver LinOp[gko::solver::Cg<double>,0x2142d60] with residual
LinOp[gko::matrix::Dense<double>,0x2147b30], solution LinOp[gko::matrix::Dense<double>,0x2143450] and

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    residual_norm LinOp[gko::LinOp const*,0]
[LOG] >> check started for stop::Criterion[gko::stop::ResidualNorm<double>,0x2148db0] at iteration 9 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>*>,0x7ffd93d14ad0] started on Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::matrix::dense::compute_norm2_operation<gko::matrix::Dense<double> const*,
gko::matrix::Dense<double>*>,0x7ffd93d14ad0] completed on Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::stop::residual_norm::residual_norm_operation<gko::matrix::Dense<double> const*&,
gko::matrix::Dense<double>*, double&, unsigned char&, bool&, gko::Array<gko::stopping_status>*&,
gko::Array<bool>*, bool*, bool*>,0x7ffd93d14b90] started on
Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::stop::residual_norm::residual_norm_operation<gko::matrix::Dense<double> const*&,
gko::matrix::Dense<double>*, double&, unsigned char&, bool&, gko::Array<gko::stopping_status>*&,
gko::Array<bool>*, bool*, bool*>,0x7ffd93d14b90] completed on
Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> check completed for stop::Criterion[gko::stop::ResidualNorm<double>,0x2148db0] at iteration 9 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,0x21400d0] with Bytes[152]
[LOG] >> allocation completed on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2149620] with
Bytes[152]
[LOG] >> copy started from Executor[gko::ReferenceExecutor,0x21400d0] to
Executor[gko::ReferenceExecutor,0x21400d0] from Location[0x21480a0] to Location[0x2149620] with
Bytes[152]
[LOG] >> copy completed from Executor[gko::ReferenceExecutor,0x21400d0] to
Executor[gko::ReferenceExecutor,0x21400d0] from Location[0x21480a0] to Location[0x2149620] with
Bytes[152]
[LOG] >> allocation started on Executor[gko::ReferenceExecutor,0x21400d0] with Bytes[152]
[LOG] >> allocation completed on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x21496c0] with
Bytes[152]
[LOG] >> copy started from Executor[gko::ReferenceExecutor,0x21400d0] to
Executor[gko::ReferenceExecutor,0x21400d0] from Location[0x2143e90] to Location[0x21496c0] with
Bytes[152]
[LOG] >> copy completed from Executor[gko::ReferenceExecutor,0x21400d0] to
Executor[gko::ReferenceExecutor,0x21400d0] from Location[0x2143e90] to Location[0x21496c0] with
Bytes[152]
[LOG] >> free started on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x21492a0]
[LOG] >> free completed on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x21492a0]
[LOG] >> free started on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2149200]
[LOG] >> free completed on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2149200]
[LOG] >> Operation[gko::solver::cg::step_1_operation<gko::matrix::Dense<double>*,
gko::matrix::Dense<double>*, gko::matrix::Dense<double>*, gko::matrix::Dense<double>*,
gko::Array<gko::stopping_status>*>,0x7ffd93d14ef0] started on
Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::solver::cg::step_1_operation<gko::matrix::Dense<double>*,
gko::matrix::Dense<double>*, gko::matrix::Dense<double>*, gko::matrix::Dense<double>*,
gko::Array<gko::stopping_status>*>,0x7ffd93d14ef0] completed on
Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::matrix::csr::spmv_operation<gko::matrix::Csr<double, int> const*,
gko::matrix::Dense<double> const*, gko::matrix::Dense<double>*>,0x7ffd93d14b80] started on
Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::matrix::csr::spmv_operation<gko::matrix::Csr<double, int> const*,
gko::matrix::Dense<double> const*, gko::matrix::Dense<double>*>,0x7ffd93d14b80] completed on
Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::matrix::dense::compute_dot_operation<gko::matrix::Dense<double> const*,
gko::matrix::Dense<double> const*, gko::matrix::Dense<double>*>,0x7ffd93d14c50] started on
Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::matrix::dense::compute_dot_operation<gko::matrix::Dense<double> const*,
gko::matrix::Dense<double> const*, gko::matrix::Dense<double>*>,0x7ffd93d14c50] completed on
Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::solver::cg::step_2_operation<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>*>,0x7ffd93d14ef0] started on
Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::solver::cg::step_2_operation<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>*>,0x7ffd93d14ef0] completed on
Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> copy started from Executor[gko::ReferenceExecutor,0x21400d0] to
Executor[gko::ReferenceExecutor,0x21400d0] from Location[0x21480a0] to Location[0x21482f0] with
Bytes[152]
[LOG] >> copy completed from Executor[gko::ReferenceExecutor,0x21400d0] to
Executor[gko::ReferenceExecutor,0x21400d0] from Location[0x21480a0] to Location[0x21482f0] 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>*>,0x7ffd93d14c50] started on
Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::matrix::dense::compute_dot_operation<gko::matrix::Dense<double> const*,
gko::matrix::Dense<double> const*, gko::matrix::Dense<double>*>,0x7ffd93d14c50] completed on
Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> iteration 10 completed with solver LinOp[gko::solver::Cg<double>,0x2142d60] with residual
LinOp[gko::matrix::Dense<double>,0x2147b30], solution LinOp[gko::matrix::Dense<double>,0x2143450] and
residual_norm LinOp[gko::LinOp const*,0]
[LOG] >> check started for stop::Criterion[gko::stop::ResidualNorm<double>,0x2148db0] at iteration 10 with
ID 1 and finalized set to 1
[LOG] >> Operation[gko::matrix::dense::compute_norm2_operation<gko::matrix::Dense<double> const*,

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    gko::matrix::Dense<double>*>,0x7ffd93d14ad0] started on Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::matrix::dense::compute_norm2_operation<gko::matrix::Dense<double> const*,
gko::matrix::Dense<double>*>,0x7ffd93d14ad0] completed on Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::stop::residual_norm::residual_norm_operation<gko::matrix::Dense<double> const*&,
gko::matrix::Dense<double>*, double&, unsigned char&, bool&, gko::Array<gko::stopping_status>*&,
gko::Array<bool>*, bool*, bool*>>,0x7ffd93d14b90] started on
Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::stop::residual_norm::residual_norm_operation<gko::matrix::Dense<double> const*&,
gko::matrix::Dense<double>*, double&, unsigned char&, bool&, gko::Array<gko::stopping_status>*&,
gko::Array<bool>*, bool*, bool*>>,0x7ffd93d14b90] completed on
Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> check completed for stop::Criterion[gko::stop::ResidualNorm<double>,0x2148db0] at iteration 10 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,0x21400d0] with Bytes[152]
[LOG] >> allocation completed on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2149450] with
Bytes[152]
[LOG] >> copy started from Executor[gko::ReferenceExecutor,0x21400d0] to
Executor[gko::ReferenceExecutor,0x21400d0] from Location[0x21480a0] to Location[0x2149450] with
Bytes[152]
[LOG] >> copy completed from Executor[gko::ReferenceExecutor,0x21400d0] to
Executor[gko::ReferenceExecutor,0x21400d0] from Location[0x21480a0] to Location[0x2149450] with
Bytes[152]
[LOG] >> allocation started on Executor[gko::ReferenceExecutor,0x21400d0] with Bytes[152]
[LOG] >> allocation completed on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2149760] with
Bytes[152]
[LOG] >> copy started from Executor[gko::ReferenceExecutor,0x21400d0] to
Executor[gko::ReferenceExecutor,0x21400d0] from Location[0x2143e90] to Location[0x2149760] with
Bytes[152]
[LOG] >> copy completed from Executor[gko::ReferenceExecutor,0x21400d0] to
Executor[gko::ReferenceExecutor,0x21400d0] from Location[0x2143e90] to Location[0x2149760] with
Bytes[152]
[LOG] >> free started on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x21496c0]
[LOG] >> free completed on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x21496c0]
[LOG] >> free started on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2149620]
[LOG] >> free completed on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2149620]
[LOG] >> Operation[gko::solver::cg::step_1_operation<gko::matrix::Dense<double>*,
gko::matrix::Dense<double>*, gko::matrix::Dense<double>*, gko::matrix::Dense<double>*,
gko::Array<gko::stopping_status>*>,0x7ffd93d14ef0] started on
Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::solver::cg::step_1_operation<gko::matrix::Dense<double>*,
gko::matrix::Dense<double>*, gko::matrix::Dense<double>*, gko::matrix::Dense<double>*,
gko::Array<gko::stopping_status>*>,0x7ffd93d14ef0] completed on
Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::matrix::csr::spmv_operation<gko::matrix::Csr<double, int> const*,
gko::matrix::Dense<double> const*, gko::matrix::Dense<double>*>,0x7ffd93d14b80] started on
Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::matrix::csr::spmv_operation<gko::matrix::Csr<double, int> const*,
gko::matrix::Dense<double> const*, gko::matrix::Dense<double>*>,0x7ffd93d14b80] completed on
Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::matrix::dense::compute_dot_operation<gko::matrix::Dense<double> const*,
gko::matrix::Dense<double> const*, gko::matrix::Dense<double>*>,0x7ffd93d14c50] started on
Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::matrix::dense::compute_dot_operation<gko::matrix::Dense<double> const*,
gko::matrix::Dense<double> const*, gko::matrix::Dense<double>*>,0x7ffd93d14c50] completed on
Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::solver::cg::step_2_operation<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>*>,0x7ffd93d14ef0] started on
Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::solver::cg::step_2_operation<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>*>,0x7ffd93d14ef0] completed on
Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> copy started from Executor[gko::ReferenceExecutor,0x21400d0] to
Executor[gko::ReferenceExecutor,0x21400d0] from Location[0x21480a0] to Location[0x21482f0] with
Bytes[152]
[LOG] >> copy completed from Executor[gko::ReferenceExecutor,0x21400d0] to
Executor[gko::ReferenceExecutor,0x21400d0] from Location[0x21480a0] to Location[0x21482f0] 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>*>,0x7ffd93d14c50] started on
Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::matrix::dense::compute_dot_operation<gko::matrix::Dense<double> const*,
gko::matrix::Dense<double> const*, gko::matrix::Dense<double>*>,0x7ffd93d14c50] completed on
Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> iteration 11 completed with solver LinOp[gko::solver::Cg<double>,0x2142d60] with residual
LinOp[gko::matrix::Dense<double>,0x2147b30], solution LinOp[gko::matrix::Dense<double>,0x2143450] and
residual_norm LinOp[gko::LinOp const*,0]
[LOG] >> check started for stop::Criterion[gko::stop::ResidualNorm<double>,0x2148db0] at iteration 11 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>*>,0x7ffd93d14ad0] started on Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::matrix::dense::compute_norm2_operation<gko::matrix::Dense<double> const*,
gko::matrix::Dense<double>*>,0x7ffd93d14ad0] completed on Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::stop::residual_norm::residual_norm_operation<gko::matrix::Dense<double> const*&,

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    gko::matrix::Dense<double>*, double&, unsigned char&, bool&, gko::Array<gko::stopping_status>* &,
    gko::Array<bool>* &, bool*, bool*>, 0x7ffd93d14b90] started on
    Executor[gko::ReferenceExecutor, 0x21400d0]
[LOG] >> Operation[gko::stop::residual_norm::residual_norm_operation<gko::matrix::Dense<double> const* &,
    gko::matrix::Dense<double>*, double&, unsigned char&, bool&, gko::Array<gko::stopping_status>* &,
    gko::Array<bool>* &, bool*, bool*>, 0x7ffd93d14b90] completed on
    Executor[gko::ReferenceExecutor, 0x21400d0]
[LOG] >> check completed for stop::Criterion[gko::stop::ResidualNorm<double>, 0x2148db0] at iteration 11 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, 0x21400d0] with Bytes[152]
[LOG] >> allocation completed on Executor[gko::ReferenceExecutor, 0x21400d0] at Location[0x2149860] with
    Bytes[152]
[LOG] >> copy started from Executor[gko::ReferenceExecutor, 0x21400d0] to
    Executor[gko::ReferenceExecutor, 0x21400d0] from Location[0x21480a0] to Location[0x2149860] with
    Bytes[152]
[LOG] >> copy completed from Executor[gko::ReferenceExecutor, 0x21400d0] to
    Executor[gko::ReferenceExecutor, 0x21400d0] from Location[0x21480a0] to Location[0x2149860] with
    Bytes[152]
[LOG] >> allocation started on Executor[gko::ReferenceExecutor, 0x21400d0] with Bytes[152]
[LOG] >> allocation completed on Executor[gko::ReferenceExecutor, 0x21400d0] at Location[0x2149900] with
    Bytes[152]
[LOG] >> copy started from Executor[gko::ReferenceExecutor, 0x21400d0] to
    Executor[gko::ReferenceExecutor, 0x21400d0] from Location[0x2143e90] to Location[0x2149900] with
    Bytes[152]
[LOG] >> copy completed from Executor[gko::ReferenceExecutor, 0x21400d0] to
    Executor[gko::ReferenceExecutor, 0x21400d0] from Location[0x2143e90] to Location[0x2149900] with
    Bytes[152]
[LOG] >> free started on Executor[gko::ReferenceExecutor, 0x21400d0] at Location[0x2149760]
[LOG] >> free completed on Executor[gko::ReferenceExecutor, 0x21400d0] at Location[0x2149760]
[LOG] >> free started on Executor[gko::ReferenceExecutor, 0x21400d0] at Location[0x2149450]
[LOG] >> free completed on Executor[gko::ReferenceExecutor, 0x21400d0] at Location[0x2149450]
[LOG] >> Operation[gko::solver::cg::step_1_operation<gko::matrix::Dense<double>*,
    gko::matrix::Dense<double>*, gko::matrix::Dense<double>*, gko::matrix::Dense<double>*,
    gko::Array<gko::stopping_status>* >, 0x7ffd93d14ef0] started on
    Executor[gko::ReferenceExecutor, 0x21400d0]
[LOG] >> Operation[gko::solver::cg::step_1_operation<gko::matrix::Dense<double>*,
    gko::matrix::Dense<double>*, gko::matrix::Dense<double>*, gko::matrix::Dense<double>*,
    gko::Array<gko::stopping_status>* >, 0x7ffd93d14ef0] completed on
    Executor[gko::ReferenceExecutor, 0x21400d0]
[LOG] >> Operation[gko::matrix::csr::spmv_operation<gko::matrix::Csr<double, int> const*,
    gko::matrix::Dense<double> const*, gko::matrix::Dense<double>* >, 0x7ffd93d14b80] started on
    Executor[gko::ReferenceExecutor, 0x21400d0]
[LOG] >> Operation[gko::matrix::csr::spmv_operation<gko::matrix::Csr<double, int> const*,
    gko::matrix::Dense<double> const*, gko::matrix::Dense<double>* >, 0x7ffd93d14b80] completed on
    Executor[gko::ReferenceExecutor, 0x21400d0]
[LOG] >> Operation[gko::matrix::dense::compute_dot_operation<gko::matrix::Dense<double> const*,
    gko::matrix::Dense<double> const*, gko::matrix::Dense<double>* >, 0x7ffd93d14c50] started on
    Executor[gko::ReferenceExecutor, 0x21400d0]
[LOG] >> Operation[gko::matrix::dense::compute_dot_operation<gko::matrix::Dense<double> const*,
    gko::matrix::Dense<double> const*, gko::matrix::Dense<double>* >, 0x7ffd93d14c50] completed on
    Executor[gko::ReferenceExecutor, 0x21400d0]
[LOG] >> Operation[gko::solver::cg::step_2_operation<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>* >, 0x7ffd93d14ef0] started on
    Executor[gko::ReferenceExecutor, 0x21400d0]
[LOG] >> Operation[gko::solver::cg::step_2_operation<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>* >, 0x7ffd93d14ef0] completed on
    Executor[gko::ReferenceExecutor, 0x21400d0]
[LOG] >> copy started from Executor[gko::ReferenceExecutor, 0x21400d0] to
    Executor[gko::ReferenceExecutor, 0x21400d0] from Location[0x21480a0] to Location[0x21482f0] with
    Bytes[152]
[LOG] >> copy completed from Executor[gko::ReferenceExecutor, 0x21400d0] to
    Executor[gko::ReferenceExecutor, 0x21400d0] from Location[0x21480a0] to Location[0x21482f0] 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>* >, 0x7ffd93d14c50] started on
    Executor[gko::ReferenceExecutor, 0x21400d0]
[LOG] >> Operation[gko::matrix::dense::compute_dot_operation<gko::matrix::Dense<double> const*,
    gko::matrix::Dense<double> const*, gko::matrix::Dense<double>* >, 0x7ffd93d14c50] completed on
    Executor[gko::ReferenceExecutor, 0x21400d0]
[LOG] >> iteration 12 completed with solver LinOp[gko::solver::Cg<double>, 0x2142d60] with residual
    LinOp[gko::matrix::Dense<double>, 0x2147b30], solution LinOp[gko::matrix::Dense<double>, 0x2143450] and
    residual_norm LinOp[gko::LinOp const*, 0]
[LOG] >> check started for stop::Criterion[gko::stop::ResidualNorm<double>, 0x2148db0] at iteration 12 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>* >, 0x7ffd93d14ad0] started on Executor[gko::ReferenceExecutor, 0x21400d0]
[LOG] >> Operation[gko::matrix::dense::compute_norm2_operation<gko::matrix::Dense<double> const*,
    gko::matrix::Dense<double>* >, 0x7ffd93d14ad0] completed on Executor[gko::ReferenceExecutor, 0x21400d0]
[LOG] >> Operation[gko::stop::residual_norm::residual_norm_operation<gko::matrix::Dense<double> const* &,
    gko::matrix::Dense<double>*, double&, unsigned char&, bool&, gko::Array<gko::stopping_status>* &,
    gko::Array<bool>* &, bool*, bool*>, 0x7ffd93d14b90] started on
    Executor[gko::ReferenceExecutor, 0x21400d0]
[LOG] >> Operation[gko::stop::residual_norm::residual_norm_operation<gko::matrix::Dense<double> const* &,

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    gko::matrix::Dense<double>*, double&, unsigned char&, bool&, gko::Array<gko::stopping_status>*&,
    gko::Array<bool>*, bool*, bool*>,0x7ffd93d14b90] completed on
    Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> check completed for stop::Criterion[gko::stop::ResidualNorm<double>,0x2148db0] at iteration 12 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,0x21400d0] with Bytes[152]
[LOG] >> allocation completed on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x21499a0] with
    Bytes[152]
[LOG] >> copy started from Executor[gko::ReferenceExecutor,0x21400d0] to
    Executor[gko::ReferenceExecutor,0x21400d0] from Location[0x21480a0] to Location[0x21499a0] with
    Bytes[152]
[LOG] >> copy completed from Executor[gko::ReferenceExecutor,0x21400d0] to
    Executor[gko::ReferenceExecutor,0x21400d0] from Location[0x21480a0] to Location[0x21499a0] with
    Bytes[152]
[LOG] >> allocation started on Executor[gko::ReferenceExecutor,0x21400d0] with Bytes[152]
[LOG] >> allocation completed on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x21493d0] with
    Bytes[152]
[LOG] >> copy started from Executor[gko::ReferenceExecutor,0x21400d0] to
    Executor[gko::ReferenceExecutor,0x21400d0] from Location[0x2143e90] to Location[0x21493d0] with
    Bytes[152]
[LOG] >> copy completed from Executor[gko::ReferenceExecutor,0x21400d0] to
    Executor[gko::ReferenceExecutor,0x21400d0] from Location[0x2143e90] to Location[0x21493d0] with
    Bytes[152]
[LOG] >> free started on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2149900]
[LOG] >> free completed on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2149900]
[LOG] >> free started on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2149860]
[LOG] >> free completed on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2149860]
[LOG] >> Operation[gko::solver::cg::step_1_operation<gko::matrix::Dense<double>*,
    gko::matrix::Dense<double>*, gko::matrix::Dense<double>*, gko::matrix::Dense<double>*,
    gko::Array<gko::stopping_status>*&,0x7ffd93d14ef0] started on
    Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::solver::cg::step_1_operation<gko::matrix::Dense<double>*,
    gko::matrix::Dense<double>*, gko::matrix::Dense<double>*, gko::matrix::Dense<double>*,
    gko::Array<gko::stopping_status>*&,0x7ffd93d14ef0] completed on
    Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::matrix::csr::spmv_operation<gko::matrix::Csr<double, int> const*,
    gko::matrix::Dense<double> const*, gko::matrix::Dense<double>*&,0x7ffd93d14b80] started on
    Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::matrix::csr::spmv_operation<gko::matrix::Csr<double, int> const*,
    gko::matrix::Dense<double> const*, gko::matrix::Dense<double>*&,0x7ffd93d14b80] completed on
    Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::matrix::dense::compute_dot_operation<gko::matrix::Dense<double> const*,
    gko::matrix::Dense<double> const*, gko::matrix::Dense<double>*&,0x7ffd93d14c50] started on
    Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::matrix::dense::compute_dot_operation<gko::matrix::Dense<double> const*,
    gko::matrix::Dense<double> const*, gko::matrix::Dense<double>*&,0x7ffd93d14c50] completed on
    Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::solver::cg::step_2_operation<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>*&,0x7ffd93d14ef0] started on
    Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::solver::cg::step_2_operation<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>*&,0x7ffd93d14ef0] completed on
    Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> copy started from Executor[gko::ReferenceExecutor,0x21400d0] to
    Executor[gko::ReferenceExecutor,0x21400d0] from Location[0x21480a0] to Location[0x21482f0] with
    Bytes[152]
[LOG] >> copy completed from Executor[gko::ReferenceExecutor,0x21400d0] to
    Executor[gko::ReferenceExecutor,0x21400d0] from Location[0x21480a0] to Location[0x21482f0] 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>*&,0x7ffd93d14c50] started on
    Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::matrix::dense::compute_dot_operation<gko::matrix::Dense<double> const*,
    gko::matrix::Dense<double> const*, gko::matrix::Dense<double>*&,0x7ffd93d14c50] completed on
    Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> iteration 13 completed with solver LinOp[gko::solver::Cg<double>,0x2142d60] with residual
    LinOp[gko::matrix::Dense<double>,0x2147b30], solution LinOp[gko::matrix::Dense<double>,0x2143450] and
    residual_norm LinOp[gko::LinOp const*,0]
[LOG] >> check started for stop::Criterion[gko::stop::ResidualNorm<double>,0x2148db0] at iteration 13 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>*&,0x7ffd93d14ad0] started on Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::matrix::dense::compute_norm2_operation<gko::matrix::Dense<double> const*,
    gko::matrix::Dense<double>*&,0x7ffd93d14ad0] completed on Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::stop::residual_norm::residual_norm_operation<gko::matrix::Dense<double> const*&,
    gko::matrix::Dense<double>*, double&, unsigned char&, bool&, gko::Array<gko::stopping_status>*&,
    gko::Array<bool>*, bool*, bool*>,0x7ffd93d14b90] started on
    Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::stop::residual_norm::residual_norm_operation<gko::matrix::Dense<double> const*&,
    gko::matrix::Dense<double>*, double&, unsigned char&, bool&, gko::Array<gko::stopping_status>*&,
    gko::Array<bool>*, bool*, bool*>,0x7ffd93d14b90] completed on
    Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> check completed for stop::Criterion[gko::stop::ResidualNorm<double>,0x2148db0] at iteration 13 with

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ID 1 and finalized set to 1. It changed one RHS 0, stopped the iteration process 0
[LOG] >> allocation started on Executor[gko::ReferenceExecutor,0x21400d0] with Bytes[152]
[LOG] >> allocation completed on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2149490] with
Bytes[152]
[LOG] >> copy started from Executor[gko::ReferenceExecutor,0x21400d0] to
Executor[gko::ReferenceExecutor,0x21400d0] from Location[0x21480a0] to Location[0x2149490] with
Bytes[152]
[LOG] >> copy completed from Executor[gko::ReferenceExecutor,0x21400d0] to
Executor[gko::ReferenceExecutor,0x21400d0] from Location[0x21480a0] to Location[0x2149490] with
Bytes[152]
[LOG] >> allocation started on Executor[gko::ReferenceExecutor,0x21400d0] with Bytes[152]
[LOG] >> allocation completed on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2149580] with
Bytes[152]
[LOG] >> copy started from Executor[gko::ReferenceExecutor,0x21400d0] to
Executor[gko::ReferenceExecutor,0x21400d0] from Location[0x2143e90] to Location[0x2149580] with
Bytes[152]
[LOG] >> copy completed from Executor[gko::ReferenceExecutor,0x21400d0] to
Executor[gko::ReferenceExecutor,0x21400d0] from Location[0x2143e90] to Location[0x2149580] with
Bytes[152]
[LOG] >> free started on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x21493d0]
[LOG] >> free completed on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x21493d0]
[LOG] >> free started on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x21499a0]
[LOG] >> free completed on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x21499a0]
[LOG] >> Operation[gko::solver::cg::step_1_operation<gko::matrix::Dense<double>*,
gko::matrix::Dense<double>*, gko::matrix::Dense<double>*, gko::matrix::Dense<double>*,
gko::Array<gko::stopping_status>*>,0x7ffd93d14ef0] started on
Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::solver::cg::step_1_operation<gko::matrix::Dense<double>*,
gko::matrix::Dense<double>*, gko::matrix::Dense<double>*, gko::matrix::Dense<double>*,
gko::Array<gko::stopping_status>*>,0x7ffd93d14ef0] completed on
Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::matrix::csr::spmv_operation<gko::matrix::Csr<double, int> const*,
gko::matrix::Dense<double> const*, gko::matrix::Dense<double>*>,0x7ffd93d14b80] started on
Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::matrix::csr::spmv_operation<gko::matrix::Csr<double, int> const*,
gko::matrix::Dense<double> const*, gko::matrix::Dense<double>*>,0x7ffd93d14b80] completed on
Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::matrix::dense::compute_dot_operation<gko::matrix::Dense<double> const*,
gko::matrix::Dense<double> const*, gko::matrix::Dense<double>*>,0x7ffd93d14c50] started on
Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::matrix::dense::compute_dot_operation<gko::matrix::Dense<double> const*,
gko::matrix::Dense<double> const*, gko::matrix::Dense<double>*>,0x7ffd93d14c50] completed on
Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::solver::cg::step_2_operation<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>*>,0x7ffd93d14ef0] started on
Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::solver::cg::step_2_operation<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>*>,0x7ffd93d14ef0] completed on
Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> copy started from Executor[gko::ReferenceExecutor,0x21400d0] to
Executor[gko::ReferenceExecutor,0x21400d0] from Location[0x21480a0] to Location[0x21482f0] with
Bytes[152]
[LOG] >> copy completed from Executor[gko::ReferenceExecutor,0x21400d0] to
Executor[gko::ReferenceExecutor,0x21400d0] from Location[0x21480a0] to Location[0x21482f0] 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>*>,0x7ffd93d14c50] started on
Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::matrix::dense::compute_dot_operation<gko::matrix::Dense<double> const*,
gko::matrix::Dense<double> const*, gko::matrix::Dense<double>*>,0x7ffd93d14c50] completed on
Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> iteration 14 completed with solver LinOp[gko::solver::Cg<double>,0x2142d60] with residual
LinOp[gko::matrix::Dense<double>,0x2147b30], solution LinOp[gko::matrix::Dense<double>,0x2143450] and
residual_norm LinOp[gko::LinOp const*,0]
[LOG] >> check started for stop::Criterion[gko::stop::ResidualNorm<double>,0x2148db0] at iteration 14 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>*>,0x7ffd93d14ad0] started on Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::matrix::dense::compute_norm2_operation<gko::matrix::Dense<double> const*,
gko::matrix::Dense<double>*>,0x7ffd93d14ad0] completed on Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::stop::residual_norm::residual_norm_operation<gko::matrix::Dense<double> const*&,
gko::matrix::Dense<double>*, double&, unsigned char&, bool&, gko::Array<gko::stopping_status>*&,
gko::Array<bool>*, bool*, bool*&>,0x7ffd93d14b90] started on
Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::stop::residual_norm::residual_norm_operation<gko::matrix::Dense<double> const*&,
gko::matrix::Dense<double>*, double&, unsigned char&, bool&, gko::Array<gko::stopping_status>*&,
gko::Array<bool>*, bool*, bool*&>,0x7ffd93d14b90] completed on
Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> check completed for stop::Criterion[gko::stop::ResidualNorm<double>,0x2148db0] at iteration 14 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,0x21400d0] with Bytes[152]
[LOG] >> allocation completed on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2149b50] with
Bytes[152]

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[LOG] >> copy started from Executor[gko::ReferenceExecutor,0x21400d0] to
      Executor[gko::ReferenceExecutor,0x21400d0] from Location[0x21480a0] to Location[0x2149b50] with
      Bytes[152]
[LOG] >> copy completed from Executor[gko::ReferenceExecutor,0x21400d0] to
      Executor[gko::ReferenceExecutor,0x21400d0] from Location[0x21480a0] to Location[0x2149b50] with
      Bytes[152]
[LOG] >> allocation started on Executor[gko::ReferenceExecutor,0x21400d0] with Bytes[152]
[LOG] >> allocation completed on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x21499c0] with
      Bytes[152]
[LOG] >> copy started from Executor[gko::ReferenceExecutor,0x21400d0] to
      Executor[gko::ReferenceExecutor,0x21400d0] from Location[0x2143e90] to Location[0x21499c0] with
      Bytes[152]
[LOG] >> copy completed from Executor[gko::ReferenceExecutor,0x21400d0] to
      Executor[gko::ReferenceExecutor,0x21400d0] from Location[0x2143e90] to Location[0x21499c0] with
      Bytes[152]
[LOG] >> free started on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2149580]
[LOG] >> free completed on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2149580]
[LOG] >> free started on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2149490]
[LOG] >> free completed on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2149490]
[LOG] >> Operation[gko::solver::cg::step_1_operation<gko::matrix::Dense<double>*,
      gko::matrix::Dense<double>*, gko::matrix::Dense<double>*, gko::matrix::Dense<double>*,
      gko::Array<gko::stopping_status>*>,0x7ffd93d14ef0] started on
      Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::solver::cg::step_1_operation<gko::matrix::Dense<double>*,
      gko::matrix::Dense<double>*, gko::matrix::Dense<double>*, gko::matrix::Dense<double>*,
      gko::Array<gko::stopping_status>*>,0x7ffd93d14ef0] completed on
      Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::matrix::csr::spmv_operation<gko::matrix::Csr<double, int> const*,
      gko::matrix::Dense<double> const*, gko::matrix::Dense<double>*>,0x7ffd93d14b80] started on
      Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::matrix::csr::spmv_operation<gko::matrix::Csr<double, int> const*,
      gko::matrix::Dense<double> const*, gko::matrix::Dense<double>*>,0x7ffd93d14b80] completed on
      Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::matrix::dense::compute_dot_operation<gko::matrix::Dense<double> const*,
      gko::matrix::Dense<double> const*, gko::matrix::Dense<double>*>,0x7ffd93d14c50] started on
      Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::matrix::dense::compute_dot_operation<gko::matrix::Dense<double> const*,
      gko::matrix::Dense<double> const*, gko::matrix::Dense<double>*>,0x7ffd93d14c50] completed on
      Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::solver::cg::step_2_operation<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>*>,0x7ffd93d14ef0] started on
      Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::solver::cg::step_2_operation<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>*>,0x7ffd93d14ef0] completed on
      Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> copy started from Executor[gko::ReferenceExecutor,0x21400d0] to
      Executor[gko::ReferenceExecutor,0x21400d0] from Location[0x21480a0] to Location[0x21482f0] with
      Bytes[152]
[LOG] >> copy completed from Executor[gko::ReferenceExecutor,0x21400d0] to
      Executor[gko::ReferenceExecutor,0x21400d0] from Location[0x21480a0] to Location[0x21482f0] 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>*>,0x7ffd93d14c50] started on
      Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::matrix::dense::compute_dot_operation<gko::matrix::Dense<double> const*,
      gko::matrix::Dense<double> const*, gko::matrix::Dense<double>*>,0x7ffd93d14c50] completed on
      Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> iteration 15 completed with solver LinOp[gko::solver::Cg<double>,0x2142d60] with residual
      LinOp[gko::matrix::Dense<double>,0x2147b30], solution LinOp[gko::matrix::Dense<double>,0x2143450] and
      residual_norm LinOp[gko::LinOp const*,0]
[LOG] >> check started for stop::Criterion[gko::stop::ResidualNorm<double>,0x2148db0] at iteration 15 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>*>,0x7ffd93d14ad0] started on Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::matrix::dense::compute_norm2_operation<gko::matrix::Dense<double> const*,
      gko::matrix::Dense<double>*>,0x7ffd93d14ad0] completed on Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::stop::residual_norm::residual_norm_operation<gko::matrix::Dense<double> const* &,
      gko::matrix::Dense<double>*, double &, unsigned char &, bool &, gko::Array<gko::stopping_status>* &,
      gko::Array<bool>*, bool*, bool* &>,0x7ffd93d14b90] started on
      Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::stop::residual_norm::residual_norm_operation<gko::matrix::Dense<double> const* &,
      gko::matrix::Dense<double>*, double &, unsigned char &, bool &, gko::Array<gko::stopping_status>* &,
      gko::Array<bool>*, bool*, bool* &>,0x7ffd93d14b90] completed on
      Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> check completed for stop::Criterion[gko::stop::ResidualNorm<double>,0x2148db0] at iteration 15 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,0x21400d0] with Bytes[152]
[LOG] >> allocation completed on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2149a70] with
      Bytes[152]
[LOG] >> copy started from Executor[gko::ReferenceExecutor,0x21400d0] to
      Executor[gko::ReferenceExecutor,0x21400d0] from Location[0x21480a0] to Location[0x2149a70] with
      Bytes[152]
[LOG] >> copy completed from Executor[gko::ReferenceExecutor,0x21400d0] to

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    Executor[gko::ReferenceExecutor,0x21400d0] from Location[0x21480a0] to Location[0x2149a70] with
    Bytes[152]
[LOG] >> allocation started on Executor[gko::ReferenceExecutor,0x21400d0] with Bytes[152]
[LOG] >> allocation completed on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2149340] with
    Bytes[152]
[LOG] >> copy started from Executor[gko::ReferenceExecutor,0x21400d0] to
    Executor[gko::ReferenceExecutor,0x21400d0] from Location[0x2143e90] to Location[0x2149340] with
    Bytes[152]
[LOG] >> copy completed from Executor[gko::ReferenceExecutor,0x21400d0] to
    Executor[gko::ReferenceExecutor,0x21400d0] from Location[0x2143e90] to Location[0x2149340] with
    Bytes[152]
[LOG] >> free started on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x21499c0]
[LOG] >> free completed on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x21499c0]
[LOG] >> free started on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2149b50]
[LOG] >> free completed on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2149b50]
[LOG] >> Operation[gko::solver::cg::step_1_operation<gko::matrix::Dense<double>*,
    gko::matrix::Dense<double>*, gko::matrix::Dense<double>*, gko::matrix::Dense<double>*,
    gko::Array<gko::stopping_status>*>,0x7ffd93d14ef0] started on
    Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::solver::cg::step_1_operation<gko::matrix::Dense<double>*,
    gko::matrix::Dense<double>*, gko::matrix::Dense<double>*, gko::matrix::Dense<double>*,
    gko::Array<gko::stopping_status>*>,0x7ffd93d14ef0] completed on
    Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::matrix::csr::spmv_operation<gko::matrix::Csr<double, int> const*,
    gko::matrix::Dense<double> const*, gko::matrix::Dense<double>*>,0x7ffd93d14b80] started on
    Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::matrix::csr::spmv_operation<gko::matrix::Csr<double, int> const*,
    gko::matrix::Dense<double> const*, gko::matrix::Dense<double>*>,0x7ffd93d14b80] completed on
    Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::matrix::dense::compute_dot_operation<gko::matrix::Dense<double> const*,
    gko::matrix::Dense<double> const*, gko::matrix::Dense<double>*>,0x7ffd93d14c50] started on
    Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::matrix::dense::compute_dot_operation<gko::matrix::Dense<double> const*,
    gko::matrix::Dense<double> const*, gko::matrix::Dense<double>*>,0x7ffd93d14c50] completed on
    Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::solver::cg::step_2_operation<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>*>,0x7ffd93d14ef0] started on
    Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::solver::cg::step_2_operation<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>*>,0x7ffd93d14ef0] completed on
    Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> copy started from Executor[gko::ReferenceExecutor,0x21400d0] to
    Executor[gko::ReferenceExecutor,0x21400d0] from Location[0x21480a0] to Location[0x21482f0] with
    Bytes[152]
[LOG] >> copy completed from Executor[gko::ReferenceExecutor,0x21400d0] to
    Executor[gko::ReferenceExecutor,0x21400d0] from Location[0x21480a0] to Location[0x21482f0] 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>*>,0x7ffd93d14c50] started on
    Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::matrix::dense::compute_dot_operation<gko::matrix::Dense<double> const*,
    gko::matrix::Dense<double> const*, gko::matrix::Dense<double>*>,0x7ffd93d14c50] completed on
    Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> iteration 16 completed with solver LinOp[gko::solver::Cg<double>,0x2142d60] with residual
    LinOp[gko::matrix::Dense<double>,0x2147b30], solution LinOp[gko::matrix::Dense<double>,0x2143450] and
    residual_norm LinOp[gko::LinOp const*,0]
[LOG] >> check started for stop::Criterion[gko::stop::ResidualNorm<double>,0x2148db0] at iteration 16 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>*>,0x7ffd93d14ad0] started on Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::matrix::dense::compute_norm2_operation<gko::matrix::Dense<double> const*,
    gko::matrix::Dense<double>*>,0x7ffd93d14ad0] completed on Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::stop::residual_norm::residual_norm_operation<gko::matrix::Dense<double> const* &,
    gko::matrix::Dense<double>*, double &, unsigned char &, bool &, gko::Array<gko::stopping_status>* &,
    gko::Array<bool>*, bool*, bool* &&,0x7ffd93d14b90] started on
    Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::stop::residual_norm::residual_norm_operation<gko::matrix::Dense<double> const* &,
    gko::matrix::Dense<double>*, double &, unsigned char &, bool &, gko::Array<gko::stopping_status>* &,
    gko::Array<bool>*, bool*, bool* &&,0x7ffd93d14b90] completed on
    Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> check completed for stop::Criterion[gko::stop::ResidualNorm<double>,0x2148db0] at iteration 16 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,0x21400d0] with Bytes[152]
[LOG] >> allocation completed on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2149970] with
    Bytes[152]
[LOG] >> copy started from Executor[gko::ReferenceExecutor,0x21400d0] to
    Executor[gko::ReferenceExecutor,0x21400d0] from Location[0x21480a0] to Location[0x2149970] with
    Bytes[152]
[LOG] >> copy completed from Executor[gko::ReferenceExecutor,0x21400d0] to
    Executor[gko::ReferenceExecutor,0x21400d0] from Location[0x21480a0] to Location[0x2149970] with
    Bytes[152]
[LOG] >> allocation started on Executor[gko::ReferenceExecutor,0x21400d0] with Bytes[152]
[LOG] >> allocation completed on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2149b10] with

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Bytes[152]
[LOG] >> copy started from Executor[gko::ReferenceExecutor,0x21400d0] to
Executor[gko::ReferenceExecutor,0x21400d0] from Location[0x2143e90] to Location[0x2149b10] with
Bytes[152]
[LOG] >> copy completed from Executor[gko::ReferenceExecutor,0x21400d0] to
Executor[gko::ReferenceExecutor,0x21400d0] from Location[0x2143e90] to Location[0x2149b10] with
Bytes[152]
[LOG] >> free started on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2149340]
[LOG] >> free completed on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2149340]
[LOG] >> free started on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2149a70]
[LOG] >> free completed on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2149a70]
[LOG] >> Operation[gko::solver::cg::step_1_operation<gko::matrix::Dense<double>*,
gko::matrix::Dense<double>*, gko::matrix::Dense<double>*, gko::matrix::Dense<double>*,
gko::Array<gko::stopping_status>*>,0x7ffd93d14ef0] started on
Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::solver::cg::step_1_operation<gko::matrix::Dense<double>*,
gko::matrix::Dense<double>*, gko::matrix::Dense<double>*, gko::matrix::Dense<double>*,
gko::Array<gko::stopping_status>*>,0x7ffd93d14ef0] completed on
Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::matrix::csr::spmv_operation<gko::matrix::Csr<double, int> const*,
gko::matrix::Dense<double> const*, gko::matrix::Dense<double>*>,0x7ffd93d14b80] started on
Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::matrix::csr::spmv_operation<gko::matrix::Csr<double, int> const*,
gko::matrix::Dense<double> const*, gko::matrix::Dense<double>*>,0x7ffd93d14b80] completed on
Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::matrix::dense::compute_dot_operation<gko::matrix::Dense<double> const*,
gko::matrix::Dense<double> const*, gko::matrix::Dense<double>*>,0x7ffd93d14c50] started on
Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::matrix::dense::compute_dot_operation<gko::matrix::Dense<double> const*,
gko::matrix::Dense<double> const*, gko::matrix::Dense<double>*>,0x7ffd93d14c50] completed on
Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::solver::cg::step_2_operation<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>*>,0x7ffd93d14ef0] started on
Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::solver::cg::step_2_operation<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>*>,0x7ffd93d14ef0] completed on
Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> copy started from Executor[gko::ReferenceExecutor,0x21400d0] to
Executor[gko::ReferenceExecutor,0x21400d0] from Location[0x21480a0] to Location[0x21482f0] with
Bytes[152]
[LOG] >> copy completed from Executor[gko::ReferenceExecutor,0x21400d0] to
Executor[gko::ReferenceExecutor,0x21400d0] from Location[0x21480a0] to Location[0x21482f0] 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>*>,0x7ffd93d14c50] started on
Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::matrix::dense::compute_dot_operation<gko::matrix::Dense<double> const*,
gko::matrix::Dense<double> const*, gko::matrix::Dense<double>*>,0x7ffd93d14c50] completed on
Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> iteration 17 completed with solver LinOp[gko::solver::Cg<double>,0x2142d60] with residual
LinOp[gko::matrix::Dense<double>,0x2147b30], solution LinOp[gko::matrix::Dense<double>,0x2143450] and
residual_norm LinOp[gko::LinOp const*,0]
[LOG] >> check started for stop::Criterion[gko::stop::ResidualNorm<double>,0x2148db0] at iteration 17 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>*>,0x7ffd93d14ad0] started on Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::matrix::dense::compute_norm2_operation<gko::matrix::Dense<double> const*,
gko::matrix::Dense<double>*>,0x7ffd93d14ad0] completed on Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::stop::residual_norm::residual_norm_operation<gko::matrix::Dense<double> const*&,
gko::matrix::Dense<double>*, double&, unsigned char&, bool&, gko::Array<gko::stopping_status>*&,
gko::Array<bool>*, bool*, bool*&>,0x7ffd93d14b90] started on
Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::stop::residual_norm::residual_norm_operation<gko::matrix::Dense<double> const*&,
gko::matrix::Dense<double>*, double&, unsigned char&, bool&, gko::Array<gko::stopping_status>*&,
gko::Array<bool>*, bool*, bool*&>,0x7ffd93d14b90] completed on
Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> check completed for stop::Criterion[gko::stop::ResidualNorm<double>,0x2148db0] at iteration 17 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,0x21400d0] with Bytes[152]
[LOG] >> allocation completed on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2149780] with
Bytes[152]
[LOG] >> copy started from Executor[gko::ReferenceExecutor,0x21400d0] to
Executor[gko::ReferenceExecutor,0x21400d0] from Location[0x21480a0] to Location[0x2149780] with
Bytes[152]
[LOG] >> copy completed from Executor[gko::ReferenceExecutor,0x21400d0] to
Executor[gko::ReferenceExecutor,0x21400d0] from Location[0x21480a0] to Location[0x2149780] with
Bytes[152]
[LOG] >> allocation started on Executor[gko::ReferenceExecutor,0x21400d0] with Bytes[152]
[LOG] >> allocation completed on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2149890] with
Bytes[152]
[LOG] >> copy started from Executor[gko::ReferenceExecutor,0x21400d0] to
Executor[gko::ReferenceExecutor,0x21400d0] from Location[0x2143e90] to Location[0x2149890] with
Bytes[152]

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[LOG] >> copy completed from Executor[gko::ReferenceExecutor,0x21400d0] to
      Executor[gko::ReferenceExecutor,0x21400d0] from Location[0x2143e90] to Location[0x2149890] with
      Bytes[152]
[LOG] >> free started on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2149b10]
[LOG] >> free completed on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2149b10]
[LOG] >> free started on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2149970]
[LOG] >> free completed on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2149970]
[LOG] >> Operation[gko::solver::cg::step_1_operation<gko::matrix::Dense<double>*,
      gko::matrix::Dense<double>*, gko::matrix::Dense<double>*, gko::matrix::Dense<double>*,
      gko::Array<gko::stopping_status>*>,0x7ffd93d14ef0] started on
      Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::solver::cg::step_1_operation<gko::matrix::Dense<double>*,
      gko::matrix::Dense<double>*, gko::matrix::Dense<double>*, gko::matrix::Dense<double>*,
      gko::Array<gko::stopping_status>*>,0x7ffd93d14ef0] completed on
      Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::matrix::csr::spmv_operation<gko::matrix::Csr<double, int> const*,
      gko::matrix::Dense<double> const*, gko::matrix::Dense<double>*>,0x7ffd93d14b80] started on
      Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::matrix::csr::spmv_operation<gko::matrix::Csr<double, int> const*,
      gko::matrix::Dense<double> const*, gko::matrix::Dense<double>*>,0x7ffd93d14b80] completed on
      Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::matrix::dense::compute_dot_operation<gko::matrix::Dense<double> const*,
      gko::matrix::Dense<double> const*, gko::matrix::Dense<double>*>,0x7ffd93d14c50] started on
      Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::matrix::dense::compute_dot_operation<gko::matrix::Dense<double> const*,
      gko::matrix::Dense<double> const*, gko::matrix::Dense<double>*>,0x7ffd93d14c50] completed on
      Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::solver::cg::step_2_operation<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::matrix::Dense<double>*,
      gko::Array<gko::stopping_status>*>,0x7ffd93d14ef0] started on
      Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::solver::cg::step_2_operation<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::matrix::Dense<double>*,
      gko::Array<gko::stopping_status>*>,0x7ffd93d14ef0] completed on
      Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> copy started from Executor[gko::ReferenceExecutor,0x21400d0] to
      Executor[gko::ReferenceExecutor,0x21400d0] from Location[0x21480a0] to Location[0x21482f0] with
      Bytes[152]
[LOG] >> copy completed from Executor[gko::ReferenceExecutor,0x21400d0] to
      Executor[gko::ReferenceExecutor,0x21400d0] from Location[0x21480a0] to Location[0x21482f0] 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>*>,0x7ffd93d14c50] started on
      Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::matrix::dense::compute_dot_operation<gko::matrix::Dense<double> const*,
      gko::matrix::Dense<double> const*, gko::matrix::Dense<double>*>,0x7ffd93d14c50] completed on
      Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> iteration 18 completed with solver LinOp[gko::solver::Cg<double>,0x2142d60] with residual
      LinOp[gko::matrix::Dense<double>,0x2147b30], solution LinOp[gko::matrix::Dense<double>,0x2143450] and
      residual_norm LinOp[gko::LinOp const*,0]
[LOG] >> check started for stop::Criterion[gko::stop::ResidualNorm<double>,0x2148db0] at iteration 18 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>*>,0x7ffd93d14ad0] started on Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::matrix::dense::compute_norm2_operation<gko::matrix::Dense<double> const*,
      gko::matrix::Dense<double>*>,0x7ffd93d14ad0] completed on Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::stop::residual_norm::residual_norm_operation<gko::matrix::Dense<double> const* &,
      gko::matrix::Dense<double>*, double &, unsigned char &, bool &, gko::Array<gko::stopping_status>* &,
      gko::Array<bool>*, bool*, bool* &>,0x7ffd93d14b90] started on
      Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::stop::residual_norm::residual_norm_operation<gko::matrix::Dense<double> const* &,
      gko::matrix::Dense<double>*, double &, unsigned char &, bool &, gko::Array<gko::stopping_status>* &,
      gko::Array<bool>*, bool*, bool* &>,0x7ffd93d14b90] completed on
      Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> check completed for stop::Criterion[gko::stop::ResidualNorm<double>,0x2148db0] at iteration 18 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,0x21400d0] with Bytes[152]
[LOG] >> allocation completed on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2149620] with
      Bytes[152]
[LOG] >> copy started from Executor[gko::ReferenceExecutor,0x21400d0] to
      Executor[gko::ReferenceExecutor,0x21400d0] from Location[0x21480a0] to Location[0x2149620] with
      Bytes[152]
[LOG] >> copy completed from Executor[gko::ReferenceExecutor,0x21400d0] to
      Executor[gko::ReferenceExecutor,0x21400d0] from Location[0x21480a0] to Location[0x2149620] with
      Bytes[152]
[LOG] >> allocation started on Executor[gko::ReferenceExecutor,0x21400d0] with Bytes[152]
[LOG] >> allocation completed on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2149cf0] with
      Bytes[152]
[LOG] >> copy started from Executor[gko::ReferenceExecutor,0x21400d0] to
      Executor[gko::ReferenceExecutor,0x21400d0] from Location[0x2143e90] to Location[0x2149cf0] with
      Bytes[152]
[LOG] >> copy completed from Executor[gko::ReferenceExecutor,0x21400d0] to
      Executor[gko::ReferenceExecutor,0x21400d0] from Location[0x2143e90] to Location[0x2149cf0] with
      Bytes[152]
[LOG] >> free started on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2149890]

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[LOG] >> free completed on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2149890]
[LOG] >> free started on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2149780]
[LOG] >> free completed on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2149780]
[LOG] >> Operation[gko::solver::cg::step_1_operation<gko::matrix::Dense<double>*,
    gko::matrix::Dense<double>*, gko::matrix::Dense<double>*, gko::matrix::Dense<double>*,
    gko::Array<gko::stopping_status>*>,0x7ffd93d14ef0] started on
    Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::solver::cg::step_1_operation<gko::matrix::Dense<double>*,
    gko::matrix::Dense<double>*, gko::matrix::Dense<double>*, gko::matrix::Dense<double>*,
    gko::Array<gko::stopping_status>*>,0x7ffd93d14ef0] completed on
    Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::matrix::csr::spmv_operation<gko::matrix::Csr<double, int> const*,
    gko::matrix::Dense<double> const*, gko::matrix::Dense<double>*>,0x7ffd93d14b80] started on
    Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::matrix::csr::spmv_operation<gko::matrix::Csr<double, int> const*,
    gko::matrix::Dense<double> const*, gko::matrix::Dense<double>*>,0x7ffd93d14b80] completed on
    Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::matrix::dense::compute_dot_operation<gko::matrix::Dense<double> const*,
    gko::matrix::Dense<double> const*, gko::matrix::Dense<double>*>,0x7ffd93d14c50] started on
    Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::matrix::dense::compute_dot_operation<gko::matrix::Dense<double> const*,
    gko::matrix::Dense<double> const*, gko::matrix::Dense<double>*>,0x7ffd93d14c50] completed on
    Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::solver::cg::step_2_operation<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>*>,0x7ffd93d14ef0] started on
    Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::solver::cg::step_2_operation<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>*>,0x7ffd93d14ef0] completed on
    Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> copy started from Executor[gko::ReferenceExecutor,0x21400d0] to
    Executor[gko::ReferenceExecutor,0x21400d0] from Location[0x21480a0] to Location[0x21482f0] with
    Bytes[152]
[LOG] >> copy completed from Executor[gko::ReferenceExecutor,0x21400d0] to
    Executor[gko::ReferenceExecutor,0x21400d0] from Location[0x21480a0] to Location[0x21482f0] 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>*>,0x7ffd93d14c50] started on
    Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::matrix::dense::compute_dot_operation<gko::matrix::Dense<double> const*,
    gko::matrix::Dense<double> const*, gko::matrix::Dense<double>*>,0x7ffd93d14c50] completed on
    Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> iteration 19 completed with solver LinOp[gko::solver::Cg<double>,0x2142d60] with residual
    LinOp[gko::matrix::Dense<double>,0x2147b30], solution LinOp[gko::matrix::Dense<double>,0x2143450] and
    residual_norm LinOp[gko::LinOp const*,0]
[LOG] >> check started for stop::Criterion[gko::stop::ResidualNorm<double>,0x2148db0] at iteration 19 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>*>,0x7ffd93d14ad0] started on Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::matrix::dense::compute_norm2_operation<gko::matrix::Dense<double> const*,
    gko::matrix::Dense<double>*>,0x7ffd93d14ad0] completed on Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::stop::residual_norm::residual_norm_operation<gko::matrix::Dense<double> const*,
    gko::matrix::Dense<double>*, double&, unsigned char&, bool&, gko::Array<gko::stopping_status>* &,
    gko::Array<bool>*, bool*, bool*>,0x7ffd93d14b90] started on
    Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::stop::residual_norm::residual_norm_operation<gko::matrix::Dense<double> const*,
    gko::matrix::Dense<double>*, double&, unsigned char&, bool&, gko::Array<gko::stopping_status>* &,
    gko::Array<bool>*, bool*, bool*>,0x7ffd93d14b90] completed on
    Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> check completed for stop::Criterion[gko::stop::ResidualNorm<double>,0x2148db0] at iteration 19 with
    ID 1 and finalized set to 1. It changed one RHS 1, stopped the iteration process 1
[LOG] >> allocation started on Executor[gko::ReferenceExecutor,0x21400d0] with Bytes[152]
[LOG] >> allocation completed on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2149890] with
    Bytes[152]
[LOG] >> copy started from Executor[gko::ReferenceExecutor,0x21400d0] to
    Executor[gko::ReferenceExecutor,0x21400d0] from Location[0x21480a0] to Location[0x2149890] with
    Bytes[152]
[LOG] >> copy completed from Executor[gko::ReferenceExecutor,0x21400d0] to
    Executor[gko::ReferenceExecutor,0x21400d0] from Location[0x21480a0] to Location[0x2149890] with
    Bytes[152]
[LOG] >> allocation started on Executor[gko::ReferenceExecutor,0x21400d0] with Bytes[152]
[LOG] >> allocation completed on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2149340] with
    Bytes[152]
[LOG] >> copy started from Executor[gko::ReferenceExecutor,0x21400d0] to
    Executor[gko::ReferenceExecutor,0x21400d0] from Location[0x2143e90] to Location[0x2149340] with
    Bytes[152]
[LOG] >> copy completed from Executor[gko::ReferenceExecutor,0x21400d0] to
    Executor[gko::ReferenceExecutor,0x21400d0] from Location[0x2143e90] to Location[0x2149340] with
    Bytes[152]
[LOG] >> free started on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2149cf0]
[LOG] >> free completed on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2149cf0]
[LOG] >> free started on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2149620]
[LOG] >> free completed on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2149620]
[LOG] >> free started on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2148ee0]

```



```

[LOG] >> free completed on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2148ee0]
[LOG] >> free started on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2147ce0]
[LOG] >> free completed on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2147ce0]
[LOG] >> free started on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2148e50]
[LOG] >> free completed on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2148e50]
[LOG] >> free started on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2147c90]
[LOG] >> free completed on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2147c90]
[LOG] >> free started on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x21482b0]
[LOG] >> free completed on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x21482b0]
[LOG] >> free started on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2148a40]
[LOG] >> free completed on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2148a40]
[LOG] >> free started on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2148a60]
[LOG] >> free completed on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2148a60]
[LOG] >> free started on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2148010]
[LOG] >> free completed on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2148010]
[LOG] >> free started on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x21486b0]
[LOG] >> free completed on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x21486b0]
[LOG] >> free started on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x21484d0]
[LOG] >> free completed on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x21484d0]
[LOG] >> free started on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x21482f0]
[LOG] >> free completed on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x21482f0]
[LOG] >> free started on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x21480a0]
[LOG] >> free completed on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x21480a0]
[LOG] >> free started on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2143410]
[LOG] >> free completed on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2143410]
[LOG] >> free started on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2142280]
[LOG] >> free completed on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2142280]
[LOG] >> apply completed on A LinOp[gko::solver::Cg<double>,0x2142d60] with b
    LinOp[gko::matrix::Dense<double>,0x2142140] and x LinOp[gko::matrix::Dense<double>,0x2143450]
Last memory copied was of size 98 FROM executor 0x21400d0 pointer 2143e90 TO executor 0x21400d0 pointer
2149340
Residual = [
    8.1654e-19
    -1.51449e-17
    2.23854e-17
    -1.0842e-19
    6.09864e-20
    -1.92446e-18
    1.97867e-18
    -4.58075e-18
    -1.55854e-18
    -2.64274e-17
    4.20128e-17
    -8.71427e-18
    -2.62919e-18
    -5.49947e-17
    5.51893e-17
    -1.57022e-16
    -4.2034e-17
    -8.71951e-16
    1.37837e-15
];
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,0x21400d0] with Bytes[8]
[LOG] >> allocation completed on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2149bb0] with
Bytes[8]
[LOG] >> allocation started on Executor[gko::ReferenceExecutor,0x21400d0] with Bytes[8]
[LOG] >> allocation completed on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2149870] with
Bytes[8]
[LOG] >> allocation started on Executor[gko::ReferenceExecutor,0x21400d0] with Bytes[8]
[LOG] >> allocation completed on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2149500] 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>*>,0x7ffd93d14e50] started on
Executor[gko::ReferenceExecutor,0x21400d0]

```

```
[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>*>,0x7ffd93d14e50] completed on
Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::matrix::dense::compute_norm2_operation<gko::matrix::Dense<double> const*,
gko::matrix::Dense<double>*>,0x7ffd93d14f70] started on Executor[gko::ReferenceExecutor,0x21400d0]
[LOG] >> Operation[gko::matrix::dense::compute_norm2_operation<gko::matrix::Dense<double> const*,
gko::matrix::Dense<double>*>,0x7ffd93d14f70] completed on Executor[gko::ReferenceExecutor,0x21400d0]
Residual norm sqrt(r^T r):
%%MatrixMarket matrix array real general
1 1
2.10788e-15
[LOG] >> free started on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2149500]
[LOG] >> free completed on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2149500]
[LOG] >> free started on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2149870]
[LOG] >> free completed on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2149870]
[LOG] >> free started on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2149870]
[LOG] >> free completed on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2149870]
[LOG] >> free started on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2149bb0]
[LOG] >> free completed on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2149bb0]
[LOG] >> free started on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2143e90]
[LOG] >> free completed on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2143e90]
[LOG] >> free started on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2143590]
[LOG] >> free completed on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2143590]
[LOG] >> free started on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2143590]
[LOG] >> free completed on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2143590]
[LOG] >> free started on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2142b10]
[LOG] >> free completed on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2142b10]
[LOG] >> free started on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2143c30]
[LOG] >> free completed on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2143c30]
[LOG] >> free started on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2143790]
[LOG] >> free completed on Executor[gko::ReferenceExecutor,0x21400d0] at Location[0x2143790]
```

Comments about programming and debugging

The plain program

```
/******<GINKGO LICENSE>*****
Copyright (c) 2017–2021, the Ginkgo authors
All rights reserved.
```

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```
*****<GINKGO LICENSE>*****/
#include <ginkgo/ginkgo.hpp>
#include <fstream>
#include <iomanip>
#include <iostream>
#include <map>
#include <string>
namespace {
template <typename ValueType>
void print_vector(const std::string &name,
                 const gko::matrix::Dense<ValueType> *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 ValueType = double;
    using RealValueType = gko::remove_complex<ValueType>;
    using IndexType = int;
    using vec = gko::matrix::Dense<ValueType>;
    using real_vec = gko::matrix::Dense<RealValueType>;
    using mtx = gko::matrix::Csr<ValueType, IndexType>;
    using cg = gko::solver::Cg<ValueType>;
    std::cout << gko::version_info::get() << std::endl;
    if (argc == 2 && (std::string(argv[1]) == "--help")) {
        std::cerr << "Usage: " << argv[0] << " [executor]" << std::endl;
        std::exit(-1);
    }
    const auto executor_string = argc >= 2 ? argv[1] : "reference";
    std::map<std::string, std::function<std::shared_ptr<gko::Executor>()>>
    exec_map{
        {"omp", [] { return gko::OmpExecutor::create(); }},
        {"cuda",
         [] {
             return gko::CudaExecutor::create(0, gko::OmpExecutor::create(),
                                              true);
         }},
        {"hip",
         [] {
             return gko::HipExecutor::create(0, gko::OmpExecutor::create(),
                                              true);
         }},
        {"dpcpp",
         [] {
             return gko::DpcppExecutor::create(0,
                                              gko::OmpExecutor::create());
         }},
        {"reference", [] { return gko::ReferenceExecutor::create(); } }
    };
    const auto exec = exec_map.at(executor_string)(); // throws if not valid
    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<ValueType>> stream_logger =
        gko::log::Stream<ValueType>::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);
    const RealValueType reduction_factor{1e-7};
    using ResidualCriterionFactory =
        gko::stop::ResidualNorm<ValueType>::Factory;
    std::shared_ptr<ResidualCriterionFactory> residual_criterion =
        ResidualCriterionFactory::create()
            .with_reduction_factor(reduction_factor)
            .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<ValueType>::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<vec>(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<real_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 32

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:

$$\begin{aligned} u &: [0, 1] \rightarrow \mathbb{R} \\ u'' &= f \\ u(0) &= u_0 \\ u(1) &= u_1 \end{aligned}$$

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:

$$\begin{aligned} u(x+h) &= u(x) + u'(x)h + \frac{1}{2}u''(x)h^2 + O(h^3) \\ u(x-h) &= u(x) - u'(x)h + \frac{1}{2}u''(x)h^2 + O(h^3) \\ \hline -u(x-h) + 2u(x) - u(x+h) &= -f(x)h^2 + O(h^3) \end{aligned}$$

For an equidistant grid with K "inner" discretization points x_1, \dots, x_K , and step size $h = 1/(K+1)$, the formula produces a system of linear equations

$$\begin{aligned} 2u_1 - u_2 &= -f_1 h^2 + u_0 \\ -u_{k-1} + 2u_k - u_{k+1} &= -f_k h^2, \quad k = 2, \dots, K-1 \\ -u_{K-1} + 2u_K &= -f_K h^2 + u_1 \end{aligned}$$

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 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

```

/ *****<DESCRIPTION>*****
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.
*****<DESCRIPTION>***** /

#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.

```

template <typename ValueType, typename IndexType>
void generate_stencil_matrix(IndexType discretization_points,
                           IndexType *row_ptrs, IndexType *col_idxes,
                           ValueType *values)
{
    IndexType pos = 0;
    const ValueType coefs[] = {-1, 2, -1};
    row_ptrs[0] = pos;
    for (IndexType 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_idxes[pos] = i + ofs;
                ++pos;
            }
        }
        row_ptrs[i + 1] = pos;
    }
}

```

Generates the RHS vector given f and the boundary conditions.

```

template <typename Closure, typename ValueType, typename IndexType>
void generate_rhs(IndexType discretization_points, Closure f, ValueType u0,
                 ValueType u1, ValueType *rhs)
{
    const ValueType h = 1.0 / (discretization_points + 1);
    for (IndexType i = 0; i < discretization_points; ++i) {
        const ValueType xi = ValueType(i + 1) * h;
        rhs[i] = -f(xi) * h * h;
    }
    rhs[0] += u0;
    rhs[discretization_points - 1] += u1;
}

```

Prints the solution u.

```

template <typename ValueType, typename IndexType>
void print_solution(IndexType discretization_points, ValueType u0, ValueType u1,
                   const ValueType *u)

```

```
{
    std::cout << u0 << '\n';
    for (IndexType 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, typename ValueType, typename IndexType>
gko::remove_complex<ValueType> calculate_error(IndexType discretization_points,
                                              const ValueType *u,
                                              Closure correct_u)
{
    const ValueType h = 1.0 / (discretization_points + 1);
    gko::remove_complex<ValueType> error = 0.0;
    for (IndexType i = 0; i < discretization_points; ++i) {
        using std::abs;
        const ValueType xi = ValueType(i + 1) * h;
        error += abs(u[i] - correct_u(xi)) / abs(correct_u(xi));
    }
    return error;
}

template <typename ValueType, typename IndexType>
void solve_system(const std::string &executor_string,
                 IndexType discretization_points, IndexType *row_ptrs,
                 IndexType *col_idxs, ValueType *values, ValueType *rhs,
                 ValueType *u, gko::remove_complex<ValueType> reduction_factor)
{

```

Some shortcuts

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

Figure out where to run the code

```
std::map<std::string, std::function<std::shared_ptr<gko::Executor>()>>
    exec_map{
        {"omp", [] { return gko::OmpExecutor::create(); }},
        {"cuda",
         [] {
             return gko::CudaExecutor::create(0, gko::OmpExecutor::create(),
                                              true);
         }},
        {"hip",
         [] {
             return gko::HipExecutor::create(0, gko::OmpExecutor::create(),
                                              true);
         }},
        {"dpcpp",
         [] {
             return gko::DpcppExecutor::create(0,
                                              gko::OmpExecutor::create());
         }},
        {"reference", [] { return 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->get_master();
```

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 SpMV's 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_idx),
    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(gko::size_type(dp))
            .on(exec),
            gko::stop::ResidualNorm<ValueType>::build()
            .with_reduction_factor(reduction_factor)
            .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[])
{
    using ValueType = double;
    using IndexType = int;

```

Print version information

```

std::cout << gko::version_info::get() << std::endl;
if (argc == 2 && std::string(argv[1]) == "--help") {
    std::cerr << "Usage: " << argv[0]
        << " [executor] [DISCRETIZATION_POINTS]" << std::endl;
    std::exit(-1);
}
const auto executor_string = argc >= 2 ? argv[1] : "reference";
const IndexType discretization_points =
    argc >= 3 ? std::atoi(argv[2]) : 100;

```

problem:

```

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

```

matrix

```

std::vector<IndexType> row_ptrs(discretization_points + 1);
std::vector<IndexType> col_idx(3 * discretization_points - 2);
std::vector<ValueType> values(3 * discretization_points - 2);

```

right hand side

```

std::vector<ValueType> rhs(discretization_points);

```

solution

```

std::vector<ValueType> u(discretization_points, 0.0);
const gko::remove_complex<ValueType> reduction_factor = 1e-7;
generate_stencil_matrix(discretization_points, row_ptrs.data(),
    col_idx.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_idx.data(), values.data(), rhs.data(), u.data(),
    reduction_factor);

```

Uncomment to print the solution `print_solution<ValueType, IndexType>(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:

The average relative error is 2.52236e-11

Comments about programming and debugging

The plain program

```

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```

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```

/*****<GINKGO LICENSE>*****/
/*****<DESCRIPTION>*****/
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:

$$\begin{aligned}
 u(x+h) &= u(x) - u'(x)h + \frac{1}{2} u''(x)h^2 + O(h^3) \\
 u(x-h) &= u(x) + u'(x)h + \frac{1}{2} u''(x)h^2 + O(h^3) \quad / + \\
 \hline
 -u(x-h) + 2u(x) - u(x+h) &= -f(x)h^2 + O(h^3)
 \end{aligned}$$

For an equidistant grid with K "inner" discretization points x_1, \dots, x_K , and step size $h = 1 / (K + 1)$, the formula produces a system of linear equations

$$\begin{aligned}
 2u_1 - u_2 &= -f_1 h^2 + u_0 \\
 -u_{(k-1)} + 2u_k - u_{(k+1)} &= -f_k h^2, \quad k = 2, \dots, K-1 \\
 -u_{(K-1)} + 2u_K &= -f_K h^2 + u_1
 \end{aligned}$$

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 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.

```

/*****<DESCRIPTION>*****/
#include <ginkgo/ginkgo.hpp>

```

```

#include <iostream>
#include <map>
#include <string>
#include <vector>
template <typename ValueType, typename IndexType>
void generate_stencil_matrix(IndexType discretization_points,
                           IndexType *row_ptrs, IndexType *col_idx,
                           ValueType *values)
{
    IndexType pos = 0;
    const ValueType coeffs[] = {-1, 2, -1};
    row_ptrs[0] = pos;
    for (IndexType i = 0; i < discretization_points; ++i) {
        for (auto ofs : {-1, 0, 1}) {
            if (0 <= i + ofs && i + ofs < discretization_points) {
                values[pos] = coeffs[ofs + 1];
                col_idx[pos] = i + ofs;
                ++pos;
            }
        }
        row_ptrs[i + 1] = pos;
    }
}

template <typename Closure, typename ValueType, typename IndexType>
void generate_rhs(IndexType discretization_points, Closure f, ValueType u0,
                 ValueType u1, ValueType *rhs)
{
    const ValueType h = 1.0 / (discretization_points + 1);
    for (IndexType i = 0; i < discretization_points; ++i) {
        const ValueType xi = ValueType(i + 1) * h;
        rhs[i] = -f(xi) * h * h;
    }
    rhs[0] += u0;
    rhs[discretization_points - 1] += u1;
}

template <typename ValueType, typename IndexType>
void print_solution(IndexType discretization_points, ValueType u0, ValueType u1,
                   const ValueType *u)
{
    std::cout << u0 << '\n';
    for (IndexType i = 0; i < discretization_points; ++i) {
        std::cout << u[i] << '\n';
    }
    std::cout << u1 << std::endl;
}

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

template <typename ValueType, typename IndexType>
void solve_system(const std::string &executor_string,
                  IndexType discretization_points, IndexType *row_ptrs,
                  IndexType *col_idx, ValueType *values, ValueType *rhs,
                  ValueType *u, gko::remove_complex<ValueType> reduction_factor)
{
    using vec = gko::matrix::Dense<ValueType>;
    using mtx = gko::matrix::Csr<ValueType, IndexType>;
    using cg = gko::solver::Cg<ValueType>;
    using bj = gko::preconditioner::Jacobi<ValueType, IndexType>;
    using val_array = gko::Array<ValueType>;
    using idx_array = gko::Array<IndexType>;
    const auto &dp = discretization_points;
    std::map<std::string, std::function<std::shared_ptr<gko::Executor>()>>
    exec_map{
        {"omp", [] { return gko::OmpExecutor::create(); }},
        {"cuda",
         [] {
             return gko::CudaExecutor::create(0, gko::OmpExecutor::create(),
                                              true);
         }},
        {"hip",
         [] {
             return gko::HipExecutor::create(0, gko::OmpExecutor::create(),
                                              true);
         }},
        {"dpcpp",
         [] {

```

```

        return gko::DpcppExecutor::create(0,
                                           gko::OmpExecutor::create());
    }},
    {"reference", [] { return gko::ReferenceExecutor::create(); }});
const auto exec = exec_map.at(executor_string)(); // throws if not valid
const auto app_exec = exec->get_master();
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(gko::size_type(dp))
                      .on(exec),
                      gko::stop::ResidualNorm<ValueType>::build()
                      .with_reduction_factor(reduction_factor)
                      .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[])
{
    using ValueType = double;
    using IndexType = int;
    std::cout << gko::version_info::get() << std::endl;
    if (argc == 2 && std::string(argv[1]) == "--help") {
        std::cerr << "Usage: " << argv[0]
                  << " [executor] [DISCRETIZATION_POINTS]" << std::endl;
        std::exit(-1);
    }
    const auto executor_string = argc >= 2 ? argv[1] : "reference";
    const IndexType discretization_points =
        argc >= 3 ? std::atoi(argv[2]) : 100;
    auto correct_u = [] (ValueType x) { return x * x * x; };
    auto f = [] (ValueType x) { return ValueType(6) * x; };
    auto u0 = correct_u(0);
    auto u1 = correct_u(1);
    std::vector<IndexType> row_ptrs(discretization_points + 1);
    std::vector<IndexType> col_idxs(3 * discretization_points - 2);
    std::vector<ValueType> values(3 * discretization_points - 2);
    std::vector<ValueType> rhs(discretization_points);
    std::vector<ValueType> u(discretization_points, 0.0);
    const gko::remove_complex<ValueType> reduction_factor = 1e-7;
    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(),
                reduction_factor);
    std::cout << "The average relative error is "
              << calculate_error(discretization_points, u.data(), correct_u) /
                discretization_points
              << std::endl;
}

```


Chapter 33

Module Documentation

33.1 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.

33.1.1 Detailed Description

A module dedicated to the implementation and usage of the CUDA executor in Ginkgo.

33.2 DPC++ Executor

A module dedicated to the implementation and usage of the DPC++ executor in Ginkgo.

Classes

- class [gko::DpcppExecutor](#)

This is the [Executor](#) subclass which represents a DPC++ enhanced device.

33.2.1 Detailed Description

A module dedicated to the implementation and usage of the DPC++ executor in Ginkgo.

33.3 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.
- [DPC++ Executor](#)
A module dedicated to the implementation and usage of the DPC++ executor in Ginkgo.
- [HIP Executor](#)
A module dedicated to the implementation and usage of the HIP 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.
- class [gko::HipExecutor](#)
This is the [Executor](#) subclass which represents the HIP enhanced device.
- class [gko::DpcppExecutor](#)
This is the [Executor](#) subclass which represents a DPC++ enhanced device.

Macros

- `#define GKO_REGISTER_OPERATION(_name, _kernel)`
Binds a set of device-specific kernels to an Operation.

33.3.1 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.

33.3.2 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;
- [HIP Executor](#) uses the HIP library to compile code for either NVIDIA or AMD GPU accelerator;
- [DPC++ Executor](#) uses the DPC++ compiler for any DPC++ supported hardware (e.g. Intel CPUs, GPU, FPGAs, ...);
- [Reference Executor](#) executes a non-optimized reference implementation, which can be used to debug the library.

33.3.3 Macro Definition Documentation

33.3.3.1 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`, `hip`, `dpcpp` and `reference`.

Parameters

| | |
|----------------------|---|
| <code>_name</code> | operation name |
| <code>_kernel</code> | kernel which will be bound to the operation |

33.3.3.2 Example

```
{c++}
// define the omp, cuda, hip 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 hip {
void my_kernel(int x) {
    // hip code
}
}
namespace dpcpp {
void my_kernel(int x) {
    // dpcpp 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 hip = HipExecutor::create(omp, 0);
    auto dpcpp = DpcppExecutor::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
    hip->run(op); // run hip kernel
    dpcpp->run(op); // run DPC++ kernel
    ref->run(op); // run reference kernel
}
```

33.4 Factorizations

A module dedicated to the implementation and usage of the Factorizations in Ginkgo.

Namespaces

- [gko::factorization](#)

The Factorization namespace.

Classes

- class [gko::factorization::lc< ValueType, IndexType >](#)
Represents an incomplete Cholesky factorization (IC(0)) of a sparse matrix.
- class [gko::factorization::llu< ValueType, IndexType >](#)
Represents an incomplete LU factorization – ILU(0) – of a sparse matrix.
- class [gko::factorization::Parlc< ValueType, IndexType >](#)
ParlC is an incomplete Cholesky factorization which is computed in parallel.
- class [gko::factorization::Parlct< ValueType, IndexType >](#)
ParlCT is an incomplete threshold-based Cholesky factorization which is computed in parallel.
- class [gko::factorization::Parllu< ValueType, IndexType >](#)
ParllU is an incomplete LU factorization which is computed in parallel.
- class [gko::factorization::Parllut< ValueType, IndexType >](#)
ParllUT is an incomplete threshold-based LU factorization which is computed in parallel.

33.4.1 Detailed Description

A module dedicated to the implementation and usage of the Factorizations in Ginkgo.

33.5 HIP Executor

A module dedicated to the implementation and usage of the HIP executor in Ginkgo.

Classes

- class `gko::HipExecutor`

This is the `Executor` subclass which represents the HIP enhanced device.

33.5.1 Detailed Description

A module dedicated to the implementation and usage of the HIP executor in Ginkgo.

33.6 Jacobi Preconditioner

A module dedicated to the implementation and usage of the Jacobi Preconditioner in Ginkgo.

Classes

- 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.

33.6.1 Detailed Description

A module dedicated to the implementation and usage of the Jacobi Preconditioner in Ginkgo.

33.7 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 $c1 * op1 + c2 * op2 + \dots$.*
- class [gko::Composition< ValueType >](#)
*The [Composition](#) class can be used to compose linear operators $op1, op2, \dots, opn$ and obtain the operator $op1 * op2 * \dots$.*
- 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::DiagonalExtractable< ValueType >](#)
The diagonal of a [LinOp](#) implementing this interface can be extracted.
- class [gko::EnableAbsoluteComputation< AbsoluteLinOp >](#)
The [EnableAbsoluteComputation](#) mixin provides the default implementations of `compute_absolute_linop` and the `absolute` interface.
- 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::factorization::lc< ValueType, IndexType >](#)
Represents an incomplete Cholesky factorization (IC(0)) of a sparse matrix.
- class [gko::factorization::llu< ValueType, IndexType >](#)
Represents an incomplete LU factorization – ILU(0) – of a sparse matrix.
- class [gko::factorization::Parlc< ValueType, IndexType >](#)
Parlc is an incomplete Cholesky factorization which is computed in parallel.
- class [gko::factorization::Parlct< ValueType, IndexType >](#)
Parlct is an incomplete threshold-based Cholesky factorization which is computed in parallel.

- class `gko::factorization::Parllu< ValueType, IndexType >`
ParLLU is an incomplete LU factorization which is computed in parallel.
- class `gko::factorization::Parllut< ValueType, IndexType >`
ParLLUT is an incomplete threshold-based LU factorization which is computed in parallel.
- 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::Diagonal< ValueType >`
This class is a utility which efficiently implements the diagonal matrix (a linear operator which scales a vector row wise).
- 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::Permutation< IndexType >`
Permutation is a matrix "format" which stores the row and column permutation arrays which can be used for re-ordering the rows and columns a matrix.
- class `gko::matrix::Sellp< ValueType, IndexType >`
SELL-P is a matrix format similar to ELL format.
- class `gko::matrix::SparsityCsr< ValueType, IndexType >`
SparsityCsr is a matrix format which stores only the sparsity pattern of a sparse matrix by compressing each row of the matrix (compressed sparse row format).
- class `gko::multigrid::AmgxPgm< ValueType, IndexType >`
Amgx parallel graph match ([AmgxPgm](#)) is the aggregate method introduced in the paper M.
- class `gko::preconditioner::Ic< LSolverType, IndexType >`
*The Incomplete Cholesky (IC) preconditioner solves the equation $LL^H * x = b$ for a given lower triangular matrix L and the right hand side b (can contain multiple right hand sides).*
- class `gko::preconditioner::Ilu< LSolverType, USolverType, ReverseApply, IndexType >`
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 `gko::preconditioner::Isai< IsaiType, ValueType, IndexType >`
The Incomplete Sparse Approximate Inverse (ISAI) Preconditioner generates an approximate inverse matrix for a given lower triangular matrix L or upper triangular matrix U.
- 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::Bicg< ValueType >`
BICG or the Biconjugate gradient method is a Krylov subspace solver.
- class `gko::solver::Bicgstab< ValueType >`
BiCGSTAB or the Bi-Conjugate Gradient-Stabilized is a Krylov subspace solver.
- class `gko::solver::CbGmres< ValueType >`
CB-GMRES or the compressed basis generalized minimal residual method is an iterative type Krylov subspace method which is suitable for nonsymmetric linear systems.

- 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::ldr< ValueType >`
IDR(s) is an efficient method for solving large nonsymmetric systems of linear equations.
- class `gko::solver::lr< 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.
- class `gko::solver::LowerTrs< ValueType, IndexType >`
`LowerTrs` is the triangular solver which solves the system $Lx = b$, when L is a lower triangular matrix.
- class `gko::solver::UpperTrs< ValueType, IndexType >`
`UpperTrs` is the triangular solver which solves the system $Ux = b$, 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.
- `#define GKO_FACTORY_PARAMETER_SCALAR(_name, _default) GKO_FACTORY_PARAMETER(_name, _default)`
Creates a scalar factory parameter in the factory parameters structure.
- `#define GKO_FACTORY_PARAMETER_VECTOR(_name, ...) GKO_FACTORY_PARAMETER(_name, _VA_ARGS_)`
Creates a vector factory parameter in the factory parameters structure.

Typedefs

- `template<typename ConcreteFactory, typename ConcreteLinOp, typename ParametersType, typename PolymorphicBase = LinOpFactory>`
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`.

33.7.1 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.

33.7.2 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.

33.7.3 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

33.7.4 Macro Definition Documentation

33.7.4.1 GKO_CREATE_FACTORY_PARAMETERS

```
#define GKO_CREATE_FACTORY_PARAMETERS(
    _parameters_name,
    _factory_name )
```

Value:

```
public:
    class _factory_name;
    struct _parameters_name##_type
        : public ::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

| | |
|-------------------------------|--|
| <code>_parameters_name</code> | name of the parameters member in the class |
| <code>_factory_name</code> | name of the generated factory type |

33.7.4.2 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

| | |
|----------------------------|--|
| <code>_factory_name</code> | the factory for which to define the method |
|----------------------------|--|

33.7.4.3 GKO_ENABLE_LIN_OP_FACTORY

```
#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.

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_SCALAR(my_value,
// a factory parameter named my_pair of type std::pair<int, int> // and default value {5, 5} std::pair<int,
int> GKO_FACTORY_PARAMETER_VECTOR(my_pair, 5, 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_*`() macros 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

<code>_lin_op</code>	concrete operator for which the factory is to be created [CRTP parameter]
<code>_parameters_name</code>	name of the parameters member in the class (its type is <code><_parameters_name>_type</code> , the protected member's name is <code><_parameters_name>_</code> , and the public getter's name is <code>get_<_parameters_name>()</code>)
<code>_factory_name</code>	name of the generated factory type

33.7.4.4 GKO_FACTORY_PARAMETER

```
#define GKO_FACTORY_PARAMETER(
    _name,
    ... )
```

Value:

```
mutable _name{__VA_ARGS__};

template <typename... Args>
auto with_##_name(Args &&... _value)
    const->const std::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

<code>_name</code>	name of the parameter
<code>VA_ARGS</code>	default value of the parameter

See also

[GKO_ENABLE_LIN_OP_FACTORY](#) for more details, and usage example

33.7.4.5 GKO_FACTORY_PARAMETER_SCALAR

```
#define GKO_FACTORY_PARAMETER_SCALAR(
    _name,
    _default ) GKO_FACTORY_PARAMETER(_name, _default)
```

Creates a scalar factory parameter in the factory parameters structure.

Scalar in this context means that the constructor for this type only takes a single parameter.

Parameters

<code>_name</code>	name of the parameter
<code>_default</code>	default value of the parameter

See also

[GKO_ENABLE_LIN_OP_FACTORY](#) for more details, and usage example

33.7.4.6 GKO_FACTORY_PARAMETER_VECTOR

```
#define GKO_FACTORY_PARAMETER_VECTOR(
    _name,
    ... ) GKO_FACTORY_PARAMETER(_name, __VA_ARGS__)
```

Creates a vector factory parameter in the factory parameters structure.

Vector in this context means that the constructor for this type takes multiple parameters.

Parameters

<code>_name</code>	name of the parameter
<code>_default</code>	default value of the parameter

See also

[GKO_ENABLE_LIN_OP_FACTORY](#) for more details, and usage example

33.7.5 Typedef Documentation

33.7.5.1 EnableDefaultLinOpFactory

```
template<typename ConcreteFactory , typename ConcreteLinOp , typename ParametersType , typename
PolymorphicBase = LinOpFactory>
using gko::EnableDefaultLinOpFactory = typedef 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](#).

Template Parameters

<i>ConcreteFactory</i>	the concrete factory which is being implemented [CRTP parameter]
<i>ConcreteLinOp</i>	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.
<i>ParametersType</i>	a subclass of enable_parameters_type template which defines all of the parameters of the factory
<i>PolymorphicBase</i>	parent of ConcreteFactory in the polymorphic hierarchy, has to be a subclass of LinOpFactory

33.8 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.

33.8.1 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.

33.9 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::Diagonal< ValueType >`
This class is a utility which efficiently implements the diagonal matrix (a linear operator which scales a vector row wise).
- 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::Permutation< IndexType >`
Permutation is a matrix "format" which stores the row and column permutation arrays which can be used for re-ordering the rows and columns a matrix.
- class `gko::matrix::Sellp< ValueType, IndexType >`
SELL-P is a matrix format similar to ELL format.
- class `gko::matrix::SparsityCsr< ValueType, IndexType >`
SparsityCsr is a matrix format which stores only the sparsity pattern of a sparse matrix by compressing each row of the matrix (compressed sparse row 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.

33.9.1 Detailed Description

A module dedicated to the implementation and usage of the various Matrix Formats in Ginkgo.

33.9.2 Function Documentation

33.9.2.1 initialize() [1/4]

```
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

<i>Matrix</i>	matrix type to initialize (Dense has to implement the ConvertibleTo<Matrix> interface)
<i>TArgs</i>	argument types for Matrix::create method (not including the implied Executor as the first argument)

Parameters

<i>stride</i>	row stride for the temporary Dense matrix
<i>vals</i>	values used to initialize the matrix
<i>exec</i>	Executor associated to the matrix
<i>create_args</i>	additional arguments passed to Matrix::create, not including the Executor , which is passed as the first argument

```
807 {
808     using dense = matrix::Dense<typename Matrix::value_type>;
809     size_type num_rows = vals.size();
810     size_type num_cols = num_rows > 0 ? begin(vals)->size() : 1;
811     auto tmp =
812         dense::create(exec->get_master(), dim<2>{num_rows, num_cols}, stride);
813     size_type ridx = 0;
814     for (const auto &row : vals) {
815         size_type cidx = 0;
816         for (const auto &elem : row) {
817             tmp->at(ridx, cidx) = elem;
818             ++cidx;
819         }
820         ++ridx;
821     }
822     auto mtx = Matrix::create(exec, std::forward<TArgs>(create_args)...);
823     tmp->move_to(mtx.get());
824     return mtx;
825 }
```

References `gko::matrix::Dense< ValueType >::at()`.

33.9.2.2 initialize() [2/4]

```
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

<i>Matrix</i>	matrix type to initialize (Dense has to implement the ConvertibleTo<Matrix> interface)
<i>TArgs</i>	argument types for Matrix::create method (not including the implied Executor as the first argument)

Parameters

<i>stride</i>	row stride for the temporary Dense matrix
<i>vals</i>	values used to initialize the vector
<i>exec</i>	Executor associated to the vector
<i>create_args</i>	additional arguments passed to Matrix::create, not including the Executor , which is passed as the first argument

References `gko::matrix::Dense< ValueType >::at()`.

33.9.2.3 initialize() [3/4]

```
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

<i>Matrix</i>	matrix type to initialize (Dense has to implement the ConvertibleTo<Matrix> interface)
<i>TArgs</i>	argument types for Matrix::create method (not including the implied Executor as the first argument)

Parameters

<i>vals</i>	values used to initialize the matrix
<i>exec</i>	Executor associated to the matrix
<i>create_args</i>	additional arguments passed to <code>Matrix::create</code> , not including the Executor , which is passed as the first argument

33.9.2.4 initialize() [4/4]

```
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

<i>Matrix</i>	matrix type to initialize (Dense has to implement the <code>ConvertibleTo<Matrix></code> interface)
<i>TArgs</i>	argument types for <code>Matrix::create</code> method (not including the implied Executor as the first argument)

Parameters

<i>vals</i>	values used to initialize the vector
<i>exec</i>	Executor associated to the vector
<i>create_args</i>	additional arguments passed to <code>Matrix::create</code> , not including the Executor , which is passed as the first argument

33.10 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).

33.10.1 Detailed Description

A module dedicated to the implementation and usage of the OpenMP executor in Ginkgo.

33.11 Preconditioners

A module dedicated to the implementation and usage of the Preconditioners in Ginkgo.

Modules

- [Jacobi Preconditioner](#)

A module dedicated to the implementation and usage of the Jacobi Preconditioner in Ginkgo.

Namespaces

- [gko::preconditioner](#)

The Preconditioner namespace.

Classes

- class [gko::Preconditionable](#)

A LinOp implementing this interface can be preconditioned.

- class [gko::preconditioner::lc< LSolverType, IndexType >](#)

*The Incomplete Cholesky (IC) preconditioner solves the equation $LL^H * x = b$ for a given lower triangular matrix L and the right hand side b (can contain multiple right hand sides).*

- class [gko::preconditioner::llu< LSolverType, USolverType, ReverseApply, IndexType >](#)

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 [gko::preconditioner::lsai< IsaiType, ValueType, IndexType >](#)

The Incomplete Sparse Approximate Inverse (ISAI) Preconditioner generates an approximate inverse matrix for a given lower triangular matrix L or upper triangular matrix U .

- 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.

33.11.1 Detailed Description

A module dedicated to the implementation and usage of the Preconditioners in Ginkgo.

33.12 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.

33.12.1 Detailed Description

A module dedicated to the implementation and usage of the Reference executor in Ginkgo.

33.13 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::Bicg< ValueType >](#)
BICG or the Biconjugate gradient method is a Krylov subspace solver.
- class [gko::solver::Bicgstab< ValueType >](#)
BiCGSTAB or the Bi-Conjugate Gradient-Stabilized is a Krylov subspace solver.
- class [gko::solver::CbGmres< ValueType >](#)
CB-GMRES or the compressed basis generalized minimal residual method is an iterative type Krylov subspace method which is suitable for nonsymmetric linear systems.
- 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::Idr< ValueType >](#)
IDR(s) is an efficient method for solving large nonsymmetric systems of linear equations.
- 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.
- class [gko::solver::LowerTrs< ValueType, IndexType >](#)
LowerTrs is the triangular solver which solves the system $Lx = b$, when L is a lower triangular matrix.
- class [gko::solver::UpperTrs< ValueType, IndexType >](#)
UpperTrs is the triangular solver which solves the system $Ux = b$, when U is an upper triangular matrix.

33.13.1 Detailed Description

A module dedicated to the implementation and usage of the Solvers in Ginkgo.

33.14 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::ResidualNormBase< ValueType >](#)

The [ResidualNormBase](#) class provides a framework for stopping criteria related to the residual norm.

- class [gko::stop::ResidualNorm< ValueType >](#)

The [ResidualNorm](#) class is a stopping criterion which stops the iteration process when the actual residual norm is below a certain threshold relative to.

- class [gko::stop::ImplicitResidualNorm< ValueType >](#)

The [ImplicitResidualNorm](#) class is a stopping criterion which stops the iteration process when the implicit residual norm is below a certain threshold relative to.

- class [gko::stop::ResidualNormReduction< ValueType >](#)

The [ResidualNormReduction](#) class is a stopping criterion which stops the iteration process when the residual norm is below a certain threshold relative to the norm of the initial residual, i.e.

- class [gko::stop::RelativeResidualNorm< ValueType >](#)

The [RelativeResidualNorm](#) class is a stopping criterion which stops the iteration process when the residual norm is below a certain threshold relative to the norm of the right-hand side, i.e.

- class [gko::stop::AbsoluteResidualNorm< ValueType >](#)

The [AbsoluteResidualNorm](#) class is a stopping criterion which stops the iteration process when the residual norm is below a certain threshold, i.e.

- 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 amount of time has passed.

Enumerations

- enum [gko::stop::mode](#)

The mode for the residual norm criterion.

Functions

- `template<typename FactoryContainer >`

`std::shared_ptr< const CriterionFactory > gko::stop::combine (FactoryContainer &&factories)`

Combines multiple criterion factories into a single combined criterion factory.

33.14.1 Detailed Description

A module dedicated to the implementation and usage of the Stopping Criteria in Ginkgo.

33.14.2 Enumeration Type Documentation

33.14.2.1 mode

```
enum gko::stop::mode [strong]
```

The mode for the residual norm criterion.

- absolute: Check for tolerance against residual norm. $\|r\| < \tau$
- initial_resnorm: Check for tolerance relative to the initial residual norm. $\frac{\|r\|}{\|r_0\|} < \tau$
- rhs_resnorm: Check for tolerance relative to the rhs norm. $\frac{\|r\|}{\|b\|} < \tau$

```
65 { absolute, initial_resnorm, rhs_norm };
```

33.14.3 Function Documentation

33.14.3.1 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

<i>FactoryContainer</i>	a random access container type
-------------------------	--------------------------------

Parameters

<i>factories</i>	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

```
124 {
125     switch (factories.size()) {
126     case 0:
127         GKO_NOT_SUPPORTED(nullptr);
128         return nullptr;
129     case 1:
130         if (factories[0] == nullptr) {
131             GKO_NOT_SUPPORTED(nullptr);
132         }
133         return factories[0];
134     default:
135         if (factories[0] == nullptr) {
136             // first factory must be valid to capture executor
137             GKO_NOT_SUPPORTED(nullptr);
138             return nullptr;
139         } else {
140             auto exec = factories[0]->get_executor();
141             return Combined::build()
142                 .with_criteria(std::forward<FactoryContainer>(factories))
143                 .on(exec);
144         }
145     }
146 }
```


Chapter 34

Namespace Documentation

34.1 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.
- [reorder](#)
The Reorder namespace.
- [solver](#)
The ginkgo Solve namespace.
- [stop](#)
The Stopping criterion namespace.
- [syn](#)
The Synthesizer namespace.
- [xstd](#)
The namespace for functionalities after C++14 standard.

Classes

- class [AbsoluteComputable](#)
The [AbsoluteComputable](#) is an interface that allows to get the component wise absolute of a [LinOp](#).
- 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.
- struct [are_all_integral](#)
Evaluates if all template arguments `Args` fulfill `std::is_integral`.
- 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 $c1 * op1 + c2 * op2 + \dots$.
- class [Composition](#)
The [Composition](#) class can be used to compose linear operators $op1, op2, \dots, opn$ and obtain the operator $op1 * op2 * \dots$.
- class [ConvertibleTo](#)
[ConvertibleTo](#) interface is used to mark that the implementer can be converted to the object of `ResultType`.
- struct [cpx_real_type](#)
Access the underlying real type of a complex number.
- 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 [CurandError](#)
[CurandError](#) is thrown when a cuRAND routine throws a non-zero error code.
- class [CusparsError](#)
[CusparsError](#) 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`.
- class [DiagonalExtractable](#)
The diagonal of a [LinOp](#) implementing this interface can be extracted.
- 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.
- class [DpcppExecutor](#)
This is the [Executor](#) subclass which represents a DPC++ enhanced device.
- class [enable_parameters_type](#)
The [enable_parameters_type](#) mixin is used to create a base implementation of the factory parameters structure.
- class [EnableAbsoluteComputation](#)
The [EnableAbsoluteComputation](#) mixin provides the default implementations of `compute_absolute_linop` and the `absolute` interface.
- 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 [HipblasError](#)

[HipblasError](#) is thrown when a hipBLAS routine throws a non-zero error code.

- class [HipError](#)

[HipError](#) is thrown when a HIP routine throws a non-zero error code.

- class [HipExecutor](#)

This is the [Executor](#) subclass which represents the HIP enhanced device.

- class [HiprandError](#)

[HiprandError](#) is thrown when a hipRAND routine throws a non-zero error code.

- class [HipsparseError](#)

[HipsparseError](#) is thrown when a hipSPARSE routine throws a non-zero error code.

- 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.

- class [MachineTopology](#)

The machine topology class represents the hierarchical topology of a machine, including NUMA nodes, cores and PCI Devices.

- class [matrix_assembly_data](#)

This structure is used as an intermediate type to assemble a sparse matrix.

- 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 [Permutable](#)
Linear operators which support permutation should implement the [Permutable](#) interface.
- 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 [Transposable](#)
Linear operators which support transposition should implement the [Transposable](#) interface.
- class [UseComposition](#)
The [UseComposition](#) class can be used to store the composition information in [LinOp](#).
- class [ValueMismatch](#)
[ValueMismatch](#) is thrown if two values are not equal.
- 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 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 is_complex_or_scalar_s = detail::is_complex_or_scalar_impl< T >`
Allows to check if T is a complex or scalar value during compile time by accessing the `value` attribute of this struct.
- `template<typename T >`
`using remove_complex = typename detail::remove_complex_s< T >::type`
Obtain the type which removed the complex of complex/scalar type or the template parameter of class by accessing the `type` attribute of this struct.
- `template<typename T >`
`using to_complex = typename detail::to_complex_s< T >::type`
Obtain the type which adds the complex of complex/scalar type or the template parameter of class by accessing the `type` attribute of this struct.
- `template<typename T >`
`using to_real = remove_complex< T >`
to_real is alias of remove_complex
- `template<typename T >`
`using next_precision = typename detail::next_precision_impl< T >::type`
Obtains the next type in the singly-linked precision list.
- `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 = std::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 bool `is_complex_or_scalar` ()
Checks if T is a complex/scalar 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 `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 std::enable_if_t<!is_complex_s< T >::value, T > real (const T &x)`
Returns the real part of the object.
- `template<typename T >`
`constexpr std::enable_if_t<!is_complex_s< T >::value, T > imag (const T &)`
Returns the imaginary part of the object.
- `template<typename T >`
`std::enable_if_t<!is_complex_s< T >::value, 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 xstd::enable_if_t<!is_complex_s< T >::value, T > abs (const T &x)`
Returns the absolute value 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 >`
`std::enable_if_t<!is_complex_s< T >::value, bool > is_finite (const T &value)`
Checks if a floating point number is finite, meaning it is neither +/- infinity nor NaN.
- `template<typename T >`
`std::enable_if_t< is_complex_s< T >::value, bool > is_finite (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)`
 - `template<typename T >`
`detail::temporary_clone< T > make_temporary_clone (std::shared_ptr< const Executor > exec, T *ptr)`
Creates a temporary_clone.
 - `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_s< Pointer >::value, 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_s< Pointer >::value, 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 , typename U >`
`std::unique_ptr< typename std::decay< T >::type > as (std::unique_ptr< U > &&obj)`
Performs polymorphic type conversion of a unique_ptr.
 - `template<typename T , typename U >`
`std::shared_ptr< typename std::decay< T >::type > as (std::shared_ptr< U > obj)`
Performs polymorphic type conversion of a shared_ptr.
 - `template<typename T , typename U >`
`std::shared_ptr< const typename std::decay< T >::type > as (std::shared_ptr< const U > obj)`
Performs polymorphic type conversion of a shared_ptr.
 - `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.

34.1.1 Detailed Description

The Ginkgo namespace.

34.1.2 Typedef Documentation

34.1.2.1 is_complex_or_scalar_s

```
template<typename T >
using gko::is_complex_or_scalar_s = typedef detail::is_complex_or_scalar_impl<T>
```

Allows to check if T is a complex or scalar value during compile time by accessing the `value` attribute of this struct.

If `value` is `true`, T is a complex/scalar type, if it is `false`, T is not a complex/scalar type.

Template Parameters

<i>T</i>	type to check
----------	---------------

34.1.2.2 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

<i>T</i>	type to check
----------	---------------

34.1.2.3 remove_complex

```
template<typename T >
using gko::remove_complex = typedef typename detail::remove_complex_s<T>::type
```

Obtain the type which removed the complex of complex/scalar type or the template parameter of class by accessing the `type` attribute of this struct.

Template Parameters

<i>T</i>	type to remove complex
----------	------------------------

Note

`remove_complex<class>` can not be used in friend class declaration.

34.1.2.4 to_complex

```
template<typename T >
using gko::to_complex = typedef typename detail::to_complex_s<T>::type
```

Obtain the type which adds the complex of complex/scalar type or the template parameter of class by accessing the `type` attribute of this struct.

Template Parameters

<i>T</i>	type to complex_type
----------	----------------------

Note

`to_complex<class>` can not be used in friend class declaration. the followings are the error message from different combination. `friend to_complex<Csr>;` error: can not recognize it is class correctly. `friend class`

to_complex<Csr>; error: using alias template specialization friend class to_complex_s<Csr<ValueType,↵
IndexType>>::type; error: can not recognize it is class correctly.

34.1.2.5 to_real

```
template<typename T >
using gko::to_real = typedef remove_complex<T>
```

to_real is alias of remove_complex

Template Parameters

<i>T</i>	type to real
----------	--------------

34.1.3 Enumeration Type Documentation

34.1.3.1 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.

```
67         {
71     array,
75     coordinate
76 };
```

34.1.4 Function Documentation

34.1.4.1 abs()

```
template<typename T >
constexpr xstd::enable_if_t<!is_complex_s<T>::value, T> gko::abs (
    const T & x ) [inline], [constexpr]
```

Returns the absolute value of the object.

Template Parameters

<i>T</i>	the type of the object
----------	------------------------

Parameters

<i>x</i>	the object
----------	------------

Returns

`x >= zero<T>() ? x : -x;`

```

906 {
907     return x >= zero<T>() ? x : -x;
908 }
```

Referenced by `is_finite()`.

34.1.4.2 as() [1/5]

```

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

<i>T</i>	requested result type
<i>U</i>	static type of the passed object

Parameters

<i>obj</i>	the object which should be converted
------------	--------------------------------------

Returns

If successful, returns a pointer to the subtype, otherwise throws [NotSupported](#).

```

316 {
317     if (auto p = dynamic_cast<const typename std::decay<T>::type *>(obj)) {
318         return p;
319     } else {
320         throw NotSupported(__FILE__, __LINE__,
321             std::string{"gko::as<" +
322                 name_demangling::get_type_name(typeid(T)) + ">",
323                 name_demangling::get_type_name(typeid(*obj))});
324     }
325 }
```

34.1.4.3 as() [2/5]

```
template<typename T , typename U >
std::shared_ptr<const typename std::decay<T>::type> gko::as (
    std::shared_ptr< const U > obj ) [inline]
```

Performs polymorphic type conversion of a `shared_ptr`.

This is the constant version of the function.

Template Parameters

<i>T</i>	requested result type
<i>U</i>	static type of the passed object

Parameters

<i>obj</i>	the <code>shared_ptr</code> to the object which should be converted.
------------	--

Returns

If successful, returns a `shared_ptr` to the subtype, otherwise throws [NotSupported](#). This pointer shares ownership with the input pointer.

34.1.4.4 as() [3/5]

```
template<typename T , typename U >
std::shared_ptr<typename std::decay<T>::type> gko::as (
    std::shared_ptr< U > obj ) [inline]
```

Performs polymorphic type conversion of a `shared_ptr`.

Template Parameters

<i>T</i>	requested result type
<i>U</i>	static type of the passed object

Parameters

<i>obj</i>	the <code>shared_ptr</code> to the object which should be converted.
------------	--

Returns

If successful, returns a `shared_ptr` to the subtype, otherwise throws [NotSupported](#). This pointer shares ownership with the input pointer.

34.1.4.5 as() [4/5]

```
template<typename T , typename U >
std::unique_ptr<typename std::decay<T>::type> gko::as (
    std::unique_ptr< U > && obj ) [inline]
```

Performs polymorphic type conversion of a `unique_ptr`.

Template Parameters

<i>T</i>	requested result type
<i>U</i>	static type of the passed object

Parameters

<i>obj</i>	the <code>unique_ptr</code> to the object which should be converted. If successful, it will be reset to a <code>nullptr</code> .
------------	--

Returns

If successful, returns a `unique_ptr` to the subtype, otherwise throws [NotSupported](#).

34.1.4.6 as() [5/5]

```
template<typename T , typename U >
std::decay<T>::type* gko::as (
    U * obj ) [inline]
```

Performs polymorphic type conversion.

Template Parameters

<i>T</i>	requested result type
<i>U</i>	static type of the passed object

Parameters

<i>obj</i>	the object which should be converted
------------	--------------------------------------

Returns

If successful, returns a pointer to the subtype, otherwise throws [NotSupported](#).

34.1.4.7 ceildiv()

```
constexpr int64 gko::ceildiv (
    int64 num,
    int64 den ) [inline], [constexpr]
```

Performs integer division with rounding up.

Parameters

<i>num</i>	numerator
<i>den</i>	denominator

Returns

returns the ceiled quotient.

Referenced by `gko::matrix::Csr< ValueType, IndexType >::load_balance::clac_size()`, `gko::preconditioner::block↔_interleaved_storage_scheme< index_type >::compute_storage_space()`, and `gko::matrix::Csr< ValueType, IndexType >::load_balance::process()`.

34.1.4.8 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

<i>Pointer</i>	type of pointer to the object (plain or smart pointer)
----------------	--

Parameters

<i>p</i>	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.

34.1.4.9 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

<i>Pointer</i>	type of pointer to the object (plain or smart pointer)
----------------	--

Parameters

<i>exec</i>	the executor where the cloned object should be stored
<i>p</i>	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.

34.1.4.10 conj()

```
template<typename T >
std::enable_if_t<!is_complex_s<T>::value, T> gko::conj (
    const T & x ) [inline]
```

Returns the conjugate of an object.

Parameters

<i>x</i>	the number to conjugate
----------	-------------------------

Returns

conjugate of the object (by default, the object itself)

Referenced by `squared_norm()`.

34.1.4.11 copy_and_convert_to() [1/4]

```
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

<i>R</i>	the type to which the object should be converted
<i>T</i>	the type of the input object

Parameters

<i>exec</i>	the executor where the result should be placed
<i>obj</i>	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.

```
490 {
491     return detail::copy_and_convert_to_impl<const R>(std::move(exec), obj);
492 }
```

34.1.4.12 copy_and_convert_to() [2/4]

```
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

<i>R</i>	the type to which the object should be converted
<i>T</i>	the type of the input object

Parameters

<i>exec</i>	the executor where the result should be placed
<i>obj</i>	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.

34.1.4.13 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

<i>R</i>	the type to which the object should be converted
<i>T</i>	the type of the input object

Parameters

<i>exec</i>	the executor where the result should be placed
<i>obj</i>	the object that should be converted

Returns

a shared pointer to the converted object

34.1.4.14 copy_and_convert_to() [4/4]

```
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

<i>R</i>	the type to which the object should be converted
<i>T</i>	the type of the input object

Parameters

<i>exec</i>	the executor where the result should be placed
<i>obj</i>	the object that should be converted

Returns

a unique pointer (with dynamically bound deleter) to the converted object

34.1.4.15 `get_significant_bit()`

```
template<typename T >
constexpr uint32 gko::get_significant_bit (
    const T & n,
    uint32 hint = 0u ) [constexpr], [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

<i>T</i>	a numeric type supporting bit shift and comparison
----------	--

Parameters

<i>n</i>	a number
<i>hint</i>	a lower bound for the position of the significant bit

Returns

maximum of `hint` and the significant bit position of `n`

34.1.4.16 `get_superior_power()`

```
template<typename T >
constexpr T gko::get_superior_power (
    const T & base,
    const T & limit,
    const T & hint = T{1} ) [constexpr], [noexcept]
```

Returns the smallest power of `base` not smaller than `limit`.

Template Parameters

<i>T</i>	a numeric type supporting multiplication and comparison
----------	---

Parameters

<i>base</i>	the base of the power to be returned
<i>limit</i>	the lower limit on the size of the power returned
<i>hint</i>	a lower bound on the result, has to be a power of <code>base</code>

Returns

the smallest power of `base` not smaller than `limit`

34.1.4.17 `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

<i>OwningPointer</i>	type of pointer with ownership to the object (has to be a smart pointer)
----------------------	--

Parameters

<i>p</i>	a pointer to the object
----------	-------------------------

Note

The original pointer `p` becomes invalid after this call.

34.1.4.18 imag()

```
template<typename T >
constexpr std::enable_if_t<!is_complex_s<T>::value, T> gko::imag (
    const T & ) [inline], [constexpr]
```

Returns the imaginary part of the object.

Template Parameters

<i>T</i>	type of the object
----------	--------------------

Parameters

<i>x</i>	the object
----------	------------

Returns

imaginary part of the object (by default, [zero<T>\(\)](#))

34.1.4.19 is_complex()

```
template<typename T >
constexpr bool gko::is_complex ( ) [inline], [constexpr]
```

Checks if T is a complex type.

Template Parameters

<i>T</i>	type to check
----------	---------------

Returns

true if T is a complex type, false otherwise

34.1.4.20 is_complex_or_scalar()

```
template<typename T >
constexpr bool gko::is_complex_or_scalar ( ) [inline], [constexpr]
```

Checks if T is a complex/scalar type.

Template Parameters

<i>T</i>	type to check
----------	---------------

Returns

`true` if `T` is a complex/scalar type, `false` otherwise

34.1.4.21 `is_finite()` [1/2]

```
template<typename T >
std::enable_if_t<!is_complex_s<T>::value, bool> gko::is_finite (
    const T & value ) [inline]
```

Checks if a floating point number is finite, meaning it is neither +/- infinity nor NaN.

Template Parameters

<i>T</i>	type of the value to check
----------	----------------------------

Parameters

<i>value</i>	value to check
--------------	----------------

Returns

`true` if the value is finite, meaning it are neither +/- infinity nor NaN.

References `abs()`.

Referenced by `is_finite()`.

34.1.4.22 `is_finite()` [2/2]

```
template<typename T >
std::enable_if_t<is_complex_s<T>::value, bool> gko::is_finite (
    const T & value ) [inline]
```

Checks if all components of a complex value are finite, meaning they are neither +/- infinity nor NaN.

Template Parameters

<i>T</i>	complex type of the value to check
----------	------------------------------------

Parameters

<i>value</i>	complex value to check
--------------	------------------------

Returns

`true` if both components of the given value are finite, meaning they are neither +/- infinity nor NaN.

References `is_finite()`.

34.1.4.23 `lend()` [1/2]

```
template<typename Pointer >
std::enable_if<detail::have_ownership_s<Pointer>::value, 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

<i>Pointer</i>	type of pointer to the object (plain or smart pointer)
----------------	--

Parameters

<i>p</i>	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::log::EnableLogging< Executor >::remove_logger()`.

34.1.4.24 `lend()` [2/2]

```
template<typename Pointer >
std::enable_if<!detail::have_ownership_s<Pointer>::value, 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

<i>Pointer</i>	type of pointer to the object (plain or smart pointer)
----------------	--

Parameters

<i>p</i>	a pointer to the object
----------	-------------------------

Note

This is the overload for non-owning (plain) pointers, that just returns *p*.

34.1.4.25 `make_temporary_clone()`

```
template<typename T >
detail::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

<i>exec</i>	the executor where the clone will be created
<i>ptr</i>	a pointer to the object of which the clone will be created

```
194 {
195     return detail::temporary_clone<T>(std::move(exec), ptr);
196 }
```

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()`.

34.1.4.26 `max()`

```
template<typename T >
constexpr T gko::max (
    const T & x,
    const T & y ) [inline], [constexpr]
```

Returns the larger of the arguments.

Template Parameters

<i>T</i>	type of the arguments
----------	-----------------------

Parameters

<i>x</i>	first argument
<i>y</i>	second argument

Returns

$$x \geq y ? x : y$$
34.1.4.27 min()

```
template<typename T >
constexpr T gko::min (
    const T & x,
    const T & y ) [inline], [constexpr]
```

Returns the smaller of the arguments.

Template Parameters

<i>T</i>	type of the arguments
----------	-----------------------

Parameters

<i>x</i>	first argument
<i>y</i>	second argument

Returns

$$x \leq y ? x : y$$

Referenced by `gko::matrix::Csr< ValueType, IndexType >::load_balance::clac_size()`.

34.1.4.28 one() [1/2]

```
template<typename T >
constexpr T gko::one ( ) [inline], [constexpr]
```

Returns the multiplicative identity for T.

Returns

the multiplicative identity for T

34.1.4.29 one() [2/2]

```
template<typename T >
constexpr T gko::one (
    const T & ) [inline], [constexpr]
```

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)`.

34.1.4.30 operator"!="() [1/3]

```
template<size_type Dimensionality, typename DimensionType >
constexpr bool gko::operator!= (
    const dim< Dimensionality, DimensionType > & x,
    const dim< Dimensionality, DimensionType > & y ) [inline], [constexpr]
```

Checks if two dim objects are different.

Template Parameters

<i>Dimensionality</i>	number of dimensions of the dim objects
<i>DimensionType</i>	datatype used to represent each dimension

Parameters

<i>x</i>	first object
<i>y</i>	second object

Returns

```
    !(x == y)

223 {
224     return !(x == y);
225 }
```

34.1.4.31 operator"!="() [2/3]

```
bool gko::operator!= (
    const stopping_status & x,
    const stopping_status & y ) [inline], [noexcept]
```

Checks if two stopping statuses are different.

Parameters

<i>x</i>	a stopping status
<i>y</i>	a stopping status

Returns

true if and only if `! (x == y)`

```
179 {
180     return x.data_ != y.data_;
181 }
```

34.1.4.32 operator"!="() [3/3]

```
constexpr bool gko::operator!= (
    precision_reduction x,
    precision_reduction y ) [constexpr], [noexcept]
```

Checks if two [precision_reduction](#) encodings are different.

Parameters

<i>x</i>	an encoding
<i>y</i>	an encoding

Returns

true if and only if *x* and *y* are different encodings.

```
394 {
395     using st = precision_reduction::storage_type;
396     return static_cast<st>(x) != static_cast<st>(y);
397 }
```

34.1.4.33 operator<<() [1/2]

```
std::ostream& gko::operator<< (
    std::ostream & os,
    const version & ver ) [inline]
```

Prints version information to a stream.

Parameters

<i>os</i>	output stream
<i>ver</i>	version structure

Returns

OS

```

131 {
132     os « ver.major « "." « ver.minor « "." « ver.patch;
133     if (ver.tag) {
134         os « " (" « ver.tag « ")";
135     }
136     return os;
137 }

```

References gko::version::major, gko::version::minor, gko::version::patch, and gko::version::tag.

34.1.4.34 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

<i>os</i>	output stream
<i>ver_info</i>	version information

Returns

OS

34.1.4.35 operator==() [1/2]

```

bool gko::operator==(
    const stopping_status & x,
    const stopping_status & y ) [inline], [noexcept]

```

Checks if two stopping statuses are equivalent.

Parameters

<i>x</i>	a stopping status
<i>y</i>	a stopping status

Returns

true if and only if both *x* and *y* have the same mask and converged and finalized state

34.1.4.36 operator==() [2/2]

```
constexpr bool gko::operator== (
    precision_reduction x,
    precision_reduction y ) [constexpr], [noexcept]
```

Checks if two [precision_reduction](#) encodings are equal.

Parameters

<i>x</i>	an encoding
<i>y</i>	an encoding

Returns

true if and only if *x* and *y* are the same encodings

34.1.4.37 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

<i>MatrixType</i>	a ReadableFromMatrixData LinOp type used to store the matrix once it's been read from disk.
<i>StreamType</i>	type of stream used to write the data to
<i>MatrixArgs</i>	additional argument types passed to MatrixType constructor

Parameters

<i>is</i>	input stream from which to read the data
<i>args</i>	additional arguments passed to MatrixType constructor

Returns

A MatrixType LinOp filled with data from filename

References [read_raw\(\)](#).

Referenced by [gko::ReadableFromMatrixData< ValueType, int32 >::read\(\)](#).

34.1.4.38 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

<i>ValueType</i>	type of matrix values
<i>IndexType</i>	type of matrix indexes

Parameters

<i>is</i>	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\(\)](#).

34.1.4.39 real()

```
template<typename T >
constexpr std::enable_if_t<!is_complex_s<T>::value, T> gko::real (
    const T & x ) [inline], [constexpr]
```

Returns the real part of the object.

Template Parameters

<i>T</i>	type of the object
----------	--------------------

Parameters

<i>x</i>	the object
----------	------------

Returns

real part of the object (by default, the object itself)

Referenced by `squared_norm()`.

34.1.4.40 round_down()

```
template<typename T >
constexpr reduce_precision<T> gko::round_down (
    T val ) [inline], [constexpr]
```

Reduces the precision of the input parameter.

Template Parameters

<i>T</i>	the original precision
----------	------------------------

Parameters

<i>val</i>	the value to round down
------------	-------------------------

Returns

the rounded down value

34.1.4.41 round_up()

```
template<typename T >
constexpr increase_precision<T> gko::round_up (
    T val ) [inline], [constexpr]
```

Increases the precision of the input parameter.

Template Parameters

<i>T</i>	the original precision
----------	------------------------

Parameters

<i>val</i>	the value to round up
------------	-----------------------

Returns

the rounded up value

34.1.4.42 share()

```
template<typename OwingPointer >
detail::shared_type<OwingPointer> gko::share (
    OwingPointer && p ) [inline]
```

Marks the object pointed to by `p` as shared.

Effectively converts a pointer with ownership to `std::shared_ptr`.

Template Parameters

<i>OwingPointer</i>	type of pointer with ownership to the object (has to be a smart pointer)
---------------------	--

Parameters

<i>p</i>	a pointer to the object
----------	-------------------------

Note

The original pointer `p` becomes invalid after this call.

Referenced by `gko::preconditioner::lc< LSolverType, IndexType >::conj_transpose()`, `gko::preconditioner::llu< LSolverType, USolverType, ReverseApply, IndexType >::conj_transpose()`, `gko::preconditioner::lc< LSolverType, IndexType >::transpose()`, and `gko::preconditioner::llu< LSolverType, USolverType, ReverseApply, IndexType >::transpose()`.

34.1.4.43 squared_norm()

```
template<typename T >
constexpr auto gko::squared_norm (
    const T & x ) -> decltype(real(conj(x) * x)) [inline], [constexpr]
```

Returns the squared norm of the object.

Template Parameters

<i>T</i>	type of the object.
----------	---------------------

Returns

The squared norm of the object.

References `conj()`, and `real()`.

34.1.4.44 transpose()

```
template<typename DimensionType >
constexpr dim<2, DimensionType> gko::transpose (
    const dim< 2, DimensionType > & dimensions ) [inline], [constexpr], [noexcept]
```

Returns a [dim](#)<2> object with its dimensions swapped.

Template Parameters

<i>DimensionType</i>	datatype used to represent each dimension
----------------------	---

Parameters

<i>dimensions</i>	original object
-------------------	-----------------

Returns

a [dim](#)<2> object with its dimensions swapped

Referenced by `gko::preconditioner::lc< LSolverType, IndexType >::conj_transpose()`, `gko::preconditioner::llu< LSolverType, USolverType, ReverseApply, IndexType >::conj_transpose()`, `gko::preconditioner::lc< LSolverType, IndexType >::transpose()`, and `gko::preconditioner::llu< LSolverType, USolverType, ReverseApply, IndexType >::transpose()`.

34.1.4.45 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

<i>MatrixType</i>	a ReadableFromMatrixData LinOp type used to store the matrix once it's been read from disk.
<i>StreamType</i>	type of stream used to write the data to

Parameters

<i>os</i>	output stream where the data is to be written
<i>matrix</i>	the matrix to write
<i>layout</i>	the layout used in the output

References `write_raw()`.

34.1.4.46 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

<i>ValueType</i>	type of matrix values
<i>IndexType</i>	type of matrix indexes

Parameters

<i>os</i>	output stream where the data is to be written
<i>data</i>	the matrix data to write
<i>layout</i>	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()`.

34.1.4.47 zero() [1/2]

```
template<typename T >
constexpr T gko::zero ( ) [inline], [constexpr]
```

Returns the additive identity for T.

Returns

additive identity for T

34.1.4.48 zero() [2/2]

```
template<typename T >
constexpr T gko::zero (
    const T & ) [inline], [constexpr]
```

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)`.

34.2 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.

34.2.1 Detailed Description

The accessor namespace.

34.3 gko::factorization Namespace Reference

The Factorization namespace.

Classes

- class [lc](#)

Represents an incomplete Cholesky factorization (IC(0)) of a sparse matrix.

- class [llu](#)

Represents an incomplete LU factorization – ILU(0) – of a sparse matrix.

- class [Parlc](#)

Parlc is an incomplete Cholesky factorization which is computed in parallel.

- class [Parlct](#)

Parlct is an incomplete threshold-based Cholesky factorization which is computed in parallel.

- class [Parllu](#)

Parllu is an incomplete LU factorization which is computed in parallel.

- class [Parllut](#)

Parllut is an incomplete threshold-based LU factorization which is computed in parallel.

34.3.1 Detailed Description

The Factorization namespace.

34.4 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.

34.4.1 Detailed Description

The logger namespace .

The Logging namespace.

[Logging](#)

34.5 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 [Diagonal](#)
This class is a utility which efficiently implements the diagonal matrix (a linear operator which scales a vector row wise).
- 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 [Permutation](#)
Permutation is a matrix "format" which stores the row and column permutation arrays which can be used for re-ordering the rows and columns a matrix.
- class [Sellp](#)
SELL-P is a matrix format similar to ELL format.
- class [SparsityCsr](#)
SparsityCsr is a matrix format which stores only the sparsity pattern of a sparse matrix by compressing each row of the matrix (compressed sparse row format).

34.5.1 Detailed Description

The matrix namespace.

34.6 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.

34.6.1 Detailed Description

The name demangling namespace.

34.6.2 Function Documentation

34.6.2.1 `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

<i>T</i>	the type of the object to demangle
----------	------------------------------------

Parameters

<i>t</i>	the object we get the dynamic type of
----------	---------------------------------------

```
101 {
102     return get_type_name(typeid(t));
103 }
```

34.6.2.2 `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

<i>T</i>	the type of the object to demangle
----------	------------------------------------

Parameters

<i>unused</i>	
---------------	--

34.7 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 [lc](#)
*The Incomplete Cholesky (IC) preconditioner solves the equation $LL^H * x = b$ for a given lower triangular matrix L and the right hand side b (can contain multiple right hand sides).*
- class [llu](#)
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 [lsai](#)
The Incomplete Sparse Approximate Inverse (ISAI) Preconditioner generates an approximate inverse matrix for a given lower triangular matrix L or upper triangular matrix U .
- class [Jacobi](#)
A block-Jacobi preconditioner is a block-diagonal linear operator, obtained by inverting the diagonal blocks of the source operator.

Enumerations

- enum [isai_type](#)
This enum lists the types of the ISAI preconditioner.

34.7.1 Detailed Description

The Preconditioner namespace.

34.7.2 Enumeration Type Documentation

34.7.2.1 isai_type

```
enum gko::preconditioner::isai_type [strong]
```

This enum lists the types of the ISAI preconditioner.

ISAI can either generate a lower triangular matrix, or an upper triangular matrix.

```
63 { lower, upper };
```

34.8 gko::reorder Namespace Reference

The Reorder namespace.

Classes

- class [Rcm](#)
[Rcm](#) is a reordering algorithm minimizing the bandwidth of a matrix.
- class [ReorderingBase](#)
The [ReorderingBase](#) class is a base class for all the reordering algorithms.
- struct [ReorderingBaseArgs](#)
This struct is used to pass parameters to the `EnableDefaultReorderingBaseFactory::generate()` method.

Typedefs

- using [ReorderingBaseFactory](#) = [AbstractFactory](#)< [ReorderingBase](#), [ReorderingBaseArgs](#) >
Declares an Abstract Factory specialized for ReorderingBases.
- template<typename ConcreteFactory , typename ConcreteReorderingBase , typename ParametersType , typename PolymorphicBase = [ReorderingBaseFactory](#)>
using [EnableDefaultReorderingBaseFactory](#) = [EnableDefaultFactory](#)< ConcreteFactory, ConcreteReorderingBase, ParametersType, PolymorphicBase >
This is an alias for the [EnableDefaultFactory](#) mixin, which correctly sets the template parameters to enable a subclass of [ReorderingBaseFactory](#).

34.8.1 Detailed Description

The Reorder namespace.

The reordering namespace.

34.8.2 Typedef Documentation

34.8.2.1 EnableDefaultReorderingBaseFactory

```
template<typename ConcreteFactory , typename ConcreteReorderingBase , typename ParametersType
, typename PolymorphicBase = ReorderingBaseFactory>
using gko::reorder::EnableDefaultReorderingBaseFactory = typedef EnableDefaultFactory<ConcreteFactory, ConcreteReorderingBase, ParametersType, PolymorphicBase>
```

This is an alias for the [EnableDefaultFactory](#) mixin, which correctly sets the template parameters to enable a subclass of [ReorderingBaseFactory](#).

Template Parameters

<i>ConcreteFactory</i>	the concrete factory which is being implemented [CRTP parameter]
<i>ConcreteReorderingBase</i>	the concrete ReorderingBase type which this factory produces, needs to have a constructor which takes a const <code>ConcreteFactory *</code> , and a const ReorderingBaseArgs * as parameters.
<i>ParametersType</i>	a subclass of enable_parameters_type template which defines all of the parameters of the factory
<i>PolymorphicBase</i>	parent of <code>ConcreteFactory</code> in the polymorphic hierarchy, has to be a subclass of ReorderingBaseFactory

34.9 gko::solver Namespace Reference

The ginkgo Solve namespace.

Classes

- class [Bicg](#)
BICG or the Biconjugate gradient method is a Krylov subspace solver.
- class [Bicgstab](#)
BiCGSTAB or the Bi-Conjugate Gradient-Stabilized is a Krylov subspace solver.
- class [CbGmres](#)
CB-GMRES or the compressed basis generalized minimal residual method is an iterative type Krylov subspace method which is suitable for nonsymmetric linear systems.
- 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.
- struct [has_with_criteria](#)
Helper structure to test if the Factory of SolverType has a function with_criteria.
- struct [has_with_criteria< SolverType, xstd::void_t< decltype\(SolverType::build\(\)\).with_criteria\(std::shared_ptr< const stop::Criteria>\)](#)
Helper structure to test if the Factory of SolverType has a function with_criteria.
- class [ldr](#)
IDR(s) is an efficient method for solving large nonsymmetric systems of linear equations.
- class [lr](#)
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 $Lx = b$, when L is a lower triangular matrix.
- class [UpperTrs](#)
UpperTrs is the triangular solver which solves the system $Ux = b$, when U is an upper triangular matrix.

34.9.1 Detailed Description

The ginkgo Solve namespace.

The ginkgo Solver namespace.

34.10 gko::stop Namespace Reference

The Stopping criterion namespace.

Classes

- class [AbsoluteResidualNorm](#)
The [AbsoluteResidualNorm](#) class is a stopping criterion which stops the iteration process when the residual norm is below a certain threshold, i.e.
- 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 `EnableDefaultCriterionFactory::generate()` method.
- class [ImplicitResidualNorm](#)
The [ImplicitResidualNorm](#) class is a stopping criterion which stops the iteration process when the implicit residual norm is below a certain threshold relative to.
- class [Iteration](#)
The [Iteration](#) class is a stopping criterion which stops the iteration process after a preset number of iterations.
- class [RelativeResidualNorm](#)
The [RelativeResidualNorm](#) class is a stopping criterion which stops the iteration process when the residual norm is below a certain threshold relative to the norm of the right-hand side, i.e.
- class [ResidualNorm](#)
The [ResidualNorm](#) class is a stopping criterion which stops the iteration process when the actual residual norm is below a certain threshold relative to.
- class [ResidualNormBase](#)
The [ResidualNormBase](#) class provides a framework for stopping criteria related to the residual norm.
- class [ResidualNormReduction](#)
The [ResidualNormReduction](#) class is a stopping criterion which stops the iteration process when the residual norm is below a certain threshold relative to the norm of the initial residual, i.e.
- class [Time](#)
The [Time](#) class is a stopping criterion which stops the iteration process after a certain amount of time has passed.

Typedefs

- using [CriterionFactory](#) = [AbstractFactory](#)< [Criterion](#), [CriterionArgs](#) >
Declares an Abstract Factory specialized for [Criteria](#)s.
- 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](#).

Enumerations

- enum [mode](#)
The mode for the residual norm criterion.

Functions

- template<typename FactoryContainer >
std::shared_ptr< const [CriterionFactory](#) > [combine](#) (FactoryContainer &&factories)
Combines multiple criterion factories into a single combined criterion factory.

34.10.1 Detailed Description

The Stopping criterion namespace.

[Stopping criteria](#)

34.10.2 Typedef Documentation

34.10.2.1 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

<i>ConcreteFactory</i>	the concrete factory which is being implemented [CRTP parameter]
<i>ConcreteCriterion</i>	the concrete Criterion type which this factory produces, needs to have a constructor which takes a const ConcreteFactory *, and a const CriterionArgs * as parameters.
<i>ParametersType</i>	a subclass of enable_parameters_type template which defines all of the parameters of the factory
<i>PolymorphicBase</i>	parent of ConcreteFactory in the polymorphic hierarchy, has to be a subclass of CriterionFactory

34.11 gko::syn Namespace Reference

The Synthesizer namespace.

34.11.1 Detailed Description

The Synthesizer namespace.

34.12 gko::xstd Namespace Reference

The namespace for functionalities after C++14 standard.

34.12.1 Detailed Description

The namespace for functionalities after C++14 standard.

Chapter 35

Class Documentation

35.1 gko::AbsoluteComputable Class Reference

The [AbsoluteComputable](#) is an interface that allows to get the component wise absolute of a LinOp.

```
#include <ginkgo/core/base/lin_op.hpp>
```

Public Member Functions

- virtual std::unique_ptr< LinOp > [compute_absolute_linop](#) () const =0
Gets the absolute LinOp.
- virtual void [compute_absolute_inplace](#) ()=0
Compute absolute inplace on each element.

35.1.1 Detailed Description

The [AbsoluteComputable](#) is an interface that allows to get the component wise absolute of a LinOp.

Use [EnableAbsoluteComputation<AbsoluteLinOp>](#) to implement this interface.

35.1.2 Member Function Documentation

35.1.2.1 compute_absolute_linop()

```
virtual std::unique_ptr<LinOp> gko::AbsoluteComputable::compute_absolute_linop ( ) const  
[pure virtual]
```

Gets the absolute LinOp.

Returns

a pointer to the new absolute LinOp

Implemented in [gko::EnableAbsoluteComputation< AbsoluteLinOp >](#), [gko::EnableAbsoluteComputation< remove_complex< Hybrid>](#), [gko::EnableAbsoluteComputation< remove_complex< Sellp< ValueType, IndexType > > >](#), [gko::EnableAbsoluteComputation< remove_complex< Coo< ValueType, IndexType > > >](#), [gko::EnableAbsoluteComputation< remove_complex< Csr< ValueType, IndexType > > >](#), and [gko::EnableAbsoluteComputation< remove_complex< SparseMatrix< ValueType, IndexType > > >](#).

The documentation for this class was generated from the following file:

- ginkgo/core/base/lin_op.hpp

35.2 gko::stop::AbsoluteResidualNorm< ValueType > Class Template Reference

The [AbsoluteResidualNorm](#) class is a stopping criterion which stops the iteration process when the residual norm is below a certain threshold, i.e.

```
#include <ginkgo/core/stop/residual_norm.hpp>
```

35.2.1 Detailed Description

```
template<typename ValueType = default_precision>
class gko::stop::AbsoluteResidualNorm< ValueType >
```

The [AbsoluteResidualNorm](#) class is a stopping criterion which stops the iteration process when the residual norm is below a certain threshold, i.e.

when $\text{norm}(\text{residual}) / \text{threshold}$. 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 `b` in order to get the number of right-hand sides. If this 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.hpp`

35.3 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.

35.3.1 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

<i>AbstractProductType</i>	the type of products the factory produces
<i>ComponentsType</i>	the type of components the factory needs to produce the product

35.3.2 Member Function Documentation

35.3.2.1 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

<i>Args</i>	types of arguments passed to the constructor of <code>ComponentsType</code>
-------------	---

Parameters

<i>args</i>	arguments passed to the constructor of <code>ComponentsType</code>
-------------	--

Returns

an instance of `AbstractProductType`

```
93     {
94         auto product = this->generate_impl({std::forward<Args>(args)...});
95         for (auto logger : this->loggers_) {
96             product->add_logger(logger);
97         }
98         return product;
99     }
```

The documentation for this class was generated from the following file:

- `ginkgo/core/base/abstract_factory.hpp`

35.4 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.

35.4.1 Detailed Description

[AllocationError](#) is thrown if a memory allocation fails.

35.4.2 Constructor & Destructor Documentation

35.4.2.1 AllocationError()

```
gko::AllocationError::AllocationError (
    const std::string & file,
    int line,
    const std::string & device,
    size\_type bytes ) [inline]
```

Initializes an allocation error.

Parameters

<i>file</i>	The name of the offending source file
<i>line</i>	The source code line number where the error occurred
<i>device</i>	The device on which the error occurred
<i>bytes</i>	The size of the memory block whose allocation failed.

```
464         : Error(file, line,
465               device + ": failed to allocate memory block of " +
466                 std::to_string(bytes) + "B")
467     {}
```

The documentation for this class was generated from the following file:

- ginkgo/core/base/exception.hpp

35.5 gko::multigrid::AmgxPgm< ValueType, IndexType > Class Template Reference

Amgx parallel graph match ([AmgxPgm](#)) is the aggregate method introduced in the paper M.

```
#include <ginkgo/core/multigrid/amgx_pgm.hpp>
```


Public Member Functions

- `std::shared_ptr< const LinOp > get_system_matrix () const`
Returns the system operator (matrix) of the linear system.
- `IndexType * get_agg () noexcept`
Returns the aggregate group.
- `const IndexType * get_const_agg () const noexcept`
Returns the aggregate group.

35.5.1 Detailed Description

```
template<typename ValueType = default_precision, typename IndexType = int32>
class gko::multigrid::AmgxPgm< ValueType, IndexType >
```

Amgx parallel graph match ([AmgxPgm](#)) is the aggregate method introduced in the paper M.

Naumov et al., "AmgX: A Library for GPU Accelerated Algebraic Multigrid and Preconditioned Iterative Methods". Current implementation only contains size = 2 version.

[AmgxPgm](#) creates the aggregate group according to the matrix value not the structure. [AmgxPgm](#) gives two steps (one-phase handshaking) to group the elements. 1: get the strongest neighbor of each unaggregated element. 2: group the elements whose strongest neighbor is each other. repeating until reaching the given conditions. After that, the un-aggregated elements are assigned to an aggregated group or are left alone.

Template Parameters

<i>ValueType</i>	precision of matrix elements
<i>IndexType</i>	precision of matrix indexes

35.5.2 Member Function Documentation

35.5.2.1 `get_agg()`

```
template<typename ValueType = default_precision, typename IndexType = int32>
IndexType* gko::multigrid::AmgxPgm< ValueType, IndexType >::get_agg ( ) [inline], [noexcept]
```

Returns the aggregate group.

Aggregate group whose size is same as the number of rows. Stores the mapping information from row index to coarse row index. i.e., `agg[row_idx] = coarse_row_idx`.

Returns

the aggregate group.

```
103 { return agg_.get_data(); }
```

References `gko::Array< ValueType >::get_data()`.

35.5.2.2 get_const_agg()

```
template<typename ValueType = default_precision, typename IndexType = int32>
const IndexType* gko::multigrid::AmgxPgm< ValueType, IndexType >::get_const_agg ( ) const
[inline], [noexcept]
```

Returns the aggregate group.

Aggregate group whose size is same as the number of rows. Stores the mapping information from row index to coarse row index. i.e., `agg[row_idx] = coarse_row_idx`.

Returns

the aggregate group.

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()`.

35.5.2.3 get_system_matrix()

```
template<typename ValueType = default_precision, typename IndexType = int32>
std::shared_ptr<const LinOp> gko::multigrid::AmgxPgm< ValueType, IndexType >::get_system_↵
matrix ( ) const [inline]
```

Returns the system operator (matrix) of the linear system.

Returns

the system operator (matrix)

The documentation for this class was generated from the following file:

- `ginkgo/core/multigrid/amgx_pgm.hpp`

35.6 gko::are_all_integral< Args > Struct Template Reference

Evaluates if all template arguments `Args` fulfill `std::is_integral`.

```
#include <ginkgo/core/base/types.hpp>
```

35.6.1 Detailed Description

```
template<typename... Args>
struct gko::are_all_integral< Args >
```

Evaluates if all template arguments `Args` fulfill `std::is_integral`.

If that is the case, this class inherits from `std::true_type`, otherwise, it inherits from `std::false_type`. If no values are passed in, `std::true_type` is inherited from.

Template Parameters

<i>Args...</i>	Arguments to test for std::is_integral
----------------	--

The documentation for this struct was generated from the following file:

- ginkgo/core/base/types.hpp

35.7 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 or view.
- [Array](#) & operator= ([Array](#) &&other)
Moves data from another array or view.
- template<typename OtherValueType >
std::enable_if_t<!std::is_same< ValueType, OtherValueType >::value, [Array](#) > & operator= (const [Array](#)< OtherValueType > &other)
Copies and converts data from another array with another data type.
- 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.
- void [fill](#) (const ValueType value)
Fill the array with the given value.
- 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](#).
- bool [is_owning](#) ()
Tells whether this [Array](#) owns its data or not.

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.

35.7.1 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

<i>ValueType</i>	the type of elements stored in the array
------------------	--

35.7.2 Constructor & Destructor Documentation

35.7.2.1 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](#).

```
115         : num_elems_(0),
116         data_(nullptr, default_deleter{nullptr}),
117         exec_(nullptr)
118     {}
```

35.7.2.2 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

<i>exec</i>	the Executor where the array data is allocated
-------------	--

35.7.2.3 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

<i>exec</i>	the Executor where the array data will be allocated
<i>num_elems</i>	the amount of memory (expressed as the number of <code>value_type</code> elements) allocated on the Executor

35.7.2.4 `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

<i>DeleterType</i>	type of the deleter
--------------------	---------------------

Parameters

<i>exec</i>	executor where <i>data</i> is located
<i>num_elems</i>	number of elements in <i>data</i>
<i>data</i>	chunk of memory used to create the array
<i>deleter</i>	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

35.7.2.5 `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

<i>exec</i>	executor where <i>data</i> is located
<i>num_elems</i>	number of elements in <i>data</i>
<i>data</i>	chunk of memory used to create the array

35.7.2.6 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

<i>RandomAccessIterator</i>	type of the iterators
-----------------------------	-----------------------

Parameters

<i>exec</i>	the Executor where the array data will be allocated
<i>begin</i>	start of range of values
<i>end</i>	end of range of values

35.7.2.7 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

<i>T</i>	type of values used to initialize the array (T has to be implicitly convertible to <code>value_type</code>)
----------	--

Parameters

<i>exec</i>	the Executor where the array data will be allocated
<i>init_list</i>	list of values used to initialize the Array

35.7.2.8 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

<i>exec</i>	the executor where the new array will be created
<i>other</i>	the Array to copy from

35.7.2.9 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

<i>other</i>	the Array to copy from
--------------	--

35.7.2.10 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

<i>exec</i>	the executor where the new array will be moved
<i>other</i>	the Array to move

35.7.2.11 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

<i>other</i>	the Array to move
--------------	-----------------------------------

35.7.3 Member Function Documentation

35.7.3.1 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`.

Referenced by `gko::Array< index_type >::operator=()`, and `gko::Array< index_type >::resize_and_reset()`.

35.7.3.2 fill()

```
template<typename ValueType>
void gko::Array< ValueType >::fill (
    const ValueType value )
```

Fill the array with the given value.

Parameters

<i>value</i>	the value to be filled
--------------	------------------------

35.7.3.3 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::preconditioner::Jacobi< ValueType, IndexType >::get_blocks()`, `gko::preconditioner::Jacobi< ValueType, IndexType >::get_conditioning()`, `gko::multigrid::AmgxPgm< ValueType, IndexType >::get_const_agg()`, `gko::matrix::SparsityCsr< ValueType, IndexType >::get_const_col_idxxs()`, `gko::matrix::Sellp< ValueType, IndexType >::get_const_col_idxxs()`, `gko::matrix::Ell< ValueType, IndexType >::get_const_col_idxxs()`, `gko::matrix::Coo< ValueType, IndexType >::get_const_col_idxxs()`, `gko::matrix::Csr< ValueType, IndexType >::get_const_col_idxxs()`, `gko::matrix::Permutation< IndexType >::get_const_permutation()`, `gko::matrix::Coo< ValueType, IndexType >::get_const_row_idxxs()`, `gko::matrix::SparsityCsr< ValueType, IndexType >::get_const_row_ptrs()`, `gko::matrix::Csr< ValueType, IndexType >::get_const_row_ptrs()`, `gko::matrix::Sellp< ValueType, IndexType >::get_const_slice_lengths()`, `gko::matrix::Sellp< ValueType, IndexType >::get_const_slice_sets()`, `gko::matrix::Csr< ValueType, IndexType >::get_const_srow()`, `gko::matrix::SparsityCsr< ValueType, IndexType >::get_const_value()`, `gko::matrix::Diagonal< ValueType >::get_const_values()`, `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::Csr< ValueType, IndexType >::get_const_values()`, `gko::Array< index_type >::operator=()`, `gko::matrix::Csr< ValueType, IndexType >::classical::process()`, `gko::matrix::Csr< ValueType, IndexType >::load_balance::process()`, `gko::matrix::Ell< ValueType, IndexType >::val_at()`, and `gko::matrix::Sellp< ValueType, IndexType >::val_at()`.

35.7.3.4 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::multigrid::AmgxPgm< ValueType, IndexType >::get_agg()`, `gko::matrix::SparsityCsr< ValueType, IndexType >::get_col_idxxs()`, `gko::matrix::Sellp< ValueType, IndexType >::get_col_idxxs()`, `gko::matrix::Ell< ValueType, IndexType >::get_col_idxxs()`, `gko::matrix::Coo< ValueType, IndexType >::get_col_idxxs()`, `gko::matrix::Csr< ValueType, IndexType >::get_col_idxxs()`, `gko::matrix::Permutation< IndexType >::get_permutation()`, `gko::matrix::Coo< ValueType, IndexType >::get_row_idxxs()`, `gko::matrix::SparsityCsr< ValueType, IndexType >::get_row_ptrs()`, `gko::matrix::Csr< ValueType, IndexType >::get_row_ptrs()`, `gko::matrix::Sellp< ValueType, IndexType >::get_slice_lengths()`, `gko::matrix::Sellp< ValueType, IndexType >::get_slice_sets()`, `gko::matrix::Csr< ValueType, IndexType >::get_srow()`, `gko::matrix::SparsityCsr< ValueType, IndexType >::get_value()`, `gko::matrix::Diagonal< ValueType >::get_values()`, `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::matrix::Csr< ValueType, IndexType >::get_values()`, `gko::Array< index_type >::operator=()`, `gko::matrix::Csr< ValueType, IndexType >::load_balance::process()`, `gko::matrix::Ell< ValueType, IndexType >::val_at()`, and `gko::matrix::Sellp< ValueType, IndexType >::val_at()`.

35.7.3.5 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()`, `gko::Array< index_type >::operator=()`, `gko::matrix::Csr< ValueType, IndexType >::classical::process()`, and `gko::matrix::Csr< ValueType, IndexType >::load_balance::process()`.

35.7.3.6 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::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::SparsityCsr< ValueType, IndexType >::get_num_nonzeros()`, `gko::matrix::Csr< ValueType, IndexType >::get_num_srow_elements()`, `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::preconditioner::Jacobi< ValueType, IndexType >::get_num_stored_elements()`, `gko::matrix::Dense< ValueType >::get_num_stored_elements()`, `gko::matrix::Csr< ValueType, IndexType >::get_num_stored_elements()`, `gko::matrix::Permutation< IndexType >::get_permutation_size()`, `gko::Array< index_type >::operator=()`, `gko::matrix::Csr< ValueType, IndexType >::classical::process()`, and `gko::matrix::Csr< ValueType, IndexType >::load_balance::process()`.

35.7.3.7 is_owning()

```
template<typename ValueType>
bool gko::Array< ValueType >::is_owning ( ) [inline]
```

Tells whether this [Array](#) owns its data or not.

Views do not own their data and this has multiple implications. They cannot be resized since the data is not owned by the [Array](#) which stores a view. It is also unclear whether custom deleter types are owning types as they could be a user-created view-type, therefore only proper [Array](#) which use the `default_deleter` are considered owning types.

Returns

whether this [Array](#) can be resized or not.

Referenced by `gko::Array< index_type >::operator=()`, and `gko::Array< index_type >::resize_and_reset()`.

35.7.3.8 operator=() [1/3]

```
template<typename ValueType>
Array& gko::Array< ValueType >::operator= (
    Array< ValueType > && other ) [inline]
```

Moves data from another array or view.

Only the pointer and deleter type change, a copy only happens when targeting another executor's data. This means that in the following situation:

```
gko::Array<int> a; // an existing array or view
gko::Array<int> b; // an existing array or view
b = std::move(a);
```

Depending on whether *a* and *b* are array or view, this happens:

- *a* and *b* are views, *b* becomes the only valid view of *a*;
- *a* and *b* are arrays, *b* becomes the only valid array of *a*;
- *a* is a view and *b* is an array, *b* frees its data and becomes the only valid view of *a* ();
- *a* is an array and *b* is a view, *b* becomes the only valid array of *a*.

In all the previous cases, *a* becomes invalid (e.g., a `nullptr`).

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

<i>other</i>	the Array to move data from
--------------	---

Returns

this

35.7.3.9 operator=() [2/3]

```
template<typename ValueType>
Array& gko::Array< ValueType >::operator= (
    const Array< ValueType > & other ) [inline]
```

Copies data from another array or view.

In the case of an array target, the array is resized to match the source's size. In the case of a view target, if the dimensions are not compatible a [gko::OutOfBoundsError](#) is thrown.

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

<i>other</i>	the Array to copy from
--------------	--

Returns

this

35.7.3.10 operator=() [3/3]

```
template<typename ValueType>
template<typename OtherValueType >
std::enable_if_t<!std::is_same<ValueType, OtherValueType>::value, Array>& gko::Array< ValueType >::operator= (
    const Array< OtherValueType > & other ) [inline]
```

Copies and converts data from another array with another data type.

In the case of an array target, the array is resized to match the source's size. In the case of a view target, if the dimensions are not compatible a [gko::OutOfBoundsError](#) is thrown.

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

<i>other</i>	the Array to copy from
--------------	--

Template Parameters

<i>OtherValueType</i>	the value type of <i>other</i>
-----------------------	--------------------------------

Returns

this

35.7.3.11 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.

For a view and other non-owning [Array](#) types, this throws an exception since these types cannot be resized.

All data stored in the array will be lost.

If the [Array](#) is not assigned an executor, an exception will be thrown.

Parameters

<i>num_elems</i>	the amount of memory (expressed as the number of <code>value_type</code> elements) allocated on the Executor
------------------	--

Referenced by `gko::Array< index_type >::operator=()`.

35.7.3.12 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

<i>exec</i>	the Executor where the data will be moved to
-------------	--

35.7.3.13 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. This array type cannot use the function `resize_and_reset` since it does not own the data it should resize.

Parameters

<i>exec</i>	executor where data is located
<i>num_elems</i>	number of elements in data
<i>data</i>	chunk of memory used to create the array

Returns

an [Array](#) constructed from `data`

Referenced by `gko::matrix::Dense< ValueType >::create_submatrix()`.

The documentation for this class was generated from the following file:

- `ginkgo/core/base/array.hpp`

35.8 gko::matrix::Hybrid< ValueType, IndexType >::automatic Class Reference

automatic is a [strategy_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.

35.8.1 Detailed Description

```
template<typename ValueType = default_precision, typename IndexType = int32>
class gko::matrix::Hybrid< ValueType, IndexType >::automatic
```

automatic is a [strategy_type](#) which decides the number of stored elements per row of the ell part automatically.

35.8.2 Member Function Documentation

35.8.2.1 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

<i>row_nnz</i>	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 >::imbalance_bounded_limit::compute_ell_num_stored_↵_elements_per_row\(\)](#).

The documentation for this class was generated from the following file:

- `ginkgo/core/matrix/hybrid.hpp`

35.9 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.

35.9.1 Detailed Description

`BadDimension` is thrown if an operation is being applied to a `LinOp` with bad dimensions.

35.9.2 Constructor & Destructor Documentation

35.9.2.1 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

<i>file</i>	The name of the offending source file
<i>line</i>	The source code line number where the error occurred
<i>func</i>	The function name where the error occurred
<i>op_name</i>	The name of the operator
<i>op_num_rows</i>	The row dimension of the operator
<i>op_num_cols</i>	The column dimension of the operator
<i>clarification</i>	An additional message further describing the error

The documentation for this class was generated from the following file:

- `ginkgo/core/base/exception.hpp`

35.10 `gko::solver::Bicg< ValueType >` Class Template Reference

BICG or the Biconjugate gradient method is a Krylov subspace solver.

```
#include <ginkgo/core/solver/bicg.hpp>
```

Public Member Functions

- `std::shared_ptr< const LinOp > get_system_matrix () const`
Gets the system operator (matrix) of the linear system.
- `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.
- `bool apply_uses_initial_guess () const override`
Return true as iterative solvers use the data in x as an initial guess.
- `std::shared_ptr< const stop::CriterionFactory > get_stop_criterion_factory () const`
Gets the stopping criterion factory of the solver.
- `void set_stop_criterion_factory (std::shared_ptr< const stop::CriterionFactory > other)`
Sets the stopping criterion of the solver.

35.10.1 Detailed Description

```
template<typename ValueType = default_precision>
class gko::solver::Bicg< ValueType >
```

BICG or the Biconjugate gradient method 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 BiCG solver are higher than of its s.p.d solver counterpart, it has the capability to solve generic systems.

BiCG is based on the bi-Lanczos tridiagonalization method and in exact arithmetic should terminate in at most N iterations ($2N$ MV's, with A and A^H). It forms the basis of many of the cheaper methods such as BiCGSTAB and CGS.

Reference: R.Fletcher, Conjugate gradient methods for indefinite systems, doi: 10.1007/BFb0080116

Template Parameters

<i>ValueType</i>	precision of matrix elements
------------------	------------------------------

35.10.2 Member Function Documentation

35.10.2.1 apply_uses_initial_guess()

```
template<typename ValueType = default_precision>
bool gko::solver::Bicg< ValueType >::apply_uses_initial_guess ( ) const [inline], [override]
```

Return true as iterative solvers use the data in x as an initial guess.

Returns

true as iterative solvers use the data in x as an initial guess.

```
107 { return true; }
```

35.10.2.2 conj_transpose()

```
template<typename ValueType = default_precision>
std::unique_ptr<LinOp> gko::solver::Bicg< 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](#).

35.10.2.3 get_stop_criterion_factory()

```
template<typename ValueType = default_precision>
std::shared_ptr<const stop::CriterionFactory> gko::solver::Bicg< ValueType >::get_stop_↵
criterion_factory ( ) const [inline]
```

Gets the stopping criterion factory of the solver.

Returns

the stopping criterion factory

35.10.2.4 get_system_matrix()

```
template<typename ValueType = default_precision>
std::shared_ptr<const LinOp> gko::solver::Bicg< ValueType >::get_system_matrix ( ) const
[inline]
```

Gets the system operator (matrix) of the linear system.

Returns

the system operator (matrix)

35.10.2.5 set_stop_criterion_factory()

```
template<typename ValueType = default_precision>
void gko::solver::Bicg< ValueType >::set_stop_criterion_factory (
    std::shared_ptr< const stop::CriterionFactory > other ) [inline]
```

Sets the stopping criterion of the solver.

Parameters

<i>other</i>	the new stopping criterion factory
--------------	------------------------------------

35.10.2.6 transpose()

```
template<typename ValueType = default_precision>
std::unique_ptr<LinOp> gko::solver::Bicg< 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](#).

The documentation for this class was generated from the following file:

- ginkgo/core/solver/bicg.hpp

35.11 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::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.
- bool [apply_uses_initial_guess](#) () const override
Return true as iterative solvers use the data in x as an initial guess.
- std::shared_ptr< const [stop::CriterionFactory](#) > [get_stop_criterion_factory](#) () const
Gets the stopping criterion factory of the solver.
- void [set_stop_criterion_factory](#) (std::shared_ptr< const [stop::CriterionFactory](#) > other)
Sets the stopping criterion of the solver.

35.11.1 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

<i>ValueType</i>	precision of the elements of the system matrix.
------------------	---

35.11.2 Member Function Documentation

35.11.2.1 `apply_uses_initial_guess()`

```
template<typename ValueType = default_precision>
bool gko::solver::Bicgstab< ValueType >::apply_uses_initial_guess ( ) const [inline], [override]
```

Return true as iterative solvers use the data in x as an initial guess.

Returns

true as iterative solvers use the data in x as an initial guess.

```
105 { return true; }
```

35.11.2.2 `conj_transpose()`

```
template<typename ValueType = default_precision>
std::unique_ptr<LinOp> gko::solver::Bicgstab< 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](#).

35.11.2.3 `get_stop_criterion_factory()`

```
template<typename ValueType = default_precision>
std::shared_ptr<const stop::CriterionFactory> gko::solver::Bicgstab< ValueType >::get_stop_↵
criterion_factory ( ) const [inline]
```

Gets the stopping criterion factory of the solver.

Returns

the stopping criterion factory

35.11.2.4 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)

35.11.2.5 set_stop_criterion_factory()

```
template<typename ValueType = default_precision>
void gko::solver::Bicgstab< ValueType >::set_stop_criterion_factory (
    std::shared_ptr< const stop::CriterionFactory > other ) [inline]
```

Sets the stopping criterion of the solver.

Parameters

<i>other</i>	the new stopping criterion factory
--------------	------------------------------------

35.11.2.6 transpose()

```
template<typename ValueType = default_precision>
std::unique_ptr<LinOp> gko::solver::Bicgstab< 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](#).

The documentation for this class was generated from the following file:

- ginkgo/core/solver/bicgstab.hpp

35.12 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.

35.12.1 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

<i>IndexType</i>	type used for storing indices of the matrix
------------------	---

35.12.2 Member Function Documentation

35.12.2.1 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

<i>num_blocks</i>	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.

```
112     {
113         return (num_blocks + 1 == size_type{0})
114             ? size_type{0}
115             : ceildiv(num_blocks, this->get_group_size()) * group_offset;
116     }
```

35.12.2.2 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

<i>block←_id</i>	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()`.

35.12.2.3 `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

<i>block_↵ _id</i>	the ID of the block
------------------------	---------------------

Returns

the offset of the block with ID `block_id`

35.12.2.4 `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

<i>block_↵ _id</i>	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()`.

35.12.2.5 `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()`.

35.12.2.6 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

35.12.3 Member Data Documentation**35.12.3.1 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 $1 \ll \text{group_power}$ elements.

Referenced by `gko::preconditioner::block_interleaved_storage_scheme< index_type >::get_group_offset()`, `gko↵::preconditioner::block_interleaved_storage_scheme< index_type >::get_group_size()`, 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`

35.13 gko::solver::CbGmres< ValueType > Class Template Reference

CB-GMRES or the compressed basis generalized minimal residual method is an iterative type Krylov subspace method which is suitable for nonsymmetric linear systems.

```
#include <ginkgo/core/solver/cb_gmres.hpp>
```

Public Member Functions

- `std::shared_ptr< const LinOp > get_system_matrix () const`
Gets the system operator (matrix) of the linear system.
- `size_type get_krylov_dim () const`
Returns the krylov dimension.
- `cb_gmres::storage_precision get_storage_precision () const`
Returns the storage precision used internally.

35.13.1 Detailed Description

```
template<typename ValueType = default_precision>
class gko::solver::CbGmres< ValueType >
```

CB-GMRES or the compressed basis 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 CB-GMRES are merged into 2 separate steps. Classical Gram-Schmidt with reorthogonalization is used.

The krylov basis can be stored in reduced precision (compressed) to reduce memory accesses, while all computations (including krylov basis operations) are performed in the same arithmetic precision `ValueType`. By default, the krylov basis are stored in one precision lower than `ValueType`.

Template Parameters

<i>ValueType</i>	the arithmetic precision and the precision of matrix elements
------------------	---

35.13.2 Member Function Documentation

35.13.2.1 `get_krylov_dim()`

```
template<typename ValueType = default_precision>
size\_type gko::solver::CbGmres< ValueType >::get\_krylov\_dim ( ) const [inline]
```

Returns the krylov dimension.

Returns

the krylov dimension

```
144 { return krylov_dim; }
```

35.13.2.2 get_storage_precision()

```
template<typename ValueType = default_precision>
cb_gmres::storage_precision gko::solver::CbGmres< ValueType >::get_storage_precision ( ) const
[inline]
```

Returns the storage precision used internally.

Returns

the storage precision used internally

35.13.2.3 get_system_matrix()

```
template<typename ValueType = default_precision>
std::shared_ptr<const LinOp> gko::solver::CbGmres< ValueType >::get_system_matrix ( ) const
[inline]
```

Gets the system operator (matrix) of the linear system.

Returns

the system operator (matrix)

The documentation for this class was generated from the following file:

- ginkgo/core/solver/cb_gmres.hpp

35.14 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::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.
- bool [apply_uses_initial_guess](#) () const override
Return true as iterative solvers use the data in x as an initial guess.
- std::shared_ptr< const [stop::CriterionFactory](#) > [get_stop_criterion_factory](#) () const
Gets the stopping criterion factory of the solver.
- void [set_stop_criterion_factory](#) (std::shared_ptr< const [stop::CriterionFactory](#) > other)
Sets the stopping criterion of the solver.

35.14.1 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

<i>ValueType</i>	precision of matrix elements
------------------	------------------------------

35.14.2 Member Function Documentation

35.14.2.1 `apply_uses_initial_guess()`

```
template<typename ValueType = default_precision>
bool gko::solver::Cg< ValueType >::apply_uses_initial_guess ( ) const [inline], [override]
```

Return true as iterative solvers use the data in x as an initial guess.

Returns

true as iterative solvers use the data in x as an initial guess.

```
101 { return true; }
```

35.14.2.2 `conj_transpose()`

```
template<typename ValueType = default_precision>
std::unique_ptr<LinOp> gko::solver::Cg< 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](#).

35.14.2.3 get_stop_criterion_factory()

```
template<typename ValueType = default_precision>
std::shared_ptr<const stop::CriterionFactory> gko::solver::Cg< ValueType >::get_stop_criterion←
_factory ( ) const [inline]
```

Gets the stopping criterion factory of the solver.

Returns

the stopping criterion factory

35.14.2.4 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)

35.14.2.5 set_stop_criterion_factory()

```
template<typename ValueType = default_precision>
void gko::solver::Cg< ValueType >::set_stop_criterion_factory (
    std::shared_ptr< const stop::CriterionFactory > other ) [inline]
```

Sets the stopping criterion of the solver.

Parameters

<i>other</i>	the new stopping criterion factory
--------------	------------------------------------

35.14.2.6 transpose()

```
template<typename ValueType = default_precision>
std::unique_ptr<LinOp> gko::solver::Cg< 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](#).

The documentation for this class was generated from the following file:

- `ginkgo/core/solver/cg.hpp`

35.15 `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::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.
- `bool apply_uses_initial_guess () const override`
Return true as iterative solvers use the data in x as an initial guess.
- `std::shared_ptr< const stop::CriterionFactory > get_stop_criterion_factory () const`
Gets the stopping criterion factory of the solver.
- `void set_stop_criterion_factory (std::shared_ptr< const stop::CriterionFactory > other)`
Sets the stopping criterion of the solver.

35.15.1 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

<i>ValueType</i>	precision of matrix elements
------------------	------------------------------

35.15.2 Member Function Documentation

35.15.2.1 apply_uses_initial_guess()

```
template<typename ValueType = default_precision>
bool gko::solver::Cgs< ValueType >::apply_uses_initial_guess ( ) const [inline], [override]
```

Return true as iterative solvers use the data in x as an initial guess.

Returns

true as iterative solvers use the data in x as an initial guess.

```
98 { return true; }
```

35.15.2.2 conj_transpose()

```
template<typename ValueType = default_precision>
std::unique_ptr<LinOp> gko::solver::Cgs< 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](#).

35.15.2.3 get_stop_criterion_factory()

```
template<typename ValueType = default_precision>
std::shared_ptr<const stop::CriterionFactory> gko::solver::Cgs< ValueType >::get_stop_↵
criterion_factory ( ) const [inline]
```

Gets the stopping criterion factory of the solver.

Returns

the stopping criterion factory

35.15.2.4 `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)

35.15.2.5 `set_stop_criterion_factory()`

```
template<typename ValueType = default_precision>
void gko::solver::Cgs< ValueType >::set_stop_criterion_factory (
    std::shared_ptr< const stop::CriterionFactory > other ) [inline]
```

Sets the stopping criterion of the solver.

Parameters

<i>other</i>	the new stopping criterion factory
--------------	------------------------------------

35.15.2.6 `transpose()`

```
template<typename ValueType = default_precision>
std::unique_ptr<LinOp> gko::solver::Cgs< 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](#).

The documentation for this class was generated from the following file:

- `ginkgo/core/solver/cgs.hpp`

35.16 `gko::matrix::Csr< ValueType, IndexType >::classical Class Reference`

`classical` is a [strategy_type](#) which uses the same number of threads on each row.

```
#include <ginkgo/core/matrix/csr.hpp>
```

Public Member Functions

- [classical](#) ()
Creates a classical strategy.
- void [process](#) (const [Array](#)< index_type > &mtx_row_ptrs, [Array](#)< index_type > *mtx_srow) override
Computes srow according to row pointers.
- int64_t [clac_size](#) (const int64_t nnz) override
Computes the srow size according to the number of nonzeros.
- std::shared_ptr< [strategy_type](#) > [copy](#) () override
Copy a strategy.

35.16.1 Detailed Description

```
template<typename ValueType = default_precision, typename IndexType = int32>
class gko::matrix::Csr< ValueType, IndexType >::classical
```

classical is a [strategy_type](#) which uses the same number of threads on each row.

Classical strategy uses multithreads to calculate on parts of rows and then do a reduction of these threads results. The number of threads per row depends on the max number of stored elements per row.

35.16.2 Member Function Documentation

35.16.2.1 clac_size()

```
template<typename ValueType = default_precision, typename IndexType = int32>
int64_t gko::matrix::Csr< ValueType, IndexType >::classical::clac_size (
    const int64_t nnz ) [inline], [override], [virtual]
```

Computes the srow size according to the number of nonzeros.

Parameters

<i>nnz</i>	the number of nonzeros
------------	------------------------

Returns

the size of srow

Implements [gko::matrix::Csr< ValueType, IndexType >::strategy_type](#).

35.16.2.2 copy()

```
template<typename ValueType = default_precision, typename IndexType = int32>
std::shared_ptr<strategy_type> gko::matrix::Csr< ValueType, IndexType >::classical::copy ( )
[inline], [override], [virtual]
```

Copy a strategy.

This is a workaround until strategies are revamped, since strategies like `automatical` do not work when actually shared.

Implements [gko::matrix::Csr< ValueType, IndexType >::strategy_type](#).

35.16.2.3 process()

```
template<typename ValueType = default_precision, typename IndexType = int32>
void gko::matrix::Csr< ValueType, IndexType >::classical::process (
    const Array< index_type > & mtx_row_ptrs,
    Array< index_type > * mtx_srow ) [inline], [override], [virtual]
```

Computes srow according to row pointers.

Parameters

<i>mtx_row_ptrs</i>	the row pointers of the matrix
<i>mtx_srow</i>	the srow of the matrix

Implements [gko::matrix::Csr< ValueType, IndexType >::strategy_type](#).

References [gko::Array< ValueType >::get_const_data\(\)](#), [gko::Array< ValueType >::get_executor\(\)](#), and [gko::Array< ValueType >::get_num_elems\(\)](#).

The documentation for this class was generated from the following file:

- `ginkgo/core/matrix/csr.hpp`

35.17 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.
- auto [get_num_columns](#) () const
Get the number of columns limit.

35.17.1 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.

35.17.2 Constructor & Destructor Documentation

35.17.2.1 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
----------------------------	---

35.17.3 Member Function Documentation

35.17.3.1 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

<code>row_nnz</code>	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](#).

35.17.3.2 `get_num_columns()`

```
template<typename ValueType = default_precision, typename IndexType = int32>
auto gko::matrix::Hybrid< ValueType, IndexType >::column_limit::get_num_columns ( ) const
[inline]
```

Get the number of columns limit.

Returns

the number of columns limit

The documentation for this class was generated from the following file:

- `ginkgo/core/matrix/hybrid.hpp`

35.18 `gko::Combination< ValueType >` Class Template Reference

The [Combination](#) class can be used to construct a linear combination of multiple linear operators $c1 * op1 + c2 * op2 + \dots$

```
#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.
- `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.

35.18.1 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 $c1 * op1 + c2 * op2 + \dots$

- $ck * opk$.

Template Parameters

<i>ValueType</i>	precision of input and result vectors
------------------	---------------------------------------

35.18.2 Member Function Documentation

35.18.2.1 conj_transpose()

```
template<typename ValueType = default_precision>
std::unique_ptr<LinOp> gko::Combination< 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](#).

35.18.2.2 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

```
72     {
73         return coefficients_;
74     }
```

35.18.2.3 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

35.18.2.4 transpose()

```
template<typename ValueType = default_precision>
std::unique_ptr<LinOp> gko::Combination< 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](#).

The documentation for this class was generated from the following file:

- ginkgo/core/base/combination.hpp

35.19 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>
```

35.19.1 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

35.20 gko::Composition< ValueType > Class Template Reference

The [Composition](#) class can be used to compose linear operators op_1 , op_2 , ..., op_n and obtain the operator $op_1 * op_2 * \dots$.

```
#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.
- `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.

35.20.1 Detailed Description

```
template<typename ValueType = default_precision>
class gko::Composition< ValueType >
```

The [Composition](#) class can be used to compose linear operators op_1 , op_2 , ..., op_n and obtain the operator $op_1 * op_2 * \dots$

- op_n .

All LinOps of the [Composition](#) must operate on Dense inputs. For an operator op_k that require an initial guess for their `apply`, [Composition](#) provides either

- the output of the previous $op_{k+1} \rightarrow apply$ if op_k has square dimension
- zero if op_k is rectangular as an initial guess.

Template Parameters

<i>ValueType</i>	precision of input and result vectors
------------------	---------------------------------------

35.20.2 Member Function Documentation

35.20.2.1 conj_transpose()

```
template<typename ValueType = default_precision>
std::unique_ptr<LinOp> gko::Composition< 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](#).

35.20.2.2 `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

```
80     {
81         return operators_;
82     }
```

35.20.2.3 `transpose()`

```
template<typename ValueType = default_precision>
std::unique_ptr<LinOp> gko::Composition< 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](#).

The documentation for this class was generated from the following file:

- `ginkgo/core/base/composition.hpp`

35.21 `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.

35.21.1 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.

35.21.2 Member Function Documentation

35.21.2.1 `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

<i>exec</i>	the executor
<i>enabled_events</i>	the events enabled for this logger. By default all events.

Returns

an std::unique_ptr to the the constructed object

```
92     {
93         return std::unique_ptr<Convergence>(
94             new Convergence(exec, enabled_events));
95     }
```

35.21.2.2 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

35.21.2.3 get_residual()

```
template<typename ValueType = default_precision>
const LinOp* gko::log::Convergence< ValueType >::get_residual ( ) const [inline], [noexcept]
```

Returns the residual.

Returns

the residual

35.21.2.4 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

The documentation for this class was generated from the following file:

- ginkgo/core/log/convergence.hpp

35.22 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.

35.22.1 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

<i>ResultType</i>	the type to which the implementer can be converted to, has to be a subclass of PolymorphicObject
-------------------	--

35.22.2 Member Function Documentation

35.22.2.1 [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

<i>result</i>	the object used to store the result of the conversion
---------------	---

Implemented in [gko::EnablePolymorphicAssignment< ConcreteType, ResultType >](#), [gko::EnablePolymorphicAssignment< Isai< IsaiType, ValueType, IndexType >, ResultType >](#), [gko::EnablePolymorphicAssignment< SparsityCsr< ValueType, IndexType >, ResultType >](#), [gko::EnablePolymorphicAssignment< Diagonal< ValueType, IndexType >, ResultType >](#), [gko::EnablePolymorphicAssignment< Dense< ValueType >, ResultType >](#), [gko::EnablePolymorphicAssignment< UpperTrs< ValueType, IndexType >, ResultType >](#), [gko::EnablePolymorphicAssignment< Hybrid< ValueType, IndexType >, ResultType >](#), [gko::EnablePolymorphicAssignment< Identity< ValueType >, ResultType >](#), [gko::EnablePolymorphicAssignment< ConcreteLinOp >](#), [gko::EnablePolymorphicAssignment< Composition< ValueType >, ResultType >](#), [gko::EnablePolymorphicAssignment< Bicgstab< ValueType >, ResultType >](#), [gko::EnablePolymorphicAssignment< LowerTrs< ValueType, IndexType >, ResultType >](#), [gko::EnablePolymorphicAssignment< Combination< ValueType >, ResultType >](#), [gko::EnablePolymorphicAssignment< Gmres< ValueType >, ResultType >](#), [gko::EnablePolymorphicAssignment< CbGmres< ValueType >, ResultType >](#), [gko::EnablePolymorphicAssignment< Csr< ValueType, IndexType >, ResultType >](#), [gko::EnablePolymorphicAssignment< Ir< ValueType >, ResultType >](#), [gko::EnablePolymorphicAssignment< Coo< ValueType, IndexType >, ResultType >](#), [gko::EnablePolymorphicAssignment< Fcg< ValueType >, ResultType >](#), [gko::EnablePolymorphicAssignment< AmgxPgm< ValueType, IndexType >, ResultType >](#), [gko::EnablePolymorphicAssignment< Rcm< ValueType, IndexType >, ResultType >](#), [gko::EnablePolymorphicAssignment< Idr< ValueType >, ResultType >](#), [gko::EnablePolymorphicAssignment< ConcreteFactory >](#), [gko::EnablePolymorphicAssignment< Cgs< ValueType >, ResultType >](#), [gko::EnablePolymorphicAssignment< Ell< ValueType, IndexType >, ResultType >](#), [gko::EnablePolymorphicAssignment< Ilu< LSolverType, USolverType >, ResultType >](#), [gko::EnablePolymorphicAssignment< Ic< LSolverType, IndexType >, ResultType >](#), [gko::EnablePolymorphicAssignment< Permutation< IndexType >, ResultType >](#), [gko::EnablePolymorphicAssignment< Jacobi< ValueType, IndexType >, ResultType >](#), [gko::EnablePolymorphicAssignment< Cg< ValueType >, ResultType >](#), [gko::EnablePolymorphicAssignment< Sellp< ValueType, IndexType >, ResultType >](#), [gko::EnablePolymorphicAssignment< Bicg< ValueType >, ResultType >](#), [gko::EnablePolymorphicAssignment< Perturbation< ValueType >, ResultType >](#), and [gko::preconditioner::Jacobi< ValueType, IndexType >](#).

35.22.2.2 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

<i>result</i>	the object used to replace 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< Isai< IsaiType, ValueType, IndexType >, ResultType >](#), [gko::EnablePolymorphicAssignment< SparsityCsr< ValueType, IndexType >, ResultType >](#), [gko::EnablePolymorphicAssignment< Diagonal< ValueType, IndexType >, ResultType >](#), [gko::EnablePolymorphicAssignment< Dense< ValueType >, ResultType >](#), [gko::EnablePolymorphicAssignment< UpperTrs< ValueType, IndexType >, ResultType >](#), [gko::EnablePolymorphicAssignment< Hybrid< ValueType, IndexType >, ResultType >](#), [gko::EnablePolymorphicAssignment< Identity< ValueType >, ResultType >](#), [gko::EnablePolymorphicAssignment< ConcreteLinOp >](#), [gko::EnablePolymorphicAssignment< Composition< ValueType >, ResultType >](#), [gko::EnablePolymorphicAssignment< Bicgstab< ValueType >, ResultType >](#), [gko::EnablePolymorphicAssignment< LowerTrs< ValueType, IndexType >, ResultType >](#), [gko::EnablePolymorphicAssignment< Combination< ValueType >, ResultType >](#), [gko::EnablePolymorphicAssignment< Gmres< ValueType >, ResultType >](#), [gko::EnablePolymorphicAssignment< CbGmres< ValueType >, ResultType >](#), [gko::EnablePolymorphicAssignment< Csr< ValueType, IndexType >, ResultType >](#), [gko::EnablePolymorphicAssignment< Ir< ValueType >, ResultType >](#), [gko::EnablePolymorphicAssignment< Coo< ValueType, IndexType >, ResultType >](#), [gko::EnablePolymorphicAssignment< Fcg< ValueType >, ResultType >](#), [gko::EnablePolymorphicAssignment< AmgxPgm< ValueType, IndexType >, ResultType >](#), [gko::EnablePolymorphicAssignment< Rcm< ValueType, IndexType >, ResultType >](#), [gko::EnablePolymorphicAssignment< Idr< ValueType >, ResultType >](#), [gko::EnablePolymorphicAssignment< ConcreteFactory >](#), [gko::EnablePolymorphicAssignment< Cgs< ValueType >, ResultType >](#), [gko::EnablePolymorphicAssignment< Ell< ValueType, IndexType >, ResultType >](#), [gko::EnablePolymorphicAssignment< Ilu< LSolverType, USolverType >, ResultType >](#), [gko::EnablePolymorphicAssignment< Ic< LSolverType, IndexType >, ResultType >](#), [gko::EnablePolymorphicAssignment< Permutation< IndexType >, ResultType >](#), [gko::EnablePolymorphicAssignment< Jacobi< ValueType, IndexType >, ResultType >](#), [gko::EnablePolymorphicAssignment< Cg< ValueType >, ResultType >](#), [gko::EnablePolymorphicAssignment< Sellp< ValueType, IndexType >, ResultType >](#), [gko::EnablePolymorphicAssignment< Bicg< ValueType >, ResultType >](#), [gko::EnablePolymorphicAssignment< Perturbation< ValueType >, ResultType >](#), and [gko::preconditioner::Jacobi< ValueType, IndexType >](#).

[gko::EnablePolymorphicAssignment< Sellp< ValueType, IndexType > >](#), [gko::EnablePolymorphicAssignment< Bicg< ValueType >](#), [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](#)

35.23 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.
- std::unique_ptr< [Diagonal](#)< ValueType > > [extract_diagonal](#) () const override
Extracts the diagonal entries of the matrix into a vector.
- std::unique_ptr< absolute_type > [compute_absolute](#) () const override
Gets the AbsoluteLinOp.
- void [compute_absolute_inplace](#) () override
Compute absolute inplace on each element.
- 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 $x = \alpha * \text{Coo} * b + x$.*
- const LinOp * [apply2](#) (const LinOp *alpha, const LinOp *b, LinOp *x) const
*Performs the operation $x = \alpha * \text{Coo} * b + x$.*

35.23.1 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 necessarily 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

<i>ValueType</i>	precision of matrix elements
<i>IndexType</i>	precision of matrix indexes

35.23.2 Member Function Documentation

35.23.2.1 apply2() [1/4]

```
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 $x = \text{alpha} * \text{Coo} * b + x$.

Parameters

<i>alpha</i>	scaling of the result of <code>Coo * b</code>
<i>b</i>	vector(s) on which the operator is applied
<i>x</i>	output vector(s)

Returns

this

```
237 {
238     this->validate_application_parameters(b, x);
239     GKO_ASSERT_EQUAL_DIMENSIONS(alpha, dim<2>(1, 1));
240     auto exec = this->get_executor();
241     this->apply2_impl(make_temporary_clone(exec, alpha).get(),
242                     make_temporary_clone(exec, b).get(),
243                     make_temporary_clone(exec, x).get());
244     return this;
245 }
```

References `gko::PolymorphicObject::get_executor()`, and `gko::make_temporary_clone()`.

35.23.2.2 apply2() [2/4]

```
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 $x = \text{alpha} * \text{Coo} * b + x$.

Parameters

<i>alpha</i>	scaling of the result of <code>Coo * b</code>
<i>b</i>	vector(s) on which the operator is applied
<i>x</i>	output vector(s)

Returns

this

References `gko::PolymorphicObject::get_executor()`, and `gko::make_temporary_clone()`.

35.23.2.3 apply2() [3/4]

```
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 $x = \text{Coo} * b + x$

Parameters

<i>b</i>	the input vector(s) on which the operator is applied
<i>x</i>	the output vector(s) where the result is stored

Returns

this

References `gko::PolymorphicObject::get_executor()`, and `gko::make_temporary_clone()`.

35.23.2.4 apply2() [4/4]

```
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()`.

35.23.2.5 compute_absolute()

```
template<typename ValueType = default_precision, typename IndexType = int32>
std::unique_ptr<absolute_type> gko::matrix::Coo< ValueType, IndexType >::compute_absolute ( )
const [override], [virtual]
```

Gets the AbsoluteLinOp.

Returns

a pointer to the new absolute object

Implements [gko::EnableAbsoluteComputation< remove_complex< Coo< ValueType, IndexType > > >](#).

35.23.2.6 extract_diagonal()

```
template<typename ValueType = default_precision, typename IndexType = int32>
std::unique_ptr<Diagonal<ValueType> > gko::matrix::Coo< ValueType, IndexType >::extract_↵
diagonal ( ) const [override], [virtual]
```

Extracts the diagonal entries of the matrix into a vector.

Parameters

<i>diag</i>	the vector into which the diagonal will be written
-------------	--

Implements [gko::DiagonalExtractable< ValueType >](#).

35.23.2.7 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\(\)](#).

35.23.2.8 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()`.

35.23.2.9 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()`.

35.23.2.10 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()`.

35.23.2.11 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().

35.23.2.12 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().

35.23.2.13 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().

35.23.2.14 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

<i>data</i>	the matrix_data structure
-------------	---

Implements [gko::ReadableFromMatrixData< ValueType, IndexType >](#).

35.23.2.15 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

<i>data</i>	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

35.24 gko::cpx_real_type< T > Struct Template Reference

Access the underlying real type of a complex number.

```
#include <ginkgo/core/base/math.hpp>
```

Public Types

- using [type](#) = T
The type.

35.24.1 Detailed Description

```
template<typename T>
struct gko::cpx_real_type< T >
```

Access the underlying real type of a complex number.

Template Parameters

<i>T</i>	the type being checked.
----------	-------------------------

35.24.2 Member Typedef Documentation

35.24.2.1 type

```
template<typename T >
using gko::cpx_real_type< T >::type = T
```

The type.

When the type is not complex, return the type itself.

The documentation for this struct was generated from the following file:

- ginkgo/core/base/math.hpp

35.25 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 stopping_id, bool set_finalized, [Array](#)< [stopping_status](#) > *stop_status, bool *one_↵ changed, const [Updater](#) &updater)
This checks whether convergence was reached for a certain criterion.

35.25.1 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.

35.25.2 Member Function Documentation

35.25.2.1 check()

```
bool gko::stop::Criterion::check (
    uint8 stopping_id,
    bool set_finalized,
    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

<i>stopping_id</i>	id of the stopping criterion
<i>set_finalized</i>	Controls if the current version should count as finalized or not
<i>stop_status</i>	status of the stopping criterion
<i>one_changed</i>	indicates if one vector's status changed
<i>updater</i>	the Updater object containing all the information

Returns

whether convergence was completely reached

```
156 {
157     this->template log<log::Logger::criterion_check_started>(
158         this, updater.num_iterations_, updater.residual_,
159         updater.residual_norm_, updater.solution_, stopping_id,
160         set_finalized);
161     auto all_converged = this->check_impl(
162         stopping_id, set_finalized, stop_status, one_changed, updater);
163     this->template log<log::Logger::criterion_check_completed>(
164         this, updater.num_iterations_, updater.residual_,
165         updater.residual_norm_, updater.solution_, stopping_id,
166         set_finalized, stop_status, *one_changed, all_converged);
167     return all_converged;
168 }
```

Referenced by `gko::stop::Criterion::Updater::check()`.

35.25.2.2 update()

```
Updater gko::stop::Criterion::update ( ) [inline]
```

Returns the updater object.

Returns

the updater object

The documentation for this class was generated from the following file:

- `ginkgo/core/stop/criterion.hpp`

35.26 gko::log::criterion_data Struct Reference

Struct representing Criterion related data.

```
#include <ginkgo/core/log/record.hpp>
```

35.26.1 Detailed Description

Struct representing Criterion related data.

The documentation for this struct was generated from the following file:

- ginkgo/core/log/record.hpp

35.27 gko::stop::CriterionArgs Struct Reference

This struct is used to pass parameters to the EnableDefaultCriterionFactoryCriterionFactory::generate() method.

```
#include <ginkgo/core/stop/criterion.hpp>
```

35.27.1 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

35.28 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>
```

Classes

- class [classical](#)
classical is a [strategy_type](#) which uses the same number of threads on each row.
- class [cuspars](#)
cuspars is a [strategy_type](#) which uses the sparselib csr.
- class [load_balance](#)
load_balance is a [strategy_type](#) which uses the load balance algorithm.
- class [merge_path](#)
merge_path is a [strategy_type](#) which uses the [merge_path](#) algorithm.
- class [sparselib](#)
sparselib is a [strategy_type](#) which uses the sparselib csr.
- class [strategy_type](#)
strategy_type is to decide how to set the csr algorithm.

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.
- std::unique_ptr< LinOp > [permute](#) (const [Array](#)< IndexType > *permutation_indices) const override
Returns a LinOp representing the symmetric row and column permutation of the [Permutable](#) object.
- std::unique_ptr< LinOp > [inverse_permute](#) (const [Array](#)< IndexType > *inverse_permutation_indices) const override
Returns a LinOp representing the symmetric inverse row and column permutation of the [Permutable](#) object.
- std::unique_ptr< LinOp > [row_permute](#) (const [Array](#)< IndexType > *permutation_indices) const override
Returns a LinOp representing the row permutation of the [Permutable](#) object.
- std::unique_ptr< LinOp > [column_permute](#) (const [Array](#)< IndexType > *permutation_indices) const override
Returns a LinOp representing the column permutation of the [Permutable](#) object.
- std::unique_ptr< LinOp > [inverse_row_permute](#) (const [Array](#)< IndexType > *inverse_permutation_indices) const override
Returns a LinOp representing the row permutation of the inverse permuted object.
- std::unique_ptr< LinOp > [inverse_column_permute](#) (const [Array](#)< IndexType > *inverse_permutation_↔ indices) const override
Returns a LinOp representing the row permutation of the inverse permuted object.
- std::unique_ptr< [Diagonal](#)< ValueType > > [extract_diagonal](#) () const override
Extracts the diagonal entries of the matrix into a vector.
- std::unique_ptr< absolute_type > [compute_absolute](#) () const override
Gets the AbsoluteLinOp.
- void [compute_absolute_inplace](#) () override
Compute absolute inplace on each element.
- 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_idx` () noexcept
Returns the column indexes of the matrix.
- `const index_type * get_const_col_idx` () const noexcept
Returns the column indexes of the matrix.
- `index_type * get_row_ptr` () noexcept
Returns the row pointers of the matrix.
- `const index_type * get_const_row_ptr` () 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.
- `void set_strategy` (std::shared_ptr< strategy_type > strategy)
Set the strategy.

35.28.1 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.

The `Csr` LinOp supports different operations:

```
matrix::Csr *A, *B, *C;           // matrices
matrix::Dense *b, *x;             // vectors tall-and-skinny matrices
matrix::Dense *alpha, *beta;      // scalars of dimension 1x1
matrix::Identity *I;              // identity matrix
// Applying to Dense matrices computes an SpMV/SpMM product
A->apply(b, x)                     // x = A*b
A->apply(alpha, b, beta, x)        // x = alpha*A*b + beta*x
// Applying to Csr matrices computes a SpGEMM product of two sparse matrices
A->apply(B, C)                     // C = A*B
A->apply(alpha, B, beta, C)        // C = alpha*A*B + beta*C
// Applying to an Identity matrix computes a SpGEAM sparse matrix addition
A->apply(alpha, I, beta, B)        // B = alpha*A + beta*B
```

Both the SpGEMM and SpGEAM operation require the input matrices to be sorted by column index, otherwise the algorithms will produce incorrect results.

Template Parameters

<i>ValueType</i>	precision of matrix elements
<i>IndexType</i>	precision of matrix indexes

35.28.2 Member Function Documentation

35.28.2.1 column_permute()

```
template<typename ValueType = default_precision, typename IndexType = int32>
std::unique_ptr<LinOp> gko::matrix::Csr< ValueType, IndexType >::column_permute (
    const Array< IndexType > * permutation_indices ) const [override], [virtual]
```

Returns a LinOp representing the column permutation of the [Permutable](#) object.

In the resulting LinOp, the column *i* contains the input column `perm[i]`.

Parameters

<i>permutation_indices</i>	the array of indices containing the permutation order <code>perm</code> .
----------------------------	---

Returns

a pointer to the new column permuted object

Implements [gko::Permutable< IndexType >](#).

35.28.2.2 compute_absolute()

```
template<typename ValueType = default_precision, typename IndexType = int32>
std::unique_ptr<absolute_type> gko::matrix::Csr< ValueType, IndexType >::compute_absolute ( )
const [override], [virtual]
```

Gets the AbsoluteLinOp.

Returns

a pointer to the new absolute object

Implements [gko::EnableAbsoluteComputation< remove_complex< Csr< ValueType, IndexType > > >](#).

35.28.2.3 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](#).

35.28.2.4 extract_diagonal()

```
template<typename ValueType = default_precision, typename IndexType = int32>
std::unique_ptr<Diagonal<ValueType> > gko::matrix::Csr< ValueType, IndexType >::extract_↵
diagonal ( ) const [override], [virtual]
```

Extracts the diagonal entries of the matrix into a vector.

Parameters

<i>diag</i>	the vector into which the diagonal will be written
-------------	--

Implements [gko::DiagonalExtractable< ValueType >](#).

35.28.2.5 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.

```
759 { return col_idxs_.get_data(); }
```

References [gko::Array< ValueType >::get_data\(\)](#).

35.28.2.6 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.

References [gko::Array< ValueType >::get_const_data\(\)](#).

35.28.2.7 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.

References `gko::Array< ValueType >::get_const_data()`.

35.28.2.8 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.

References `gko::Array< ValueType >::get_const_data()`.

35.28.2.9 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.

References `gko::Array< ValueType >::get_const_data()`.

35.28.2.10 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)

References gko::Array< ValueType >::get_num_elems().

35.28.2.11 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

References gko::Array< ValueType >::get_num_elems().

35.28.2.12 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.

References gko::Array< ValueType >::get_data().

35.28.2.13 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.

References `gko::Array< ValueType >::get_data()`.

35.28.2.14 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

35.28.2.15 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.

References `gko::Array< ValueType >::get_data()`.

35.28.2.16 inverse_column_permute()

```
template<typename ValueType = default_precision, typename IndexType = int32>
std::unique_ptr<LinOp> gko::matrix::Csr< ValueType, IndexType >::inverse_column_permute (
    const Array< IndexType > * permutation_indices ) const [override], [virtual]
```

Returns a `LinOp` representing the row permutation of the inverse permuted object.

In the resulting `LinOp`, the column `perm[i]` contains the input column `i`.

Parameters

<i>permutation_indices</i>	the array of indices containing the permutation order <code>perm</code> .
----------------------------	---

Returns

a pointer to the new inverse permuted object

Implements [gko::Permutable< IndexType >](#).

35.28.2.17 inverse_permute()

```
template<typename ValueType = default_precision, typename IndexType = int32>
std::unique_ptr<LinOp> gko::matrix::Csr< ValueType, IndexType >::inverse_permute (
    const Array< IndexType > * permutation_indices ) const [override], [virtual]
```

Returns a LinOp representing the symmetric inverse row and column permutation of the [Permutable](#) object.

In the resulting LinOp, the entry at location `(perm[i], perm[j])` contains the input value `(i, j)`.

Parameters

<i>permutation_indices</i>	the array of indices containing the permutation order.
----------------------------	--

Returns

a pointer to the new permuted object

Reimplemented from [gko::Permutable< IndexType >](#).

35.28.2.18 inverse_row_permute()

```
template<typename ValueType = default_precision, typename IndexType = int32>
std::unique_ptr<LinOp> gko::matrix::Csr< ValueType, IndexType >::inverse_row_permute (
    const Array< IndexType > * permutation_indices ) const [override], [virtual]
```

Returns a LinOp representing the row permutation of the inverse permuted object.

In the resulting LinOp, the row `perm[i]` contains the input row `i`.

Parameters

<i>permutation_indices</i>	the array of indices containing the permutation order <code>perm</code> .
----------------------------	---

Returns

a pointer to the new inverse permuted object

Implements [gko::Permutable< IndexType >](#).

35.28.2.19 permute()

```
template<typename ValueType = default_precision, typename IndexType = int32>
std::unique_ptr<LinOp> gko::matrix::Csr< ValueType, IndexType >::permute (
    const Array< IndexType > * permutation_indices ) const [override], [virtual]
```

Returns a LinOp representing the symmetric row and column permutation of the [Permutable](#) object.

In the resulting LinOp, the entry at location (i, j) contains the input value $(\text{perm}[i], \text{perm}[j])$.

Parameters

<i>permutation_indices</i>	the array of indices containing the permutation order.
----------------------------	--

Returns

a pointer to the new permuted object

Reimplemented from [gko::Permutable< IndexType >](#).

35.28.2.20 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

<i>data</i>	the matrix_data structure
-------------	---

Implements [gko::ReadableFromMatrixData< ValueType, IndexType >](#).

35.28.2.21 row_permute()

```
template<typename ValueType = default_precision, typename IndexType = int32>
std::unique_ptr<LinOp> gko::matrix::Csr< ValueType, IndexType >::row_permute (
    const Array< IndexType > * permutation_indices ) const [override], [virtual]
```

Returns a LinOp representing the row permutation of the [Permutable](#) object.

In the resulting LinOp, the row `i` contains the input row `perm[i]`.

Parameters

<i>permutation_indices</i>	the array of indices containing the permutation order.
----------------------------	--

Returns

a pointer to the new permuted object

Implements [gko::Permutable< IndexType >](#).

35.28.2.22 set_strategy()

```
template<typename ValueType = default_precision, typename IndexType = int32>
void gko::matrix::Csr< ValueType, IndexType >::set_strategy (
    std::shared_ptr< strategy_type > strategy ) [inline]
```

Set the strategy.

Parameters

<i>strategy</i>	the csr strategy
-----------------	------------------

35.28.2.23 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](#).

35.28.2.24 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

<i>data</i>	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](#)
- [ginkgo/core/matrix/csr.hpp](#)

35.29 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.

35.29.1 Detailed Description

[CublasError](#) is thrown when a cuBLAS routine throws a non-zero error code.

35.29.2 Constructor & Destructor Documentation

35.29.2.1 CublasError()

```
gko::CublasError::CublasError (
    const std::string & file,
    int line,
    const std::string & func,
    int64 error_code ) [inline]
```

Initializes a cuBLAS error.

Parameters

<i>file</i>	The name of the offending source file
<i>line</i>	The source code line number where the error occurred
<i>func</i>	The name of the cuBLAS routine that failed
<i>error_code</i>	The resulting cuBLAS error code

The documentation for this class was generated from the following file:

- ginkgo/core/base/exception.hpp

35.30 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.

35.30.1 Detailed Description

[CudaError](#) is thrown when a CUDA routine throws a non-zero error code.

35.30.2 Constructor & Destructor Documentation

35.30.2.1 CudaError()

```
gko::CudaError::CudaError (
    const std::string & file,
    int line,
    const std::string & func,
    int64 error_code ) [inline]
```

Initializes a CUDA error.

Parameters

<i>file</i>	The name of the offending source file
<i>line</i>	The source code line number where the error occurred
<i>func</i>	The name of the CUDA routine that failed
<i>error_code</i>	The resulting CUDA error code

The documentation for this class was generated from the following file:

- ginkgo/core/base/exception.hpp

35.31 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_warps_per_sm ()` const noexcept
Get the number of warps 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_warp_size ()` const noexcept
Get the warp size 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.
- `std::vector< int > get_closest_pus ()` const
Get the closest PUs.
- `int get_closest_numa ()` const
Get the closest NUMA node.

Static Public Member Functions

- `static std::shared_ptr< CudaExecutor > create (int device_id, std::shared_ptr< Executor > master, bool device_reset=false)`
Creates a new [CudaExecutor](#).
- `static int get_num_devices ()`
Get the number of devices present on the system.

35.31.1 Detailed Description

This is the [Executor](#) subclass which represents the CUDA device.

35.31.2 Member Function Documentation

35.31.2.1 create()

```
static std::shared_ptr<CudaExecutor> gko::CudaExecutor::create (
    int device_id,
    std::shared_ptr< Executor > master,
    bool device_reset = false ) [static]
```

Creates a new [CudaExecutor](#).

Parameters

<i>device_id</i>	the CUDA device id of this device
<i>master</i>	an executor on the host that is used to invoke the device kernels

35.31.2.2 get_closest_numa()

```
int gko::CudaExecutor::get_closest_numa ( ) const [inline]
```

Get the closest NUMA node.

Returns

the closest NUMA node closest to this device

```
1348 { return this->get_exec_info().numa_node; }
```

35.31.2.3 get_closest_pus()

```
std::vector<int> gko::CudaExecutor::get_closest_pus ( ) const [inline]
```

Get the closest PUs.

Returns

the array of PUs closest to this device

35.31.2.4 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

35.31.2.5 get_cuspars_handle()

```
cusparsContext* gko::CudaExecutor::get_cuspars_handle ( ) const [inline]
```

Get the cuspars handle for this executor.

Returns

the cuspars handle (cusparsContext*) for this executor

35.31.2.6 get_master() [1/2]

```
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](#).

35.31.2.7 get_master() [2/2]

```
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](#).

35.31.2.8 run()

```
void gko::CudaExecutor::run (
    const Operation & op ) const [override], [virtual]
```

Runs the specified [Operation](#) using this [Executor](#).

Parameters

<i>op</i>	the operation to run
-----------	----------------------

Implements [gko::Executor](#).

The documentation for this class was generated from the following file:

- ginkgo/core/base/executor.hpp

35.32 gko::CurandError Class Reference

[CurandError](#) is thrown when a cuRAND routine throws a non-zero error code.

```
#include <ginkgo/core/base/exception.hpp>
```

Public Member Functions

- [CurandError](#) (const std::string &file, int line, const std::string &func, [int64](#) error_code)
Initializes a cuRAND error.

35.32.1 Detailed Description

[CurandError](#) is thrown when a cuRAND routine throws a non-zero error code.

35.32.2 Constructor & Destructor Documentation

35.32.2.1 CurandError()

```
gko::CurandError::CurandError (
    const std::string & file,
    int line,
    const std::string & func,
    int64 error_code ) [inline]
```

Initializes a cuRAND error.

Parameters

<i>file</i>	The name of the offending source file
<i>line</i>	The source code line number where the error occurred
<i>func</i>	The name of the cuRAND routine that failed
<i>error_code</i>	The resulting cuRAND error code

The documentation for this class was generated from the following file:

- ginkgo/core/base/exception.hpp

35.33 gko::matrix::Csr< ValueType, IndexType >::cusparse Class Reference

cusparse is a [strategy_type](#) which uses the sparselib csr.

```
#include <ginkgo/core/matrix/csr.hpp>
```

Public Member Functions

- [cusparse](#) ()
Creates a cusparse strategy.
- void [process](#) (const [Array](#)< index_type > &mtx_row_ptrs, [Array](#)< index_type > *mtx_srow) override
Computes srow according to row pointers.
- int64_t [clac_size](#) (const int64_t nnz) override
Computes the srow size according to the number of nonzeros.
- std::shared_ptr< [strategy_type](#) > [copy](#) () override
Copy a strategy.

35.33.1 Detailed Description

```
template<typename ValueType = default_precision, typename IndexType = int32>
class gko::matrix::Csr< ValueType, IndexType >::cusparse
```

cusparse is a [strategy_type](#) which uses the sparselib csr.

Note

cusparse is also known to the hip executor which converts between cuda and hip.

35.33.2 Member Function Documentation

35.33.2.1 clac_size()

```
template<typename ValueType = default_precision, typename IndexType = int32>
int64_t gko::matrix::Csr< ValueType, IndexType >::cusparse::clac_size (
    const int64_t nnz ) [inline], [override], [virtual]
```

Computes the srow size according to the number of nonzeros.

Parameters

<i>nnz</i>	the number of nonzeros
------------	------------------------

Returns

the size of srow

Implements [gko::matrix::Csr< ValueType, IndexType >::strategy_type](#).

35.33.2.2 copy()

```
template<typename ValueType = default_precision, typename IndexType = int32>
std::shared_ptr<strategy_type> gko::matrix::Csr< ValueType, IndexType >::cusparse::copy ( )
[inline], [override], [virtual]
```

Copy a strategy.

This is a workaround until strategies are revamped, since strategies like `automatical` do not work when actually shared.

Implements [gko::matrix::Csr< ValueType, IndexType >::strategy_type](#).

35.33.2.3 process()

```
template<typename ValueType = default_precision, typename IndexType = int32>
void gko::matrix::Csr< ValueType, IndexType >::cusparse::process (
    const Array< index_type > & mtx_row_ptrs,
    Array< index_type > * mtx_srow ) [inline], [override], [virtual]
```

Computes srow according to row pointers.

Parameters

<i>mtx_row_ptrs</i>	the row pointers of the matrix
<i>mtx_srow</i>	the srow of the matrix

Implements [gko::matrix::Csr< ValueType, IndexType >::strategy_type](#).

The documentation for this class was generated from the following file:

- ginkgo/core/matrix/csr.hpp

35.34 gko::CusparsedError Class Reference

[CusparsedError](#) is thrown when a cuSPARSE routine throws a non-zero error code.

```
#include <ginkgo/core/base/exception.hpp>
```

Public Member Functions

- [CusparsedError](#) (const std::string &file, int line, const std::string &func, [int64](#) error_code)
Initializes a cuSPARSE error.

35.34.1 Detailed Description

[CusparsedError](#) is thrown when a cuSPARSE routine throws a non-zero error code.

35.34.2 Constructor & Destructor Documentation

35.34.2.1 CusparsedError()

```
gko::CusparsedError::CusparsedError (
    const std::string & file,
    int line,
    const std::string & func,
    int64 error_code ) [inline]
```

Initializes a cuSPARSE error.

Parameters

<i>file</i>	The name of the offending source file
<i>line</i>	The source code line number where the error occurred
<i>func</i>	The name of the cuSPARSE routine that failed
<i>error_code</i>	The resulting cuSPARSE error code

The documentation for this class was generated from the following file:

- ginkgo/core/base/exception.hpp

35.35 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.

35.35.1 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

<code>S</code>	source type
<code>R</code>	result type

35.35.2 Member Function Documentation

35.35.2.1 operator>()

```
template<typename S , typename R >
R gko::default_converter< S, R >::operator() (
    S val ) [inline]
```

Converts the object to result type.

Parameters

<code>val</code>	the object to convert
------------------	-----------------------

Returns

the converted object

The documentation for this struct was generated from the following file:

- `ginkgo/core/base/math.hpp`

35.36 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.
- `std::unique_ptr< LinOp > permute (const Array< int32 > *permutation_indices)` const override
Returns a LinOp representing the symmetric row and column permutation of the [Permutable](#) object.
- `std::unique_ptr< LinOp > permute (const Array< int64 > *permutation_indices)` const override
Returns a LinOp representing the symmetric row and column permutation of the [Permutable](#) object.
- `std::unique_ptr< LinOp > inverse_permute (const Array< int32 > *permutation_indices)` const override
Returns a LinOp representing the symmetric inverse row and column permutation of the [Permutable](#) object.
- `std::unique_ptr< LinOp > inverse_permute (const Array< int64 > *permutation_indices)` const override
Returns a LinOp representing the symmetric inverse row and column permutation of the [Permutable](#) object.
- `std::unique_ptr< LinOp > row_permute (const Array< int32 > *permutation_indices)` const override
Returns a LinOp representing the row permutation of the [Permutable](#) object.
- `std::unique_ptr< LinOp > row_permute (const Array< int64 > *permutation_indices)` const override
Returns a LinOp representing the row permutation of the [Permutable](#) object.
- `void fill (const ValueType value)`
Fill the dense matrix with a given value.
- `std::unique_ptr< Dense > row_gather (const Array< int32 > *gather_indices)` const
Create a [Dense](#) matrix consisting of the given rows from this matrix.
- `std::unique_ptr< Dense > row_gather (const Array< int64 > *gather_indices)` const
Create a [Dense](#) matrix consisting of the given rows from this matrix.
- `void row_gather (const Array< int32 > *gather_indices, Dense *row_gathered)` const
Copies the given rows from this matrix into `row_gathered`
- `void row_gather (const Array< int64 > *gather_indices, Dense *row_gathered)` const
Copies the given rows from this matrix into `row_gathered`
- `std::unique_ptr< LinOp > column_permute (const Array< int32 > *permutation_indices)` const override
Returns a LinOp representing the column permutation of the [Permutable](#) object.
- `std::unique_ptr< LinOp > column_permute (const Array< int64 > *permutation_indices)` const override
Returns a LinOp representing the column permutation of the [Permutable](#) object.
- `std::unique_ptr< LinOp > inverse_row_permute (const Array< int32 > *permutation_indices)` const override
Returns a LinOp representing the row permutation of the inverse permuted object.
- `std::unique_ptr< LinOp > inverse_row_permute (const Array< int64 > *permutation_indices)` const override
Returns a LinOp representing the row permutation of the inverse permuted object.
- `std::unique_ptr< LinOp > inverse_column_permute (const Array< int32 > *permutation_indices)` const override
Returns a LinOp representing the row permutation of the inverse permuted object.
- `std::unique_ptr< LinOp > inverse_column_permute (const Array< int64 > *permutation_indices)` const override
Returns a LinOp representing the row permutation of the inverse permuted object.
- `std::unique_ptr< Diagonal< ValueType > > extract_diagonal ()` const override
Extracts the diagonal entries of the matrix into a vector.
- `std::unique_ptr< absolute_type > compute_absolute ()` const override
Gets the AbsoluteLinOp.
- `void compute_absolute_inplace ()` override
Compute absolute inplace on each element.
- `std::unique_ptr< complex_type > make_complex ()` const
Creates a complex copy of the original matrix.
- `void make_complex (Dense< to_complex< ValueType >> *result)` const

- Writes a complex copy of the original matrix to a given complex matrix.*
- `std::unique_ptr< absolute_type > get_real () const`
Creates a new real matrix and extracts the real part of the original matrix into that.
- `void get_real (Dense< remove_complex< ValueType >> *result) const`
Extracts the real part of the original matrix into a given real matrix.
- `std::unique_ptr< absolute_type > get_imag () const`
Creates a new real matrix and extracts the imaginary part of the original matrix into that.
- `void get_imag (Dense< remove_complex< ValueType >> *result) const`
Extracts the imaginary part of the original matrix into a given real matrix.
- `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.
- `std::unique_ptr< Dense > create_submatrix (const span &rows, const span &columns)`
Create a submatrix from the original matrix.
- `std::unique_ptr< Dense< remove_complex< ValueType >> > create_real_view ()`
Create a real view of the (potentially) complex original matrix.
- `std::unique_ptr< const Dense< remove_complex< ValueType >> > create_real_view () const`
Create a real view of the (potentially) complex 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.

35.36.1 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

<i>ValueType</i>	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.

35.36.2 Member Function Documentation

35.36.2.1 `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

<i>alpha</i>	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).
<i>b</i>	a matrix of the same dimension as this

References `gko::PolymorphicObject::get_executor()`, and `gko::make_temporary_clone()`.

35.36.2.2 `at()` [1/4]

```
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

<i>idx</i>	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()`.

35.36.2.3 at() [2/4]

```
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

<i>idx</i>	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()`.

35.36.2.4 at() [3/4]

```
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

<i>row</i>	the row of the requested element
<i>col</i>	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()`.

35.36.2.5 at() [4/4]

```
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

<i>row</i>	the row of the requested element
<i>col</i>	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()`.

35.36.2.6 column_permute() [1/2]

```
template<typename ValueType = default_precision>
std::unique_ptr<LinOp> gko::matrix::Dense< ValueType >::column_permute (
    const Array< int32 > * permutation_indices ) const [override], [virtual]
```

Returns a `LinOp` representing the column permutation of the [Permutable](#) object.

In the resulting `LinOp`, the column `i` contains the input column `perm[i]`.

Parameters

<i>permutation_indices</i>	the array of indices containing the permutation order <code>perm</code> .
----------------------------	---

Returns

a pointer to the new column permuted object

Implements [gko::Permutable< int32 >](#).

35.36.2.7 column_permute() [2/2]

```
template<typename ValueType = default_precision>
std::unique_ptr<LinOp> gko::matrix::Dense< ValueType >::column_permute (
    const Array< int64 > * permutation_indices ) const [override], [virtual]
```

Returns a LinOp representing the column permutation of the [Permutable](#) object.

In the resulting LinOp, the column `i` contains the input column `perm[i]`.

Parameters

<i>permutation_indices</i>	the array of indices containing the permutation order <code>perm</code> .
----------------------------	---

Returns

a pointer to the new column permuted object

Implements [gko::Permutable< int64 >](#).

35.36.2.8 compute_absolute()

```
template<typename ValueType = default_precision>
std::unique_ptr<absolute_type> gko::matrix::Dense< ValueType >::compute_absolute ( ) const
[override], [virtual]
```

Gets the AbsoluteLinOp.

Returns

a pointer to the new absolute object

Implements [gko::EnableAbsoluteComputation< remove_complex< Dense< ValueType > > >](#).

35.36.2.9 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

<i>b</i>	a Dense matrix of same dimension as this
<i>result</i>	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()`.

35.36.2.10 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

<i>result</i>	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()`.

35.36.2.11 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](#).

35.36.2.12 create_real_view() [1/2]

```
template<typename ValueType = default_precision>
std::unique_ptr<Dense<remove_complex<ValueType> > > gko::matrix::Dense< ValueType >::create_↵
_real_view ( ) [inline]
```

Create a real view of the (potentially) complex original matrix.

If the original matrix is real, nothing changes. If the original matrix is complex, the result is created by viewing the complex matrix with as real with a reinterpret_cast with twice the number of columns and double the stride.

References gko::PolymorphicObject::get_executor(), gko::matrix::Dense< ValueType >::get_stride(), and gko↵
::matrix::Dense< ValueType >::get_values().

35.36.2.13 create_real_view() [2/2]

```
template<typename ValueType = default_precision>
std::unique_ptr<const Dense<remove_complex<ValueType> > > gko::matrix::Dense< ValueType >↵
::create_real_view ( ) const [inline]
```

Create a real view of the (potentially) complex original matrix.

If the original matrix is real, nothing changes. If the original matrix is complex, the result is created by viewing the complex matrix with as real with a reinterpret_cast with twice the number of columns and double the stride.

References gko::matrix::Dense< ValueType >::get_const_values(), gko::PolymorphicObject::get_executor(), and
gko::matrix::Dense< ValueType >::get_stride().

35.36.2.14 create_submatrix() [1/2]

```
template<typename ValueType = default_precision>
std::unique_ptr<Dense> gko::matrix::Dense< ValueType >::create_submatrix (
    const span & rows,
    const span & columns ) [inline]
```

Create a submatrix from the original matrix.

Parameters

<i>rows</i>	row span
<i>columns</i>	column span

References gko::matrix::Dense< ValueType >::create_submatrix(), and gko::matrix::Dense< ValueType >::get_↵
stride().

35.36.2.15 create_submatrix() [2/2]

```
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

<i>rows</i>	row span
<i>columns</i>	column span
<i>stride</i>	stride of the new submatrix.

References gko::span::begin, gko::PolymorphicObject::get_executor(), gko::matrix::Dense< ValueType >::get_stride(), gko::matrix::Dense< ValueType >::get_values(), and gko::Array< ValueType >::view().

Referenced by gko::matrix::Dense< ValueType >::create_submatrix().

35.36.2.16 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

<i>other</i>	The other matrix whose configuration needs to copied.
--------------	---

35.36.2.17 extract_diagonal()

```
template<typename ValueType = default_precision>
std::unique_ptr<Diagonal<ValueType> > gko::matrix::Dense< ValueType >::extract_diagonal ( )
const [override], [virtual]
```

Extracts the diagonal entries of the matrix into a vector.

Parameters

<i>diag</i>	the vector into which the diagonal will be written
-------------	--

Implements [gko::DiagonalExtractable< ValueType >](#).

35.36.2.18 fill()

```
template<typename ValueType = default_precision>
void gko::matrix::Dense< ValueType >::fill (
    const ValueType value )
```

Fill the dense matrix with a given value.

Parameters

<i>value</i>	the value to be filled
--------------	------------------------

35.36.2.19 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\(\)](#).

Referenced by [gko::matrix::Dense< ValueType >::create_real_view\(\)](#).

35.36.2.20 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\(\)](#).

35.36.2.21 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_real_view()`, and `gko::matrix::Dense< ValueType >↵::create_submatrix()`.

35.36.2.22 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_real_view()`, and `gko::matrix::Dense< ValueType >↵::create_submatrix()`.

35.36.2.23 inverse_column_permute() [1/2]

```
template<typename ValueType = default_precision>
std::unique_ptr<LinOp> gko::matrix::Dense< ValueType >::inverse_column_permute (
    const Array< int32 > * permutation_indices ) const [override], [virtual]
```

Returns a `LinOp` representing the row permutation of the inverse permuted object.

In the resulting `LinOp`, the column `perm[i]` contains the input column `i`.

Parameters

<i>permutation_indices</i>	the array of indices containing the permutation order <code>perm</code> .
----------------------------	---

Returns

a pointer to the new inverse permuted object

Implements [gko::Permutable< int32 >](#).

35.36.2.24 inverse_column_permute() [2/2]

```
template<typename ValueType = default_precision>
std::unique_ptr<LinOp> gko::matrix::Dense< ValueType >::inverse_column_permute (
    const Array< int64 > * permutation_indices ) const [override], [virtual]
```

Returns a LinOp representing the row permutation of the inverse permuted object.

In the resulting LinOp, the column `perm[i]` contains the input column `i`.

Parameters

<i>permutation_indices</i>	the array of indices containing the permutation order <code>perm</code> .
----------------------------	---

Returns

a pointer to the new inverse permuted object

Implements [gko::Permutable< int64 >](#).

35.36.2.25 inverse_permute() [1/2]

```
template<typename ValueType = default_precision>
std::unique_ptr<LinOp> gko::matrix::Dense< ValueType >::inverse_permute (
    const Array< int32 > * permutation_indices ) const [override], [virtual]
```

Returns a LinOp representing the symmetric inverse row and column permutation of the [Permutable](#) object.

In the resulting LinOp, the entry at location `(perm[i], perm[j])` contains the input value `(i, j)`.

Parameters

<i>permutation_indices</i>	the array of indices containing the permutation order.
----------------------------	--

Returns

a pointer to the new permuted object

Reimplemented from [gko::Permutable< int32 >](#).

35.36.2.26 inverse_permute() [2/2]

```
template<typename ValueType = default_precision>
std::unique_ptr<LinOp> gko::matrix::Dense< ValueType >::inverse_permute (
    const Array< int64 > * permutation_indices ) const [override], [virtual]
```

Returns a LinOp representing the symmetric inverse row and column permutation of the [Permutable](#) object.

In the resulting LinOp, the entry at location `(perm[i], perm[j])` contains the input value `(i, j)`.

Parameters

<i>permutation_indices</i>	the array of indices containing the permutation order.
----------------------------	--

Returns

a pointer to the new permuted object

Reimplemented from [gko::Permutable< int64 >](#).

35.36.2.27 inverse_row_permute() [1/2]

```
template<typename ValueType = default_precision>
std::unique_ptr<LinOp> gko::matrix::Dense< ValueType >::inverse_row_permute (
    const Array< int32 > * permutation_indices ) const [override], [virtual]
```

Returns a LinOp representing the row permutation of the inverse permuted object.

In the resulting LinOp, the row `perm[i]` contains the input row `i`.

Parameters

<i>permutation_indices</i>	the array of indices containing the permutation order <code>perm</code> .
----------------------------	---

Returns

a pointer to the new inverse permuted object

Implements [gko::Permutable< int32 >](#).

35.36.2.28 inverse_row_permute() [2/2]

```
template<typename ValueType = default_precision>
std::unique_ptr<LinOp> gko::matrix::Dense< ValueType >::inverse_row_permute (
    const Array< int64 > * permutation_indices ) const [override], [virtual]
```

Returns a LinOp representing the row permutation of the inverse permuted object.

In the resulting LinOp, the row `perm[i]` contains the input row `i`.

Parameters

<i>permutation_indices</i>	the array of indices containing the permutation order perm.
----------------------------	---

Returns

a pointer to the new inverse permuted object

Implements [gko::Permutable< int64 >](#).

35.36.2.29 make_complex() [1/2]

```
template<typename ValueType = default_precision>
std::unique_ptr<complex_type> gko::matrix::Dense< ValueType >::make_complex ( ) const
```

Creates a complex copy of the original matrix.

If the original matrix was real, the imaginary part of the result will be zero.

35.36.2.30 make_complex() [2/2]

```
template<typename ValueType = default_precision>
void gko::matrix::Dense< ValueType >::make_complex (
    Dense< to_complex< ValueType >> * result ) const
```

Writes a complex copy of the original matrix to a given complex matrix.

If the original matrix was real, the imaginary part of the result will be zero.

35.36.2.31 permute() [1/2]

```
template<typename ValueType = default_precision>
std::unique_ptr<LinOp> gko::matrix::Dense< ValueType >::permute (
    const Array< int32 > * permutation_indices ) const [override], [virtual]
```

Returns a LinOp representing the symmetric row and column permutation of the [Permutable](#) object.

In the resulting LinOp, the entry at location (i, j) contains the input value (perm[i], perm[j]).

Parameters

<i>permutation_indices</i>	the array of indices containing the permutation order.
----------------------------	--

Returns

a pointer to the new permuted object

Reimplemented from [gko::Permutable< int32 >](#).

35.36.2.32 permute() [2/2]

```
template<typename ValueType = default_precision>
std::unique_ptr<LinOp> gko::matrix::Dense< ValueType >::permute (
    const Array< int64 > * permutation_indices ) const [override], [virtual]
```

Returns a LinOp representing the symmetric row and column permutation of the [Permutable](#) object.

In the resulting LinOp, the entry at location (i, j) contains the input value $(\text{perm}[i], \text{perm}[j])$.

Parameters

<i>permutation_indices</i>	the array of indices containing the permutation order.
----------------------------	--

Returns

a pointer to the new permuted object

Reimplemented from [gko::Permutable< int64 >](#).

35.36.2.33 row_gather() [1/4]

```
template<typename ValueType = default_precision>
std::unique_ptr<Dense> gko::matrix::Dense< ValueType >::row_gather (
    const Array< int32 > * gather_indices ) const
```

Create a [Dense](#) matrix consisting of the given rows from this matrix.

Parameters

<i>gather_indices</i>	pointer to an array containing row indices from this matrix. It may contain duplicates.
-----------------------	---

Returns

[Dense](#) matrix on the same executor with the same number of columns and `gather_indices->get_num_elems()` rows containing the gathered rows from this matrix: `output(i, j) = input(gather_indices(i), j)`

35.36.2.34 row_gather() [2/4]

```
template<typename ValueType = default_precision>
void gko::matrix::Dense< ValueType >::row_gather (
```

```
const Array< int32 > * gather_indices,
Dense< ValueType > * row_gathered ) const
```

Copies the given rows from this matrix into `row_gathered`

Parameters

<i>gather_indices</i>	pointer to an array containing row indices from this matrix. It may contain duplicates.
<i>row_gathered</i>	pointer to a Dense matrix that will store the gathered rows: <code>output(i, j) = input(gather_indices(i), j)</code> It must have the same number of columns as this matrix and <code>gather_indices->get_num_elems()</code> rows.

35.36.2.35 row_gather() [3/4]

```
template<typename ValueType = default_precision>
std::unique_ptr<Dense> gko::matrix::Dense< ValueType >::row_gather (
    const Array< int64 > * gather_indices ) const
```

Create a [Dense](#) matrix consisting of the given rows from this matrix.

Parameters

<i>gather_indices</i>	pointer to an array containing row indices from this matrix. It may contain duplicates.
-----------------------	---

Returns

[Dense](#) matrix on the same executor with the same number of columns and `gather_indices->get_num_elems()` rows containing the gathered rows from this matrix: `output(i, j) = input(gather_indices(i), j)`

35.36.2.36 row_gather() [4/4]

```
template<typename ValueType = default_precision>
void gko::matrix::Dense< ValueType >::row_gather (
    const Array< int64 > * gather_indices,
    Dense< ValueType > * row_gathered ) const
```

Copies the given rows from this matrix into `row_gathered`

Parameters

<i>gather_indices</i>	pointer to an array containing row indices from this matrix. It may contain duplicates.
<i>row_gathered</i>	pointer to a Dense matrix that will store the gathered rows: <code>output(i, j) = input(gather_indices(i), j)</code> It must have the same number of columns as this matrix and <code>gather_indices->get_num_elems()</code> rows.

35.36.2.37 row_permute() [1/2]

```
template<typename ValueType = default_precision>
std::unique_ptr<LinOp> gko::matrix::Dense< ValueType >::row_permute (
    const Array< int32 > * permutation_indices ) const [override], [virtual]
```

Returns a LinOp representing the row permutation of the [Permutable](#) object.

In the resulting LinOp, the row *i* contains the input row `perm[i]`.

Parameters

<i>permutation_indices</i>	the array of indices containing the permutation order.
----------------------------	--

Returns

a pointer to the new permuted object

Implements [gko::Permutable< int32 >](#).

35.36.2.38 row_permute() [2/2]

```
template<typename ValueType = default_precision>
std::unique_ptr<LinOp> gko::matrix::Dense< ValueType >::row_permute (
    const Array< int64 > * permutation_indices ) const [override], [virtual]
```

Returns a LinOp representing the row permutation of the [Permutable](#) object.

In the resulting LinOp, the row *i* contains the input row `perm[i]`.

Parameters

<i>permutation_indices</i>	the array of indices containing the permutation order.
----------------------------	--

Returns

a pointer to the new permuted object

Implements [gko::Permutable< int64 >](#).

35.36.2.39 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

<i>alpha</i>	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()`.

35.36.2.40 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](#).

The documentation for this class was generated from the following files:

- `ginkgo/core/matrix/coo.hpp`
- `ginkgo/core/matrix/dense.hpp`

35.37 gko::matrix::Diagonal< ValueType > Class Template Reference

This class is a utility which efficiently implements the diagonal matrix (a linear operator which scales a vector row wise).

```
#include <ginkgo/core/matrix/diagonal.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.
- `std::unique_ptr< absolute_type > compute_absolute () const` override
Gets the AbsoluteLinOp.
- `void compute_absolute_inplace ()` override
Compute absolute inplace on each element.
- `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.
- `void rapply (const LinOp *b, LinOp *x) const`
Applies the diagonal matrix from the right side to a matrix b, which means scales the columns of b with the according diagonal entries.

35.37.1 Detailed Description

```
template<typename ValueType = default_precision>
class gko::matrix::Diagonal< ValueType >
```

This class is a utility which efficiently implements the diagonal matrix (a linear operator which scales a vector row wise).

Objects of the [Diagonal](#) class always represent a square matrix, and require one array to store their values.

Template Parameters

<i>ValueType</i>	precision of matrix elements
<i>IndexType</i>	precision of matrix indexes of a CSR matrix the diagonal is applied or converted to.

35.37.2 Member Function Documentation

35.37.2.1 compute_absolute()

```
template<typename ValueType = default_precision>
std::unique_ptr<absolute_type> gko::matrix::Diagonal< ValueType >::compute_absolute ( ) const
[override], [virtual]
```

Gets the AbsoluteLinOp.

Returns

a pointer to the new absolute object

Implements [gko::EnableAbsoluteComputation< remove_complex< Diagonal< ValueType > > >](#).

35.37.2.2 conj_transpose()

```
template<typename ValueType = default_precision>
std::unique_ptr<LinOp> gko::matrix::Diagonal< 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](#).

35.37.2.3 get_const_values()

```
template<typename ValueType = default_precision>
const value_type* gko::matrix::Diagonal< 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.

```
126     {
127         return values_.get_const_data();
128     }
```

References `gko::Array< ValueType >::get_const_data()`.

35.37.2.4 get_values()

```
template<typename ValueType = default_precision>
value_type* gko::matrix::Diagonal< 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()`.

35.37.2.5 rapply()

```
template<typename ValueType = default_precision>
void gko::matrix::Diagonal< ValueType >::rapply (
    const LinOp * b,
    LinOp * x ) const [inline]
```

Applies the diagonal matrix from the right side to a matrix b, which means scales the columns of b with the according diagonal entries.

Parameters

<i>b</i>	the input vector(s) on which the diagonal matrix is applied
<i>x</i>	the output vector(s) where the result is stored

35.37.2.6 transpose()

```
template<typename ValueType = default_precision>
std::unique_ptr<LinOp> gko::matrix::Diagonal< 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](#).

The documentation for this class was generated from the following files:

- ginkgo/core/base/lin_op.hpp
- ginkgo/core/matrix/diagonal.hpp

35.38 gko::DiagonalExtractable< ValueType > Class Template Reference

The diagonal of a LinOp implementing this interface can be extracted.

```
#include <ginkgo/core/base/lin_op.hpp>
```

Public Member Functions

- virtual std::unique_ptr< [matrix::Diagonal](#)< ValueType > > [extract_diagonal](#) () const =0
Extracts the diagonal entries of the matrix into a vector.

35.38.1 Detailed Description

```
template<typename ValueType>
class gko::DiagonalExtractable< ValueType >
```

The diagonal of a LinOp implementing this interface can be extracted.

[extract_diagonal](#) extracts the elements whose col and row index are the same and stores the result in a min(nrows, ncols) x 1 dense matrix.

35.38.2 Member Function Documentation

35.38.2.1 extract_diagonal()

```
template<typename ValueType >
virtual std::unique_ptr<matrix::Diagonal<ValueType> > gko::DiagonalExtractable< ValueType >::extract_diagonal ( ) const [pure virtual]
```

Extracts the diagonal entries of the matrix into a vector.

Parameters

<i>diag</i>	the vector into which the diagonal will be written
-------------	--

Implemented in [gko::matrix::Csr< ValueType, IndexType >](#), [gko::matrix::Hybrid< ValueType, IndexType >](#), [gko::matrix::Dense< ValueType >](#), [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](#)

35.39 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 friend bool [operator==](#) (const [dim](#) &x, const [dim](#) &y)
Checks if two dim objects are equal.
- constexpr friend [dim operator*](#) (const [dim](#) &x, const [dim](#) &y)
Multiplies two dim objects.

35.39.1 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

<i>Dimensionality</i>	number of dimensions of the object
<i>DimensionType</i>	datatype used to represent each dimension

35.39.2 Constructor & Destructor Documentation

35.39.2.1 dim() [1/2]

```
template<size_type Dimensionality, typename DimensionType = size_type>
constexpr gko::dim< Dimensionality, DimensionType >::dim (
    const dimension_type & size = dimension_type{} ) [inline], [constexpr]
```

Creates a dimension object with all dimensions set to the same value.

Parameters

<i>size</i>	the size of each dimension
-------------	----------------------------

35.39.2.2 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], [constexpr]
```

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

<i>first</i>	first dimension
<i>rest</i>	other dimensions

35.39.3 Member Function Documentation

35.39.3.1 operator bool()

```
template<size_type Dimensionality, typename DimensionType = size_type>
constexpr gko::dim< Dimensionality, DimensionType >::operator bool ( ) const [inline], [explicit],
[constexpr]
```

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

Note

This operator is explicit to avoid implicit dim-to-int casts. It will still be used in contextual conversions (if, &&, ||, !)

35.39.3.2 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], [constexpr], [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

<i>dimension</i>	the requested dimension
------------------	-------------------------

Returns

the dimension-th dimension

35.39.3.3 operator[]() [2/2]

```
template<size_type Dimensionality, typename DimensionType = size_type>
dimension_type& gko::dim< Dimensionality, DimensionType >::operator[] (
    const size_type & dimension ) [inline], [noexcept]
```

35.39.4 Friends And Related Function Documentation

35.39.4.1 operator*

```
template<size_type Dimensionality, typename DimensionType = size_type>
constexpr friend dim operator* (
    const dim< Dimensionality, DimensionType > & x,
    const dim< Dimensionality, DimensionType > & y ) [friend]
```

Multiplies two dim objects.

Parameters

<i>x</i>	first object
<i>y</i>	second object

Returns

a dim object representing the size of the tensor product $x * y$

35.39.4.2 operator==

```
template<size_type Dimensionality, typename DimensionType = size_type>
constexpr friend bool operator== (
    const dim< Dimensionality, DimensionType > & x,
    const dim< Dimensionality, DimensionType > & y ) [friend]
```

Checks if two dim objects are equal.

Parameters

<i>x</i>	first object
<i>y</i>	second object

Returns

true if and only if all dimensions of both objects are equal.

The documentation for this struct was generated from the following file:

- ginkgo/core/base/dim.hpp

35.40 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.

35.40.1 Detailed Description

[DimensionMismatch](#) is thrown if an operation is being applied to LinOps of incompatible size.

35.40.2 Constructor & Destructor Documentation

35.40.2.1 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

<i>file</i>	The name of the offending source file
<i>line</i>	The source code line number where the error occurred
<i>func</i>	The function name where the error occurred
<i>first_name</i>	The name of the first operator
<i>first_rows</i>	The output dimension of the first operator
<i>first_cols</i>	The input dimension of the first operator
<i>second_name</i>	The name of the second operator
<i>second_rows</i>	The output dimension of the second operator
<i>second_cols</i>	The input dimension of the second operator
<i>clarification</i>	An additional message describing the error further

The documentation for this class was generated from the following file:

- ginkgo/core/base/exception.hpp

35.41 gko::DpcppExecutor Class Reference

This is the [Executor](#) subclass which represents a DPC++ enhanced 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 DPCPP device id of the device associated to this executor.
- `const std::vector< int > & get_subgroup_sizes ()` const noexcept
Get the available subgroup sizes for this device.
- `int get_num_computing_units ()` const noexcept
Get the number of Computing Units of this executor.
- `const std::vector< int > & get_max_workitem_sizes ()` const noexcept
Get the maximum work item sizes.
- `int get_max_workgroup_size ()` const noexcept
Get the maximum workgroup size.
- `int get_max_subgroup_size ()` const noexcept
Get the maximum subgroup size.
- `std::string get_device_type ()` const noexcept
Get a string representing the device type.

Static Public Member Functions

- `static std::shared_ptr< DpcppExecutor > create (int device_id, std::shared_ptr< Executor > master, std::string device_type="all")`
Creates a new [DpcppExecutor](#).
- `static int get_num_devices (std::string device_type)`
Get the number of devices present on the system.

35.41.1 Detailed Description

This is the [Executor](#) subclass which represents a DPC++ enhanced device.

35.41.2 Member Function Documentation

35.41.2.1 create()

```
static std::shared_ptr<DpcppExecutor> gko::DpcppExecutor::create (
    int device_id,
    std::shared_ptr< Executor > master,
    std::string device_type = "all" ) [static]
```

Creates a new [DpcppExecutor](#).

Parameters

<i>device_id</i>	the DPCPP device id of this device
<i>master</i>	an executor on the host that is used to invoke the device kernels
<i>device_type</i>	a string representing the type of device to consider (accelerator, cpu, gpu or all).

35.41.2.2 get_device_id()

```
int gko::DpcppExecutor::get_device_id ( ) const [inline], [noexcept]
```

Get the DPCPP device id of the device associated to this executor.

Returns

the DPCPP device id of the device associated to this executor

35.41.2.3 get_device_type()

```
std::string gko::DpcppExecutor::get_device_type ( ) const [inline], [noexcept]
```

Get a string representing the device type.

Returns

a string representing the device type

35.41.2.4 get_master() [1/2]

```
std::shared_ptr<const Executor> gko::DpcppExecutor::get_master ( ) const [override], [virtual], [noexcept]
```

Returns the master [OmpExecutor](#) of this [Executor](#).

Returns

the master [OmpExecutor](#) of this [Executor](#).

Implements [gko::Executor](#).

35.41.2.5 get_master() [2/2]

```
std::shared_ptr<Executor> gko::DpcppExecutor::get_master ( ) [override], [virtual], [noexcept]
```

Returns the master [OmpExecutor](#) of this [Executor](#).

Returns

the master [OmpExecutor](#) of this [Executor](#).

Implements [gko::Executor](#).

35.41.2.6 get_max_subgroup_size()

```
int gko::DpcppExecutor::get_max_subgroup_size ( ) const [inline], [noexcept]
```

Get the maximum subgroup size.

Returns

the maximum subgroup size

35.41.2.7 get_max_workgroup_size()

```
int gko::DpcppExecutor::get_max_workgroup_size ( ) const [inline], [noexcept]
```

Get the maximum workgroup size.

Returns

the maximum workgroup size

35.41.2.8 get_max_workitem_sizes()

```
const std::vector<int>& gko::DpcppExecutor::get_max_workitem_sizes ( ) const [inline], [noexcept]
```

Get the maximum work item sizes.

Returns

the maximum work item sizes

35.41.2.9 get_num_computing_units()

```
int gko::DpcppExecutor::get_num_computing_units ( ) const [inline], [noexcept]
```

Get the number of Computing Units of this executor.

Returns

the number of Computing Units of this executor

35.41.2.10 get_num_devices()

```
static int gko::DpcppExecutor::get_num_devices (
    std::string device_type ) [static]
```

Get the number of devices present on the system.

Parameters

<i>device_type</i>	a string representing the device type
--------------------	---------------------------------------

Returns

the number of devices present on the system

35.41.2.11 get_subgroup_sizes()

```
const std::vector<int>& gko::DpcppExecutor::get_subgroup_sizes ( ) const [inline], [noexcept]
```

Get the available subgroup sizes for this device.

Returns

the available subgroup sizes for this device

35.41.2.12 run()

```
void gko::DpcppExecutor::run (
    const Operation & op ) const [override], [virtual]
```

Runs the specified [Operation](#) using this [Executor](#).

Parameters

<i>op</i>	the operation to run
-----------	----------------------

Implements [gko::Executor](#).

The documentation for this class was generated from the following file:

- ginkgo/core/base/executor.hpp

35.42 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.
- std::unique_ptr< [Diagonal](#)< ValueType > > [extract_diagonal](#) () const override
Extracts the diagonal entries of the matrix into a vector.
- std::unique_ptr< absolute_type > [compute_absolute](#) () const override
Gets the AbsoluteLinOp.
- void [compute_absolute_inplace](#) () override
Compute absolute inplace on each element.
- 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_idxxs](#) () noexcept
Returns the column indexes of the matrix.
- const index_type * [get_const_col_idxxs](#) () 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 .

35.42.1 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

<i>ValueType</i>	precision of matrix elements
<i>IndexType</i>	precision of matrix indexes

35.42.2 Member Function Documentation

35.42.2.1 `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 ) const [inline], [noexcept]
```

Returns the `idx`-th column index of the `row`-th row .

Parameters

<i>row</i>	the row of the requested element
<i>idx</i>	the <code>idx</code> -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)

```

229     {
230         return this->get_const_col_idxs() [this->linearize_index(row, idx)];
231     }

```

References `gko::matrix::Ell< ValueType, IndexType >::get_const_col_idxs()`.

35.42.2.2 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 ) [inline], [noexcept]

```

Returns the `idx`-th column index of the `row`-th row .

Parameters

<i>row</i>	the row of the requested element
<i>idx</i>	the <code>idx</code> -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()`.

35.42.2.3 compute_absolute()

```

template<typename ValueType = default_precision, typename IndexType = int32>
std::unique_ptr<absolute_type> gko::matrix::Ell< ValueType, IndexType >::compute_absolute ( )
const [override], [virtual]

```

Gets the AbsoluteLinOp.

Returns

a pointer to the new absolute object

Implements `gko::EnableAbsoluteComputation< remove_complex< Ell< ValueType, IndexType > > >`.

35.42.2.4 extract_diagonal()

```

template<typename ValueType = default_precision, typename IndexType = int32>
std::unique_ptr<Diagonal<ValueType> > gko::matrix::Ell< ValueType, IndexType >::extract_↵
diagonal ( ) const [override], [virtual]

```

Extracts the diagonal entries of the matrix into a vector.

Parameters

<i>diag</i>	the vector into which the diagonal will be written
-------------	--

Implements [gko::DiagonalExtractable< ValueType >](#).

35.42.2.5 get_col_idxes()

```
template<typename ValueType = default_precision, typename IndexType = int32>
index_type* gko::matrix::Ell< ValueType, IndexType >::get_col_idxes ( ) [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\(\)](#).

35.42.2.6 get_const_col_idxes()

```
template<typename ValueType = default_precision, typename IndexType = int32>
const index_type* gko::matrix::Ell< ValueType, IndexType >::get_const_col_idxes ( ) 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\(\)](#).

35.42.2.7 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()`.

35.42.2.8 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()`.

35.42.2.9 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.

35.42.2.10 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.

35.42.2.11 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()`.

35.42.2.12 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

<i>data</i>	the <code>matrix_data</code> structure
-------------	--

Implements `gko::ReadableFromMatrixData< ValueType, IndexType >`.

35.42.2.13 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 ) const [inline], [noexcept]
```

Returns the `idx`-th non-zero element of the `row`-th row .

Parameters

<i>row</i>	the row of the requested element
<i>idx</i>	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()`.

35.42.2.14 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 ) [inline], [noexcept]
```

Returns the `idx`-th non-zero element of the `row`-th row .

Parameters

<i>row</i>	the row of the requested element
<i>idx</i>	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()`.

35.42.2.15 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

<i>data</i>	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
- ginkgo/core/matrix/ell.hpp

35.43 gko::enable_parameters_type< ConcreteParametersType, Factory > Class 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.

35.43.1 Detailed Description

```
template<typename ConcreteParametersType, typename Factory>
class 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

<i>ConcreteParametersType</i>	the concrete parameters type which is being implemented [CRTP parameter]
<i>Factory</i>	the concrete factory for which these parameters are being used

35.43.2 Member Function Documentation

35.43.2.1 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

<code>exec</code>	the executor where the factory will be created
-------------------	--

Returns

a new factory instance

The documentation for this class was generated from the following file:

- `ginkgo/core/base/abstract_factory.hpp`

35.44 `gko::EnableAbsoluteComputation< AbsoluteLinOp >` Class Template Reference

The [EnableAbsoluteComputation](#) mixin provides the default implementations of `compute_absolute_linop` and the absolute interface.

```
#include <ginkgo/core/base/lin_op.hpp>
```

Public Member Functions

- `std::unique_ptr< LinOp > compute_absolute_linop ()` const override
Gets the absolute LinOp.
- `virtual std::unique_ptr< absolute_type > compute_absolute ()` const =0
Gets the AbsoluteLinOp.

35.44.1 Detailed Description

```
template<typename AbsoluteLinOp>
class gko::EnableAbsoluteComputation< AbsoluteLinOp >
```

The [EnableAbsoluteComputation](#) mixin provides the default implementations of `compute_absolute_linop` and the absolute interface.

`compute_absolute` gets a new `AbsoluteLinOp`. `compute_absolute_inplace` applies absolute inplace, so it still keeps the `value_type` of the class.

Template Parameters

<code>AbsoluteLinOp</code>	the absolute LinOp which is being returned [CRTP parameter]
----------------------------	---

35.44.2 Member Function Documentation

35.44.2.1 compute_absolute()

```
template<typename AbsoluteLinOp>
virtual std::unique_ptr<absolute_type> gko::EnableAbsoluteComputation< AbsoluteLinOp >↔
::compute_absolute ( ) const [pure virtual]
```

Gets the AbsoluteLinOp.

Returns

a pointer to the new absolute object

Implemented in [gko::matrix::Csr< ValueType, IndexType >](#), [gko::matrix::Hybrid< ValueType, IndexType >](#), [gko::matrix::Dense< ValueType >](#), [gko::matrix::Coo< ValueType, IndexType >](#), [gko::matrix::Ell< ValueType, IndexType >](#), [gko::matrix::Sellp< ValueType, IndexType >](#), and [gko::matrix::Diagonal< ValueType >](#).

Referenced by [gko::EnableAbsoluteComputation< remove_complex< Ell< ValueType, IndexType > > >](#)↔
::compute_absolute_linop().

35.44.2.2 compute_absolute_linop()

```
template<typename AbsoluteLinOp>
std::unique_ptr<LinOp> gko::EnableAbsoluteComputation< AbsoluteLinOp >::compute_absolute_↔
linop ( ) const [inline], [override], [virtual]
```

Gets the absolute LinOp.

Returns

a pointer to the new absolute LinOp

Implements [gko::AbsoluteComputable](#).

```
721 {
722     return this->compute_absolute();
723 }
```

The documentation for this class was generated from the following file:

- [ginkgo/core/base/lin_op.hpp](#)

35.45 gko::EnableAbstractPolymorphicObject< AbstractObject, 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>
```

35.45.1 Detailed Description

```
template<typename AbstractObject, typename PolymorphicBase = PolymorphicObject>
class gko::EnableAbstractPolymorphicObject< AbstractObject, 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

<i>AbstractObject</i>	the abstract class which is being implemented [CRTP parameter]
<i>PolymorphicBase</i>	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

35.46 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>
```

35.46.1 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

<i>ConcreteObject</i>	the concrete type for which <code>create()</code> is being implemented [CRTP parameter]
-----------------------	---

The documentation for this class was generated from the following file:

- ginkgo/core/base/polymorphic_object.hpp

35.47 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.

35.47.1 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

<i>ConcreteFactory</i>	the concrete factory which is being implemented [CRTP parameter]
<i>ProductType</i>	the concrete type of products which this factory produces, has to be a subclass of <code>PolymorphicBase::abstract_product_type</code>
<i>ParametersType</i>	a type representing the parameters of the factory, has to inherit from the enable_parameters_type mixin
<i>PolymorphicBase</i>	parent of <code>ConcreteFactory</code> in the polymorphic hierarchy, has to be a subclass of AbstractFactory

35.47.2 Member Function Documentation

35.47.2.1 `create()`

```
template<typename ConcreteFactory , typename ProductType , typename ParametersType , typename
PolymorphicBase >
static parameters_type gko::EnableDefaultFactory< ConcreteFactory, ProductType, ParametersType, 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

35.47.2.2 `get_parameters()`

```
template<typename ConcreteFactory , typename ProductType , typename ParametersType , typename
PolymorphicBase >
const parameters_type& gko::EnableDefaultFactory< ConcreteFactory, ProductType, ParametersType, PolymorphicBase >::get_parameters ( ) const [inline], [noexcept]
```

Returns the parameters of the factory.

Returns

the parameters of the factory

The documentation for this class was generated from the following file:

- `ginkgo/core/base/abstract_factory.hpp`

35.48 `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**35.48.1 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

<i>ConcreteLinOp</i>	the concrete LinOp which is being implemented [CRTP parameter]
<i>PolymorphicBase</i>	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

35.49 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.

35.49.1 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

<i>ConcreteLoggable</i>	the object being logged [CRTP parameter]
<i>PolymorphicBase</i>	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.

35.49.2 Member Function Documentation

35.49.2.1 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

<i>logger</i>	the logger to add
---------------	-------------------

Implements [gko::log::Loggable](#).

```
532     {
533         loggers_.push_back(logger);
534     }
```

35.49.2.2 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

<i>logger</i>	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](#).

The documentation for this class was generated from the following file:

- ginkgo/core/log/logger.hpp

35.50 gko::multigrid::EnableMultigridLevel< ValueType > Class Template Reference

The [EnableMultigridLevel](#) gives the default implementation of [MultigridLevel](#) with composition and provides `set↔_multigrid_level` function.

```
#include <ginkgo/core/multigrid/multigrid_level.hpp>
```

Public Member Functions

- `std::shared_ptr< const LinOp > get_fine_op ()` const override
Returns the operator on fine level.
- `std::shared_ptr< const LinOp > get_restrict_op ()` const override
Returns the restrict operator.
- `std::shared_ptr< const LinOp > get_coarse_op ()` const override
Returns the operator on coarse level.
- `std::shared_ptr< const LinOp > get_prolong_op ()` const override
Returns the prolong operator.

35.50.1 Detailed Description

```
template<typename ValueType>
class gko::multigrid::EnableMultigridLevel< ValueType >
```

The [EnableMultigridLevel](#) gives the default implementation of [MultigridLevel](#) with composition and provides `set↔_multigrid_level` function.

A class inherit from [EnableMultigridLevel](#) should use the `this->get_compositions()->apply(...)` as its own `apply`, which represents `op(b) = prolong(coarse(restrict(b)))`.

35.50.2 Member Function Documentation

35.50.2.1 `get_coarse_op()`

```
template<typename ValueType >
std::shared_ptr<const LinOp> gko::multigrid::EnableMultigridLevel< ValueType >::get_coarse_op
( ) const [inline], [override], [virtual]
```

Returns the operator on coarse level.

Returns

the operator on coarse level.

Implements [gko::multigrid::MultigridLevel](#).

```
121 {
122     return this->get_operator_at(1);
123 }
```

References [gko::UseComposition](#)< ValueType >::`get_operator_at`()

35.50.2.2 `get_fine_op()`

```
template<typename ValueType >
std::shared_ptr<const LinOp> gko::multigrid::EnableMultigridLevel< ValueType >::get_fine_op (
) const [inline], [override], [virtual]
```

Returns the operator on fine level.

Returns

the operator on fine level.

Implements [gko::multigrid::MultigridLevel](#).

35.50.2.3 `get_prolong_op()`

```
template<typename ValueType >
std::shared_ptr<const LinOp> gko::multigrid::EnableMultigridLevel< ValueType >::get_prolong↵
_op ( ) const [inline], [override], [virtual]
```

Returns the prolong operator.

Returns

the prolong operator.

Implements [gko::multigrid::MultigridLevel](#).

References [gko::UseComposition< ValueType >::get_operator_at\(\)](#).

35.50.2.4 `get_restrict_op()`

```
template<typename ValueType >
std::shared_ptr<const LinOp> gko::multigrid::EnableMultigridLevel< ValueType >::get_restrict↵
_op ( ) const [inline], [override], [virtual]
```

Returns the restrict operator.

Returns

the restrict operator.

Implements [gko::multigrid::MultigridLevel](#).

References [gko::UseComposition< ValueType >::get_operator_at\(\)](#).

The documentation for this class was generated from the following file:

- `ginkgo/core/multigrid/multigrid_level.hpp`

35.51 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.

35.51.1 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

<i>ConcreteType</i>	the concrete type from which the copy_from is being enabled [CRTP parameter]
<i>ResultType</i>	the type to which copy_from is being enabled

35.51.2 Member Function Documentation

35.51.2.1 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

<i>result</i>	the object used to store the result of the conversion
---------------	---

Implements [gko::ConvertibleTo< ResultType >](#).

35.51.2.2 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

<i>result</i>	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 >](#).

The documentation for this class was generated from the following file:

- `ginkgo/core/base/polymorphic_object.hpp`

35.52 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>
```

35.52.1 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 virtual 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

<i>ConcreteObject</i>	the concrete type which is being implemented [CRTP parameter]
<i>PolymorphicBase</i>	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`

35.53 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.

35.53.1 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 occurred, write the message to screen and exit
        std::cout << e.what() << std::endl;
        return -1;
    }
    return 0;
}
```

35.53.2 Constructor & Destructor Documentation

35.53.2.1 Error()

```
gko::Error::Error (
    const std::string & file,
    int line,
    const std::string & what ) [inline]
```

Initializes an error.

Parameters

<i>file</i>	The name of the offending source file
<i>line</i>	The source code line number where the error occurred
<i>what</i>	The error message

The documentation for this class was generated from the following file:

- ginkgo/core/base/exception.hpp

35.54 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 , typename ClosureHip , typename ClosureDpcpp >
void [run](#) (const ClosureOmp &op_omp, const ClosureCuda &op_cuda, const ClosureHip &op_hip, const ClosureDpcpp &op_dpcpp) 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](#).
- template<typename T >
void [copy](#) ([size_type](#) num_elems, const T *src_ptr, T *dest_ptr) const
Copies data within this [Executor](#).

- `template<typename T>`
`T copy_val_to_host (const T *ptr) const`
Retrieves a single element at the given location from executor memory.
- `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.
- `bool memory_accessible (const std::shared_ptr< const Executor > &other) const`
Verifies whether the executors share the same memory.

35.54.1 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;
- [HipExecutor](#) specifies that the data should be stored and the operations executed on either an NVIDIA or AMD GPU accelerator;
- [DpcppExecutor](#) specifies that the data should be stored and the operations executed on an hardware supporting DPC++;
- [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.

35.54.2 Member Function Documentation

35.54.2.1 alloc()

```
template<typename T >
T* gko::Executor::alloc (
    size_type num_elems ) const [inline]
```

Allocates memory in this [Executor](#).

Template Parameters

<i>T</i>	datatype to allocate
----------	----------------------

Parameters

<i>num_elems</i>	number of elements of type T to allocate
------------------	--

Exceptions

AllocationError	if the allocation failed
---------------------------------	--------------------------

Returns

pointer to allocated memory

35.54.2.2 copy()

```
template<typename T >
void gko::Executor::copy (
    size_type num_elems,
    const T * src_ptr,
    T * dest_ptr ) const [inline]
```

Copies data within this [Executor](#).

Template Parameters

<i>T</i>	datatype to copy
----------	------------------

Parameters

<i>num_elems</i>	number of elements of type T to copy
<i>src_ptr</i>	pointer to a block of memory containing the data to be copied
<i>dest_ptr</i>	pointer to an allocated block of memory where the data will be copied to

References [copy_from\(\)](#).

35.54.2.3 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

<i>T</i>	datatype to copy
----------	------------------

Parameters

<i>src_exec</i>	Executor from which the memory will be copied
<i>num_elems</i>	number of elements of type T to copy
<i>src_ptr</i>	pointer to a block of memory containing the data to be copied
<i>dest_ptr</i>	pointer to an allocated block of memory where the data will be copied to

References [get_master\(\)](#).

Referenced by [copy\(\)](#).

35.54.2.4 `copy_val_to_host()`

```
template<typename T >
T gko::Executor::copy_val_to_host (
    const T * ptr ) const [inline]
```

Retrieves a single element at the given location from executor memory.

Template Parameters

<i>T</i>	datatype to copy
----------	------------------

Parameters

<i>ptr</i>	the pointer to the element to be copied
------------	---

Returns

the value stored at *ptr*

References `get_master()`.

35.54.2.5 `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

<i>ptr</i>	pointer to the allocated memory block
------------	---------------------------------------

35.54.2.6 `get_master()` [1/2]

```
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::DpcppExecutor](#), [gko::HipExecutor](#), [gko::CudaExecutor](#), and [gko::OmpExecutor](#).

35.54.2.7 get_master() [2/2]

```
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::DpcppExecutor](#), [gko::HipExecutor](#), [gko::CudaExecutor](#), and [gko::OmpExecutor](#).

Referenced by [copy_from\(\)](#), and [copy_val_to_host\(\)](#).

35.54.2.8 memory_accessible()

```
bool gko::Executor::memory_accessible (
    const std::shared_ptr< const Executor > & other ) const [inline]
```

Verifies whether the executors share the same memory.

Parameters

<i>other</i>	the other Executor to compare against
--------------	---

Returns

whether the executors this and other share the same memory.

35.54.2.9 run() [1/2]

```
template<typename ClosureOmp , typename ClosureCuda , typename ClosureHip , typename ClosureDpcpp >
void gko::Executor::run (
    const ClosureOmp & op_omp,
    const ClosureCuda & op_cuda,
    const ClosureHip & op_hip,
    const ClosureDpcpp & op_dpcpp ) const [inline]
```

Runs one of the passed in functors, depending on the [Executor](#) type.

Template Parameters

<i>ClosureOmp</i>	type of <i>op_omp</i>
<i>ClosureCuda</i>	type of <i>op_cuda</i>
<i>ClosureHip</i>	type of <i>op_hip</i>

Parameters

<i>op_omp</i>	functor to run in case of a OmpExecutor or ReferenceExecutor
<i>op_cuda</i>	functor to run in case of a CudaExecutor
<i>op_hip</i>	functor to run in case of a HipExecutor

References [run\(\)](#).

35.54.2.10 [run\(\)](#) [2/2]

```
virtual void gko::Executor::run (
    const Operation & op ) const [pure virtual]
```

Runs the specified [Operation](#) using this [Executor](#).

Parameters

<i>op</i>	the operation to run
-----------	----------------------

Implemented in [gko::DpcppExecutor](#), [gko::HipExecutor](#), [gko::CudaExecutor](#), and [gko::ReferenceExecutor](#).

Referenced by [run\(\)](#).

The documentation for this class was generated from the following file:

- [ginkgo/core/base/executor.hpp](#)

35.55 [gko::log::executor_data](#) Struct Reference

Struct representing [Executor](#) related data.

```
#include <ginkgo/core/log/record.hpp>
```

35.55.1 Detailed Description

Struct representing [Executor](#) related data.

The documentation for this struct was generated from the following file:

- [ginkgo/core/log/record.hpp](#)

35.56 [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.

35.56.1 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

<code>T</code>	the type of object being deleted
----------------	----------------------------------

35.56.2 Constructor & Destructor Documentation

35.56.2.1 executor_deleter()

```
template<typename T >
gko::executor_deleter< T >::executor_deleter (
    std::shared_ptr< const Executor > exec ) [inline], [explicit]
```

Creates a new deleter.

Parameters

<code>exec</code>	the executor used to free the data
-------------------	------------------------------------

35.56.3 Member Function Documentation

35.56.3.1 operator>()()

```
template<typename T >
void gko::executor_deleter< T >::operator() (
    pointer ptr ) const [inline]
```

Deletes the object.

Parameters

<i>ptr</i>	pointer to the object being deleted
------------	-------------------------------------

The documentation for this class was generated from the following file:

- ginkgo/core/base/executor.hpp

35.57 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::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.
- `bool apply_uses_initial_guess () const override`
Return true as iterative solvers use the data in x as an initial guess.
- `std::shared_ptr< const stop::CriterionFactory > get_stop_criterion_factory () const`
Gets the stopping criterion factory of the solver.
- `void set_stop_criterion_factory (std::shared_ptr< const stop::CriterionFactory > other)`
Sets the stopping criterion of the solver.

35.57.1 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

<i>ValueType</i>	precision of matrix elements
------------------	------------------------------

35.57.2 Member Function Documentation

35.57.2.1 apply_uses_initial_guess()

```
template<typename ValueType = default_precision>
bool gko::solver::Fcg< ValueType >::apply_uses_initial_guess ( ) const [inline], [override]
```

Return true as iterative solvers use the data in x as an initial guess.

Returns

true as iterative solvers use the data in x as an initial guess.

```
106 { return true; }
```

35.57.2.2 conj_transpose()

```
template<typename ValueType = default_precision>
std::unique_ptr<LinOp> gko::solver::Fcg< 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](#).

35.57.2.3 get_stop_criterion_factory()

```
template<typename ValueType = default_precision>
std::shared_ptr<const stop::CriterionFactory> gko::solver::Fcg< ValueType >::get_stop_↵
criterion_factory ( ) const [inline]
```

Gets the stopping criterion factory of the solver.

Returns

the stopping criterion factory

35.57.2.4 `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)

35.57.2.5 `set_stop_criterion_factory()`

```
template<typename ValueType = default_precision>
void gko::solver::Fcg< ValueType >::set_stop_criterion_factory (
    std::shared_ptr< const stop::CriterionFactory > other ) [inline]
```

Sets the stopping criterion of the solver.

Parameters

<i>other</i>	the new stopping criterion factory
--------------	------------------------------------

35.57.2.6 `transpose()`

```
template<typename ValueType = default_precision>
std::unique_ptr<LinOp> gko::solver::Fcg< 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](#).

The documentation for this class was generated from the following file:

- `ginkgo/core/solver/fcg.hpp`

35.58 `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::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.
- `bool apply_uses_initial_guess () const override`
Return true as iterative solvers use the data in x as an initial guess.
- `size_type get_krylov_dim () const`
Gets the krylov dimension of the solver.
- `void set_krylov_dim (const size_type &other)`
Sets the krylov dimension.
- `std::shared_ptr< const stop::CriterionFactory > get_stop_criterion_factory () const`
Gets the stopping criterion factory of the solver.
- `void set_stop_criterion_factory (std::shared_ptr< const stop::CriterionFactory > other)`
Sets the stopping criterion of the solver.

35.58.1 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. Modified Gram-Schmidt is used.

Template Parameters

<i>ValueType</i>	precision of matrix elements
------------------	------------------------------

35.58.2 Member Function Documentation

35.58.2.1 `apply_uses_initial_guess()`

```
template<typename ValueType = default_precision>
bool gko::solver::Gmres< ValueType >::apply\_uses\_initial\_guess ( ) const [inline], [override]
```

Return true as iterative solvers use the data in x as an initial guess.

Returns

true as iterative solvers use the data in x as an initial guess.

```
101 { return true; }
```

35.58.2.2 conj_transpose()

```
template<typename ValueType = default_precision>
std::unique_ptr<LinOp> gko::solver::Gmres< 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](#).

35.58.2.3 get_krylov_dim()

```
template<typename ValueType = default_precision>
size_type gko::solver::Gmres< ValueType >::get_krylov_dim ( ) const [inline]
```

Gets the krylov dimension of the solver.

Returns

the krylov dimension

35.58.2.4 get_stop_criterion_factory()

```
template<typename ValueType = default_precision>
std::shared_ptr<const stop::CriterionFactory> gko::solver::Gmres< ValueType >::get_stop_←
criterion_factory ( ) const [inline]
```

Gets the stopping criterion factory of the solver.

Returns

the stopping criterion factory

35.58.2.5 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)

35.58.2.6 set_krylov_dim()

```
template<typename ValueType = default_precision>
void gko::solver::Gmres< ValueType >::set_krylov_dim (
    const size_type & other ) [inline]
```

Sets the krylov dimension.

Parameters

<i>other</i>	the new krylov dimension
--------------	--------------------------

35.58.2.7 set_stop_criterion_factory()

```
template<typename ValueType = default_precision>
void gko::solver::Gmres< ValueType >::set_stop_criterion_factory (
    std::shared_ptr< const stop::CriterionFactory > other ) [inline]
```

Sets the stopping criterion of the solver.

Parameters

<i>other</i>	the new stopping criterion factory
--------------	------------------------------------

35.58.2.8 transpose()

```
template<typename ValueType = default_precision>
std::unique_ptr<LinOp> gko::solver::Gmres< 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](#).

The documentation for this class was generated from the following file:

- ginkgo/core/solver/gmres.hpp

35.59 gko::solver::has_with_criteria< SolverType, typename > Struct Template Reference

Helper structure to test if the Factory of SolverType has a function with_criteria.

```
#include <ginkgo/core/solver/solver_traits.hpp>
```

35.59.1 Detailed Description

```
template<typename SolverType, typename = void>
struct gko::solver::has_with_criteria< SolverType, typename >
```

Helper structure to test if the Factory of SolverType has a function with_criteria.

Contains a constexpr boolean value, which is true if the Factory class of SolverType has a with_criteria, and false otherwise.

Template Parameters

<i>SolverType</i>	Solver to test if its factory has a <code>with_criteria</code> function.
-------------------	--

The documentation for this struct was generated from the following file:

- `ginkgo/core/solver/solver_traits.hpp`

35.60 `gko::solver::has_with_criteria< SolverType, xstd::void_t< decltype(SolverType::build().with_criteria(std::shared_ptr< const stop::CriterionFactory >()))> > Struct Template Reference`

Helper structure to test if the Factory of `SolverType` has a function `with_criteria`.

```
#include <ginkgo/core/solver/solver_traits.hpp>
```

35.60.1 Detailed Description

```
template<typename SolverType>
struct gko::solver::has_with_criteria< SolverType, xstd::void_t< decltype(SolverType::build().with_criteria(std::shared_ptr<
const stop::CriterionFactory >()))> >
```

Helper structure to test if the Factory of `SolverType` has a function `with_criteria`.

Contains a constexpr boolean `value`, which is true if the Factory class of `SolverType` has a `with_criteria`, and false otherwise.

Template Parameters

<i>SolverType</i>	Solver to test if its factory has a <code>with_criteria</code> function.
-------------------	--

The documentation for this struct was generated from the following file:

- `ginkgo/core/solver/solver_traits.hpp`

35.61 `gko::HipblasError` Class Reference

[HipblasError](#) is thrown when a hipBLAS routine throws a non-zero error code.

```
#include <ginkgo/core/base/exception.hpp>
```

Public Member Functions

- [HipblasError](#) (const std::string &file, int line, const std::string &func, [int64](#) error_code)
Initializes a hipBLAS error.

35.61.1 Detailed Description

[HipblasError](#) is thrown when a hipBLAS routine throws a non-zero error code.

35.61.2 Constructor & Destructor Documentation

35.61.2.1 HipblasError()

```
gko::HipblasError::HipblasError (
    const std::string & file,
    int line,
    const std::string & func,
    int64 error_code ) [inline]
```

Initializes a hipBLAS error.

Parameters

<i>file</i>	The name of the offending source file
<i>line</i>	The source code line number where the error occurred
<i>func</i>	The name of the hipBLAS routine that failed
<i>error_code</i>	The resulting hipBLAS error code

The documentation for this class was generated from the following file:

- ginkgo/core/base/exception.hpp

35.62 gko::HipError Class Reference

[HipError](#) is thrown when a HIP routine throws a non-zero error code.

```
#include <ginkgo/core/base/exception.hpp>
```

Public Member Functions

- [HipError](#) (const std::string &file, int line, const std::string &func, int64 error_code)
Initializes a HIP error.

35.62.1 Detailed Description

[HipError](#) is thrown when a HIP routine throws a non-zero error code.

35.62.2 Constructor & Destructor Documentation

35.62.2.1 HipError()

```
gko::HipError::HipError (
    const std::string & file,
    int line,
    const std::string & func,
    int64 error_code ) [inline]
```

Initializes a HIP error.

Parameters

<i>file</i>	The name of the offending source file
<i>line</i>	The source code line number where the error occurred
<i>func</i>	The name of the HIP routine that failed
<i>error_code</i>	The resulting HIP error code

The documentation for this class was generated from the following file:

- ginkgo/core/base/exception.hpp

35.63 gko::HipExecutor Class Reference

This is the [Executor](#) subclass which represents the HIP enhanced 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 HIP device id of the device associated to this executor.
- `int get_num_warps_per_sm ()` const noexcept
Get the number of warps per SM of this executor.
- `int get_num_multiprocessor ()` const noexcept
Get the number of multiprocessor 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.
- int [get_num_warps](#) () const noexcept
Get the number of warps of this executor.
- int [get_warp_size](#) () const noexcept
Get the warp size of this executor.
- hipblasContext * [get_hipblas_handle](#) () const
Get the hipblas handle for this executor.
- hipsparsContext * [get_hipsparse_handle](#) () const
Get the hipsparse handle for this executor.
- int [get_closest_numa](#) () const
Get the closest NUMA node.
- std::vector< int > [get_closest_pus](#) () const
Get the closest PUs.

Static Public Member Functions

- static std::shared_ptr< [HipExecutor](#) > [create](#) (int device_id, std::shared_ptr< [Executor](#) > master, bool device_reset=false)
Creates a new [HipExecutor](#).
- static int [get_num_devices](#) ()
Get the number of devices present on the system.

35.63.1 Detailed Description

This is the [Executor](#) subclass which represents the HIP enhanced device.

35.63.2 Member Function Documentation

35.63.2.1 [create\(\)](#)

```
static std::shared_ptr<HipExecutor> gko::HipExecutor::create (
    int device_id,
    std::shared_ptr< Executor > master,
    bool device_reset = false ) [static]
```

Creates a new [HipExecutor](#).

Parameters

<i>device_id</i>	the HIP device id of this device
<i>master</i>	an executor on the host that is used to invoke the device kernels

35.63.2.2 `get_closest_numa()`

```
int gko::HipExecutor::get_closest_numa ( ) const [inline]
```

Get the closest NUMA node.

Returns

the closest NUMA node closest to this device

35.63.2.3 `get_closest_pus()`

```
std::vector<int> gko::HipExecutor::get_closest_pus ( ) const [inline]
```

Get the closest PUs.

Returns

the array of PUs closest to this device

35.63.2.4 `get_hipblas_handle()`

```
hipblasContext* gko::HipExecutor::get_hipblas_handle ( ) const [inline]
```

Get the hipblas handle for this executor.

Returns

the hipblas handle (`hipblasContext*`) for this executor

35.63.2.5 `get_hipsparse_handle()`

```
hipsparseContext* gko::HipExecutor::get_hipsparse_handle ( ) const [inline]
```

Get the hipsparse handle for this executor.

Returns

the hipsparse handle (`hipsparseContext*`) for this executor

35.63.2.6 get_master() [1/2]

```
std::shared_ptr<const Executor> gko::HipExecutor::get_master ( ) const [override], [virtual],
[noexcept]
```

Returns the master [OmpExecutor](#) of this [Executor](#).

Returns

the master [OmpExecutor](#) of this [Executor](#).

Implements [gko::Executor](#).

35.63.2.7 get_master() [2/2]

```
std::shared_ptr<Executor> gko::HipExecutor::get_master ( ) [override], [virtual], [noexcept]
```

Returns the master [OmpExecutor](#) of this [Executor](#).

Returns

the master [OmpExecutor](#) of this [Executor](#).

Implements [gko::Executor](#).

35.63.2.8 run()

```
void gko::HipExecutor::run (
    const Operation & op ) const [override], [virtual]
```

Runs the specified [Operation](#) using this [Executor](#).

Parameters

<i>op</i>	the operation to run
-----------	----------------------

Implements [gko::Executor](#).

The documentation for this class was generated from the following file:

- ginkgo/core/base/executor.hpp

35.64 gko::HiprandError Class Reference

[HiprandError](#) is thrown when a hipRAND routine throws a non-zero error code.

```
#include <ginkgo/core/base/exception.hpp>
```

Public Member Functions

- [HiprandError](#) (const std::string &file, int line, const std::string &func, [int64](#) error_code)
Initializes a hipRAND error.

35.64.1 Detailed Description

[HiprandError](#) is thrown when a hipRAND routine throws a non-zero error code.

35.64.2 Constructor & Destructor Documentation

35.64.2.1 HiprandError()

```
gko::HiprandError::HiprandError (
    const std::string & file,
    int line,
    const std::string & func,
    int64 error_code ) [inline]
```

Initializes a hipRAND error.

Parameters

<i>file</i>	The name of the offending source file
<i>line</i>	The source code line number where the error occurred
<i>func</i>	The name of the hipRAND routine that failed
<i>error_code</i>	The resulting hipRAND error code

The documentation for this class was generated from the following file:

- ginkgo/core/base/exception.hpp

35.65 gko::HipsparseError Class Reference

[HipsparseError](#) is thrown when a hipSPARSE routine throws a non-zero error code.

```
#include <ginkgo/core/base/exception.hpp>
```

Public Member Functions

- [HipsparseError](#) (const std::string &file, int line, const std::string &func, [int64](#) error_code)
Initializes a hipSPARSE error.

35.65.1 Detailed Description

[HipsparseError](#) is thrown when a hipSPARSE routine throws a non-zero error code.

35.65.2 Constructor & Destructor Documentation

35.65.2.1 HipsparseError()

```
gko::HipsparseError::HipsparseError (
    const std::string & file,
    int line,
    const std::string & func,
    int64 error_code ) [inline]
```

Initializes a hipSPARSE error.

Parameters

<i>file</i>	The name of the offending source file
<i>line</i>	The source code line number where the error occurred
<i>func</i>	The name of the hipSPARSE routine that failed
<i>error_code</i>	The resulting hipSPARSE error code

The documentation for this class was generated from the following file:

- ginkgo/core/base/exception.hpp

35.66 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 [strategy_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 [strategy_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 [strategy_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.
- std::unique_ptr< [Diagonal](#)< ValueType > > [extract_diagonal](#) () const override
Extracts the diagonal entries of the matrix into a vector.
- std::unique_ptr< absolute_type > [compute_absolute](#) () const override
Gets the AbsoluteLinOp.
- void [compute_absolute_inplace](#) () override
Compute absolute inplace on each element.
- 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_idxes ()` noexcept
Returns the row indexes of the coo part.
- `const index_type * get_const_coo_row_idxes ()` 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.
- `template<typename HybType >`
`std::shared_ptr< typename HybType::strategy_type > get_strategy ()` const
Returns the current strategy allowed in given hybrid format.
- `Hybrid & operator= (const Hybrid &other)`
Copies data from another Hybrid.

35.66.1 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

<i>ValueType</i>	precision of matrix elements
<i>IndexType</i>	precision of matrix indexes

35.66.2 Member Function Documentation

35.66.2.1 compute_absolute()

```
template<typename ValueType = default_precision, typename IndexType = int32>
std::unique_ptr<absolute_type> gko::matrix::Hybrid< ValueType, IndexType >::compute_absolute
( ) const [override], [virtual]
```

Gets the AbsoluteLinOp.

Returns

a pointer to the new absolute object

Implements `gko::EnableAbsoluteComputation< remove_complex< Hybrid< ValueType, IndexType > > >`.

35.66.2.2 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 ) const [inline], [noexcept]
```

Returns the `idx`-th column index of the `row`-th row in the ell part.

Parameters

<i>row</i>	the row of the requested element
<i>idx</i>	the <code>idx</code> -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)

```
514     {
515         return ell->col_at(row, idx);
516     }
```

35.66.2.3 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 ) [inline], [noexcept]
```

Returns the `idx`-th column index of the `row`-th row in the ell part.

Parameters

<i>row</i>	the row of the requested element
<i>idx</i>	the <code>idx</code> -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)

35.66.2.4 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 ) const [inline], [noexcept]
```

Returns the `idx`-th non-zero element of the `row`-th row in the ell part.

Parameters

<i>row</i>	the row of the requested element
<i>idx</i>	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)

35.66.2.5 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 ) [inline], [noexcept]
```

Returns the *idx*-th non-zero element of the *row*-th row in the ell part.

Parameters

<i>row</i>	the row of the requested element
<i>idx</i>	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)

35.66.2.6 extract_diagonal()

```
template<typename ValueType = default_precision, typename IndexType = int32>
std::unique_ptr<Diagonal<ValueType> > gko::matrix::Hybrid< ValueType, IndexType >::extract←
_diagonal ( ) const [override], [virtual]
```

Extracts the diagonal entries of the matrix into a vector.

Parameters

<i>diag</i>	the vector into which the diagonal will be written
-------------	--

Implements [gko::DiagonalExtractable< ValueType >](#).

35.66.2.7 `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.

35.66.2.8 `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.

35.66.2.9 `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.

35.66.2.10 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.

35.66.2.11 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.

35.66.2.12 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

35.66.2.13 `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.

35.66.2.14 `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

35.66.2.15 `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.

35.66.2.16 `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.

35.66.2.17 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

35.66.2.18 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

35.66.2.19 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

35.66.2.20 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

35.66.2.21 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

35.66.2.22 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

35.66.2.23 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

35.66.2.24 get_strategy() [1/2]

```
template<typename ValueType = default_precision, typename IndexType = int32>
template<typename HybType >
std::shared_ptr<typename HybType::strategy_type> gko::matrix::Hybrid< ValueType, IndexType >::get_strategy ( ) const
```

Returns the current strategy allowed in given hybrid format.

Template Parameters

<i>HybType</i>	hybrid type
----------------	-------------

Returns

the strategy

35.66.2.25 get_strategy() [2/2]

```
template<typename ValueType = default_precision, typename IndexType = int32>
std::shared_ptr< typename HybType::strategy_type > gko::matrix::Hybrid< ValueType, IndexType
>::get_strategy ( ) const [inline], [noexcept]
```

Returns the strategy.

Returns

the strategy

35.66.2.26 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

<i>other</i>	the Hybrid to copy from
--------------	---

Returns

this

35.66.2.27 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

<i>data</i>	the matrix_data structure
-------------	---

Implements [gko::ReadableFromMatrixData< ValueType, IndexType >](#).

35.66.2.28 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

<i>data</i>	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
- ginkgo/core/matrix/hybrid.hpp

35.67 gko::factorization::lc< ValueType, IndexType > Class Template Reference

Represents an incomplete Cholesky factorization (IC(0)) of a sparse matrix.

```
#include <ginkgo/core/factorization/ic.hpp>
```

Additional Inherited Members

35.67.1 Detailed Description

```
template<typename ValueType = gko::default_precision, typename IndexType = gko::int32>
class gko::factorization::lc< ValueType, IndexType >
```

Represents an incomplete Cholesky factorization (IC(0)) of a sparse matrix.

More specifically, it consists of a lower triangular factor L and its conjugate transpose L^H with sparsity pattern $S(L + L^H) = S(A)$ fulfilling $LL^H = A$ at every non-zero location of A .

Template Parameters

<i>ValueType</i>	Type of the values of all matrices used in this class
<i>IndexType</i>	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/ic.hpp

35.68 gko::preconditioner::lc< LSolverType, IndexType > Class Template Reference

The Incomplete Cholesky (IC) preconditioner solves the equation $LL^H * x = b$ for a given lower triangular matrix L and the right hand side b (can contain multiple right hand sides).

```
#include <ginkgo/core/preconditioner/ic.hpp>
```

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 lh_solver_type > get_lh_solver () const`
Returns the solver which is used for the $L^H H$ matrix.
- `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.

35.68.1 Detailed Description

```
template<typename LSolverType = solver::LowerTrs<>, typename IndexType = int32>
class gko::preconditioner::lc< LSolverType, IndexType >
```

The Incomplete Cholesky (IC) preconditioner solves the equation $LL^H * x = b$ for a given lower triangular matrix L and the right hand side b (can contain multiple right hand sides).

It allows to set both the solver for L defaulting to `solver::LowerTrs`, which is a direct triangular solvers. The solver for $L^H H$ is the conjugate-transposed solver for L , ensuring that the preconditioner is symmetric and positive-definite. For this L solver, a factory can be provided (using `with_l_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 triangular 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.

An object of this class can be created with a matrix or a `gko::Composition` containing two matrices. If created with a matrix, it is factorized before creating the solver. If a `gko::Composition` (containing two matrices) is used, the first operand will be taken as the L matrix, the second will be considered the $L^H H$ matrix, which helps to avoid the otherwise necessary transposition of L inside the solver. `Parlc` can be directly used, since it orders the factors in the correct way.

Note

When providing a [gko::Composition](#), the first matrix must be the lower matrix (L), and the second matrix must be its conjugate-transpose (L^H). If they are swapped, solving might crash or return the wrong result.

Do not use symmetric solvers (like CG) for the L solver since both matrices (L and L^H) are, by design, not symmetric.

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

<i>LSolverType</i>	type of the solver used for the L matrix. Defaults to solver::LowerTrs
<i>IndexType</i>	type of the indices when Parlc is used to generate the L and L^H factors. Irrelevant otherwise.

35.68.2 Member Function Documentation**35.68.2.1 conj_transpose()**

```
template<typename LSolverType = solver::LowerTrs<>, typename IndexType = int32>
std::unique_ptr<LinOp> gko::preconditioner::Ic< LSolverType, IndexType >::conj_transpose ( )
const [inline], [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](#).

```
176     {
177         std::unique_ptr<transposed_type> transposed{
178             new transposed_type{this->get_executor()}};
179         transposed->set_size(gko::transpose(this->get_size()));
180         transposed->l_solver_ =
181             share(as<typename lh_solver_type::transposed_type>(
182                 this->get_lh_solver()->conj_transpose()));
183         transposed->lh_solver_ =
184             share(as<typename l_solver_type::transposed_type>(
185                 this->get_l_solver()->conj_transpose()));
186
187         return std::move(transposed);
188     }
```

References [gko::PolymorphicObject::get_executor\(\)](#), [gko::preconditioner::Ic< LSolverType, IndexType >::get_l_solver\(\)](#), [gko::preconditioner::Ic< LSolverType, IndexType >::get_lh_solver\(\)](#), [gko::share\(\)](#), and [gko::transpose\(\)](#).

35.68.2.2 get_l_solver()

```
template<typename LSolverType = solver::LowerTrs<>, typename IndexType = int32>
std::shared_ptr<const l_solver_type> gko::preconditioner::lc< LSolverType, IndexType >::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

Referenced by gko::preconditioner::lc< LSolverType, IndexType >::conj_transpose(), and gko::preconditioner::lc< LSolverType, IndexType >::transpose().

35.68.2.3 get_lh_solver()

```
template<typename LSolverType = solver::LowerTrs<>, typename IndexType = int32>
std::shared_ptr<const lh_solver_type> gko::preconditioner::lc< LSolverType, IndexType >::get_lh_solver ( ) const [inline]
```

Returns the solver which is used for the L^H matrix.

Returns

the solver which is used for the L^H matrix

Referenced by gko::preconditioner::lc< LSolverType, IndexType >::conj_transpose(), and gko::preconditioner::lc< LSolverType, IndexType >::transpose().

35.68.2.4 transpose()

```
template<typename LSolverType = solver::LowerTrs<>, typename IndexType = int32>
std::unique_ptr<LinOp> gko::preconditioner::lc< LSolverType, IndexType >::transpose ( ) const [inline], [override], [virtual]
```

Returns a LinOp representing the transpose of the [Transposable](#) object.

Returns

a pointer to the new transposed object

Implements [gko::Transposable](#).

References gko::PolymorphicObject::get_executor(), gko::preconditioner::lc< LSolverType, IndexType >::get_l_solver(), gko::preconditioner::lc< LSolverType, IndexType >::get_lh_solver(), gko::share(), and gko::transpose().

The documentation for this class was generated from the following file:

- ginkgo/core/preconditioner/ic.hpp

35.69 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>
```

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.

35.69.1 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

<i>ValueType</i>	precision of matrix elements
------------------	------------------------------

35.69.2 Member Function Documentation

35.69.2.1 conj_transpose()

```
template<typename ValueType = default_precision>
std::unique_ptr<LinOp> gko::matrix::Identity< 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](#).

35.69.2.2 transpose()

```
template<typename ValueType = default_precision>
std::unique_ptr<LinOp> gko::matrix::Identity< 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](#).

The documentation for this class was generated from the following file:

- ginkgo/core/matrix/identity.hpp

35.70 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**35.70.1 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

<i>ValueType</i>	precision of matrix elements
------------------	------------------------------

35.70.2 Member Function Documentation

35.70.2.1 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

<i>exec</i>	the executor where the Identity operator will be stored
-------------	---

Returns

a unique pointer to the newly created factory

```
147 {
148     return std::unique_ptr<IdentityFactory>(
149         new IdentityFactory(std::move(exec)));
150 }
```

The documentation for this class was generated from the following file:

- ginkgo/core/matrix/identity.hpp

35.71 gko::solver::Idr< ValueType > Class Template Reference

IDR(s) is an efficient method for solving large nonsymmetric systems of linear equations.

```
#include <ginkgo/core/solver/idr.hpp>
```

Public Member Functions

- std::shared_ptr< const LinOp > [get_system_matrix](#) () const
Gets the system operator (matrix) of the linear system.
- 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.
- bool [apply_uses_initial_guess](#) () const override

- Return true as iterative solvers use the data in x as an initial guess.*
- `std::shared_ptr< const stop::CriterionFactory > get_stop_criterion_factory () const`
Gets the stopping criterion factory of the solver.
- `void set_stop_criterion_factory (std::shared_ptr< const stop::CriterionFactory > other)`
Sets the stopping criterion of the solver.
- `size_type get_subspace_dim () const`
Gets the subspace dimension of the solver.
- `void set_subspace_dim (const size_type other)`
Sets the subspace dimension of the solver.
- `remove_complex< ValueType > get_kappa () const`
Gets the kappa parameter of the solver.
- `void set_kappa (const remove_complex< ValueType > other)`
Sets the kappa parameter of the solver.
- `bool get_deterministic () const`
Gets the deterministic parameter of the solver.
- `void set_deterministic (const bool other)`
Sets the deterministic parameter of the solver.
- `bool get_complex_subspace () const`
Gets the complex_subspace parameter of the solver.
- `void set_complex_subspace (const bool other)`
Sets the complex_subspace parameter of the solver.

35.71.1 Detailed Description

```
template<typename ValueType = default_precision>
class gko::solver::ldr< ValueType >
```

IDR(s) is an efficient method for solving large nonsymmetric systems of linear equations.

The implemented version is the one presented in the paper "Algorithm 913: An elegant IDR(s) variant that efficiently exploits biorthogonality properties" by M. B. Van Gijzen and P. Sonneveld.

The method is based on the induced dimension reduction theorem which provides a way to construct subsequent residuals that lie in a sequence of shrinking subspaces. These subspaces are spanned by s vectors which are first generated randomly and then orthonormalized. They are stored in a dense matrix.

Template Parameters

<i>ValueType</i>	precision of the elements of the system matrix.
------------------	---

35.71.2 Member Function Documentation

35.71.2.1 apply_uses_initial_guess()

```
template<typename ValueType = default_precision>
bool gko::solver::ldr< ValueType >::apply_uses_initial_guess ( ) const [inline], [override]
```

Return true as iterative solvers use the data in x as an initial guess.

Returns

true as iterative solvers use the data in x as an initial guess.

```
111 { return true; }
```

35.71.2.2 conj_transpose()

```
template<typename ValueType = default_precision>
std::unique_ptr<LinOp> gko::solver::Idr< 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](#).

35.71.2.3 get_complex_subspace()

```
template<typename ValueType = default_precision>
bool gko::solver::Idr< ValueType >::get_complex_subspace ( ) const [inline]
```

Gets the complex_subspace parameter of the solver.

Returns

the complex_subspace parameter

35.71.2.4 get_deterministic()

```
template<typename ValueType = default_precision>
bool gko::solver::Idr< ValueType >::get_deterministic ( ) const [inline]
```

Gets the deterministic parameter of the solver.

Returns

the deterministic parameter

35.71.2.5 get_kappa()

```
template<typename ValueType = default_precision>
remove_complex<ValueType> gko::solver::Idr< ValueType >::get_kappa ( ) const [inline]
```

Gets the kappa parameter of the solver.

Returns

the kappa parameter

35.71.2.6 get_stop_criterion_factory()

```
template<typename ValueType = default_precision>
std::shared_ptr<const stop::CriterionFactory> gko::solver::Idr< ValueType >::get_stop_criterion_factory ( ) const [inline]
```

Gets the stopping criterion factory of the solver.

Returns

the stopping criterion factory

35.71.2.7 get_subspace_dim()

```
template<typename ValueType = default_precision>
size_type gko::solver::Idr< ValueType >::get_subspace_dim ( ) const [inline]
```

Gets the subspace dimension of the solver.

Returns

the subspace Dimension

35.71.2.8 get_system_matrix()

```
template<typename ValueType = default_precision>
std::shared_ptr<const LinOp> gko::solver::Idr< ValueType >::get_system_matrix ( ) const [inline]
```

Gets the system operator (matrix) of the linear system.

Returns

the system operator (matrix)

35.71.2.9 set_complex_subspace()

```
template<typename ValueType = default_precision>
void gko::solver::Idr< ValueType >::set_complex_subspace (
    const bool other ) [inline]
```

Sets the complex_subspace parameter of the solver.

Parameters

<i>other</i>	the new complex_subspace parameter
--------------	------------------------------------

35.71.2.10 set_deterministic()

```
template<typename ValueType = default_precision>
void gko::solver::Idr< ValueType >::set_deterministic (
    const bool other ) [inline]
```

Sets the deterministic parameter of the solver.

Parameters

<i>other</i>	the new deterministic parameter
--------------	---------------------------------

35.71.2.11 set_kappa()

```
template<typename ValueType = default_precision>
void gko::solver::Idr< ValueType >::set_kappa (
    const remove_complex< ValueType > other ) [inline]
```

Sets the kappa parameter of the solver.

Parameters

<i>other</i>	the new kappa parameter
--------------	-------------------------

35.71.2.12 set_stop_criterion_factory()

```
template<typename ValueType = default_precision>
void gko::solver::Idr< ValueType >::set_stop_criterion_factory (
    std::shared_ptr< const stop::CriterionFactory > other ) [inline]
```

Sets the stopping criterion of the solver.

Parameters

<i>other</i>	the new stopping criterion factory
--------------	------------------------------------

35.71.2.13 set_subspace_dim()

```
template<typename ValueType = default_precision>
void gko::solver::Idr< ValueType >::set_subspace_dim (
    const size_type other ) [inline]
```

Sets the subspace dimension of the solver.

Parameters

<i>other</i>	the new subspace Dimension
--------------	----------------------------

35.71.2.14 transpose()

```
template<typename ValueType = default_precision>
std::unique_ptr<LinOp> gko::solver::Idr< 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](#).

The documentation for this class was generated from the following file:

- ginkgo/core/solver/idr.hpp

35.72 gko::factorization::llu< ValueType, IndexType > Class Template Reference

Represents an incomplete LU factorization – ILU(0) – of a sparse matrix.

```
#include <ginkgo/core/factorization/ilu.hpp>
```

Additional Inherited Members**35.72.1 Detailed Description**

```
template<typename ValueType = gko::default_precision, typename IndexType = gko::int32>
class gko::factorization::llu< ValueType, IndexType >
```

Represents an incomplete LU factorization – ILU(0) – of a sparse matrix.

More specifically, it consists of a lower unitriangular factor L and an upper triangular factor U with sparsity pattern $S(L + U) = S(A)$ fulfilling $LU = A$ at every non-zero location of A .

Template Parameters

<i>ValueType</i>	Type of the values of all matrices used in this class
<i>IndexType</i>	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/ilu.hpp

35.73 gko::preconditioner::ilu< LSolverType, USolverType, ReverseApply, IndexType > 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>
```

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.
- `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.

35.73.1 Detailed Description

```
template<typename LSolverType = solver::LowerTrs<>, typename USolverType = solver::UpperTrs<>, bool ReverseApply = false, typename IndexType = int32>
class gko::preconditioner::ilu< LSolverType, USolverType, ReverseApply, IndexType >
```

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 triangular 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.

An object of this class can be created with a matrix or a [gko::Composition](#) containing two matrices. If created with a matrix, it is factorized before creating the solver. If a [gko::Composition](#) (containing two matrices) is used, the first operand will be taken as the L matrix, the second will be considered the U matrix. Parllu can be directly used, since it orders the factors in the correct way.

Note

When providing a [gko::Composition](#), the first matrix must be the lower matrix (L), and the second matrix must be the upper matrix (U). If they are swapped, solving might crash or return the wrong result.

Do not use symmetric solvers (like CG) for L or U solvers since both matrices (L and U) are, by design, not symmetric.

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

<i>LSolverType</i>	type of the solver used for the L matrix. Defaults to solver::LowerTrs
<i>USolverType</i>	type of the solver used for the U matrix Defaults to solver::UpperTrs
<i>ReverseApply</i>	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.
<i>IndexTypeParllu</i>	Type of the indices when Parllu is used to generate both L and U factors. Irrelevant otherwise.

35.73.2 Member Function Documentation

35.73.2.1 conj_transpose()

```
template<typename LSolverType = solver::LowerTrs<>, typename USolverType = solver::UpperTrs<>,
bool ReverseApply = false, typename IndexType = int32>
std::unique_ptr<LinOp> gko::preconditioner::llu< LSolverType, USolverType, ReverseApply,
IndexType >::conj_transpose ( ) const [inline], [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](#).

```
194 {
195     std::unique_ptr<transposed_type> transposed{
196         new transposed_type(this->get_executor());
197         transposed->set_size(gko::transpose(this->get_size()));
198         transposed->l_solver_ =
199             share(as<typename u_solver_type::transposed_type>(
200                 this->get_u_solver()->conj_transpose()));
201         transposed->u_solver_ =
202             share(as<typename l_solver_type::transposed_type>(
203                 this->get_l_solver()->conj_transpose()));
204
205         return std::move(transposed);
206     }
```

References [gko::PolymorphicObject::get_executor\(\)](#), [gko::preconditioner::llu< LSolverType, USolverType, ReverseApply, IndexType >::get_l_solver\(\)](#), [gko::preconditioner::llu< LSolverType, USolverType, ReverseApply, IndexType >::get_u_solver\(\)](#), [gko::share\(\)](#), and [gko::transpose\(\)](#).

35.73.2.2 `get_l_solver()`

```
template<typename LSolverType = solver::LowerTrs<>, typename USolverType = solver::Upper↵
Trs<>, bool ReverseApply = false, typename IndexType = int32>
std::shared_ptr<const l_solver_type> gko::preconditioner::Ilu< LSolverType, USolverType,
ReverseApply, IndexType >::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

Referenced by `gko::preconditioner::Ilu< LSolverType, USolverType, ReverseApply, IndexType >::conj_transpose()`, and `gko::preconditioner::Ilu< LSolverType, USolverType, ReverseApply, IndexType >::transpose()`.

35.73.2.3 `get_u_solver()`

```
template<typename LSolverType = solver::LowerTrs<>, typename USolverType = solver::Upper↵
Trs<>, bool ReverseApply = false, typename IndexType = int32>
std::shared_ptr<const u_solver_type> gko::preconditioner::Ilu< LSolverType, USolverType,
ReverseApply, IndexType >::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

Referenced by `gko::preconditioner::Ilu< LSolverType, USolverType, ReverseApply, IndexType >::conj_transpose()`, and `gko::preconditioner::Ilu< LSolverType, USolverType, ReverseApply, IndexType >::transpose()`.

35.73.2.4 `transpose()`

```
template<typename LSolverType = solver::LowerTrs<>, typename USolverType = solver::Upper↵
Trs<>, bool ReverseApply = false, typename IndexType = int32>
std::unique_ptr<LinOp> gko::preconditioner::Ilu< LSolverType, USolverType, ReverseApply,
IndexType >::transpose ( ) const [inline], [override], [virtual]
```

Returns a `LinOp` representing the transpose of the [Transposable](#) object.

Returns

a pointer to the new transposed object

Implements [gko::Transposable](#).

References `gko::PolymorphicObject::get_executor()`, `gko::preconditioner::Ilu< LSolverType, USolverType, ReverseApply, IndexType >::get_l_solver()`, `gko::preconditioner::Ilu< LSolverType, USolverType, ReverseApply, IndexType >::get_u_solver()`, `gko::share()`, and `gko::transpose()`.

The documentation for this class was generated from the following file:

- `ginkgo/core/preconditioner/ilu.hpp`

35.74 gko::matrix::Hybrid< ValueType, IndexType >::imbalance_bounded_limit Class Reference

[imbalance_bounded_limit](#) is a [strategy_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](#) (double percent=0.8, double 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.
- auto [get_percentage](#) () const
Get the percent setting.
- auto [get_ratio](#) () const
Get the ratio setting.

35.74.1 Detailed Description

```
template<typename ValueType = default_precision, typename IndexType = int32>
class gko::matrix::Hybrid< ValueType, IndexType >::imbalance_bounded_limit
```

[imbalance_bounded_limit](#) is a [strategy_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.

35.74.2 Member Function Documentation

35.74.2.1 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

<code>row_nnz</code>	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 >::imbalance_limit::compute_ell_num_stored_elements_per_row\(\)](#), and [gko::Array< ValueType >::get_num_elems\(\)](#).

Referenced by [gko::matrix::Hybrid< ValueType, IndexType >::automatic::compute_ell_num_stored_elements_per_row\(\)](#).

35.74.2.2 get_percentage()

```
template<typename ValueType = default_precision, typename IndexType = int32>
auto gko::matrix::Hybrid< ValueType, IndexType >::imbalance_bounded_limit::get_percentage ( )
const [inline]
```

Get the percent setting.

@retrun percent

References [gko::matrix::Hybrid< ValueType, IndexType >::imbalance_limit::get_percentage\(\)](#).

35.74.2.3 get_ratio()

```
template<typename ValueType = default_precision, typename IndexType = int32>
auto gko::matrix::Hybrid< ValueType, IndexType >::imbalance_bounded_limit::get_ratio ( ) const
[inline]
```

Get the ratio setting.

@retrun ratio

The documentation for this class was generated from the following file:

- [ginkgo/core/matrix/hybrid.hpp](#)

35.75 [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](#) (double 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.
- auto [get_percentage](#) () const
Get the percent setting.

35.75.1 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.

35.75.2 Constructor & Destructor Documentation

35.75.2.1 imbalance_limit()

```
template<typename ValueType = default_precision, typename IndexType = int32>
gko::matrix::Hybrid< ValueType, IndexType >::imbalance_limit (
    double percent = 0.8 ) [inline], [explicit]
```

Creates a [imbalance_limit](#) strategy.

Parameters

<i>percent</i>	the row_nnz[floor(num_rows*percent)] is the number of stored elements per row of the ell part
----------------	---

35.75.3 Member Function Documentation

35.75.3.1 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

<code>row_nnz</code>	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\(\)](#).

Referenced by [gko::matrix::Hybrid< ValueType, IndexType >::imbalance_bounded_limit::compute_ell_num_stored_elements_per_row\(\)](#), and [gko::matrix::Hybrid< ValueType, IndexType >::minimal_storage_limit::compute_ell_num_stored_elements_per_row\(\)](#).

35.75.3.2 `get_percentage()`

```
template<typename ValueType = default_precision, typename IndexType = int32>
auto gko::matrix::Hybrid< ValueType, IndexType >::imbalance\_limit::get\_percentage ( ) const
[inline]
```

Get the percent setting.

@retrun percent

Referenced by [gko::matrix::Hybrid< ValueType, IndexType >::imbalance_bounded_limit::get_percentage\(\)](#), and [gko::matrix::Hybrid< ValueType, IndexType >::minimal_storage_limit::get_percentage\(\)](#).

The documentation for this class was generated from the following file:

- `ginkgo/core/matrix/hybrid.hpp`

35.76 `gko::stop::ImplicitResidualNorm< ValueType >` Class Template Reference

The [ImplicitResidualNorm](#) class is a stopping criterion which stops the iteration process when the implicit residual norm is below a certain threshold relative to.

```
#include <ginkgo/core/stop/residual_norm.hpp>
```

35.76.1 Detailed Description

```
template<typename ValueType = default_precision>
class gko::stop::ImplicitResidualNorm< ValueType >
```

The [ImplicitResidualNorm](#) class is a stopping criterion which stops the iteration process when the implicit residual norm is below a certain threshold relative to.

1. the norm of the right-hand side, $\text{implicit_resnorm} / \text{norm}(\text{right_hand_side}) < \text{threshold}$
2. the initial residual, $\text{implicit_resnorm} / \text{norm}(\text{initial_residual}) < < \text{threshold}$.
3. one, $\text{implicit_resnorm} < \text{threshold}$.

Note

To use this stopping criterion there are some dependencies. The constructor depends on either `b` or the `initial_residual` in order to compute their norms. If this 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.hpp`

35.77 gko::solver::lr< 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::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.
- `bool apply_uses_initial_guess () const override`
Return true as iterative solvers use the data in `x` as an initial guess.
- `std::shared_ptr< const LinOp > get_solver () const`
Returns the solver operator used as the inner solver.
- `void set_solver (std::shared_ptr< const LinOp > new_solver)`
Sets the solver operator used as the inner solver.
- `std::shared_ptr< const stop::CriterionFactory > get_stop_criterion_factory () const`
Gets the stopping criterion factory of the solver.
- `void set_stop_criterion_factory (std::shared_ptr< const stop::CriterionFactory > other)`
Sets the stopping criterion of the solver.

35.77.1 Detailed Description

```
template<typename ValueType = default_precision>
class gko::solver::lr< 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.

Moreover, it can be also considered as preconditioned Richardson iteration with relaxation factor = 1.

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, $e = x - \text{solution}$ (with x being the exact solution) can be obtained as the solution to the residual equation $Ae = \text{residual}$, since $Ae = Ax - A \text{ solution} = b - A \text{ solution} = \text{residual}$. Then, the real solution is computed as $x = \text{relaxation_factor} * \text{solution} + e$. Instead of accurately solving the residual equation $Ae = \text{residual}$, 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 + relaxation_factor * error
```

With `relaxation_factor` equal to 1 (default), the solver is Iterative Refinement, with `relaxation_factor` equal to a value other than 1, the solver is a Richardson iteration, with possibility for additional preconditioning.

Assuming that `solver` has accuracy c , i.e., $|e - \text{error}| \leq c |e|$, iterative refinement will converge with a convergence rate of c . Indeed, from $e - \text{error} = x - \text{solution} - \text{error} = x - \text{solution} * \text{inv}(A) \text{ residual} = x - \text{solution} * \text{inv}(A) (b - \text{inv}(A) A \text{ solution}) = x - \text{solution} *$ it follows that $|x - \text{solution}| \leq c |x - \text{solution}|$.

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 λ have to satisfy the equation $|\text{relaxation_factor} * \lambda - 1| < 1$).

Template Parameters

<code>ValueType</code>	precision of matrix elements
------------------------	------------------------------

35.77.2 Member Function Documentation

35.77.2.1 `apply_uses_initial_guess()`

```
template<typename ValueType = default_precision>
bool gko::solver::lr< ValueType >::apply_uses_initial_guess ( ) const [inline], [override]
```

Return true as iterative solvers use the data in `x` as an initial guess.

Returns

true as iterative solvers use the data in x as an initial guess.

```
133 { return true; }
```

35.77.2.2 conj_transpose()

```
template<typename ValueType = default_precision>
std::unique_ptr<LinOp> gko::solver::Ir< 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](#).

35.77.2.3 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

35.77.2.4 get_stop_criterion_factory()

```
template<typename ValueType = default_precision>
std::shared_ptr<const stop::CriterionFactory> gko::solver::Ir< ValueType >::get_stop_criterion←
_factory ( ) const [inline]
```

Gets the stopping criterion factory of the solver.

Returns

the stopping criterion factory

35.77.2.5 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)

35.77.2.6 set_solver()

```
template<typename ValueType = default_precision>
void gko::solver::Ir< ValueType >::set_solver (
    std::shared_ptr< const LinOp > new_solver ) [inline]
```

Sets the solver operator used as the inner solver.

Parameters

<i>new_solver</i>	the new inner solver
-------------------	----------------------

35.77.2.7 set_stop_criterion_factory()

```
template<typename ValueType = default_precision>
void gko::solver::Ir< ValueType >::set_stop_criterion_factory (
    std::shared_ptr< const stop::CriterionFactory > other ) [inline]
```

Sets the stopping criterion of the solver.

Parameters

<i>other</i>	the new stopping criterion factory
--------------	------------------------------------

35.77.2.8 transpose()

```
template<typename ValueType = default_precision>
std::unique_ptr<LinOp> gko::solver::Ir< 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](#).

The documentation for this class was generated from the following file:

- ginkgo/core/solver/ir.hpp

35.78 gko::preconditioner::lsai< IsaiType, ValueType, IndexType > Class Template Reference

The Incomplete Sparse Approximate Inverse (ISAI) Preconditioner generates an approximate inverse matrix for a given lower triangular matrix L or upper triangular matrix U.

```
#include <ginkgo/core/preconditioner/isai.hpp>
```

Public Member Functions

- `std::shared_ptr< const Csr > get_approximate_inverse () const`
Returns the approximate inverse of the given matrix (either L or U, depending on the template parameter IsaiType).
- `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.

35.78.1 Detailed Description

```
template<isai_type IsaiType, typename ValueType, typename IndexType>
class gko::preconditioner::lsai< IsaiType, ValueType, IndexType >
```

The Incomplete Sparse Approximate Inverse (ISAI) Preconditioner generates an approximate inverse matrix for a given lower triangular matrix L or upper triangular matrix U.

Using the preconditioner computes $aiU * x$ or $aiL * x$ (depending on the type of the [lsai](#)) for a given vector x (may have multiple right hand sides). aiU and aiL are the approximate inverses for U and L respectively.

The sparsity pattern used for the approximate inverse is the same as the sparsity pattern of the respective triangular matrix.

For more details on the algorithm, see the paper [Incomplete Sparse Approximate Inverses for Parallel Preconditioning](#), which is the basis for this work.

Note

GPU implementations can only handle the vector unit width `width` (warp size for CUDA) as number of elements per row in the sparse matrix. If there are more than `width` elements per row, the remaining elements will be ignored.

Template Parameters

<i>IsaiType</i>	determines if the ISAI is generated for a lower triangular matrix or an upper triangular matrix
<i>ValueType</i>	precision of matrix elements
<i>IndexType</i>	precision of matrix indexes

35.78.2 Member Function Documentation

35.78.2.1 conj_transpose()

```
template<isai_type IsaiType, typename ValueType , typename IndexType >
std::unique_ptr<LinOp> gko::preconditioner::Isai< IsaiType, 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](#).

35.78.2.2 get_approximate_inverse()

```
template<isai_type IsaiType, typename ValueType , typename IndexType >
std::shared_ptr<const Csr> gko::preconditioner::Isai< IsaiType, ValueType, IndexType >::get_↔
_approximate_inverse ( ) const [inline]
```

Returns the approximate inverse of the given matrix (either L or U, depending on the template parameter IsaiType).

Returns

the generated approximate inverse

35.78.2.3 transpose()

```
template<isai_type IsaiType, typename ValueType , typename IndexType >
std::unique_ptr<LinOp> gko::preconditioner::Isai< IsaiType, 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](#).

The documentation for this class was generated from the following file:

- ginkgo/core/preconditioner/isai.hpp

35.79 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>
```

35.79.1 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`

35.80 gko::log::iteration_complete_data Struct Reference

Struct representing iteration complete related data.

```
#include <ginkgo/core/log/record.hpp>
```

35.80.1 Detailed Description

Struct representing iteration complete related data.

The documentation for this struct was generated from the following file:

- `ginkgo/core/log/record.hpp`

35.81 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.
- 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.

35.81.1 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

<i>ValueType</i>	precision of matrix elements
<i>IndexType</i>	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.

35.81.2 Member Function Documentation**35.81.2.1 conj_transpose()**

```
template<typename ValueType = default_precision, typename IndexType = int32>
std::unique_ptr<LinOp> gko::preconditioner::Jacobi< 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](#).

35.81.2.2 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

<i>result</i>	the object used to store the result of the conversion
---------------	---

Implements [gko::ConvertibleTo< matrix::Dense< ValueType > >](#).

35.81.2.3 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

References `gko::Array< ValueType >::get_const_data()`.

35.81.2.4 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.

References `gko::Array< ValueType >::get_const_data()`.

35.81.2.5 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

35.81.2.6 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::Array< ValueType >::get_num_elems()`.

35.81.2.7 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

35.81.2.8 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

<i>result</i>	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 > >](#).

35.81.2.9 transpose()

```
template<typename ValueType = default_precision, typename IndexType = int32>
std::unique_ptr<LinOp> gko::preconditioner::Jacobi< 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](#).

35.81.2.10 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

<i>data</i>	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](#)

35.82 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.

35.82.1 Detailed Description

[KernelNotFound](#) is thrown if Ginkgo cannot find a kernel which satisfies the criteria imposed by the input arguments.

35.82.2 Constructor & Destructor Documentation

35.82.2.1 KernelNotFound()

```
gko::KernelNotFound::KernelNotFound (
    const std::string & file,
    int line,
    const std::string & func ) [inline]
```

Initializes a [KernelNotFound](#) error.

Parameters

<i>file</i>	The name of the offending source file
<i>line</i>	The source code line number where the error occurred
<i>func</i>	The name of the function where the error occurred

The documentation for this class was generated from the following file:

- ginkgo/core/base/exception.hpp

35.83 gko::log::linop_data Struct Reference

Struct representing LinOp related data.

```
#include <ginkgo/core/log/record.hpp>
```

35.83.1 Detailed Description

Struct representing LinOp related data.

The documentation for this struct was generated from the following file:

- ginkgo/core/log/record.hpp

35.84 gko::log::linop_factory_data Struct Reference

Struct representing LinOp factory related data.

```
#include <ginkgo/core/log/record.hpp>
```

35.84.1 Detailed Description

Struct representing LinOp factory related data.

The documentation for this struct was generated from the following file:

- ginkgo/core/log/record.hpp

35.85 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

35.85.1 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)

35.85.1.1 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`

35.86 `gko::matrix::Csr< ValueType, IndexType >::load_balance` Class Reference

`load_balance` is a [strategy_type](#) which uses the load balance algorithm.

```
#include <ginkgo/core/matrix/csr.hpp>
```

Public Member Functions

- [load_balance](#) ()
Creates a [load_balance](#) strategy.
- [load_balance](#) (std::shared_ptr< const [CudaExecutor](#) > exec)
Creates a [load_balance](#) strategy with CUDA executor.
- [load_balance](#) (std::shared_ptr< const [HipExecutor](#) > exec)
Creates a [load_balance](#) strategy with HIP executor.
- [load_balance](#) (int64_t nwarps, int warp_size=32, bool cuda_strategy=true)
Creates a [load_balance](#) strategy with specified parameters.
- void [process](#) (const [Array](#)< index_type > &mtx_row_ptrs, [Array](#)< index_type > *mtx_srow) override
Computes srow according to row pointers.
- int64_t [clac_size](#) (const int64_t nnz) override
Computes the srow size according to the number of nonzeros.
- std::shared_ptr< [strategy_type](#) > [copy](#) () override
Copy a strategy.

35.86.1 Detailed Description

```
template<typename ValueType = default_precision, typename IndexType = int32>
class gko::matrix::Csr< ValueType, IndexType >::load_balance
```

[load_balance](#) is a [strategy_type](#) which uses the load balance algorithm.

35.86.2 Constructor & Destructor Documentation

35.86.2.1 [load_balance\(\)](#) [1/3]

```
template<typename ValueType = default_precision, typename IndexType = int32>
gko::matrix::Csr< ValueType, IndexType >::load_balance::load_balance (
    std::shared_ptr< const CudaExecutor > exec ) [inline]
```

Creates a [load_balance](#) strategy with CUDA executor.

Parameters

<code>exec</code>	the CUDA executor
-------------------	-------------------

35.86.2.2 [load_balance\(\)](#) [2/3]

```
template<typename ValueType = default_precision, typename IndexType = int32>
gko::matrix::Csr< ValueType, IndexType >::load_balance::load_balance (
    std::shared_ptr< const HipExecutor > exec ) [inline]
```

Creates a [load_balance](#) strategy with HIP executor.

Parameters

<i>exec</i>	the HIP executor
-------------	------------------

35.86.2.3 load_balance() [3/3]

```
template<typename ValueType = default_precision, typename IndexType = int32>
gko::matrix::Csr< ValueType, IndexType >::load_balance::load_balance (
    int64_t nwarps,
    int warp_size = 32,
    bool cuda_strategy = true ) [inline]
```

Creates a [load_balance](#) strategy with specified parameters.

Parameters

<i>nwarps</i>	the number of warps in the executor
<i>warp_size</i>	the warp size of the executor
<i>cuda_strategy</i>	whether the <code>cuda_strategy</code> needs to be used.

Note

The `warp_size` must be the size of full warp. When using this constructor, `set_strategy` needs to be called with correct parameters which is replaced during the conversion.

35.86.3 Member Function Documentation

35.86.3.1 clac_size()

```
template<typename ValueType = default_precision, typename IndexType = int32>
int64_t gko::matrix::Csr< ValueType, IndexType >::load_balance::clac_size (
    const int64_t nnz ) [inline], [override], [virtual]
```

Computes the srow size according to the number of nonzeros.

Parameters

<i>nnz</i>	the number of nonzeros
------------	------------------------

Returns

the size of srow

Implements [gko::matrix::Csr< ValueType, IndexType >::strategy_type](#).

References `gko::ceildiv()`, and `gko::min()`.

35.86.3.2 `copy()`

```
template<typename ValueType = default_precision, typename IndexType = int32>
std::shared_ptr<strategy_type> gko::matrix::Csr< ValueType, IndexType >::load_balance::copy (
) [inline], [override], [virtual]
```

Copy a strategy.

This is a workaround until strategies are revamped, since strategies like `automatical` do not work when actually shared.

Implements `gko::matrix::Csr< ValueType, IndexType >::strategy_type`.

35.86.3.3 `process()`

```
template<typename ValueType = default_precision, typename IndexType = int32>
void gko::matrix::Csr< ValueType, IndexType >::load_balance::process (
    const Array< index_type > & mtx_row_ptrs,
    Array< index_type > * mtx_srow ) [inline], [override], [virtual]
```

Computes srow according to row pointers.

Parameters

<i>mtx_row_ptrs</i>	the row pointers of the matrix
<i>mtx_srow</i>	the srow of the matrix

Implements `gko::matrix::Csr< ValueType, IndexType >::strategy_type`.

References `gko::ceildiv()`, `gko::Array< ValueType >::get_const_data()`, `gko::Array< ValueType >::get_data()`, `gko::Array< ValueType >::get_executor()`, and `gko::Array< ValueType >::get_num_elems()`.

The documentation for this class was generated from the following file:

- `ginkgo/core/matrix/csr.hpp`

35.87 `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.

35.87.1 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.

35.87.2 Member Function Documentation

35.87.2.1 [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

<i>logger</i>	the logger to add
---------------	-------------------

Implemented in [gko::log::EnableLogging< ConcreteLoggable, PolymorphicBase >](#), [gko::log::EnableLogging< PolymorphicObject >](#), and [gko::log::EnableLogging< Executor >](#).

35.87.2.2 [remove_logger\(\)](#)

```
virtual void gko::log::Loggable::remove_logger (
    const Logger * logger ) [pure virtual]
```

Removes a logger from the list of subscribed loggers.

Parameters

<i>logger</i>	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`

35.88 gko::log::Record::logged_data Struct Reference

Struct storing the actually logged data.

```
#include <ginkgo/core/log/record.hpp>
```

35.88.1 Detailed Description

Struct storing the actually logged data.

The documentation for this struct was generated from the following file:

- `ginkgo/core/log/record.hpp`

35.89 gko::solver::LowerTrs< ValueType, IndexType > Class Template Reference

[LowerTrs](#) is the triangular solver which solves the system $Lx = b$, 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::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.

35.89.1 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 $Lx = b$, 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

<i>ValueType</i>	precision of matrix elements
<i>IndexType</i>	precision of matrix indices

35.89.2 Member Function Documentation

35.89.2.1 conj_transpose()

```
template<typename ValueType = default_precision, typename IndexType = int32>
std::unique_ptr<LinOp> gko::solver::LowerTrs< 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](#).

35.89.2.2 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)

```
101     {
102         return system_matrix_;
103     }
```

35.89.2.3 transpose()

```
template<typename ValueType = default_precision, typename IndexType = int32>
std::unique_ptr<LinOp> gko::solver::LowerTrs< 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](#).

The documentation for this class was generated from the following file:

- ginkgo/core/solver/lower_trs.hpp

35.90 gko::MachineTopology Class Reference

The machine topology class represents the hierarchical topology of a machine, including NUMA nodes, cores and PCI Devices.

```
#include <ginkgo/core/base/machine_topology.hpp>
```

Public Member Functions

- void [bind_to_cores](#) (const std::vector< int > &ids, const bool singlify=true) const
Bind the calling process to the CPU cores associated with the ids.
- void [bind_to_core](#) (const int &id) const
Bind to a single core.
- void [bind_to_pus](#) (const std::vector< int > &ids, const bool singlify=true) const
Bind the calling process to PUs associated with the ids.
- void [bind_to_pu](#) (const int &id) const
Bind to a Processing unit (PU)
- const normal_obj_info * [get_pu](#) ([size_type](#) id) const
Get the object of type PU associated with the id.
- const normal_obj_info * [get_core](#) ([size_type](#) id) const
Get the object of type core associated with the id.
- const io_obj_info * [get_pci_device](#) ([size_type](#) id) const
Get the object of type pci device associated with the id.
- const io_obj_info * [get_pci_device](#) (const std::string &pci_bus_id) const
Get the object of type pci device associated with the PCI bus id.
- [size_type](#) [get_num_pus](#) () const
Get the number of PU objects stored in this Topology tree.
- [size_type](#) [get_num_cores](#) () const
Get the number of core objects stored in this Topology tree.
- [size_type](#) [get_num_pci_devices](#) () const
Get the number of PCI device objects stored in this Topology tree.
- [size_type](#) [get_num_numas](#) () const
Get the number of NUMA objects stored in this Topology tree.

Static Public Member Functions

- static [MachineTopology](#) * [get_instance](#) ()

Returns an instance of the [MachineTopology](#) object.

35.90.1 Detailed Description

The machine topology class represents the hierarchical topology of a machine, including NUMA nodes, cores and PCI Devices.

Various information of the machine are gathered with the help of the Hardware Locality library (hwloc).

This class also provides functionalities to bind objects in the topology to the execution objects. Binding can enhance performance by allowing data to be closer to the executing object.

See the hwloc documentation (<https://www.open-mpi.org/projects/hwloc/doc/>) for more detailed information on topology detection and binding interfaces.

Note

A global object of [MachineTopology](#) type is created in a thread safe manner and only destroyed at the end of the program. This means that any subsequent queries will be from the same global object and hence use an extra atomic read.

35.90.2 Member Function Documentation

35.90.2.1 bind_to_core()

```
void gko::MachineTopology::bind_to_core (
    const int & id ) const [inline]
```

Bind to a single core.

Parameters

<i>ids</i>	The ids of the core to be bound to the calling process.
------------	---

```
241     {
242         MachineTopology::get\_instance()->bind\_to\_cores(std::vector<int>{id});
243     }
```

References [bind_to_cores\(\)](#), and [get_instance\(\)](#).

35.90.2.2 bind_to_cores()

```
void gko::MachineTopology::bind_to_cores (
    const std::vector< int > & ids,
    const bool singlify = true ) const [inline]
```

Bind the calling process to the CPU cores associated with the ids.

Parameters

<i>ids</i>	The ids of cores to be bound.
<i>singlify</i>	The ids of PUs are singlified to prevent possibly expensive migrations by the OS. This means that the binding is performed for only one of the ids in the set of ids passed in. See hwloc doc for singlify

Referenced by `bind_to_core()`.

35.90.2.3 `bind_to_pu()`

```
void gko::MachineTopology::bind_to_pu (
    const int & id ) const [inline]
```

Bind to a Processing unit (PU)

Parameters

<i>ids</i>	The ids of PUs to be bound to the calling process.
------------	--

References `bind_to_pus()`, and `get_instance()`.

35.90.2.4 `bind_to_pus()`

```
void gko::MachineTopology::bind_to_pus (
    const std::vector< int > & ids,
    const bool singlify = true ) const [inline]
```

Bind the calling process to PUs associated with the ids.

Parameters

<i>ids</i>	The ids of PUs to be bound.
<i>singlify</i>	The ids of PUs are singlified to prevent possibly expensive migrations by the OS. This means that the binding is performed for only one of the ids in the set of ids passed in. See hwloc doc for singlify

Referenced by `bind_to_pu()`.

35.90.2.5 `get_core()`

```
const normal_obj_info* gko::MachineTopology::get_core (
    size_type id ) const [inline]
```

Get the object of type core associated with the id.

Parameters

<i>id</i>	The id of the core
-----------	--------------------

Returns

the core object struct.

35.90.2.6 get_instance()

```
static MachineTopology* gko::MachineTopology::get_instance ( ) [inline], [static]
```

Returns an instance of the [MachineTopology](#) object.

Returns

the [MachineTopology](#) instance

Referenced by `bind_to_core()`, and `bind_to_pu()`.

35.90.2.7 get_num_cores()

```
size_type gko::MachineTopology::get_num_cores ( ) const [inline]
```

Get the number of core objects stored in this Topology tree.

Returns

the number of cores.

35.90.2.8 get_num_numas()

```
size_type gko::MachineTopology::get_num_numas ( ) const [inline]
```

Get the number of NUMA objects stored in this Topology tree.

Returns

the number of NUMA objects.

35.90.2.9 get_num_pci_devices()

```
size_type gko::MachineTopology::get_num_pci_devices ( ) const [inline]
```

Get the number of PCI device objects stored in this Topology tree.

Returns

the number of PCI devices.

35.90.2.10 get_num_pus()

```
size_type gko::MachineTopology::get_num_pus ( ) const [inline]
```

Get the number of PU objects stored in this Topology tree.

Returns

the number of PUs.

35.90.2.11 get_pci_device() [1/2]

```
const io_obj_info* gko::MachineTopology::get_pci_device (
    const std::string & pci_bus_id ) const
```

Get the object of type pci device associated with the PCI bus id.

Parameters

<i>pci_bus_id</i>	The PCI bus id of the pci device
-------------------	----------------------------------

Returns

the PCI object struct.

35.90.2.12 get_pci_device() [2/2]

```
const io_obj_info* gko::MachineTopology::get_pci_device (
    size_type id ) const [inline]
```

Get the object of type pci device associated with the id.

Parameters

<i>id</i>	The id of the pci device
-----------	--------------------------

Returns

the PCI object struct.

35.90.2.13 get_pu()

```
const normal_obj_info* gko::MachineTopology::get_pu (
    size_type id ) const [inline]
```

Get the object of type PU associated with the id.

Parameters

<i>id</i>	The id of the PU
-----------	------------------

Returns

the PU object struct.

The documentation for this class was generated from the following file:

- ginkgo/core/base/machine_topology.hpp

35.91 gko::matrix_assembly_data< ValueType, IndexType > Class Template Reference

This structure is used as an intermediate type to assemble a sparse matrix.

```
#include <ginkgo/core/base/matrix_assembly_data.hpp>
```

Public Member Functions

- void [add_value](#) (index_type row, index_type col, value_type val)
Sets the matrix value at (row, col).
- void [set_value](#) (index_type row, index_type col, value_type val)
Sets the matrix value at (row, col).
- value_type [get_value](#) (index_type row, index_type col)
Gets the matrix value at (row, col).
- bool [contains](#) (index_type row, index_type col)
Returns true iff the matrix contains an entry at (row, col).
- [dim](#)< 2 > [get_size](#) () const noexcept
- [size_type](#) [get_num_stored_elements](#) () const noexcept
- [matrix_data](#)< ValueType, IndexType > [get_ordered_data](#) () const

35.91.1 Detailed Description

```
template<typename ValueType = default_precision, typename IndexType = int32>
class gko::matrix_assembly_data< ValueType, IndexType >
```

This structure is used as an intermediate type to assemble a sparse matrix.

The matrix is stored as a set of nonzero elements, where each element is a triplet of the form (row_index, column_index, value).

New values can be added by using the [matrix_assembly_data::add_value](#) or [matrix_assembly_data::set_value](#)

Template Parameters

<i>ValueType</i>	type of matrix values stored in the structure
<i>IndexType</i>	type of matrix indexes stored in the structure

35.91.2 Member Function Documentation

35.91.2.1 add_value()

```
template<typename ValueType = default_precision, typename IndexType = int32>
void gko::matrix_assembly_data< ValueType, IndexType >::add_value (
    index_type row,
    index_type col,
    value_type val ) [inline]
```

Sets the matrix value at (row, col).

If there is an existing value, it will be set to the sum of the existing and new value, otherwise the value will be inserted.

Parameters

<i>row</i>	the row where the value should be added
<i>col</i>	the column where the value should be added
<i>val</i>	the value to be added to (row, col)

```
106     {
107         auto ind = std::make_pair(row, col);
108         nonzeros_[ind] += val;
109     }
```

35.91.2.2 contains()

```
template<typename ValueType = default_precision, typename IndexType = int32>
bool gko::matrix_assembly_data< ValueType, IndexType >::contains (
```



```
index_type row,
index_type col ) [inline]
```

Returns true iff the matrix contains an entry at (row, col).

Parameters

<i>row</i>	the row index
<i>col</i>	the column index

Returns

true if the value at (row, col) exists, false otherwise

35.91.2.3 get_num_stored_elements()

```
template<typename ValueType = default_precision, typename IndexType = int32>
size_type gko::matrix_assembly_data< ValueType, IndexType >::get_num_stored_elements ( ) const
[inline], [noexcept]
```

Returns

the number of non-zeros in the (partially) assembled matrix

35.91.2.4 get_ordered_data()

```
template<typename ValueType = default_precision, typename IndexType = int32>
matrix_data<ValueType, IndexType> gko::matrix_assembly_data< ValueType, IndexType >::get_↵
ordered_data ( ) const [inline]
```

Returns

a [matrix_data](#) instance containing the assembled non-zeros in row-major order to be used by all matrix formats.

Referenced by `gko::ReadableFromMatrixData< ValueType, int32 >::read()`.

35.91.2.5 get_size()

```
template<typename ValueType = default_precision, typename IndexType = int32>
dim<2> gko::matrix_assembly_data< ValueType, IndexType >::get_size ( ) const [inline], [noexcept]
```

Returns

the dimensions of the matrix being assembled

35.91.2.6 `get_value()`

```
template<typename ValueType = default_precision, typename IndexType = int32>
value_type gko::matrix_assembly_data< ValueType, IndexType >::get_value (
    index_type row,
    index_type col ) [inline]
```

Gets the matrix value at (row, col).

Parameters

<i>row</i>	the row index
<i>col</i>	the column index

Returns

the value at (row, col) or 0 if it doesn't exist.

35.91.2.7 `set_value()`

```
template<typename ValueType = default_precision, typename IndexType = int32>
void gko::matrix_assembly_data< ValueType, IndexType >::set_value (
    index_type row,
    index_type col,
    value_type val ) [inline]
```

Sets the matrix value at (row, col).

If there is an existing value, it will be overwritten by the new value.

Parameters

<i>row</i>	the row index
<i>col</i>	the column index
<i>val</i>	the value to be written to (row, col)

The documentation for this class was generated from the following file:

- ginkgo/core/base/matrix_assembly_data.hpp

35.92 `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, RandomDistribution &&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, RandomDistribution &&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.

35.92.1 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

<i>ValueType</i>	type of matrix values stored in the structure
<i>IndexType</i>	type of matrix indexes stored in the structure

35.92.2 Constructor & Destructor Documentation

35.92.2.1 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

<i>size_↔</i>	dimensions of the matrix
<i>value</i>	value used to fill the elements of the matrix

```

144                                     {}, ValueType value = zero<ValueType>())
145     : size{size_}
146     {
147         if (value == zero<ValueType>()) {
148             return;
149         }
150         for (size_type row = 0; row < size[0]; ++row) {
151             for (size_type col = 0; col < size[1]; ++col) {
152                 nonzeros.emplace_back(row, col, value);
153             }
154         }
155     }

```

35.92.2.2 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

<i>RandomDistribution</i>	random distribution type
<i>RandomEngine</i>	random engine type

Parameters

<i>size</i> ↔	dimensions of the matrix
—	
<i>dist</i>	random distribution of the elements of the matrix
<i>engine</i>	random engine used to generate random values

35.92.2.3 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

<i>values</i>	a 2D braced-init-list of matrix values.
---------------	---

35.92.2.4 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

<i>size_</i>	dimensions of the matrix
<i>nonzeros_</i>	list of nonzero elements

35.92.2.5 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

<i>size</i>	size of the block-matrix (in blocks)
<i>diag_block</i>	matrix block used to fill the complete matrix

References `gko::matrix_data< ValueType, IndexType >::size`.

35.92.2.6 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

<i>Accessor</i>	accessor type of the input range
-----------------	----------------------------------

Parameters

<i>data</i>	range used to initialize the matrix
-------------	-------------------------------------

References gko::range< Accessor >::length().

35.92.3 Member Function Documentation

35.92.3.1 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 ) [inline], [static]
```

Initializes a random dense matrix with a specific condition number.

The matrix is generated by applying a series of random Householder 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

<i>RandomDistribution</i>	the type of the random distribution
<i>RandomEngine</i>	the type of the random engine

Parameters

<i>size</i>	number of rows and columns of the matrix
<i>condition_number</i>	condition number of the matrix
<i>dist</i>	random distribution used to generate reflectors
<i>engine</i>	random engine used to generate reflectors

Returns

the dense matrix with the specified condition number

References gko::matrix_data< ValueType, IndexType >::cond(), and gko::matrix_data< ValueType, IndexType >↵::size.

35.92.3.2 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,
    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

<i>RandomDistribution</i>	the type of the random distribution
<i>RandomEngine</i>	the type of the random engine

Parameters

<i>size</i>	number of rows and columns of the matrix
<i>condition_number</i>	condition number of the matrix
<i>dist</i>	random distribution used to generate reflectors
<i>engine</i>	random engine used to generate reflectors
<i>num_reflectors</i>	number of reflectors to apply from each side

Returns

the dense matrix with the specified condition number

References `gko::matrix_data< ValueType, IndexType >::size`.

Referenced by `gko::matrix_data< ValueType, IndexType >::cond()`.

35.92.3.3 diag() [1/5]

```
template<typename ValueType = default_precision, typename IndexType = int32>
static matrix_data gko::matrix_data< ValueType, IndexType >::diag (
    dim< 2 > size_,
    const matrix_data< ValueType, IndexType > & block ) [inline], [static]
```

Initializes a block-diagonal matrix.

Parameters

<i>size_</i>	the size of the matrix
<i>diag_block</i>	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.

35.92.3.4 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

<i>size_</i>	dimensions of the matrix
<i>nonzeros_↔</i>	list of diagonal elements
—	

Returns

the diagonal matrix

References gko::matrix_data< ValueType, IndexType >::nonzeros.

35.92.3.5 diag() [3/5]

```
template<typename ValueType = default_precision, typename IndexType = int32>
static matrix_data gko::matrix_data< ValueType, IndexType >::diag (
    dim< 2 > size_,
    ValueType value ) [inline], [static]
```

Initializes a diagonal matrix.

Parameters

<i>size_↔</i>	dimensions of the matrix
—	
<i>value</i>	value used to fill the elements of the matrix

Returns

the diagonal matrix

References `gko::matrix_data< ValueType, IndexType >::nonzeros`.

Referenced by `gko::matrix_data< ValueType, IndexType >::diag()`.

35.92.3.6 `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

<i>ForwardIterator</i>	type of list iterator
------------------------	-----------------------

Parameters

<i>begin</i>	the first iterator of the list
<i>end</i>	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`.

35.92.3.7 `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

<i>blocks</i>	a list of blocks to initialize from
---------------	-------------------------------------

Returns

the block-diagonal matrix with diagonal blocks set to the blocks passed in *blocks*

References gko::matrix_data< ValueType, IndexType >::diag().

35.92.4 Member Data Documentation

35.92.4.1 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(), and gko::matrix_data< ValueType, IndexType >::ensure_row_major_order().

The documentation for this struct was generated from the following file:

- ginkgo/core/base/matrix_data.hpp

35.93 gko::matrix::Csr< ValueType, IndexType >::merge_path Class Reference

[merge_path](#) is a [strategy_type](#) which uses the [merge_path](#) algorithm.

```
#include <ginkgo/core/matrix/csr.hpp>
```

Public Member Functions

- [merge_path](#) ()
Creates a [merge_path](#) strategy.
- void [process](#) (const [Array](#)< index_type > &mtx_row_ptrs, [Array](#)< index_type > *mtx_srow) override
Computes srow according to row pointers.
- int64_t [clac_size](#) (const int64_t nnz) override
Computes the srow size according to the number of nonzeros.
- std::shared_ptr< [strategy_type](#) > [copy](#) () override
Copy a strategy.

35.93.1 Detailed Description

```
template<typename ValueType = default_precision, typename IndexType = int32>
class gko::matrix::Csr< ValueType, IndexType >::merge_path
```

[merge_path](#) is a [strategy_type](#) which uses the [merge_path](#) algorithm.

[merge_path](#) is according to Merrill and Garland: Merge-Based Parallel Sparse Matrix-Vector Multiplication

35.93.2 Member Function Documentation

35.93.2.1 `clac_size()`

```
template<typename ValueType = default_precision, typename IndexType = int32>
int64_t gko::matrix::Csr< ValueType, IndexType >::merge_path::clac_size (
    const int64_t nnz ) [inline], [override], [virtual]
```

Computes the srow size according to the number of nonzeros.

Parameters

<i>nnz</i>	the number of nonzeros
------------	------------------------

Returns

the size of srow

Implements [gko::matrix::Csr< ValueType, IndexType >::strategy_type](#).

35.93.2.2 `copy()`

```
template<typename ValueType = default_precision, typename IndexType = int32>
std::shared_ptr<strategy_type> gko::matrix::Csr< ValueType, IndexType >::merge_path::copy ( )
[inline], [override], [virtual]
```

Copy a strategy.

This is a workaround until strategies are revamped, since strategies like `automatical` do not work when actually shared.

Implements [gko::matrix::Csr< ValueType, IndexType >::strategy_type](#).

35.93.2.3 `process()`

```
template<typename ValueType = default_precision, typename IndexType = int32>
void gko::matrix::Csr< ValueType, IndexType >::merge_path::process (
    const Array< index_type > & mtx_row_ptrs,
    Array< index_type > * mtx_srow ) [inline], [override], [virtual]
```

Computes srow according to row pointers.

Parameters

<i>mtx_row_ptrs</i>	the row pointers of the matrix
<i>mtx_srow</i>	the srow of the matrix

Implements [gko::matrix::Csr< ValueType, IndexType >::strategy_type](#).

The documentation for this class was generated from the following file:

- ginkgo/core/matrix/csr.hpp

35.94 gko::matrix::Hybrid< ValueType, IndexType >::minimal_storage_limit Class Reference

[minimal_storage_limit](#) is a [strategy_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.
- auto [get_percentage](#) ()
Get the percent setting.

35.94.1 Detailed Description

```
template<typename ValueType = default_precision, typename IndexType = int32>
class gko::matrix::Hybrid< ValueType, IndexType >::minimal_storage_limit
```

[minimal_storage_limit](#) is a [strategy_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.

35.94.2 Member Function Documentation

35.94.2.1 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

<code>row_nnz</code>	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 >::imbalance_limit::compute_ell_num_stored_elements_per_row\(\)](#).

35.94.2.2 get_percentage()

```
template<typename ValueType = default_precision, typename IndexType = int32>
auto gko::matrix::Hybrid< ValueType, IndexType >::minimal_storage_limit::get_percentage ( )
[inline]
```

Get the percent setting.

@return percent

References [gko::matrix::Hybrid< ValueType, IndexType >::imbalance_limit::get_percentage\(\)](#).

The documentation for this class was generated from the following file:

- [ginkgo/core/matrix/hybrid.hpp](#)

35.95 gko::multigrid::MultigridLevel Class Reference

This class represents two levels in a multigrid hierarchy.

```
#include <ginkgo/core/multigrid/multigrid_level.hpp>
```

Public Member Functions

- virtual `std::shared_ptr< const LinOp >` [get_fine_op](#) () const =0
Returns the operator on fine level.
- virtual `std::shared_ptr< const LinOp >` [get_restrict_op](#) () const =0
Returns the restrict operator.
- virtual `std::shared_ptr< const LinOp >` [get_coarse_op](#) () const =0
Returns the operator on coarse level.
- virtual `std::shared_ptr< const LinOp >` [get_prolong_op](#) () const =0
Returns the prolong operator.

35.95.1 Detailed Description

This class represents two levels in a multigrid hierarchy.

The [MultigridLevel](#) is an interface that allows to get the individual components of multigrid level. Each implementation of a multigrid level should inherit from this interface. Use [EnableMultigridLevel<ValueType>](#) to implement this interface with composition by default.

35.95.2 Member Function Documentation

35.95.2.1 get_coarse_op()

```
virtual std::shared_ptr<const LinOp> gko::multigrid::MultigridLevel::get_coarse_op ( ) const  
[pure virtual]
```

Returns the operator on coarse level.

Returns

the operator on coarse level.

Implemented in [gko::multigrid::EnableMultigridLevel<ValueType>](#).

35.95.2.2 get_fine_op()

```
virtual std::shared_ptr<const LinOp> gko::multigrid::MultigridLevel::get_fine_op ( ) const  
[pure virtual]
```

Returns the operator on fine level.

Returns

the operator on fine level.

Implemented in [gko::multigrid::EnableMultigridLevel<ValueType>](#).

35.95.2.3 get_prolong_op()

```
virtual std::shared_ptr<const LinOp> gko::multigrid::MultigridLevel::get_prolong_op ( ) const  
[pure virtual]
```

Returns the prolong operator.

Returns

the prolong operator.

Implemented in [gko::multigrid::EnableMultigridLevel<ValueType>](#).

35.95.2.4 `get_restrict_op()`

```
virtual std::shared_ptr<const LinOp> gko::multigrid::MultigridLevel::get_restrict_op ( ) const
[pure virtual]
```

Returns the restrict operator.

Returns

the restrict operator.

Implemented in [gko::multigrid::EnableMultigridLevel< ValueType >](#).

The documentation for this class was generated from the following file:

- `ginkgo/core/multigrid/multigrid_level.hpp`

35.96 `gko::matrix_data< ValueType, IndexType >::nonzero_type` Struct Reference

Type used to store nonzeros.

```
#include <ginkgo/core/base/matrix_data.hpp>
```

35.96.1 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`

35.97 `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.

35.97.1 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.

35.97.2 Constructor & Destructor Documentation

35.97.2.1 NotCompiled()

```
gko::NotCompiled::NotCompiled (
    const std::string & file,
    int line,
    const std::string & func,
    const std::string & module ) [inline]
```

Initializes a [NotCompiled](#) error.

Parameters

<i>file</i>	The name of the offending source file
<i>line</i>	The source code line number where the error occurred
<i>func</i>	The name of the function that has not been compiled
<i>module</i>	The name of the module which contains the function

The documentation for this class was generated from the following file:

- ginkgo/core/base/exception.hpp

35.98 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.

35.98.1 Detailed Description

[NotImplemented](#) is thrown in case an operation has not yet been implemented (but will be implemented in the future).

35.98.2 Constructor & Destructor Documentation

35.98.2.1 NotImplemented()

```
gko::NotImplemented::NotImplemented (
    const std::string & file,
    int line,
    const std::string & func ) [inline]
```

Initializes a [NotImplemented](#) error.

Parameters

<i>file</i>	The name of the offending source file
<i>line</i>	The source code line number where the error occurred
<i>func</i>	The name of the not-yet implemented function

The documentation for this class was generated from the following file:

- ginkgo/core/base/exception.hpp

35.99 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.

35.99.1 Detailed Description

[NotSupported](#) is thrown in case it is not possible to perform the requested operation on the given object type.

35.99.2 Constructor & Destructor Documentation

35.99.2.1 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

<i>file</i>	The name of the offending source file
<i>line</i>	The source code line number where the error occurred
<i>func</i>	The name of the function where the error occurred
<i>obj_type</i>	The object type on which the requested operation cannot be performed.

The documentation for this class was generated from the following file:

- ginkgo/core/base/exception.hpp

35.100 gko::null_deleter< T > Class Template Reference

This is a deleter that does not delete the object.

```
#include <ginkgo/core/base/utils_helper.hpp>
```

Public Member Functions

- void [operator\(\)](#) (pointer) const noexcept
Deletes the object.

35.100.1 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.

35.100.2 Member Function Documentation

35.100.2.1 operator>()

```
template<typename T >
void gko::null\_deleter< T >::operator() (
    pointer ) const [inline], [noexcept]
```

Deletes the object.

Parameters

<i>ptr</i>	pointer to the object being deleted
------------	-------------------------------------

The documentation for this class was generated from the following file:

- ginkgo/core/base/utils_helper.hpp

35.101 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](#).

35.101.1 Detailed Description

This is the [Executor](#) subclass which represents the OpenMP device (typically CPU).

35.101.2 Member Function Documentation

35.101.2.1 get_master() [1/2]

```
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](#).

35.101.2.2 get_master() [2/2]

```
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](#).

The documentation for this class was generated from the following file:

- ginkgo/core/base/executor.hpp

35.102 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.

35.102.1 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() << ")"; }
    void run(const gko::HipExecutor *exec) const override
    { os_ << "HIP(" << exec->get_device_id() << ")"; }
    void run(const gko::DpcppExecutor *exec) const override
    { os_ << "DPC++(" << 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::HipExecutor::create(0, omp) << std::endl
    << *gko::DpcppExecutor::create(0, omp) << std::endl
    << *gko::ReferenceExecutor::create() << std::endl;
```

which produces the expected output:

```
OMP
CUDA(0)
HIP(0)
DPC++(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 three closures as input: one which is run for OMP, one for CUDA executors, one for HIP executors, and the last one for DPC++ 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()
            << ")"; },
        [&]() { os << "HIP(" // HIP closure
            << static_cast<gko::HipExecutor&>(exec)
                .get_device_id()
            << ")"; },
        [&]() { os << "DPC++(" // DPC++ closure
            << static_cast<gko::DpcppExecutor&>(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.

35.102.2 Member Function Documentation

35.102.2.1 `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`

35.103 gko::log::operation_data Struct Reference

Struct representing Operator related data.

```
#include <ginkgo/core/log/record.hpp>
```

35.103.1 Detailed Description

Struct representing Operator related data.

The documentation for this struct was generated from the following file:

- ginkgo/core/log/record.hpp

35.104 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](#).

35.104.1 Detailed Description

[OutOfBoundsError](#) is thrown if a memory access is detected to be out-of-bounds.

35.104.2 Constructor & Destructor Documentation

35.104.2.1 OutOfBoundsError()

```
gko::OutOfBoundsError::OutOfBoundsError (
    const std::string & file,
    int line,
    size\_type index,
    size\_type bound ) [inline]
```

Initializes an [OutOfBoundsError](#).

Parameters

<i>file</i>	The name of the offending source file
<i>line</i>	The source code line number where the error occurred
<i>index</i>	The position that was accessed
<i>bound</i>	The first out-of-bound index

The documentation for this class was generated from the following file:

- ginkgo/core/base/exception.hpp

35.105 gko::factorization::ParlC< ValueType, IndexType > Class Template Reference

ParlC is an incomplete Cholesky factorization which is computed in parallel.

```
#include <ginkgo/core/factorization/par_ic.hpp>
```

Additional Inherited Members

35.105.1 Detailed Description

```
template<typename ValueType = default_precision, typename IndexType = int32>
class gko::factorization::ParlC< ValueType, IndexType >
```

ParlC is an incomplete Cholesky factorization which is computed in parallel.

L is a lower triangular matrix, which approximates a given matrix A with $A \approx LL^H$. Here, $L + L^H$ has the same sparsity pattern as A , which is also called IC(0).

The ParlC algorithm generates the incomplete factors iteratively, using a fixed-point iteration of the form

$$F(L) = \begin{cases} \sqrt{a_{ii} - \sum_{k=1}^{i-1} |l_{ik}|^2}, & i == j \\ a_{ij} - \sum_{k=1}^{i-1} l_{ik} u_{kj}, & i < j \end{cases}$$

In general, the entries of L can be iterated in parallel and in asynchronous fashion, the algorithm asymptotically converges to the incomplete factors L and L^H fulfilling $(R = A - L \cdot L^H)|_S = 0|_S$ where S is the pre-defined sparsity pattern (in case of IC(0) the sparsity pattern of the system matrix A). The number of ParlC sweeps needed for convergence depends on the parallelism level: For sequential execution, a single sweep is sufficient, for fine-grained parallelism, the number of sweeps necessary to get a good approximation of the incomplete factors depends heavily on the problem. On the OpenMP executor, 3 sweeps usually give a decent approximation in our experiments, while GPU executors can take 10 or more iterations.

The ParlC 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

<i>ValueType</i>	Type of the values of all matrices used in this class
<i>IndexType</i>	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_ic.hpp

35.106 gko::factorization::Parlct< ValueType, IndexType > Class Template Reference

ParlCT is an incomplete threshold-based Cholesky factorization which is computed in parallel.

```
#include <ginkgo/core/factorization/par_ict.hpp>
```

Additional Inherited Members

35.106.1 Detailed Description

```
template<typename ValueType = default_precision, typename IndexType = int32>
class gko::factorization::Parlct< ValueType, IndexType >
```

ParlCT is an incomplete threshold-based Cholesky factorization which is computed in parallel.

L is a lower triangular matrix which approximates a given symmetric positive definite matrix A with $A \approx LL^T$. Here, L has a sparsity pattern that is improved iteratively based on its element-wise magnitude. The initial sparsity pattern is chosen based on the lower triangle of A .

One iteration of the ParlCT algorithm consists of the following steps:

1. Calculating the residual $R = A - LL^T$
2. Adding new non-zero locations from R to L . The new non-zero locations are initialized based on the corresponding residual value.
3. Executing a fixed-point iteration on L according to $F(L) = \begin{cases} \frac{1}{l_{jj}} \left(a_{ij} - \sum_{k=1}^{j-1} l_{ik} l_{jk} \right), & i \neq j \\ \sqrt{a_{ij} - \sum_{k=1}^{j-1} l_{ik} l_{jk}}, & i = j \end{cases}$
4. Removing the smallest entries (by magnitude) from L
5. Executing a fixed-point iteration on the (now sparser) L

This ParlCT algorithm thus improves the sparsity pattern and the approximation of L simultaneously.

The implementation follows the design of H. Anzt et al., ParlLUT - A Parallel Threshold ILU for GPUs, 2019 IEEE International Parallel and Distributed Processing Symposium (IPDPS), pp. 231–241.

Template Parameters

<i>ValueType</i>	Type of the values of all matrices used in this class
<i>IndexType</i>	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_ict.hpp

35.107 gko::factorization::Parllu< 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

35.107.1 Detailed Description

```
template<typename ValueType = default_precision, typename IndexType = int32>
class gko::factorization::Parllu< 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 $(R = A - L \cdot U)|_{\mathcal{S}} = 0|_{\mathcal{S}}$ 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, the number of sweeps necessary to get a good approximation of the incomplete factors depends heavily on the problem. On the OpenMP executor, 3 sweeps usually give a decent approximation in our experiments, while GPU executors can take 10 or more iterations.

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

<i>ValueType</i>	Type of the values of all matrices used in this class
<i>IndexType</i>	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

35.108 gko::factorization::Parllut< ValueType, IndexType > Class Template Reference

ParLLUT is an incomplete threshold-based LU factorization which is computed in parallel.

```
#include <ginkgo/core/factorization/par_ilut.hpp>
```

Additional Inherited Members

35.108.1 Detailed Description

```
template<typename ValueType = default_precision, typename IndexType = int32>
class gko::factorization::Parllut< ValueType, IndexType >
```

ParLLUT is an incomplete threshold-based 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 a sparsity pattern that is improved iteratively based on their element-wise magnitude. The initial sparsity pattern is chosen based on the $ILU(0)$ factorization of A .

One iteration of the ParLLUT algorithm consists of the following steps:

1. Calculating the residual $R = A - LU$
2. Adding new non-zero locations from R to L and U . The new non-zero locations are initialized based on the corresponding residual value.
3. Executing a fixed-point iteration on L and U according to $F(L, U) = \begin{cases} \frac{1}{u_{jj}} \left(a_{ij} - \sum_{k=1}^{j-1} l_{ik} u_{kj} \right), & i > j \\ a_{ij} - \sum_{k=1}^{i-1} l_{ik} u_{kj}, & i \leq j \end{cases}$
For a more detailed description of the fixed-point iteration, see [Parllu](#).
4. Removing the smallest entries (by magnitude) from L and U
5. Executing a fixed-point iteration on the (now sparser) L and U

This ParLLUT algorithm thus improves the sparsity pattern and the approximation of L and U simultaneously.

The implementation follows the design of H. Anzt et al., ParLLUT - A Parallel Threshold ILU for GPUs, 2019 IEEE International Parallel and Distributed Processing Symposium (IPDPS), pp. 231–241.

Template Parameters

<i>ValueType</i>	Type of the values of all matrices used in this class
<i>IndexType</i>	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_ilut.hpp

35.109 gko::Permutable< IndexType > Class Template Reference

Linear operators which support permutation should implement the [Permutable](#) interface.

```
#include <ginkgo/core/base/lin_op.hpp>
```

Public Member Functions

- virtual std::unique_ptr< LinOp > [permute](#) (const [Array](#)< IndexType > *permutation_indices) const
Returns a LinOp representing the symmetric row and column permutation of the [Permutable](#) object.
- virtual std::unique_ptr< LinOp > [inverse_permute](#) (const [Array](#)< IndexType > *permutation_indices) const
Returns a LinOp representing the symmetric inverse row and column permutation of the [Permutable](#) object.
- virtual std::unique_ptr< LinOp > [row_permute](#) (const [Array](#)< IndexType > *permutation_indices) const =0
Returns a LinOp representing the row permutation of the [Permutable](#) object.
- virtual std::unique_ptr< LinOp > [column_permute](#) (const [Array](#)< IndexType > *permutation_indices) const =0
Returns a LinOp representing the column permutation of the [Permutable](#) object.
- virtual std::unique_ptr< LinOp > [inverse_row_permute](#) (const [Array](#)< IndexType > *permutation_indices) const =0
Returns a LinOp representing the row permutation of the inverse permuted object.
- virtual std::unique_ptr< LinOp > [inverse_column_permute](#) (const [Array](#)< IndexType > *permutation_indices) const =0
Returns a LinOp representing the column permutation of the inverse permuted object.

35.109.1 Detailed Description

```
template<typename IndexType>
class gko::Permutable< IndexType >
```

Linear operators which support permutation should implement the [Permutable](#) interface.

It provides functions to permute the rows and columns of a LinOp, independently or symmetrically, and with a regular or inverted permutation.

After a regular row permutation with permutation array `perm` the row `i` in the output LinOp contains the row `perm[i]` from the input LinOp. After an inverse row permutation, the row `perm[i]` in the output LinOp contains the row `i` from the input LinOp. Equivalently, after a column permutation, the output stores in column `i` the column `perm[i]` from the input, and an inverse column permutation stores in column `perm[i]` the column `i` from the input. A symmetric permutation is functionally equivalent to calling `as<Permutable>(A->row_permute(perm)) ->column_permute(perm)`, but the implementation can provide better performance due to kernel fusion.

35.109.1.1 Example: Permuting a Csr matrix:

```
{c++}
//Permuting an object of LinOp type.
//The object you want to permute.
auto op = matrix::Csr::create(exec);
//Permute the object by first converting it to a Permutable type.
auto perm = op->row_permute(permutation_indices);
```

35.109.2 Member Function Documentation**35.109.2.1 column_permute()**

```
template<typename IndexType>
virtual std::unique_ptr<LinOp> gko::Permutable< IndexType >::column_permute (
    const Array< IndexType > * permutation_indices ) const [pure virtual]
```

Returns a LinOp representing the column permutation of the [Permutable](#) object.

In the resulting LinOp, the column `i` contains the input column `perm[i]`.

Parameters

<code>permutation_indices</code>	the array of indices containing the permutation order <code>perm</code> .
----------------------------------	---

Returns

a pointer to the new column permuted object

Implemented in [gko::matrix::Dense< ValueType >](#), [gko::matrix::Dense< ValueType >](#), and [gko::matrix::Csr< ValueType, IndexType](#)

35.109.2.2 inverse_column_permute()

```
template<typename IndexType>
virtual std::unique_ptr<LinOp> gko::Permutable< IndexType >::inverse_column_permute (
    const Array< IndexType > * permutation_indices ) const [pure virtual]
```

Returns a LinOp representing the row permutation of the inverse permuted object.

In the resulting LinOp, the column `perm[i]` contains the input column `i`.

Parameters

<code>permutation_indices</code>	the array of indices containing the permutation order <code>perm</code> .
----------------------------------	---

Returns

a pointer to the new inverse permuted object

Implemented in [gko::matrix::Dense< ValueType >](#), [gko::matrix::Dense< ValueType >](#), and [gko::matrix::Csr< ValueType, IndexType](#)

35.109.2.3 inverse_permute()

```
template<typename IndexType>
virtual std::unique_ptr<LinOp> gko::Permutable< IndexType >::inverse_permute (
    const Array< IndexType > * permutation_indices ) const [inline], [virtual]
```

Returns a LinOp representing the symmetric inverse row and column permutation of the [Permutable](#) object.

In the resulting LinOp, the entry at location `(perm[i], perm[j])` contains the input value `(i, j)`.

Parameters

<i>permutation_indices</i>	the array of indices containing the permutation order.
----------------------------	--

Returns

a pointer to the new permuted object

Reimplemented in [gko::matrix::Dense< ValueType >](#), [gko::matrix::Dense< ValueType >](#), and [gko::matrix::Csr< ValueType, IndexType](#)

35.109.2.4 inverse_row_permute()

```
template<typename IndexType>
virtual std::unique_ptr<LinOp> gko::Permutable< IndexType >::inverse_row_permute (
    const Array< IndexType > * permutation_indices ) const [pure virtual]
```

Returns a LinOp representing the row permutation of the inverse permuted object.

In the resulting LinOp, the row `perm[i]` contains the input row `i`.

Parameters

<i>permutation_indices</i>	the array of indices containing the permutation order <code>perm</code> .
----------------------------	---

Returns

a pointer to the new inverse permuted object

Implemented in [gko::matrix::Dense< ValueType >](#), [gko::matrix::Dense< ValueType >](#), and [gko::matrix::Csr< ValueType, IndexType](#)

35.109.2.5 permute()

```
template<typename IndexType>
virtual std::unique_ptr<LinOp> gko::Permutable< IndexType >::permute (
    const Array< IndexType > * permutation_indices ) const [inline], [virtual]
```

Returns a LinOp representing the symmetric row and column permutation of the [Permutable](#) object.

In the resulting LinOp, the entry at location (i, j) contains the input value (perm[i], perm[j]).

Parameters

<i>permutation_indices</i>	the array of indices containing the permutation order.
----------------------------	--

Returns

a pointer to the new permuted object

Reimplemented in [gko::matrix::Dense< ValueType >](#), [gko::matrix::Dense< ValueType >](#), and [gko::matrix::Csr< ValueType, IndexType >](#).

35.109.2.6 row_permute()

```
template<typename IndexType>
virtual std::unique_ptr<LinOp> gko::Permutable< IndexType >::row_permute (
    const Array< IndexType > * permutation_indices ) const [pure virtual]
```

Returns a LinOp representing the row permutation of the [Permutable](#) object.

In the resulting LinOp, the row i contains the input row perm[i].

Parameters

<i>permutation_indices</i>	the array of indices containing the permutation order.
----------------------------	--

Returns

a pointer to the new permuted object

Implemented in [gko::matrix::Dense< ValueType >](#), [gko::matrix::Dense< ValueType >](#), and [gko::matrix::Csr< ValueType, IndexType >](#).

The documentation for this class was generated from the following file:

- ginkgo/core/base/lin_op.hpp

35.110 gko::matrix::Permutation< IndexType > Class Template Reference

[Permutation](#) is a matrix "format" which stores the row and column permutation arrays which can be used for re-ordering the rows and columns a matrix.

```
#include <ginkgo/core/matrix/permutation.hpp>
```

Public Member Functions

- `index_type * get_permutation ()` noexcept
Returns a pointer to the array of permutation.
- `const index_type * get_const_permutation ()` const noexcept
Returns a pointer to the array of permutation.
- `size_type get_permutation_size ()` const noexcept
Returns the number of elements explicitly stored in the permutation array.
- `mask_type get_permute_mask ()` const
Get the permute masks.
- `void set_permute_mask (mask_type permute_mask)`
Set the permute masks.

35.110.1 Detailed Description

```
template<typename IndexType = int32>
class gko::matrix::Permutation< IndexType >
```

[Permutation](#) is a matrix "format" which stores the row and column permutation arrays which can be used for re-ordering the rows and columns a matrix.

Template Parameters

<i>IndexType</i>	precision of permutation array indices.
------------------	---

Note

This format is used mainly to allow for an abstraction of the permutation/re-ordering and provides the user with an `apply` method which calls the respective LinOp's `permute` operation if the respective LinOp implements the [Permutable](#) interface. As such it only stores an array of the permutation indices.

35.110.2 Member Function Documentation

35.110.2.1 `get_const_permutation()`

```
template<typename IndexType = int32>
const index_type* gko::matrix::Permutation< IndexType >::get_const_permutation ( ) const [inline],
[noexcept]
```

Returns a pointer to the array of permutation.

Returns

the pointer to the row permutation array.

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.

```
102     {
103         return permutation_.get_const_data();
104     }
```

References gko::Array< ValueType >::get_const_data().

35.110.2.2 get_permutation()

```
template<typename IndexType = int32>
index_type* gko::matrix::Permutation< IndexType >::get_permutation ( ) [inline], [noexcept]
```

Returns a pointer to the array of permutation.

Returns

the pointer to the row permutation array.

References gko::Array< ValueType >::get_data().

35.110.2.3 get_permutation_size()

```
template<typename IndexType = int32>
size_type gko::matrix::Permutation< IndexType >::get_permutation_size ( ) const [inline],
[noexcept]
```

Returns the number of elements explicitly stored in the permutation array.

Returns

the number of elements explicitly stored in the permutation array.

References gko::Array< ValueType >::get_num_elems().

35.110.2.4 get_permute_mask()

```
template<typename IndexType = int32>
mask_type gko::matrix::Permutation< IndexType >::get_permute_mask ( ) const [inline]
```

Get the permute masks.

Returns

permute_mask the permute masks

35.110.2.5 set_permute_mask()

```
template<typename IndexType = int32>
void gko::matrix::Permutation< IndexType >::set_permute_mask (
    mask_type permute_mask ) [inline]
```

Set the permute masks.

Parameters

<code>permute_mask</code>	the permute masks
---------------------------	-------------------

The documentation for this class was generated from the following file:

- `ginkgo/core/matrix/permutation.hpp`

35.111 `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.

35.111.1 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

<code>ValueType</code>	precision of input and result vectors
------------------------	---------------------------------------

Note

the apply operations of `Perturbation` class are not thread safe

35.111.2 Member Function Documentation

35.111.2.1 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

```
81     {
82         return basis_;
83     }
```

35.111.2.2 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

35.111.2.3 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

The documentation for this class was generated from the following file:

- ginkgo/core/base/perturbation.hpp

35.112 gko::log::polymorphic_object_data Struct Reference

Struct representing [PolymorphicObject](#) related data.

```
#include <ginkgo/core/log/record.hpp>
```

35.112.1 Detailed Description

Struct representing [PolymorphicObject](#) related data.

The documentation for this struct was generated from the following file:

- ginkgo/core/log/record.hpp

35.113 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.

35.113.1 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 overridden 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](#)).

35.113.2 Member Function Documentation

35.113.2.1 `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

35.113.2.2 clone() [1/2]

```
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.

35.113.2.3 clone() [2/2]

```
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

<i>exec</i>	the executor where the clone will be created
-------------	--

Returns

A clone of the LinOp.

References `create_default()`.

35.113.2.4 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

<i>other</i>	the object to copy
--------------	--------------------

Returns

this

35.113.2.5 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

<i>other</i>	the object to move from
--------------	-------------------------

Returns

this

35.113.2.6 create_default() [1/2]

```
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()`.

35.113.2.7 create_default() [2/2]

```
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

<code>exec</code>	the executor where the object will be created
-------------------	---

Returns

a polymorphic object of the same type as this

35.113.2.8 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::preconditioner::lc< LSolverType, IndexType >::conj_transpose()`, `gko::preconditioner::llu< LSolverType, USolverType, ReverseApply, IndexType >::conj_transpose()`, `gko::matrix::Dense< ValueType >::create_real_view()`, `gko::matrix::Dense< ValueType >::create_submatrix()`, `gko::matrix::Dense< ValueType >::scale()`, `gko::preconditioner::lc< LSolverType, IndexType >::transpose()`, and `gko::preconditioner::llu< LSolverType, USolverType, ReverseApply, IndexType >::transpose()`.

The documentation for this class was generated from the following file:

- `ginkgo/core/base/polymorphic_object.hpp`

35.114 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

- constexpr static [precision_reduction](#) autodetect () noexcept
Returns a special encoding which instructs the algorithm to automatically detect the best precision.
- constexpr static [precision_reduction](#) common ([precision_reduction](#) x, [precision_reduction](#) y) noexcept
Returns the common encoding of input encodings.

35.114.1 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.

35.114.2 Constructor & Destructor Documentation

35.114.2.1 `precision_reduction()` [1/2]

```
constexpr gko::precision_reduction::precision_reduction ( ) [inline], [constexpr], [noexcept]
```

Creates a default [precision_reduction](#) encoding.

This encoding represents the case where no conversions are performed.

Referenced by `common()`.

35.114.2.2 `precision_reduction()` [2/2]

```
constexpr gko::precision_reduction::precision_reduction (
    storage_type preserving,
    storage_type nonpreserving ) [inline], [constexpr], [noexcept]
```

Creates a [precision_reduction](#) encoding with the specified number of conversions.

Parameters

<i>preserving</i>	the number of range preserving conversion
<i>nonpreserving</i>	the number of range non-preserving conversions

35.114.3 Member Function Documentation

35.114.3.1 `autodetect()`

```
constexpr static precision_reduction gko::precision_reduction::autodetect ( ) [inline], [static],
[constexpr], [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.

35.114.3.2 common()

```
constexpr static precision_reduction gko::precision_reduction::common (
    precision_reduction x,
    precision_reduction y ) [inline], [static], [constexpr], [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

<i>x</i>	an encoding
<i>y</i>	an encoding

Returns

the common encoding of *x* and *y*

References `precision_reduction()`.

35.114.3.3 get_nonpreserving()

```
constexpr storage_type gko::precision_reduction::get_nonpreserving ( ) const [inline], [constexpr],
[noexcept]
```

Returns the number of non-preserving conversions in the encoding.

Returns

the number of non-preserving conversions in the encoding.

35.114.3.4 get_preserving()

```
constexpr storage_type gko::precision_reduction::get_preserving ( ) const [inline], [constexpr],
[noexcept]
```

Returns the number of preserving conversions in the encoding.

Returns

the number of preserving conversions in the encoding.

35.114.3.5 operator storage_type()

```
constexpr gko::precision_reduction::operator storage_type ( ) const [inline], [constexpr],
[noexcept]
```

Extracts the raw data of the encoding.

Returns

the raw data of the encoding

The documentation for this class was generated from the following file:

- ginkgo/core/base/types.hpp

35.115 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
Returns the preconditioner operator used by the [Preconditionable](#).
- virtual void [set_preconditioner](#) (std::shared_ptr< const LinOp > new_precond)
Sets the preconditioner operator used by the [Preconditionable](#).

35.115.1 Detailed Description

A LinOp implementing this interface can be preconditioned.

35.115.2 Member Function Documentation

35.115.2.1 get_preconditioner()

```
virtual std::shared_ptr<const LinOp> gko::Preconditionable::get_preconditioner ( ) const
[inline], [virtual]
```

Returns the preconditioner operator used by the [Preconditionable](#).

Returns

the preconditioner operator used by the [Preconditionable](#)

35.115.2.2 set_preconditioner()

```
virtual void gko::Preconditionable::set_preconditioner (
    std::shared_ptr< const LinOp > new_precond ) [inline], [virtual]
```

Sets the preconditioner operator used by the [Preconditionable](#).

Parameters

<code>new_precond</code>	the new preconditioner operator used by the Preconditionable
--------------------------	--

The documentation for this class was generated from the following file:

- `ginkgo/core/base/lin_op.hpp`

35.116 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

- `~range()`=default
Use the default destructor.
- `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.

35.116.1 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.

35.116.1.1 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.

35.116.1.2 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` and `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 `alpha * 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 its 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)
```

35.116.1.3 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-performance 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.

35.116.1.4 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 `spans` 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

<code>Accessor</code>	underlying accessor of the range
-----------------------	----------------------------------

35.116.2 Constructor & Destructor Documentation

35.116.2.1 range()

```
template<typename Accessor>
template<typename... AccessorParams>
constexpr gko::range< Accessor >::range (
    AccessorParams &&... params ) [inline], [explicit], [constexpr]
```

Creates a new range.

Template Parameters

<i>AccessorParam</i>	types of parameters forwarded to the accessor constructor
----------------------	---

Parameters

<i>params</i>	parameters forwarded to Accessor constructor.
---------------	---

```

325         : accessor_{std::forward<AccessorParams>(params)...}
326     {}

```

35.116.3 Member Function Documentation

35.116.3.1 `get_accessor()`

```

template<typename Accessor>
constexpr const accessor& gko::range< Accessor >::get_accessor ( ) const [inline], [constexpr],
[noexcept]

```

`Returns a reference to the accessor.

Returns

reference to the accessor

Referenced by `gko::range< Accessor >::operator=()`.

35.116.3.2 `length()`

```

template<typename Accessor>
constexpr size_type gko::range< Accessor >::length (
    size_type dimension ) const [inline], [constexpr]

```

Returns the length of the specified dimension of the range.

Parameters

<i>dimension</i>	the dimensions whose length is returned
------------------	---

Returns

the length of the `dimension`-th dimension of the range

Referenced by `gko::matrix_data< ValueType, IndexType >::matrix_data()`.

35.116.3.3 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], [constexpr]
```

Returns a value (or a sub-range) with the specified indexes.

Template Parameters

<i>DimensionTypes</i>	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

<i>dimensions</i>	the indexes of the values.
-------------------	----------------------------

Returns

a value on position (*dimensions...*).

References gko::range< Accessor >::dimensionality.

35.116.3.4 operator->()

```
template<typename Accessor>
constexpr const accessor* gko::range< Accessor >::operator-> ( ) const    [inline], [constexpr],
[noexcept]
```

Returns a pointer to the accessor.

Can be used to access data and functions of a specific accessor.

Returns

pointer to the accessor

35.116.3.5 operator=() [1/2]

```
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

<i>other</i>	the range to copy the data from
--------------	---------------------------------

References `gko::range< Accessor >::get_accessor()`.

35.116.3.6 operator=() [2/2]

```
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

<i>OtherAccessor</i>	accessor of the other range
----------------------	-----------------------------

The documentation for this class was generated from the following file:

- `ginkgo/core/base/range.hpp`

35.117 gko::reorder::Rcm< ValueType, IndexType > Class Template Reference

`Rcm` is a reordering algorithm minimizing the bandwidth of a matrix.

```
#include <ginkgo/core/reorder/rcm.hpp>
```

Public Member Functions

- `std::shared_ptr< const PermutationMatrix > get_permutation () const`
Gets the permutation (permutation matrix, output of the algorithm) of the linear operator.
- `std::shared_ptr< const PermutationMatrix > get_inverse_permutation () const`
Gets the inverse permutation (permutation matrix, output of the algorithm) of the linear operator.

35.117.1 Detailed Description

```
template<typename ValueType = default_precision, typename IndexType = int32>
class gko::reorder::Rcm< ValueType, IndexType >
```

`Rcm` is a reordering algorithm minimizing the bandwidth of a matrix.

Such a reordering typically also significantly reduces fill-in, though usually not as effective as more complex algorithms, specifically AMD and nested dissection schemes. The advantage of this algorithm is its low runtime.

Note

This class is derived from polymorphic object but is not a LinOp as it does not make sense for this class to implement the apply methods. The objective of this class is to generate a reordering/permutation vector (in the form of the Permutation matrix), which can be used to apply to reorder a matrix as required.

There are two "starting strategies" currently available: minimum degree and pseudo-peripheral. These strategies control how a starting vertex for a connected component is chosen, which is then renumbered as first vertex in the component, starting the algorithm from there. In general, the bandwidths obtained by choosing a pseudo-peripheral vertex are slightly smaller than those obtained from choosing a vertex of minimum degree. On the other hand, this strategy is much more expensive, relatively. The algorithm for finding a pseudo-peripheral vertex as described in "Computer Solution of Sparse Linear Systems" (George, Liu, Ng, Oak Ridge National Laboratory, 1994) is implemented here.

Template Parameters

<i>ValueType</i>	Type of the values of all matrices used in this class
<i>IndexType</i>	Type of the indices of all matrices used in this class

35.117.2 Member Function Documentation**35.117.2.1 get_inverse_permutation()**

```
template<typename ValueType = default_precision, typename IndexType = int32>
std::shared_ptr<const PermutationMatrix> gko::reorder::Rcm< ValueType, IndexType >::get_←
inverse_permutation ( ) const [inline]
```

Gets the inverse permutation (permutation matrix, output of the algorithm) of the linear operator.

Returns

the inverse permutation (permutation matrix)

```
124     {
125         return inv_permutation_;
126     }
```

35.117.2.2 get_permutation()

```
template<typename ValueType = default_precision, typename IndexType = int32>
std::shared_ptr<const PermutationMatrix> gko::reorder::Rcm< ValueType, IndexType >::get_←
permutation ( ) const [inline]
```

Gets the permutation (permutation matrix, output of the algorithm) of the linear operator.

Returns

the permutation (permutation matrix)

The documentation for this class was generated from the following file:

- ginkgo/core/reorder/rcm.hpp

35.118 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.
- void [read](#) (const [matrix_assembly_data](#)< ValueType, IndexType > &data)
Reads a matrix from a [matrix_assembly_data](#) structure.

35.118.1 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.

35.118.2 Member Function Documentation

35.118.2.1 [read\(\)](#) [1/2]

```
template<typename ValueType, typename IndexType>
void gko::ReadableFromMatrixData< ValueType, IndexType >::read (
    const matrix\_assembly\_data< ValueType, IndexType > & data ) [inline]
```

Reads a matrix from a [matrix_assembly_data](#) structure.

Parameters

<i>data</i>	the matrix_assembly_data structure
-------------	--

35.118.2.2 [read\(\)](#) [2/2]

```
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

<i>data</i>	the matrix_data structure
-------------	---

Implemented in [gko::matrix::Csr< ValueType, IndexType >](#), [gko::matrix::Hybrid< ValueType, IndexType >](#), [gko::matrix::Coo< ValueType, IndexType >](#), [gko::matrix::Ell< ValueType, IndexType >](#), [gko::matrix::Sellp< ValueType, IndexType >](#), and [gko::matrix::SparsityCsr< ValueType, IndexType >](#).

The documentation for this class was generated from the following file:

- [ginkgo/core/base/lin_op.hpp](#)

35.119 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.

35.119.1 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.

35.119.2 Member Function Documentation

35.119.2.1 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

<i>exec</i>	the executor
<i>enabled_events</i>	the events enabled for this logger. By default all events.
<i>max_storage</i>	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

```
407 {
408     return std::unique_ptr<Record>(
409         new Record(exec, enabled_events, max_storage));
410 }
```

35.119.2.2 get() [1/2]

```
const logged_data& gko::log::Record::get ( ) const [inline], [noexcept]
```

Returns the logged data.

Returns

the logged data

35.119.2.3 get() [2/2]

```
logged_data& gko::log::Record::get ( ) [inline], [noexcept]
```

The documentation for this class was generated from the following file:

- `ginkgo/core/log/record.hpp`

35.120 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

35.120.1 Detailed Description

This is a specialization of the [OmpExecutor](#), which runs the reference implementations of the kernels used for debugging purposes.

35.120.2 Member Function Documentation

35.120.2.1 run()

```
void gko::ReferenceExecutor::run (
    const Operation & op ) const [inline], [override], [virtual]
```

Runs the specified [Operation](#) using this [Executor](#).

Parameters

<i>op</i>	the operation to run
-----------	----------------------

Implements [gko::Executor](#).

The documentation for this class was generated from the following file:

- ginkgo/core/base/executor.hpp

35.121 gko::stop::RelativeResidualNorm< ValueType > Class Template Reference

The [RelativeResidualNorm](#) class is a stopping criterion which stops the iteration process when the residual norm is below a certain threshold relative to the norm of the right-hand side, i.e.

```
#include <ginkgo/core/stop/residual_norm.hpp>
```

35.121.1 Detailed Description

```
template<typename ValueType = default_precision>
class gko::stop::RelativeResidualNorm< ValueType >
```

The [RelativeResidualNorm](#) class is a stopping criterion which stops the iteration process when the residual norm is below a certain threshold relative to the norm of the right-hand side, i.e.

when $\text{norm}(\text{residual}) / \text{norm}(\text{right_hand_side}) < \text{threshold}$. 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 `b` in order to compute the norm of the right-hand side. If this 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.hpp`

35.122 gko::reorder::ReorderingBase Class Reference

The [ReorderingBase](#) class is a base class for all the reordering algorithms.

```
#include <ginkgo/core/reorder/reordering_base.hpp>
```

Additional Inherited Members

35.122.1 Detailed Description

The [ReorderingBase](#) class is a base class for all the reordering algorithms.

It contains a factory to instantiate the reorderings. It is up to each specific reordering to decide what to do with the data that is passed to it.

The documentation for this class was generated from the following file:

- `ginkgo/core/reorder/reordering_base.hpp`

35.123 gko::reorder::ReorderingBaseArgs Struct Reference

This struct is used to pass parameters to the `EnableDefaultReorderingBaseFactory::generate()` method.

```
#include <ginkgo/core/reorder/reordering_base.hpp>
```


35.123.1 Detailed Description

This struct is used to pass parameters to the `EnableDefaultReorderingBaseFactory::generate()` method.

It is the `ComponentsType` of `ReorderingBaseFactory`.

The documentation for this struct was generated from the following file:

- `ginkgo/core/reorder/reordering_base.hpp`

35.124 gko::stop::ResidualNorm< ValueType > Class Template Reference

The [ResidualNorm](#) class is a stopping criterion which stops the iteration process when the actual residual norm is below a certain threshold relative to.

```
#include <ginkgo/core/stop/residual_norm.hpp>
```

35.124.1 Detailed Description

```
template<typename ValueType = default_precision>
class gko::stop::ResidualNorm< ValueType >
```

The [ResidualNorm](#) class is a stopping criterion which stops the iteration process when the actual residual norm is below a certain threshold relative to.

1. the norm of the right-hand side, $\text{norm}(\text{residual}) / \text{norm}(\text{right_hand_side}) < \text{threshold}$
2. the initial residual, $\text{norm}(\text{residual}) / \text{norm}(\text{initial_residual}) < \text{threshold}$.
3. one, $\text{norm}(\text{residual}) < \text{threshold}$.

For better performance, the checks are run on the executor where the algorithm is executed.

Note

To use this stopping criterion there are some dependencies. The constructor depends on either `b` or the `initial_residual` in order to compute their norms. If this 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.hpp`

35.125 `gko::stop::ResidualNormBase< ValueType >` Class Template Reference

The `ResidualNormBase` class provides a framework for stopping criteria related to the residual norm.

```
#include <ginkgo/core/stop/residual_norm.hpp>
```

35.125.1 Detailed Description

```
template<typename ValueType>
class gko::stop::ResidualNormBase< ValueType >
```

The `ResidualNormBase` class provides a framework for stopping criteria related to the residual norm.

These criteria differ in the way they initialize `starting_tau_`, so in the value they compare the residual norm against. The provided `check_impl` uses the actual residual to check for convergence.

The documentation for this class was generated from the following file:

- `ginkgo/core/stop/residual_norm.hpp`

35.126 `gko::stop::ResidualNormReduction< ValueType >` Class Template Reference

The `ResidualNormReduction` class is a stopping criterion which stops the iteration process when the residual norm is below a certain threshold relative to the norm of the initial residual, i.e.

```
#include <ginkgo/core/stop/residual_norm.hpp>
```

35.126.1 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 residual norm is below a certain threshold relative to the norm of the initial residual, i.e.

when $\text{norm}(\text{residual}) / \text{norm}(\text{initial_residual}) < \text{threshold}$. 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.hpp`

35.127 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.

35.127.1 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

<i>ValueType</i>	type of values this accessor returns
<i>Dimensionality</i>	number of dimensions of this accessor (has to be 2)

35.127.2 Member Function Documentation

35.127.2.1 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.

Warning

Do not use this function since it is not optimized for a specific executor. It will always be performed sequentially. Please write an optimized version (adjusted to the architecture) by iterating through the values yourself.

Template Parameters

<i>OtherAccessor</i>	type of the other accessor
----------------------	----------------------------

Parameters

<i>other</i>	other accessor
--------------	----------------

```
170     {
171         for (size_type i = 0; i < lengths[0]; ++i) {
172             for (size_type j = 0; j < lengths[1]; ++j) {
173                 (*this)(i, j) = other(i, j);
174             }
175         }
176     }
```

References `gko::accessor::row_major< ValueType, Dimensionality >::lengths`.

35.127.2.2 length()

```
template<typename ValueType , size_type Dimensionality>
constexpr size_type gko::accessor::row_major< ValueType, Dimensionality >::length (
    size_type dimension ) const [inline], [constexpr]
```

Returns the length in dimension `dimension`.

Parameters

<i>dimension</i>	a dimension index
------------------	-------------------

Returns

length in dimension *dimension*

References gko::accessor::row_major< ValueType, Dimensionality >::lengths.

35.127.2.3 operator>() [1/2]

```
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], [constexpr]
```

Returns the sub-range spanning the range (rows, cols)

Parameters

<i>rows</i>	row span
<i>cols</i>	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.

35.127.2.4 operator>() [2/2]

```
template<typename ValueType , size_type Dimensionality>
constexpr value_type& gko::accessor::row_major< ValueType, Dimensionality >::operator() (
    size_type row,
    size_type col ) const [inline], [constexpr]
```

Returns the data element at position (row, col)

Parameters

<i>row</i>	row index
<i>col</i>	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`.

The documentation for this class was generated from the following file:

- `ginkgo/core/base/range_accessors.hpp`

35.128 `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.
- `std::unique_ptr< Diagonal< ValueType > >` `extract_diagonal` () const override
Extracts the diagonal entries of the matrix into a vector.
- `std::unique_ptr< absolute_type >` `compute_absolute` () const override
Gets the AbsoluteLinOp.
- void `compute_absolute_inplace` () override
Compute absolute inplace on each element.
- `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.

35.128.1 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

<i>ValueType</i>	precision of matrix elements
<i>IndexType</i>	precision of matrix indexes

35.128.2 Member Function Documentation

35.128.2.1 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 ) const [inline], [noexcept]
```

Returns the idx-th column index of the row-th row with slice_set slice set.

Parameters

<i>row</i>	the row of the requested element in the slice
<i>slice_set</i>	the slice set of the slice
<i>idx</i>	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)

```

280     {
281         return this
282         ->get_const_col_idxs() [this->linearize_index(row, slice_set, idx)];
283     }

```

35.128.2.2 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 ) [inline], [noexcept]

```

Returns the `idx`-th column index of the `row`-th row with `slice_set` slice set.

Parameters

<i>row</i>	the row of the requested element in the slice
<i>slice_set</i>	the slice set of the slice
<i>idx</i>	the <code>idx</code> -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()`.

35.128.2.3 compute_absolute()

```

template<typename ValueType = default_precision, typename IndexType = int32>
std::unique_ptr<absolute_type> gko::matrix::Sellp< ValueType, IndexType >::compute_absolute (
    ) const [override], [virtual]

```

Gets the `AbsoluteLinOp`.

Returns

a pointer to the new absolute object

Implements `gko::EnableAbsoluteComputation< remove_complex< Sellp< ValueType, IndexType > > >`.

35.128.2.4 extract_diagonal()

```

template<typename ValueType = default_precision, typename IndexType = int32>
std::unique_ptr<Diagonal<ValueType> > gko::matrix::Sellp< ValueType, IndexType >::extract_↵
diagonal ( ) const [override], [virtual]

```

Extracts the diagonal entries of the matrix into a vector.

Parameters

<i>diag</i>	the vector into which the diagonal will be written
-------------	--

Implements [gko::DiagonalExtractable< ValueType >](#).

35.128.2.5 get_col_idxes()

```
template<typename ValueType = default_precision, typename IndexType = int32>
index_type* gko::matrix::Sellp< ValueType, IndexType >::get_col_idxes ( ) [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\(\)](#).

35.128.2.6 get_const_col_idxes()

```
template<typename ValueType = default_precision, typename IndexType = int32>
const index_type* gko::matrix::Sellp< ValueType, IndexType >::get_const_col_idxes ( ) 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\(\)](#).

35.128.2.7 get_const_slice_lengths()

```
template<typename ValueType = default_precision, typename IndexType = int32>
const size_type* gko::matrix::Selp< 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()`.

35.128.2.8 get_const_slice_sets()

```
template<typename ValueType = default_precision, typename IndexType = int32>
const size_type* gko::matrix::Selp< 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()`.

35.128.2.9 get_const_values()

```
template<typename ValueType = default_precision, typename IndexType = int32>
const value_type* gko::matrix::Selp< 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()`.

35.128.2.10 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().

35.128.2.11 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().

35.128.2.12 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().

35.128.2.13 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.

35.128.2.14 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.

35.128.2.15 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.

35.128.2.16 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()`.

35.128.2.17 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

<i>data</i>	the matrix_data structure
-------------	---

Implements [gko::ReadableFromMatrixData< ValueType, IndexType >](#).

35.128.2.18 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 ) const [inline], [noexcept]
```

Returns the *idx*-th non-zero element of the *row*-th row with *slice_set* slice set.

Parameters

<i>row</i>	the row of the requested element in the slice
<i>slice_set</i>	the slice set of the slice
<i>idx</i>	the <i>idx</i> -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\(\)](#).

35.128.2.19 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 ) [inline], [noexcept]
```

Returns the *idx*-th non-zero element of the *row*-th row with *slice_set* slice set.

Parameters

<i>row</i>	the row of the requested element in the slice
<i>slice_set</i>	the slice set of the slice
<i>idx</i>	the <i>idx</i> -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()`.

35.128.2.20 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

<i>data</i>	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`
- `ginkgo/core/matrix/sellp.hpp`

35.129 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.

35.129.1 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. $x \leq y$ ($y \geq x$) 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: $x < y$, $x > y$, $x == y$, $x \leq y$, $x \geq y$. 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, $x \leq y$ is not equivalent to $x < y \parallel x == y$.

35.129.2 Constructor & Destructor Documentation

35.129.2.1 span() [1/2]

```
constexpr gko::span::span (
    size_type point ) [inline], [constexpr], [noexcept]
```

Creates a span representing a point `point`.

The `begin` of this span is set to `point`, and the `end` to `point + 1`.

Parameters

<code>point</code>	the point which the span represents
--------------------	-------------------------------------

35.129.2.2 span() [2/2]

```
constexpr gko::span::span (
    size_type begin,
    size_type end ) [inline], [constexpr], [noexcept]
```

Creates a span.

Parameters

<i>begin</i>	the beginning of the span
<i>end</i>	the end of the span

References begin.

35.129.3 Member Function Documentation

35.129.3.1 `is_valid()`

```
constexpr bool gko::span::is_valid ( ) const [inline], [constexpr]
```

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()()`.

The documentation for this struct was generated from the following file:

- `ginkgo/core/base/range.hpp`

35.130 `gko::matrix::Csr< ValueType, IndexType >::sparselib` Class Reference

`sparselib` is a [strategy_type](#) which uses the `sparselib` csr.

```
#include <ginkgo/core/matrix/csr.hpp>
```

Public Member Functions

- [sparselib](#) ()
Creates a sparselib strategy.
- void [process](#) (const [Array](#)< index_type > &mtx_row_ptrs, [Array](#)< index_type > *mtx_srow) override
Computes srow according to row pointers.
- int64_t [clac_size](#) (const int64_t nnz) override
Computes the srow size according to the number of nonzeros.
- std::shared_ptr< [strategy_type](#) > [copy](#) () override
Copy a strategy.

35.130.1 Detailed Description

```
template<typename ValueType = default_precision, typename IndexType = int32>
class gko::matrix::Csr< ValueType, IndexType >::sparselib
```

sparselib is a [strategy_type](#) which uses the sparselib csr.

Note

Uses cusparse in cuda and hipsparse in hip.

35.130.2 Member Function Documentation

35.130.2.1 clac_size()

```
template<typename ValueType = default_precision, typename IndexType = int32>
int64_t gko::matrix::Csr< ValueType, IndexType >::sparselib::clac_size (
    const int64_t nnz ) [inline], [override], [virtual]
```

Computes the srow size according to the number of nonzeros.

Parameters

<i>nnz</i>	the number of nonzeros
------------	------------------------

Returns

the size of srow

Implements [gko::matrix::Csr< ValueType, IndexType >::strategy_type](#).

35.130.2.2 copy()

```
template<typename ValueType = default_precision, typename IndexType = int32>
std::shared_ptr<strategy_type> gko::matrix::Csr< ValueType, IndexType >::sparselib::copy ( )
[inline], [override], [virtual]
```

Copy a strategy.

This is a workaround until strategies are revamped, since strategies like `automatical` do not work when actually shared.

Implements [gko::matrix::Csr< ValueType, IndexType >::strategy_type](#).

35.130.2.3 process()

```
template<typename ValueType = default_precision, typename IndexType = int32>
void gko::matrix::Csr< ValueType, IndexType >::sparselib::process (
    const Array< index_type > & mtx_row_ptrs,
    Array< index_type > * mtx_srow ) [inline], [override], [virtual]
```

Computes srow according to row pointers.

Parameters

<i>mtx_row_ptrs</i>	the row pointers of the matrix
<i>mtx_srow</i>	the srow of the matrix

Implements [gko::matrix::Csr< ValueType, IndexType >::strategy_type](#).

The documentation for this class was generated from the following file:

- [ginkgo/core/matrix/csr.hpp](#)

35.131 gko::matrix::SparsityCsr< ValueType, IndexType > Class Template Reference

[SparsityCsr](#) is a matrix format which stores only the sparsity pattern of a sparse matrix by compressing each row of the matrix (compressed sparse row format).

```
#include <ginkgo/core/matrix/sparsity_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.
- std::unique_ptr< [SparsityCsr](#) > [to_adjacency_matrix](#) () const
Transforms the sparsity matrix to an adjacency matrix.
- void [sort_by_column_index](#) ()
Sorts each row by column index.
- index_type * [get_col_idxs](#) () noexcept
Returns the column indices of the matrix.
- const index_type * [get_const_col_idxs](#) () const noexcept
Returns the column indices 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.
- `value_type * get_value ()` `noexcept`
Returns the value stored in the matrix.
- `const value_type * get_const_value ()` `const noexcept`
Returns the value stored in the matrix.
- `size_type get_num_nonzeros ()` `const noexcept`
Returns the number of elements explicitly stored in the matrix.

35.131.1 Detailed Description

```
template<typename ValueType = default_precision, typename IndexType = int32>
class gko::matrix::SparsityCsr< ValueType, IndexType >
```

[SparsityCsr](#) is a matrix format which stores only the sparsity pattern of a sparse matrix by compressing each row of the matrix (compressed sparse row format).

The values of the nonzero elements are stored as a value array of length 1. All the values in the matrix are equal to this value. By default, this value is set to 1.0. A row pointer array also stores the linearized starting index of each row. An additional column index array is used to identify the column where a nonzero is present.

Template Parameters

<i>ValueType</i>	precision of vectors in apply
<i>IndexType</i>	precision of matrix indexes

35.131.2 Member Function Documentation

35.131.2.1 conj_transpose()

```
template<typename ValueType = default_precision, typename IndexType = int32>
std::unique_ptr<LinOp> gko::matrix::SparsityCsr< 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](#).

35.131.2.2 get_col_idxxs()

```
template<typename ValueType = default_precision, typename IndexType = int32>
index_type* gko::matrix::SparsityCsr< ValueType, IndexType >::get_col_idxxs ( ) [inline],
[noexcept]
```

Returns the column indices of the matrix.

Returns

the column indices of the matrix.

```
127 { return col_idxxs_.get_data(); }
```

References gko::Array< ValueType >::get_data().

35.131.2.3 get_const_col_idxxs()

```
template<typename ValueType = default_precision, typename IndexType = int32>
const index_type* gko::matrix::SparsityCsr< ValueType, IndexType >::get_const_col_idxxs ( )
const [inline], [noexcept]
```

Returns the column indices of the matrix.

Returns

the column indices 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().

35.131.2.4 get_const_row_ptrs()

```
template<typename ValueType = default_precision, typename IndexType = int32>
const index_type* gko::matrix::SparsityCsr< 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.

References gko::Array< ValueType >::get_const_data().

35.131.2.5 get_const_value()

```
template<typename ValueType = default_precision, typename IndexType = int32>
const value_type* gko::matrix::SparsityCsr< ValueType, IndexType >::get_const_value ( ) const
[inline], [noexcept]
```

Returns the value stored in the matrix.

Returns

the value 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().

35.131.2.6 get_num_nonzeros()

```
template<typename ValueType = default_precision, typename IndexType = int32>
size_type gko::matrix::SparsityCsr< ValueType, IndexType >::get_num_nonzeros ( ) 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().

35.131.2.7 get_row_ptrs()

```
template<typename ValueType = default_precision, typename IndexType = int32>
index_type* gko::matrix::SparsityCsr< ValueType, IndexType >::get_row_ptrs ( ) [inline],
[noexcept]
```

Returns the row pointers of the matrix.

Returns

the row pointers of the matrix.

References gko::Array< ValueType >::get_data().

35.131.2.8 get_value()

```
template<typename ValueType = default_precision, typename IndexType = int32>
value_type* gko::matrix::SparsityCsr< ValueType, IndexType >::get_value ( ) [inline], [noexcept]
```

Returns the value stored in the matrix.

Returns

the value of the matrix.

References `gko::Array< ValueType >::get_data()`.

35.131.2.9 read()

```
template<typename ValueType = default_precision, typename IndexType = int32>
void gko::matrix::SparsityCsr< ValueType, IndexType >::read (
    const mat_data & data ) [override], [virtual]
```

Reads a matrix from a `matrix_data` structure.

Parameters

<code>data</code>	the <code>matrix_data</code> structure
-------------------	--

Implements `gko::ReadableFromMatrixData< ValueType, IndexType >`.

35.131.2.10 to_adjacency_matrix()

```
template<typename ValueType = default_precision, typename IndexType = int32>
std::unique_ptr<SparsityCsr> gko::matrix::SparsityCsr< ValueType, IndexType >::to_adjacency↵
_matrix ( ) const
```

Transforms the sparsity matrix to an adjacency matrix.

As the adjacency matrix has to be square, the input `SparsityCsr` matrix for this function to work has to be square.

Note

The adjacency matrix in this case is the sparsity pattern but with the diagonal ones removed. This is mainly used for the reordering/partitioning as taken in by graph libraries such as METIS.

35.131.2.11 transpose()

```
template<typename ValueType = default_precision, typename IndexType = int32>
std::unique_ptr<LinOp> gko::matrix::SparsityCsr< 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](#).

35.131.2.12 write()

```
template<typename ValueType = default_precision, typename IndexType = int32>
void gko::matrix::SparsityCsr< ValueType, IndexType >::write (
    mat_data & data ) const [override], [virtual]
```

Writes a matrix to a [matrix_data](#) structure.

Parameters

<i>data</i>	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
- ginkgo/core/matrix/sparsity_csr.hpp

35.132 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 occurred due to a hard limit (and convergence was not reached).
- `void converge (uint8 id, bool set_finalized=true)` `noexcept`
Call if convergence occurred.
- `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.

35.132.1 Detailed Description

This class is used to keep track of the stopping status of one vector.

35.132.2 Member Function Documentation

35.132.2.1 converge()

```
void gko::stopping_status::converge (
    uint8 id,
    bool set_finalized = true ) [inline], [noexcept]
```

Call if convergence occurred.

Parameters

<i>id</i>	id of the stopping criteria.
<i>set_finalized</i>	Controls if the current version should count as finalized (set to true) or not (set to false).

References `has_stopped()`.

35.132.2.2 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()`.

35.132.2.3 has_converged()

```
bool gko::stopping_status::has_converged ( ) const [inline], [noexcept]
```

Check if convergence was reached.

Returns

Returns true if convergence was reached.

35.132.2.4 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()`.

35.132.2.5 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.

35.132.2.6 stop()

```
void gko::stopping_status::stop (
    uint8 id,
    bool set_finalized = true ) [inline], [noexcept]
```

Call if a stop occurred due to a hard limit (and convergence was not reached).

Parameters

<i>id</i>	id of the stopping criteria.
<i>set_finalized</i>	Controls if the current version should count as finalized (set to true) or not (set to false).

References `has_stopped()`.

35.132.3 Friends And Related Function Documentation

35.132.3.1 `operator!=`

```
bool operator!= (
    const stopping_status & x,
    const stopping_status & y ) [friend]
```

Checks if two stopping statuses are different.

Parameters

<i>x</i>	a stopping status
<i>y</i>	a stopping status

Returns

true if and only if `! (x == y)`

35.132.3.2 `operator==`

```
bool operator== (
    const stopping_status & x,
    const stopping_status & y ) [friend]
```

Checks if two stopping statuses are equivalent.

Parameters

<i>x</i>	a stopping status
<i>y</i>	a stopping status

Returns

true if and only if both `x` and `y` have the same mask and converged and finalized state

The documentation for this class was generated from the following file:

- ginkgo/core/stop/stopping_status.hpp

35.133 gko::matrix::Csr< ValueType, IndexType >::strategy_type Class Reference

[strategy_type](#) is to decide how to set the csr algorithm.

```
#include <ginkgo/core/matrix/csr.hpp>
```

Public Member Functions

- [strategy_type](#) (std::string name)
Creates a [strategy_type](#).
- std::string [get_name](#) ()
Returns the name of strategy.
- virtual void [process](#) (const [Array](#)< index_type > &mtx_row_ptrs, [Array](#)< index_type > *mtx_srow)=0
Computes srow according to row pointers.
- virtual int64_t [clac_size](#) (const int64_t nnz)=0
Computes the srow size according to the number of nonzeros.
- virtual std::shared_ptr< [strategy_type](#) > [copy](#) ()=0
Copy a strategy.

35.133.1 Detailed Description

```
template<typename ValueType = default_precision, typename IndexType = int32>
class gko::matrix::Csr< ValueType, IndexType >::strategy_type
```

[strategy_type](#) is to decide how to set the csr algorithm.

The practical strategy method should inherit [strategy_type](#) and implement its `process`, `clac_size` function and the corresponding device kernel.

35.133.2 Constructor & Destructor Documentation

35.133.2.1 strategy_type()

```
template<typename ValueType = default_precision, typename IndexType = int32>
gko::matrix::Csr< ValueType, IndexType >::strategy_type::strategy_type (
    std::string name ) [inline]
```

Creates a [strategy_type](#).

Parameters

<i>name</i>	the name of strategy
-------------	----------------------

35.133.3 Member Function Documentation

35.133.3.1 `clac_size()`

```
template<typename ValueType = default_precision, typename IndexType = int32>
virtual int64_t gko::matrix::Csr< ValueType, IndexType >::strategy_type::clac_size (
    const int64_t nnz ) [pure virtual]
```

Computes the srow size according to the number of nonzeros.

Parameters

<i>nnz</i>	the number of nonzeros
------------	------------------------

Returns

the size of srow

Implemented in [gko::matrix::Csr< ValueType, IndexType >::load_balance](#), [gko::matrix::Csr< ValueType, IndexType >::sparselib](#), [gko::matrix::Csr< ValueType, IndexType >::cusparse](#), [gko::matrix::Csr< ValueType, IndexType >::merge_path](#), and [gko::matrix::Csr< ValueType, IndexType >::classical](#).

35.133.3.2 `copy()`

```
template<typename ValueType = default_precision, typename IndexType = int32>
virtual std::shared_ptr<strategy_type> gko::matrix::Csr< ValueType, IndexType >::strategy_type::copy ( ) [pure virtual]
```

Copy a strategy.

This is a workaround until strategies are revamped, since strategies like `automatical` do not work when actually shared.

Implemented in [gko::matrix::Csr< ValueType, IndexType >::load_balance](#), [gko::matrix::Csr< ValueType, IndexType >::sparselib](#), [gko::matrix::Csr< ValueType, IndexType >::cusparse](#), [gko::matrix::Csr< ValueType, IndexType >::merge_path](#), and [gko::matrix::Csr< ValueType, IndexType >::classical](#).

35.133.3.3 get_name()

```
template<typename ValueType = default_precision, typename IndexType = int32>
std::string gko::matrix::Csr< ValueType, IndexType >::strategy_type::get_name ( ) [inline]
```

Returns the name of strategy.

Returns

the name of strategy

35.133.3.4 process()

```
template<typename ValueType = default_precision, typename IndexType = int32>
virtual void gko::matrix::Csr< ValueType, IndexType >::strategy_type::process (
    const Array< index_type > & mtx_row_ptrs,
    Array< index_type > * mtx_srow ) [pure virtual]
```

Computes srow according to row pointers.

Parameters

<i>mtx_row_ptrs</i>	the row pointers of the matrix
<i>mtx_srow</i>	the srow of the matrix

Implemented in [gko::matrix::Csr< ValueType, IndexType >::load_balance](#), [gko::matrix::Csr< ValueType, IndexType >::sparselib](#), [gko::matrix::Csr< ValueType, IndexType >::cusparse](#), [gko::matrix::Csr< ValueType, IndexType >::merge_path](#), and [gko::matrix::Csr< ValueType, IndexType >::classical](#).

The documentation for this class was generated from the following file:

- [ginkgo/core/matrix/csr.hpp](#)

35.134 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.

35.134.1 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.

35.134.2 Member Function Documentation

35.134.2.1 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

<code>row_nnz</code>	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`, `gko::matrix::Hybrid< ValueType, IndexType >::imbalance_bounded_limit`, `gko::matrix::Hybrid< ValueType, IndexType >::imbalance_bound` and `gko::matrix::Hybrid< ValueType, IndexType >::column_limit`.

Referenced by `gko::matrix::Hybrid< ValueType, IndexType >::strategy_type::compute_hybrid_config()`.

35.134.2.2 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

<i>row_nnz</i>	the number of nonzeros of each row
<i>ell_num_stored_elements_per_row</i>	the output number of stored elements per row of the ell part
<i>coo_nnz</i>	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\(\)](#).

35.134.2.3 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

35.134.2.4 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

The documentation for this class was generated from the following file:

- [ginkgo/core/matrix/hybrid.hpp](#)

35.135 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.

35.135.1 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

<i>ValueType</i>	the type of values stored in the class (i.e. ValueType template parameter of the concrete Loggable this class will log)
------------------	---

35.135.2 Member Function Documentation

35.135.2.1 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

<i>exec</i>	the executor
<i>enabled_events</i>	the events enabled for this logger. By default all events.
<i>os</i>	the stream used for this logger
<i>verbose</i>	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

```

184     {
185         return std::unique_ptr<Stream>(
186             new Stream(exec, enabled_events, os, verbose));
187     }

```

The documentation for this class was generated from the following file:

- ginkgo/core/log/stream.hpp

35.136 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.

35.136.1 Detailed Description

[StreamError](#) is thrown if accessing a stream failed.

35.136.2 Constructor & Destructor Documentation

35.136.2.1 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

<i>file</i>	The name of the offending source file
<i>line</i>	The source code line number where the error occurred
<i>func</i>	The name of the function that tried to access the file
<i>message</i>	The error message

The documentation for this class was generated from the following file:

- ginkgo/core/base/exception.hpp

35.137 gko::stop::Time Class Reference

The [Time](#) class is a stopping criterion which stops the iteration process after a certain amount of time has passed.

```
#include <ginkgo/core/stop/time.hpp>
```

35.137.1 Detailed Description

The [Time](#) class is a stopping criterion which stops the iteration process after a certain amount of time has passed.

The documentation for this class was generated from the following file:

- ginkgo/core/stop/time.hpp

35.138 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.

35.138.1 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, $B = A^H$.

35.138.1.1 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();
```

35.138.2 Member Function Documentation**35.138.2.1 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 >](#), [gko::preconditioner::Jacobi< ValueType, IndexType >](#), [gko::matrix::Dense< ValueType >](#), [gko::preconditioner::ilu< LSolverType, USolverType, ReverseApply, IndexType >](#), [gko::preconditioner::lc< LSolverType, IndexType >](#), [gko::preconditioner::lsai< IsaiType, ValueType, IndexType >](#), [gko::solver::lr< ValueType >](#), [gko::solver::LowerTrs< ValueType, IndexType >](#), [gko::solver::UpperTrs< ValueType, IndexType >](#), [gko::solver::ldr< ValueType >](#), [gko::solver::Bicg< ValueType >](#), [gko::solver::Fcgs< ValueType >](#), [gko::solver::Bicgstab< ValueType >](#), [gko::matrix::Diagonal< ValueType >](#), [gko::matrix::SparsityCsr< ValueType, IndexType >](#), [gko::solver::Cg< ValueType >](#), [gko::solver::Gmres< ValueType >](#), [gko::solver::Cgs< ValueType >](#), [gko::Combination< ValueType >](#), [gko::Composition< ValueType >](#) and [gko::matrix::Identity< ValueType >](#).

35.138.2.2 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 >](#), [gko::preconditioner::Jacobi< ValueType, IndexType >](#), [gko::matrix::Dense< ValueType >](#), [gko::preconditioner::ilu< LSolverType, USolverType, ReverseApply, IndexType >](#), [gko::preconditioner::lc< LSolverType, IndexType >](#), [gko::preconditioner::lsai< IsaiType, ValueType, IndexType >](#), [gko::solver::lr< ValueType >](#), [gko::solver::LowerTrs< ValueType, IndexType >](#), [gko::solver::UpperTrs< ValueType, IndexType >](#), [gko::solver::ldr< ValueType >](#), [gko::solver::Bicg< ValueType >](#), [gko::solver::Fcgs< ValueType >](#), [gko::solver::Bicgstab< ValueType >](#), [gko::matrix::Diagonal< ValueType >](#), [gko::matrix::SparsityCsr< ValueType, IndexType >](#), [gko::solver::Cg< ValueType >](#), [gko::solver::Gmres< ValueType >](#), [gko::solver::Cgs< ValueType >](#), [gko::Combination< ValueType >](#), [gko::Composition< ValueType >](#) and [gko::matrix::Identity< ValueType >](#).

The documentation for this class was generated from the following file:

- [ginkgo/core/base/lin_op.hpp](#)

35.139 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 stopping_id, bool set_finalized, [Array](#)< [stopping_status](#) > *stop_status, bool *one_↔changed) const
Calls the parent [Criterion](#) object's check method.

35.139.1 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) .implicit_sq_residual_norm(implicit_sq_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.

35.139.2 Member Function Documentation

35.139.2.1 check()

```
bool gko::stop::Criterion::Updater::check (
    uint8 stopping_id,
    bool set_finalized,
    Array< stopping_status > * stop_status,
    bool * one_changed ) const [inline]
```

Calls the parent [Criterion](#) object's check method.

References [gko::stop::Criterion::check\(\)](#).

The documentation for this class was generated from the following file:

- [ginkgo/core/stop/criterion.hpp](#)

35.140 gko::solver::UpperTrs< ValueType, IndexType > Class Template Reference

[UpperTrs](#) is the triangular solver which solves the system $Ux = b$, 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::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.

35.140.1 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 $Ux = b$, 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

<i>ValueType</i>	precision of matrix elements
<i>IndexType</i>	precision of matrix indices

35.140.2 Member Function Documentation

35.140.2.1 conj_transpose()

```
template<typename ValueType = default_precision, typename IndexType = int32>
std::unique_ptr<LinOp> gko::solver::UpperTrs< 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](#).

35.140.2.2 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)

```
101     {
102         return system_matrix_;
103     }
```

35.140.2.3 transpose()

```
template<typename ValueType = default_precision, typename IndexType = int32>
std::unique_ptr<LinOp> gko::solver::UpperTrs< 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](#).

The documentation for this class was generated from the following files:

- [ginkgo/core/solver/lower_trs.hpp](#)
- [ginkgo/core/solver/upper_trs.hpp](#)

35.141 gko::UseComposition< ValueType > Class Template Reference

The [UseComposition](#) class can be used to store the composition information in LinOp.

```
#include <ginkgo/core/base/composition.hpp>
```

Public Member Functions

- `std::shared_ptr< Composition< ValueType > > get_composition () const`
Returns the composition operator.
- `std::shared_ptr< const LinOp > get_operator_at (size_type index) const`
Returns the operator at index-th position of composition.

35.141.1 Detailed Description

```
template<typename ValueType = default_precision>
class gko::UseComposition< ValueType >
```

The [UseComposition](#) class can be used to store the composition information in LinOp.

Template Parameters

<i>ValueType</i>	precision of input and result vectors
------------------	---------------------------------------

35.141.2 Member Function Documentation**35.141.2.1 `get_composition()`**

```
template<typename ValueType = default_precision>
std::shared_ptr<Composition<ValueType> > gko::UseComposition< ValueType >::get_composition (
) const [inline]
```

Returns the composition operator.

Returns

composition

35.141.2.2 `get_operator_at()`

```
template<typename ValueType = default_precision>
std::shared_ptr<const LinOp> gko::UseComposition< ValueType >::get_operator_at (
    size_type index ) const [inline]
```

Returns the operator at index-th position of composition.

Returns

index-th operator

Note

when this composition is not set, this function always returns nullptr. However, when this composition is set, it will throw exception when exceeding index.

Exceptions

<i>std::out_of_range</i>	if index is out of bound when composition is existed.
--------------------------	---

Referenced by `gko::multigrid::EnableMultigridLevel< ValueType >::get_coarse_op()`, `gko::multigrid::EnableMultigridLevel< ValueType >::get_prolong_op()`, and `gko::multigrid::EnableMultigridLevel< ValueType >::get_restrict_op()`.

The documentation for this class was generated from the following file:

- ginkgo/core/base/composition.hpp

35.142 gko::ValueMismatch Class Reference

[ValueMismatch](#) is thrown if two values are not equal.

```
#include <ginkgo/core/base/exception.hpp>
```

Public Member Functions

- [ValueMismatch](#) (const std::string &file, int line, const std::string &func, [size_type](#) val1, [size_type](#) val2, const std::string &clarification)
Initializes a value mismatch error.

35.142.1 Detailed Description

[ValueMismatch](#) is thrown if two values are not equal.

35.142.2 Constructor & Destructor Documentation

35.142.2.1 ValueMismatch()

```
gko::ValueMismatch::ValueMismatch (
    const std::string & file,
    int line,
    const std::string & func,
    size\_type val1,
    size\_type val2,
    const std::string & clarification ) [inline]
```

Initializes a value mismatch error.

Parameters

<i>file</i>	The name of the offending source file
<i>line</i>	The source code line number where the error occurred
<i>func</i>	The function name where the error occurred
<i>val1</i>	The first value to be compared.
<i>val2</i>	The second value to be compared.
<i>clarification</i>	An additional message further describing the error

The documentation for this class was generated from the following file:

- ginkgo/core/base/exception.hpp

35.143 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.

35.143.1 Detailed Description

This structure is used to represent versions of various Ginkgo modules.

Version structures can be compared using the usual relational operators.

35.143.2 Member Data Documentation

35.143.2.1 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

35.144 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.
- [version_hip_version](#)
Contains version information of the HIP module.
- [version_dpcpp_version](#)
Contains version information of the DPC++ module.

35.144.1 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 and 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, HIP). To obtain an instance of [version_info](#) filled with information about the current version of Ginkgo, call the [version_info::get\(\)](#) static method.

35.144.2 Member Function Documentation

35.144.2.1 get()

```
static const version\_info& gko::version_info::get ( ) [inline], [static]
```

Returns an instance of [version_info](#).

Returns

an instance of version info

35.144.3 Member Data Documentation

35.144.3.1 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".

35.144.3.2 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".

35.144.3.3 dpcpp_version

```
version gko::version_info::dpcpp_version
```

Contains version information of the DPC++ module.

This is the version of the static/shared library called "ginkgo_dpcpp".

35.144.3.4 hip_version

```
version gko::version_info::hip_version
```

Contains version information of the HIP module.

This is the version of the static/shared library called "ginkgo_hip".

35.144.3.5 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".

35.144.3.6 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

35.145 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.

35.145.1 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.

35.145.2 Member Function Documentation

35.145.2.1 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

<i>data</i>	the matrix_data structure
-------------	---

Implemented in [gko::matrix::Csr< ValueType, IndexType >](#), [gko::matrix::Hybrid< ValueType, IndexType >](#), [gko::preconditioner::Jacobi< ValueType, IndexType >](#), [gko::matrix::Coo< ValueType, IndexType >](#), [gko::matrix::Ell< ValueType, IndexType >](#), [gko::matrix::Sellp< ValueType, IndexType >](#), and [gko::matrix::SparsityCsr< ValueType, IndexType >](#).

The documentation for this class was generated from the following file:

- [ginkgo/core/base/lin_op.hpp](#)

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